UNIVERSIDADE FEDERAL DO CEARÁ
CENTRO DE CIÊNCIAS AGRÁRIAS
DEPARTAMENTO DE ENGENHARIA AGRÍCOLA
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA AGRÍCOLA

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HYDROLOGICAL SEASONS IN THE BRAZILIAN SEMI-ARID REGION: DATABASE ORGANISATION, SEASONS IDENTIFICATION, AND MODELLING OF RIVER INTERMITTENCE

FORTALEZA
2023

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Orientador: Prof. Dr. Carlos Alexandre Gomes Costa.
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FORTALEZA

2023

Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Sistema de Bibliotecas
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

S655h Soares, Nazaré Suziane.
Hydrological seasons in the Brazilian semi-arid region: : database organisation, identification of hydrological seasons and modelling of river intermittence / Nazaré Suziane Soares. – 2023.
116 f. : il. color.

Tese (doutorado) – Universidade Federal do Ceará, , Fortaleza, 2023.
Orientação: Prof. Dr. Carlos Alexandre Gomes Costa.
Coorientação: Prof. Dr. José Carlos de Araújo.

1. Sazonalidade. 2. Período chuvoso. 3. Rios intermitentes. 4. Caatinga. I. Título.
CDD

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Aprovada em: 18/12/2022.

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AGRADECIMENTOS

To my advisors, Prof. Dr. Carlos Alexandre Gomes Costa and Prof. José Carlos de Araújo for their excellent guidance, company and trust. I acquired much more than a title during this work and I thank you for making this possible.

To Prof. Dr. Pedro Henrique Augusto Medeiros, Dr. Till Francke and Prof. Dr. Axel Bronstert for all the support during the sandwich doctorate.

To the other committee members, Prof. Dr. Antônio Alves Meira Neto and Prof. Dr. Everton Alves Rodrigues Pinheiro for accepting to participate in this defense.

To the committee members in my Qualifying Exam, Prof. Dr. Adunias Teixeira, Prof. Dr. Christine Farias and Prof. Dr. Cristiano Almeida, for the valuable contributions and encouragement.

To my doctoral colleagues, to the other members of HIDROSED, and to the members of HyKli for the reflections, criticisms and suggestions received. The doctorate period was immensely easier with the support of these people.

To the group that helped with data collection in the field, especially Thales Lima, for participating in all campaigns.

To Dona Socorro and Ozana for their support in Aiuaba.

To the Federal University of Ceará, which, through professors, employees and outsourced workers, made this work possible.

To CAPES, for the financial support with the maintenance of the grant. This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001.

To the University of Potsdam for the welcome and support during the sandwich doctorate period. Part of this work was carried out during a grant updated by the PROBRAL International Cooperation Program at the University of Potsdam, funded by CAPES.

To my family who supported and encouraged me immensely. Thank you for believing in me and being part of this process.

"I gave my blood, sweat, and tears for this"

(Taylor Swift)

RESUMO

O período chuvoso é de extrema importância na hidrologia do semiárido brasileiro, devido a atividades biológicas e econômicas, já que uma série de processos hidrológicos podem ser mais bem observados neste período. Devido à alta variabilidade da precipitação na região, o estudo da sazonalidade é um fator essencial para a hidrologia. A intermitência é predominante na maioria dos rios do semiárido brasileiro. Por isso, é evidente a importância do estudo da distribuição de água ao longo do rio principalmente em períodos sem escoamento contínuo. O objetivo deste trabalho é avaliar a variabilidade temporal dos processos hidrológicos, considerando a dinâmica desse sistema na região semiárida brasileira. A área de estudo corresponde à bacia do açude Benguê (1000 km²) e à Bacia Experimental de Aiuaba – BEA (12 km²), aninhada à bacia do Benguê. A tese é composta por três capítulos temáticos: i) Organização e estruturação do banco de dados da BEA; ii) Identificação das estações hidrológicas e análise de duas décadas de monitoramento; e iii) Modelagem da intermitência de rio com dados de drone e modelo *Random Forest*. O primeiro capítulo trata da compilação e sistematização dos dados adquiridos nos últimos 20 anos na BEA (2003 a 2022). Partindo desses dados, desenvolveu-se um método para delimitação das estações hidrológicas na área de estudo com série de dados de precipitação, umidade do solo e resposta espectral da vegetação. No Capítulo III, tem-se o mapeamento e modelagem da intermitência do rio principal (Rio Umbuzeiro) da bacia do Benguê. A organização e catalogação dos dados adquiridos nos últimos 20 anos na BEA foi importante para melhor compreensão hidrológica da região, contribuindo enormemente para o trabalho atual e futuro na região, facilitando a manutenção e o uso do banco de dados. A proposta e aplicação do novo método para identificação de estações hidrológicas permitiu a caracterização das estações no semiárido brasileiro utilizando critérios baseados em precipitação, umidade do solo e vegetação. Concluiu-se que a aplicação do método permitiu o estudo de tendências relacionadas a estações, sendo possível a identificação da tendência de aumento da estação de transição chuvosa-seca. A modelagem da intermitência em rio foi possível com acurácia de cerca de 80% para modelos desenvolvidos no trabalho. A aplicação do modelo a todo o rio permitiu uma avaliação da distribuição espacial e temporal da intermitência fluvial, concluindo que o modelo utilizando imagens Sentinel com o *Modified Normalized Difference Water Index* (MNDWI) teve o melhor desempenho na extrapolação do modelo para todo o rio.

Palavras-chave: sazonalidade; período chuvoso; rios intermitentes; caatinga.

ABSTRACT

The rainy season is extremely important in the hydrology of the Brazilian semi-arid region, due to biological and economic activities, as a series of hydrological processes can be better observed in this period. Due to the high variability of precipitation in the region, the study of seasonality is an essential factor for hydrology. Intermittency is predominant in most rivers in the Brazilian semi-arid region. Hence, the importance of studying water distribution along the river, especially in periods without continuous flow, is evident. The objective of this work is to evaluate the temporal variability of hydrological processes, considering the dynamics of this system in the Brazilian semi-arid region. The study area corresponds to the Benguê reservoir basin (1000 km²) and the Aiuaba Experimental Basin – AEB (12 km²), nested into the Benguê basin. The thesis is composed of three thematic chapters: i) Organisation and structuring of the AEB database; ii) Identification of hydrological stations and analysis of two decades of monitoring; and iii) Modelling river intermittency with drone data and random forest models. The first chapter deals with the compilation and systematisation of data acquired over the last 20 years at AEB (2003 to 2022). Based on data from the database, a method was developed to delimit hydrological seasons in the study area with data series of precipitation, soil moisture and spectral response of vegetation. In Chapter III, there is the mapping and modelling of the intermittency of the main river (Rio Umbuzeiro) of the Benguê basin. The organisation and cataloguing of data acquired over the last 20 years at AEB was important for a better hydrological understanding of the region, contributing enormously to current and future work in the region and facilitating database maintenance and use. The proposal and application of the new method for identifying hydrological stations allowed the characterisation of seasons in the Brazilian semi-arid region using criteria based on precipitation, soil moisture and vegetation. It was concluded that the application of the method allowed the study of trends related to seasons, making it possible to identify the trend towards an increase in the rainy-dry transition season. Modelling river intermittency was possible with an accuracy of around 80% for models developed in the work. The application of the model to the entire river allowed an assessment of the spatial and temporal distribution of river intermittency, concluding that the model using Sentinel images with the Modified Normalised Difference Water Index (MNDWI) had the best performance in extrapolating the model to the entire river.

Keywords: seasonality; rainy season; intermittent rivers; caatinga.

SUMÁRIO

1 GENERAL INTRODUCTION

The rainy season is an extremely important period in the Brazilian semi-arid region, especially from a hydrological point of view, as a range of hydrological processes can be better observed during this period. An example of the relevance of this period is that the largest contribution to the reservoirs occurs, being a source of supply for the population in the following months. Several other terms can be used to refer to the rainy season in Northeast Brazil: rainy or wet season, "winter", water season or green season. A notable feature about this period is the uncertainty and variety about the time interval in which it occurs. This fact is also a motivation for studying this period, since there are issues that remain without consensus.

When does the rainy season start and when does it end? Would it be possible to determine the time interval in which hydrological processes are prominent? In order to find a concrete definition for the time that comprises the rainy season, preliminary studies are of utmost importance, as a combination of factors can be used to better encompass the different characteristics of this process.

The beginning of the present study is based on the analysis, adjustment, compilation and systematisation of the Aiuaba Experimental Basin Database (AEBD) (Chapter I). For hydrological analysis, years of measured, consistent and easy-to-handle data can be necessary. Therefore, the database systematisation study can add value to the analysis of seasonality, so the following chapter benefits from this first one due to better data consistency and the general organisation of data collected there.

In the study of seasonality in the semi-arid climate, one of the main hydrological variables is rainfall, as this is a determining factor in triggering several other processes. However, other variables can be important to observe and analyse the hydrological seasonality in the Brazilian semi-arid region, such as soil moisture and vegetation dynamics. The identification of hydrological seasons is studied in Chapter II, proposing a method to identify the rainy, dry and transition seasons. In addition to analysing seasonality, the study can advance the observation of interannual changes that may occur in each season.

Finally, taking as a basis the seasonality in the Brazilian Semiarid, the presence of water in the riverbed is studied in Chapter III. Analysing the different characteristics and factors that influence this process, UAV-driven data is used to classify water occurrence. Random Forest models were implemented to model river intermittence and to identify the main drivers of this process.

1.1 Scientific questions and hypotheses

The scientific questions will be presented in three blocks according to our three chapters. Firstly, the questions referring to the organisation of a hydrological database:

1. Does a systematisation scheme of folders according to the different data type help a broader comprehension of the database?
2. What steps are necessary to consolidate the database?

For this analysis, it is hypothesised that the organisation of a database helps the use of the data and future update. In the second block, it is discussed the hydrological seasons in the Brazilian semi-arid region:

1. When do the hydrological seasons happen in the Brazilian semi-arid climate?
2. Is it possible to observe trends in different aspects of the hydrological season: duration, amount of precipitation, dates of start and end?

Taking into account these questions, it is hypothesised that hydrological data can be used for the identification of the start and end of hydrological seasons. Finally, in the third block the distribution of water along intermittent rivers is taken into account:

1. Is it possible to model and follow the dynamics of drying and filling of isolated reaches in intermittent rivers?
2. Is topography the main predictor of water accumulation?

In order to investigate the scientific questions, it is hypothesised that it is possible to identify the main drivers of intermittence and to model the dynamics of isolated reaches in intermittent rivers.

1.2 Objectives

Considering the presented questions, the objective of this work is to evaluate the temporal variability of hydrological processes, considering the dynamics of this system in the Brazilian semi-arid region. In in chapter, the objectives are: i) to organise the data acquired over the last 20 years in Aiuaba Experimental Basin (AEB); ii) to establish a method for hydrological seasons partitioning in the semi-arid Caatinga Biome in northeastern Brazil, considering precipitation, soil moisture and vegetation; and iii) to model the spatial and temporal dynamics of water occurrence of an intermittent river in the Brazilian semi-arid region.

2 CHAPTER I - AIUABA EXPERIMENTAL BASIN: DATABASE SYSTEMATISATION AND ORGANISATION

Abstract: A better understanding of the hydrological processes in semi-arid regions depend fundamentally on long-term hydrological monitoring. In addition to a good quality in monitoring, the database must be systematised and organised so that consistent analyses are possible. The objective of this work was to organise the data acquired over the last 20 years in Aiuaba Experimental Basin (AEB), specifically aiming to (i) characterise the types of data that are most relevant and used in the work carried out in the area, and (ii) facilitate the updating of new data, helping to consolidate the Aiuaba Experimental Basin Database. The data processing, reviewing and organising started with the implementation of a new general organisation of the Aiuaba Experimental Basin Database (AEBD). The organisation took into consideration the different variables. Consistency analyses were carried out in most of the variables present in AEBD, when the data units, comments, and general monitoring scheme were checked. For precipitation data, for example, a full consistency analysis was carried out for the multiple rain gauges and afterwards it was possible to perform the filling of missing data for the entire 20-year period of study. Organising and cataloguing of AEBD data was important to better consolidate the work carried out in the experimental basin. Data consistency analyses of most of the variables present in AEBD allowed a better data quality assessment. Not only the analyses were important for database maintenance and use, the documentation of this processing will allow future reference of the entire process.

Keywords: Hydrological monitoring. Consistency analysis. Semi-arid climate. Brazilian semi-arid region.

2.1 Introduction

Understanding the hydrology of semi-arid regions has been a challenge worsened by data scarcity. This understanding fundamentally depends on long-term hydrological monitoring. In general, hydrological monitoring sites in the Southern Hemisphere are rare. According to Fullhart *et al.* (2022), only three sites in Africa and South America of sub-daily precipitation records (5 min) were available for validation within an analysed period of 20 years. One of them was the Aiuaba Experimental Basin (AEB).

The time and effort spent collecting data in the field can be wasted due to the lack of an efficient and robust data processing system (TETZLAFF *et al.*, 2017). Data processing in hydrology refers to the various processing steps. Measurements of hydrological processes carried out in the field are subject to processing before they can be efficiently stored and/or made available for analysis (HUGHES, 2006). Data has value when it is used; only when hydrological data is analysed and used as part of understanding processes or water management planning does it become truly valuable (STEWART, 2014). Good quality long-term records are necessary to quantify the seasonal and inter-annual average and variability of any hydrological variable (XU; CHEN, 2018). Therefore, the hydrological data processing activity represents the essential interface between data collection and use.

Storing measurements of hydrological processes is an important step in hydrological data processing and can be done in databases. A database can be described simply as a filing system for electronic data (WMO, 2008). Any organised assembly of digital data is, in effect, a database. Most importantly, a database system is purely a means of storing digital data. Good file management can only be achieved with good data management (TETZLAFF *et al.*, 2014).

A very important consideration within the field of hydrological data management is which of the various data sets produced should be stored, as each of the many stages in the data management process generates one or more distinct data sets (WMO, 2008) . If all possible permutations of data were stored in this process, the result would be a confusing and cumbersome file. At the other extreme, if a hydrological archive existed only as a static data set of processed and validated data, there would be no way to understand how the data was derived or measured, or the potential limitations of the final data set. Therefore, it is necessary to decide on a data storage mechanism that meets the needs and requirements of data users.

A well-established and well-managed hydrological archive should consolidate the work put into data collection and provide high-quality and reliable data, encompassing the different processes studied and the different types of data obtained (HORSBURGH *et al.*, 2016). A lack of forethought in database foundation or poor management can lead to years of excessive data collection or modelling work and subsequently poor decision making (TETZLAFF *et al.*, 2017).

The objective of this work was to organise the data acquired over the last 20 years in Aiuaba Experimental Basin (AEB), specifically aiming to (i) characterise the types of data that are most relevant and used in the work carried out in the area; (ii) perform consistency analyses on available variables, such as precipitation; and (iii) facilitate the updating of new data, helping to consolidate the Aiuaba Experimental Basin Database.

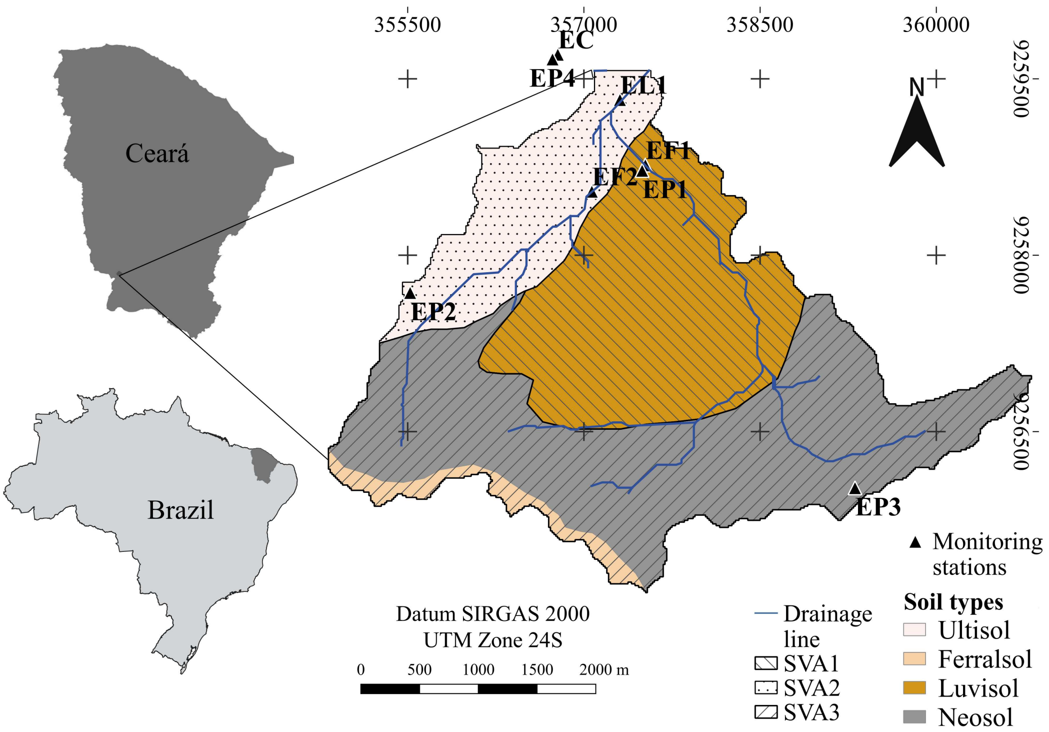
2.2 Aiuaba Experimental Basin (AEB)

The Aiuaba experimental basin (AEB) is nested into the Benguê catchment and has an area of approximately 12 km^2 (Figure 1). The basin is a preserved area and is entirely covered with dense caatinga-arboreal forest, being controlled by the Boqueirão reservoir (60 hm^3) at its outlet. Located within the Aiuaba Ecological Station (Aiuaba ESEC), it is the largest federal conservation unit in the Caatinga biome managed by IBAMA (DE ARAÚJO; PIEDRA, 2009). Thus, this area plays an important role in the region's hydrological cycle, mainly due to its dense forest cover, being associated with the maintenance of florist and faunal biodiversity in the Caatinga biome (ALMEIDA *et al.*, 2019). From the perspective of hydrological studies carried out at river basin scales in preserved areas, it is common to adopt the main association between soil and vegetation in order to better represent spatial variability. In AEB, soil-vegetation associations (SVA) were adopted, which are relatively homogeneous units for studies of environmental variables (COSTA *et al.*, 2013; PINHEIRO *et al.*, 2013).

The climate of AEB is semi-arid tropical, "Bs" according to the Köppen classification, with average annual precipitation of 549 mm, average annual potential evaporation of 2600 mm and aridity coefficient of 0.26 (Class A evaporation pan) (DE ARAÚJO; PIEDRA, 2009; MEDEIROS *et al.*, 2014). The region's rainfall regime presents high intra- and interannual variability with precipitation mainly convective and concentrated in a few high-intensity events (FIGUEIREDO *et al.*, 2016; MEDEIROS *et al.*, 2009). The region's rainfall characteristics mainly produce surface runoff of the Hortonian type, in which the intensity of the rain exceeds the infiltration capacity of the soil (MEDEIROS *et al.*, 2010).

AEB has been monitored by the Hydrosedimentological Research Group in the

Figure 1 – Monitoring stations in the Aiuaba Experimental Basin (AEB), with river gauges (EF1 and EF2), rain gauges (EP1, EP2, EP3 and EP4), water level station (EL1), and climatic station (EC). SVA correspond to the Soil-Vegetation Associations.



Semiarid (HIDROSED) since its implementation in Jan 2003, as part of the FINEP/IBESA project, with the main objective of measuring hydrological variables in the Brazilian semi-arid region (COSTA, 2012). Studies carried out in the area include the analysis of hydrological processes such as precipitation (MEDEIROS; DE ARAÚJO, 2014; DE ARAÚJO; PIEDRA, 2009; RODRIGUES; DE ARAÚJO, 2019; BARBOSA *et al.*, 2018), evapotranspiration (COSTA *et al.*, 2021; SOARES, 2019; TEIXEIRA, 2018), evaporation (COSTA, 2007), transpiration (FIGUEIREDO, 2018), intercept (MEDEIROS *et al.*, 2009), soil-plant-atmosphere relationship (ALMEIDA *et al.*, 2019; PINHEIRO *et al.*, 2016; PINHEIRO *et al.*, 2017) and surface runoff (FIGUEIREDO *et al.*, 2016), as well as sedimentological studies (ARAÚJO, 2012; FARIAS *et al.*, 2019) and hydrogeological studies (COSTA *et al.*, 2013). Table 1 shows the works carried out in AEB and the data used by them.

The data collected by the Hydrosedimentological Research Group in the Semiarid (HIDROSED) in the AEB primarily forms the AEBD. Measurements of climatic, hydrological and sediment production variables have been carried out since 2003 at different points in the basin. Monitoring at AEB occurs mainly with the use of rain gauge stations: EP1, EP2 and EP3 (until 2009), which record precipitation data every 5 minutes, 1 hour and 6 hours. Furthermore,

Table 1 – Work carried out in the Aiuaba Experimental Basin (AEB) by the Hydrosedimentological Research Group in the Semiarid (HIDROSED)

Citation of works	Topics studied	Data used
Costa (2007)	Main hydrological processes	Precipitation, reservoir level, runoff, evaporation
De Araújo and Piedra (2009)	Comparative hydrology	Precipitation, reservoir level, runoff
Medeiros *et al.* (2009)	Calculation of interception	Precipitation
Araújo (2012)	Siltation estimate	Soils, sediments, use and occupation
Costa *et al.* (2013)	Soil moisture in the root zone	Soil moisture, soil type, meteorological data, topography
Pinheiro *et al.* (2013)	Effective root depth	Soil type
Medeiros and de Araújo (2014)	Temporal variability of rain	Precipitation, reservoir level, sediment
Carvalho *et al.* (2016)	Relationship between NDVI and Leaf area index (LAI)	LAI, Landsat images
Figueiredo *et al.* (2016)	Runoff initiation	Precipitation, soil moisture
Pinheiro *et al.* (2016)	Modeling soil-water-plant relationship	Soil moisture, soil type, meteorological data, topography
Pinheiro *et al.* (2017)	Climate change scenarios	Precipitation
Lourenço *et al.* (2017)	Separation of soil classes with sensor	Use of sensor close to the soil
Pinheiro *et al.* (2018)	Water availability for plants	Soil moisture, soil type, meteorological data, topography
Teixeira (2018)	Evapotranspiration and water balance	Rapideye images, precipitation, soil moisture, meteorological data
Barbosa *et al.* (2018)	Sub-hourly precipitation pattern	
Almeida *et al.* (2019)	Relationship between LAI and spectral and hydrological variables	Leaf area index, Landsat images, soil moisture, precipitation, evapotranspiration
Rodrigues and de Araújo (2019)	IDF Curves	Precipitation
Morais (2019)	Vegetation succession	Phytosociological survey
Soares (2019)	Modelled evapotranspiration	Soil moisture, soil type, meteorological data, topography
Farias *et al.* (2019)	Unpaved rural roads as a source of sediment	Precipitation, erosion
Tilesse *et al.* (2021)	Water storage potential in plants	Phytosociological survey, turgidity of trunks
Costa *et al.* (2021)	Actual evapotranspiration from satellite images	Climatological data and Landsat images
Fullhart *et al.* (2022)	Climate parameterization	Precipitation
Fullhart *et al.* (2023)	Precipitation extremes	Precipitation
Costa *et al.* (2023)	Water storage	Climatological data and in situ measurements

hourly soil moisture is captured by a TDR sensor (Time Domain Reflectometry) installed in the 0 – 20 cm layer of the soil, a layer in which around 50% of the root mass (PINHEIRO *et al.*, 2013) are present. Figure 1 shows the location of all stations, and Table 2 presents the list of stations in operation, in addition to the monitored variables and measurement intervals.

Table 2 – Monitoring stations operated by the HIDROSED Research Group in Aiuaba Experimental Basin (AEB), Ceará

Station	Location	Instrument	Variable	Measurement interval	Observation period
EP1	SVA1*	Rain Gauge	Rain	5 min	Since 2003
		TDR	Soil moisture	1 hour	Since 2003
		Class A evaporation pan	Evaporation	1 hour	2003 to 2006
		Sap Flow Sensor	Transpiration	1 hour	2016 to 2018
		Stem Moisture Sensor			
		Stem Moisture Sensor soil			
		Soil temperature sensor			
		Anemometer			
		Thermo-hygrometer	Actual evapotranspiration	10 min	Since 2021
		Radiation sensor			
		Canopy temperature sensor			
		Weighing lysimeter			
EP2	SVA2	Rain Gauge	Rain	5 min	Since 2003
		TDR	Soil moisture	1 hour	Since 2003
EP3	SVA3	Rain gauge	Rain	5 min	2003 to 2010
		TDR	Soil moisture	1 hour	2003 to 2010
EP4	Next to the experimental basin	Rain gauge	Rain	5 min	2004 to 2005
		TDR	Soil moisture	1 hour	2004 to 2005
		Class A evaporation pan	Evaporation	1 day	Since 2003
		Automatic sensor	Water level	15 min	2003 - 2017
EP5	Near the experimental basin		Rain	1 hour	Since 2021
			Temperature	1 hour	
			Relative air humidity	1 hour	
			Wind speed	1 hour	
			Solar radiation	1 hour	
EL1	Boqueirão Reservoir	Linimetric ruler	Water level	1 day	Since 2003
		Automatic sensor	Water level	15 min	2003 - 2017
EF1	Riacho Boqueirão	Calha Parshall	Streamflow	30 min	2003 to 2013
EF2	Secondary stream	Triangular section	Flow	30 min	2007 to 2010

*SVA: Soil-Vegetation Associations

Table 2 – Monitoring stations operated by the HIDROSED Research Group in Aiuaba Experimental Basin (AEB), Ceará (continued)

Station	**Location**	**Instrument**	**Variable**	**Measurement interval**	**Observation period**
EC1	AIUABA ESEC Headquarters		Rain	1 hour	2005 to 2008
			Temperature	1 hour	
			Relative air humidity	1 hour	
			Wind speed	1 hour	
			Wind direction	1 hour	
			Atmospheric pressure	1 hour	
			Shortwave radiation	1 hour	

2.3 Aiuaba Experimental Basin Database

The Aiuaba Experimental Basin Database (AEBD) consolidates and organises the data present in the AEB. The document presented in Appendix A consists of a description of the structure and organisation of data in the database. It also contains all the information to instruct the use of the data present in the AEBD with references to works that may be useful or that initiated the collection of a certain data. Unfortunately, the document is only available in Portuguese, so here we give an overview of its most important aspects.

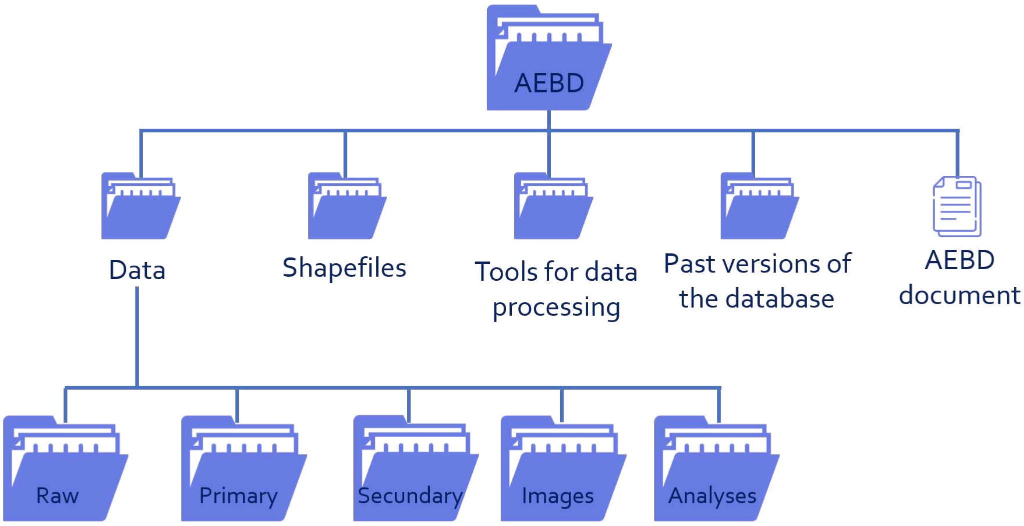
The data collected at AEB by the HIDROSED group and secondary data collected in the vicinity of the basin were structured over the years in a single file, organised in Microsoft Access (.accbd), which was updated by several members of the group. In this file, the data is organised into several tables, according to the type of data measured and/or the location of the station. However, other data has accumulated over the years, such as remote sensing images or processed rainfall data. The size of the files and the wide variety of data made the organisation and compilation of this material difficult.

In this context, a new data organisation proposal was created to incorporate different aspects of the database (Figure 2). In the new proposal, the data is organised in different folders and sub-folders along with the file with instructions and general information about the database (Appendix A). In general, the database structure consists of four directories, namely: Data, Tools for data processing, Shapefiles, and Past versions of the database. "Data"contains the main database information such as raw data, primary data from continuous and one-time measurements, secondary data, processed data (product of papers or thesis), as well as remote sensing images. The “Tools for data processing” folder consists of a place to insert files used to organise the database and instructions for collecting data from dataloggers installed in the field, for example. In “Shapefiles”, the various files relating to georeferenced information are presented. The past versions of this database are allocated in the last folder.

2.3.1 Data overview

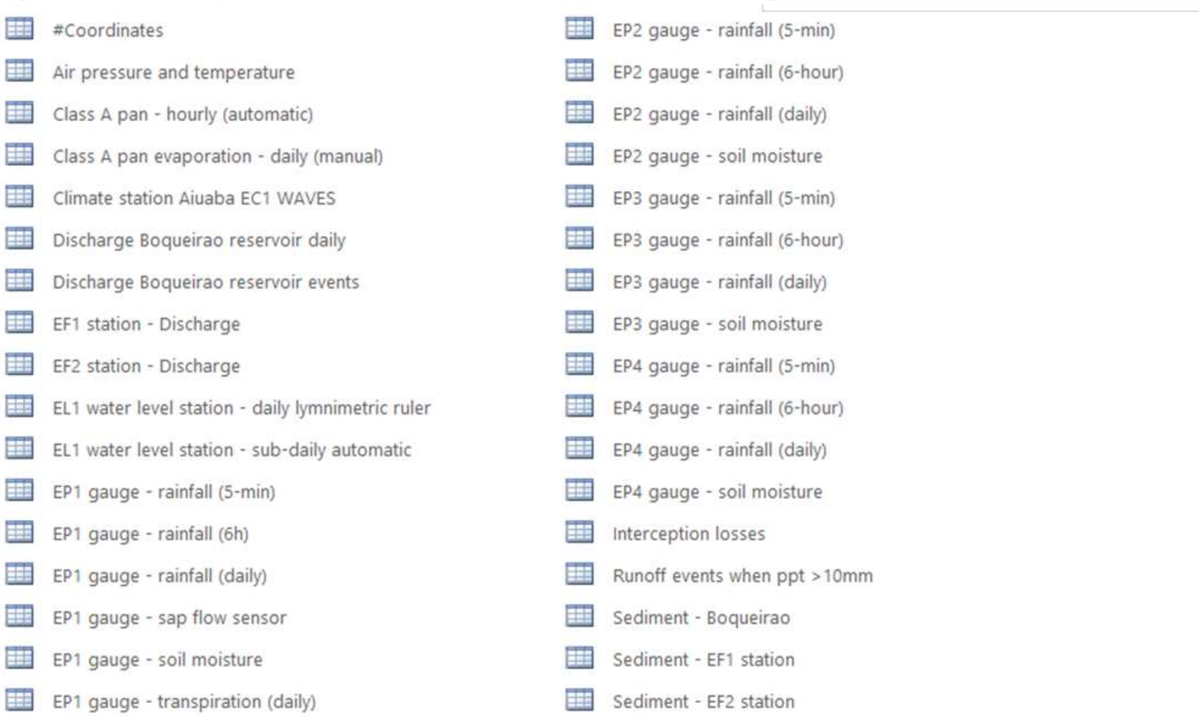
When data is collected in one of the field campaigns, it is first stored in the folder "Raw data", identified by the campaigns’ date and put together with any other documents collected in the occasion (reports, photos etc.). Data is then processed with the "Tools for data processing"that contains tables to facilitate organisation. Afterwards, data is stored in the

Figure 2 – General scheme of the organisation of the Aiuaba Experimental Basin Database (AEBD)



"Primary data"folder according to the type of data. This way, data collected at AEB by the HIDROSED group over the years of monitoring are mainly present in this section. Figure 3 shows the how the tables of the continuous primary data is presented in the database.

Figure 3 – Primary data collected continuously in Aiauba Experimental Basin (AEB)



The different variables are: rainfall (5-min, 6-hour, daily), soil moisture (1-hour average), reservoir water level, runoff events, sediment assessment, interception losses, meteorological data, evaporation, and transpiration. The references, units, sensors and general information about each of data type is detailed in Appendix A, with some information also in the table notes.

Secondary data refers to data from stations surrounding AEB. It was included active stations under monitoring by the government agencies FUNCEME (http://funceme.br/app-calendario/postos) and INMET (https://portal.inmet.gov.br/paginas/catalogoaut). These data have been useful for several hydrological studies including modelling (MAMEDE *et al.*, 2018; LIMA *et al.*, 2022) and assessments of specific processes, such as evapotranspiration (TEIXEIRA, 2018).

The remote sensing images are sorted by type of satellite or means by which they were obtained. More information about the images is in the metadata files in each sub-folder. Other important data stored here are the images and processing results of flights carried out with the DJI Phantom 4 pro and SenseFly eBee SQ drones with Sequoia Parrot+ camera.

The data present in the "Analyses"folder was obtained through the processing of primary or secondary data. An example is a group of variables related to the leaf area index (LAI), used in the work of Almeida *et al.* (2019) and details on how the data was obtained can be found in that work and in Carvalho *et al.* (2016).

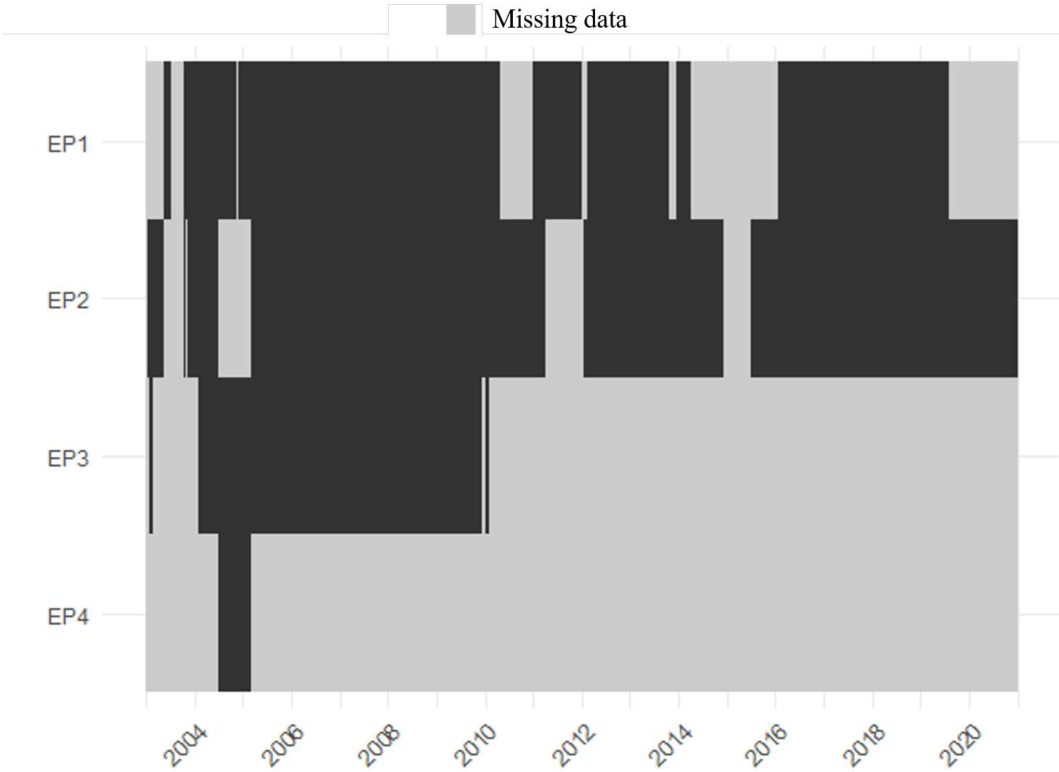
2.3.2 Data consistency analysis

In order to assure good data quality, some measures were taken to help verify and improve data consistency. The analysis consisted of unity check and correction (soil moisture and climate station data), removal of outliers due to errors in measurement (evaporation), and missing data verification and interpolation when suited (Boqueirão water level and evaporation).

These analyses were extensive and required a review of the entire database of each of these variables. For soil moisture data, for example, a consistency analysis was required to review periods when the measurements were stored in the database with the wrong unit. In addition, some periods the wrong equation was used for data conversion. For the Boqueirão water level, a review of all the comments was necessary to compute if a given missing period was due to lack of measurements or to empty reservoir. The reviewing process is detailed in Appendix A.

For precipitation data, three analyses were performed: (i) consistency analysis to check extreme values; (ii) comparison among the three rainfall gauges (EP1, EP2, and EP3); (iii) Filling of missing data. In AEB, three main stations (EP1, EP2 and EP3) were installed in 2003 with TB4 devices (Tipping Bucket rainfall gauge), which take readings every minute and store the sum of 5 minutes. In Figure 4, we see the present/missing data pattern for the three main stations and EP4, which was a temporary rainfall gauge.

Figure 4 – Missing data on daily precipitation measurements present in the AEBD



i. Consistency analysis to check extreme values

Precipitation data consistency analysis took into account precipitation at rain gauge stations within AEB. Auxiliary data obtained from rainfall stations around AEB were considered along with soil moisture measurements on site. Firstly, soil moisture was investigated when the equipment showed extreme measurements in months that generally do not occur significant precipitation (July to December). When there was no significant increase in soil moisture concomitant with the recorded events, other stations in the region were consulted. If the soil moisture result corroborates the absence of any precipitation record in the region, the data from the evaluated station were discarded. This process was especially important when there was an interference in measurements during the dry season of 2019.

ii. Comparison among the three rainfall gauges (EP1, EP2, and EP3)

A comparative analysis was carried out between the stations. Due to the great difference in the availability of data from the three rainfall stations, this analysis is important to decide whether or not we could use just one of the stations in order to facilitate filling in the missing data and have a more complete time series. For this, a period without failures was defined in the three stations (03/06/2005 to 02/25/2009), as seen in Figure 4. It is important to note that this period represented years that did not have excessively high or low precipitation, making it an interesting period to analyse and is possibly more representative.

An analysis of variance (ANOVA) was carried out in order to identify more precisely how the points differ in relation to the spatial resolution of the data. To do this, the moving average and accumulated precipitation in recent days were taken into account. The analysis was carried out with the sum and moving average of daily precipitation, the analysis was implemented with a variable number of days (2 to 365 days). Thus, both daily precipitation assessments can be analysed, as well as the accumulated and average precipitation in a year.

Analysing the difference between the stations during the period in which the three were operating, it was observed that at a significance level of 5% there was a difference only in the daily precipitation data ($p = 0.025$). The values were the same for both accumulated precipitation and the moving average. The accumulated precipitation over two, three and four days has a probability value that ranged from 0.0530 to 0.0536. The highest p-value was observed in the sum of 154 to 156 days in which the value was above 0.46.

iii. Filling of missing data

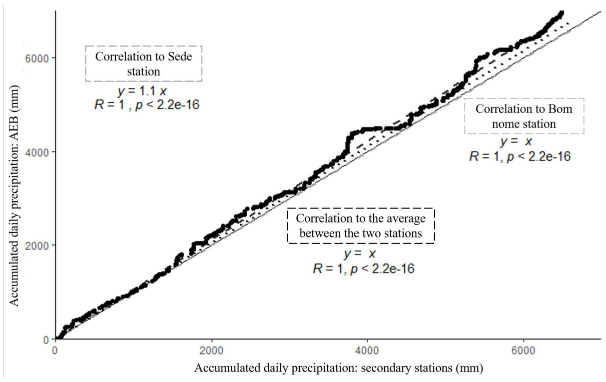
In order to be able to generate a complete data series, EP2 was taken as a basis, as it is the station with the lowest percentage of missing data. Based on the analysis that confirmed high similarity between the rainfall stations, data from other stations located in AEB were used, filling them directly. During the period from 2004 to 2005 EP2 was far from the original point and the data was stored as EP4. For periods with data in EP1, these were used for completion.

For periods that continued with failures, secondary data from surrounding stations were used in the consistency analysis of the historical series, which was obtained through the Double Mass Method developed by the United States Geological Survey (SEARCY; HARDISON, 1960), as explored by Villela and Mattos. Location and availability of data for surrounding stations can be checked in FUNCEME's website (http://funceme.br/app-calendario/postos). Cumulative data from two stations with fewer missing data percentage and the mean between them was used in the analysis. The secondary data was compared to EP2 cumulative data. It was selected data from the same period of available data in EP2.

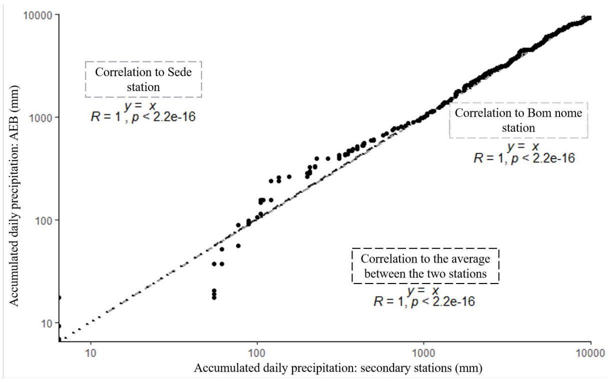
Figure 5 shows the analysis on a daily scale on the standard scale (Figure 5a) and on the logarithmic scale (Figure 5b). In addition, annual data are also analysed (Figure 5c). The analysis showed a high correlation among the stations. AEB values were considered equal to those of the Bom Nome station and the average between the two stations in the daily analyses. The Sede station showed precipitation around 10% higher when using values in standard scale and equal to the AEB precipitation when using values on a logarithmic scale. The annual analysis showed a slight slope in the regression lines corresponding to the data from the Bom Nome station and the average between the stations considered.

Figure 5 – Precipitation between the years 2003 and 2020 showing the relationship between Aiuaba Experimental Basin (AEB) and two rainfall stations located close to the basin (Sede and Bom Nome stations) and the average between the two stations

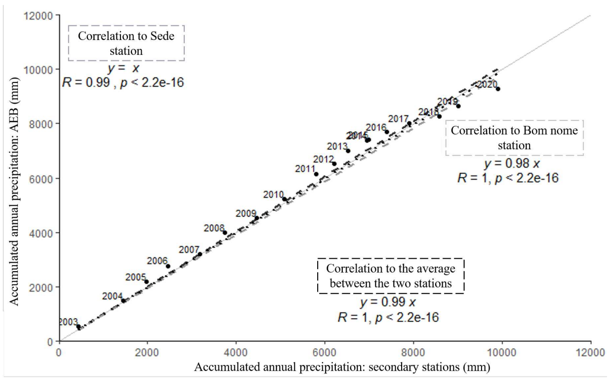
(a) Accumulated daily precipitation



(b) Accumulated daily precipitation: log scale

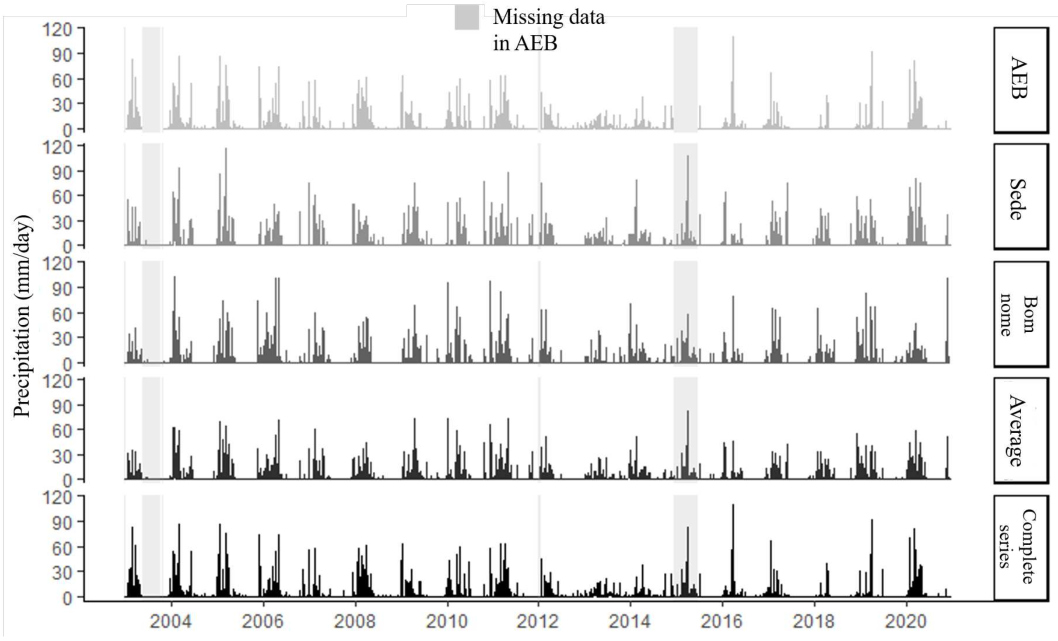


(c) Accumulated annual precipitation



Based on double-mass analysis, gaps in the AEB history series were filled in with daily average data between the stations at the municipal headquarters and Bom Nome (Figure 6). It is observed that the seasonal pattern is similar in all stations analysed, as well as the marking of extreme events. The biggest differences are found in the concentration of precipitation during the rainy season, as it can be more concentrated in time, as in the municipal headquarters, or more distributed, as in the AEB and Bom Nome stations.

Figure 6 – Temporal distribution of precipitation in the Aiuaba Experimental Basin (AEB), the rainfall stations considered in the double mass analysis (Sede, Bom Nome, and the average between the two stations), and the complete series with the data filled in highlighted for periods of missing in AEB



2.4 Conclusion

The organisation and cataloguing of data acquired over the last 20 years in Aiuaba Experimental Basin (AEB) was important to better consolidate the work carried out in the experimental basin. This way, it is possible to preserve data acquired in the high-density monitoring scheme in preserved Caatinga conditions in AEB.

Data consistency analyses of most of the variables present in AEBD permitted a better data quality assessment. Not only the analyses were important for database maintenance and use, the documentation of this processing will allow future reference of the entire process.

Analysing data consistency in precipitation data, it is clear that the greatest importance of high monitoring density in the region would not be to observe variability between stations, but on the contrary, to use the similarity between them (attested by the comparison analysis between stations) to fill in data and obtain longer series with fewer interruptions.

The new data organisation proposal presents challenges due to the different types of data handled, but it can contribute a lot to current and future work developed in the region. This documentation will be useful for future users of the database, but also for current and continuous work, facilitating the updating of new data collected every campaign.

3 CHAPTER II - METHOD FOR IDENTIFICATION OF HYDROLOGICAL SEASONS IN THE SEMI-ARID CAATINGA BIOME[1]

Abstract: Semi-arid regions are strongly dependent on the rainfall regime. Yet, season identification is still ambiguous and lacks clear definition regarding which variables and criteria to be used. The objective of this work is to establish a method for hydrological season partitioning in the semi-arid Caatinga Biome in northeastern Brazil considering precipitation, soil moisture and vegetation. The following four periods were employed for this purpose: i) dry-rainy transition, ii) rainy, iii) rainy-dry transition and iv) dry season. The method was applied to the Aiuaba Experimental Basin (AEB) from 2003 to 2022. We observed a large interannual variability in the duration of seasons and a tendency of the rainy-dry transition season to increase, facts which may indicate changes in the hydrological regime of the region. This novel combination of precipitation, soil moisture, and vegetation data for identification of hydrological seasons within the Caatinga Biome allows a detailed hydrological seasonal behaviour analysis.

Keywords: Seasonality. Climate change. Rainfall. Soil moisture. Vegetation dynamics

[1] SOARES, N. S.; COSTA, C. A. G.; LIMA, J. B. C. DE; FRANCKE, T.; DE ARAÚJO, J. C. Method for identification of hydrological seasons in the semi-arid Caatinga Biome, Brazil. **Hydrological Sciences Journal**, accepted for publication after minor revision in November 2023.

3.1 Introduction

Drylands are strongly affected by the spatio-temporal variability of precipitation, which makes them susceptible to hydrological extremes (DE ARAÚJO; BRONSTERT, 2016). The Brazilian semi-arid region, as well as other drylands in the world, presents a water deficit associated with high evapotranspiration fluxes and low precipitation. Climate, soil, and vegetation characteristics result in the intermittence of most rivers and generate a strong dependence on the rainfall regime (MESSAGER *et al.*, 2021; NASCIMENTO *et al.*, 2019; PEREIRA *et al.*, 2019; ZHANG *et al.*, 2018).

The climate in the Brazilian semi-arid region, which encompasses the Caatinga Biome, does not vary significantly with the classical seasons (Summer, Autumn, Winter, Spring) due to its proximity to the Equator: Hydrologic seasonal variation is rather marked by intense, concentrated rainfall, long dry periods and transitional phases.

In general, the precipitation patterns characterising the rainy season are driven by global circulation, such as the Intertropical Convergence Zone (MARENGO; BERNASCONI, 2015); it strongly influences precipitation, which is usually concentrated in a few months and distributed in condensed short-term events (BARBOSA *et al.*, 2018; BRASIL *et al.*, 2018). During the rainy season, soil water availability and rainfall are the primary limiting factors for the growth of above-ground biomass of the deciduous Caatinga vegetation (SOUZA *et al.*, 2019).

The dry season is characterised by little rainfall with high potential evapotranspiration rates (MEDEIROS; DE ARAÚJO, 2014). Changes between rainy and dry seasons are usually considered to happen in transitional periods due to gradual changes in hydrological processes. These transition seasons can also be absent in some years that present an acute beginning and/or end of rainfall (SPARACINO *et al.*, 2021). Thus, a hydrologically relevant season partitioning should make it possible to define annual rainy and dry seasons, as well as their transition seasons.

The study of seasonality can help the identification of recurrence patterns or trends thereof, and contribute to indicating climate change. According to the most recent Intergovernmental Panel on Climate Change report (IPCC, 2021), there may be a substantial increase in temperature, accentuation of aridity, reduction in precipitation and the occurrence of longer dry periods, which may accentuate the water scarcity problem in the Brazilian semi-arid region and require even more knowledge of the region's seasonality (PILZ *et al.*, 2019; PINHEIRO *et al.*, 2017).

Season identification is still not clear or unanimous in several parts of the world

(ADANE *et al.*, 2020; MARENGO *et al.*, 2001; MUPANGWA *et al.*, 2011; SALACK *et al.*, 2016). Apart from determining the onset of rainy season, previous works also considered the relationship between dry spells and season partitioning. The presence of a dry spell following the start of the rainy season can be evidence of a false start (BENOIT, 1977; BANNAYAN *et al.*, 2011; MUPANGWA *et al.*, 2011; SALACK *et al.*, 2016). Therefore, dry spells were either considered when having started immediately after the rainfall event (BENOIT, 1977; SALACK *et al.*, 2013) or within a time window following the event (MUPANGWA *et al.*, 2011; SALACK *et al.*, 2016; SIVAKUMAR, 1992).

Reliable and hydrologically justified criteria to identify the beginning and end of seasons are usually not available, especially in data-scarce regions. Most methods rely only on rainfall data to separate seasons (AMEKUDZI *et al.*, 2015; GÜNTNER, 2002; MARQUES *et al.*, 2020; SPARACINO *et al.*, 2021). While precipitation is the primary and immediate driver for the rainy season, we can look at other processes that respond to precipitation. The combination of other variables, such as soil moisture and vegetation state allows a wider coverage of the seasonality of hydrological processes. Considering soil moisture dynamics, an intermediate response to precipitation can be evaluated. Soil moisture, in turn, triggers phenological responses in vegetation, which can be somewhat delayed; as they take longer to happen, this response becomes more stable and less sensitive to short-term rainfall dynamics.

Some attempts have already been made to capture seasonal changes in the Caatinga Biome (BRASIL *et al.*, 2022; MARQUES *et al.*, 2020; SPARACINO *et al.*, 2021), but most studies still consider fixed dates for annual seasonality (BRASIL *et al.*, 2018; COSTA *et al.*, 2021; MEDEIROS; DE ARAÚJO, 2014). Marques *et al.* (2020) reckoned with some variability in season identification based on daily accumulated rainfall while studying evapotranspiration. Sparacino *et al.* (2021) performed a characterization of rainy and dry seasons in the Brazilian Semiarid and used an anomalous rainfall accumulation to separate the seasons. Although these attempts captured seasonality, we are proposing for the first time the combination of multiple hydrological criteria in a single method to determine seasonality in the Brazilian Semiarid. Traditionally, past methodologies have relied solely on precipitation data, yet the precipitation-only approach exhibits constraints within the semi-arid Caatinga Biome, where soil moisture and vegetation also effectively define hydrological seasons.

The objective of this research is to propose a method for a hydrologically founded annual seasonal partitioning (rainy, dry and transition seasons), considering precipitation, soil moisture and vegetation as proxy. The method, which is useful to analyse precipitation-driven processes, dry spell-driven processes, and intra-annual climate change patterns was then applied to a dataset from the dryland Caatinga Biome in northeastern Brazil, so as to identify potential climate changes during the past two decades.

3.2 Study area and data sources

The Caatinga is a dry forest also recognized as a biome, it encompasses 18% ($\approx 10^6$ km^2) of the total Brazilian territory and supplies water to nine federal states (MARENGO; BERNASCONI, 2015). The region is one of the most populated dry forests worldwide with averages of 20 - 30 inhabitants km^2 (SILVA *et al.*, 2017). Despite its importance, the Caatinga Biome is a data-scarce region and this fact makes it difficult to understand some of its hydrological processes (ALMEIDA *et al.*, 2019; COSTA *et al.*, 2021; TILESSE *et al.*, 2021).

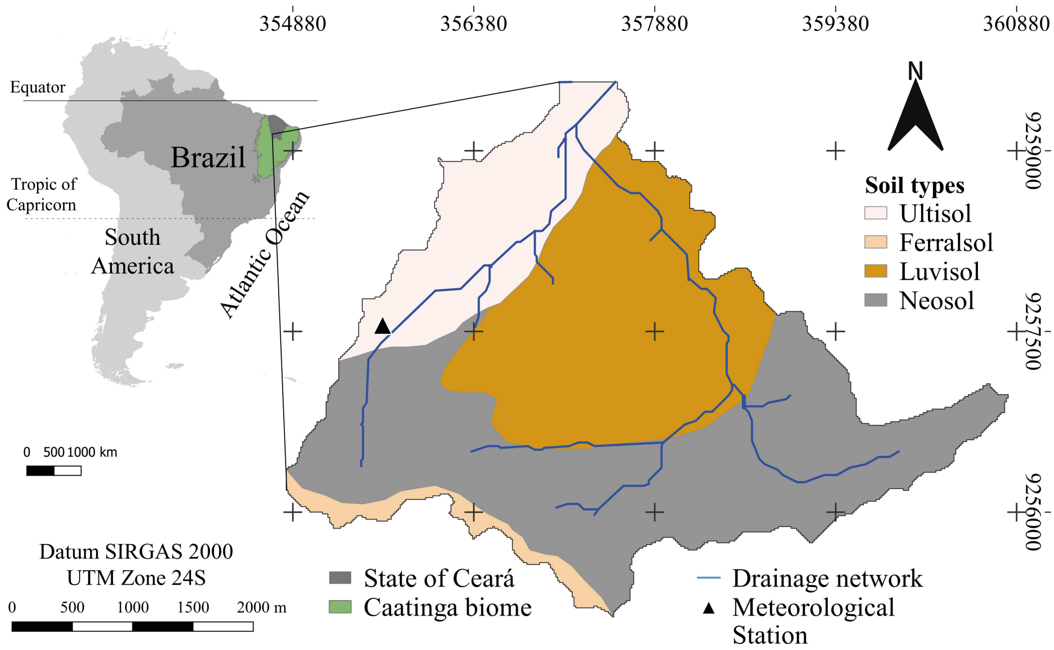
The Caatinga vegetation is characterised by both herbaceous and arborescent plants that are typically deciduous (ALMEIDA *et al.*, 2019; PINHEIRO *et al.*, 2013). The native vegetation in this biome has morphological, anatomical and ecophysiological traits which confer drought tolerance (SANTOS *et al.*, 2014). In general, the aspect of Caatinga vegetation is a patchy mixture of trees, bushes and cacti forming a woody vegetation with discontinuous canopy and varying height and density (SANTOS *et al.*, 2012).

The climate is predominantly semi-arid with average precipitation below 700 mm year^{-1} and potential evapotranspiration above 2200 mm year^{-1} (PINHEIRO *et al.*, 2016). The region is affected by recurrent drought episodes (DE ARAÚJO; BRONSTERT, 2016). The soils are frequently characterised as shallow with crystalline bedrock (DE ARAÚJO; PIEDRA, 2009).

The present study was conducted at the Aiuaba Experimental Basin (AEB; 12 km^2; Figure 7), located in a preserved area fully covered by a dense dry tropical arboreal Caatinga forest. AEB has three rainfall stations coupled with soil moisture sensors, two river flow gauges and also contains the so-called Boqueirão reservoir (60 10^3 m^3) which is located at its outlet. AEB has been monitored by the Hydrosedimentological Research Group of the Semiarid (HIDROSED) since Jan 2003 (ALMEIDA *et al.*, 2019; COSTA *et al.*, 2013; FIGUEIREDO *et al.*, 2016; PINHEIRO *et al.*, 2016).

The choice of this study area is justified by its high preservation status and the fact that its hydrological variables are continuously monitored. Although the experimental basin is relatively small and may not represent the entire heterogeneity of Caatinga, it is a naturally preserved area, under the auspices of the Brazilian government since 1978 (ALMEIDA *et al.*, 2019). Since we are considering changes in vegetation as a proxy in our method, it is important that those changes happen in a preserved area that can better represent the natural condition of Caatinga vegetation without being affected by human use.

Figure 7 – Location of the Caatinga Biome and the Aiuaba Experimental Basin (AEB), Brazil



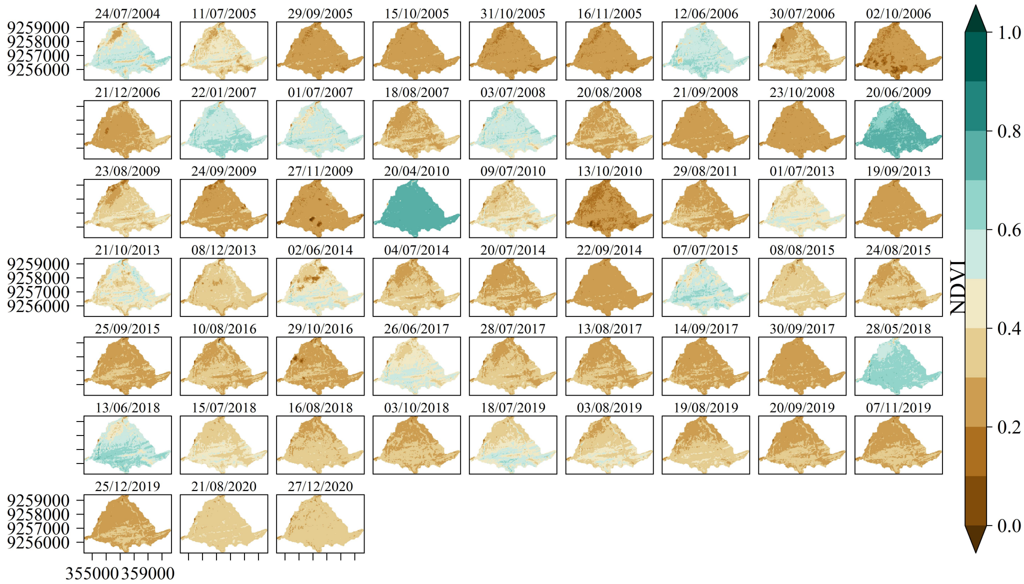
The analysed period is from Jan 2003 to Dec 2022. Rainfall data are recorded at 5-minute intervals with a tipping bucket rainfall gauge (TB4, Campbell Scientific, US) and a resolution of 0.125 mm. For more information on the rainfall dataset consistency, consult Fullhart *et al.* (2022), Fullhart *et al.* (2023). Soil moisture is measured as an average in the 0 – 20 cm soil layer (COSTA *et al.*, 2013), recorded hourly and measured by a Time Domain Reflectometry sensor (CS616 Water Content Reflectometer, Campbell Scientific, US). For more information about the measurements and details on unit conversion, please refer to Costa *et al.* (2013).

Actual evapotranspiration data is calculated through measurements of canopy temperature, global solar radiation, air temperature, air humidity and wind speed with sensors installed above the plant canopy. For detailed information on methods and sensors refer to de Araújo *et al.* (2022) and Araújo (2022), respectively.

Vegetation data were acquired from satellite images to assess values of NDVI (Normalised Difference Vegetation Index) during 2003 - 2020, the period of data availability. Landsat 5 (TM) images were used for the years 2003 to 2011 and Landsat 8 (OLI) from 2013 to 2020 (Figure 8). Landsat images have a spatial and temporal resolution of roughly 30 m and

16 days, respectively. Annually, the Landsat project collects approximately 23 images of the region of the AEB. In the 18 years of analysis, 329 images were collected, of which only 57 yielded representative information about AEB (e.g., no clouds), representing 17.3% of the total imagery. Almeida *et al.* (2019) associated NDVI with leaf area index (LAI) in AEB and this correlation is also used in our work.

Figure 8 – NDVI values for the Aiuaba Experimental Basin (AEB, 12 km²) from 2003 to 2020



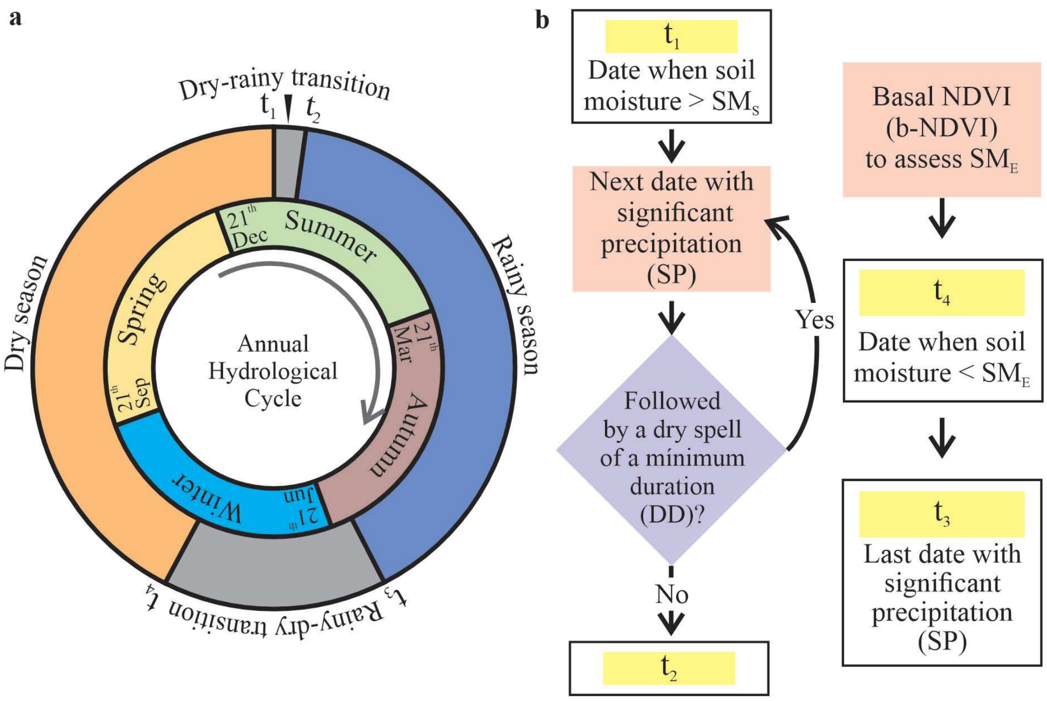
3.3 Method for Identification of Seasonality in Drylands – MISD

Figure 9 presents the flowchart of the proposed Method for Identification of Seasonality in Drylands (MISD). In Figure 9a, we depict the annual hydrological cycle with four key dates: (t_1) start of the dry-rainy transition season; (t_2) start of the rainy season; (t_3) start of the rainy-dry transition season; (t_4) start of the dry season. For comparison, Figure 9 also presents the classical seasons and their respective beginning dates in the Southern Hemisphere.

Figure 9b depicts the methodological steps to identify the beginning of each season using MISD. Date t_1, which corresponds to the beginning of the dry-rainy transition season, is the date when soil moisture rises to a threshold value (SM_S). Since soil moisture is at its minimum during the dry season, SM_S is a threshold value that indicates that the processes related to the rainy season (frequent rainfall events and leaf development) start to prevail.

Date t_2 corresponds to the beginning of the raining season eliminating false starts, which are isolated precipitation events followed by dry spells, i.e. consecutive days with no

Figure 9 – Concept of the MISD – Method for Identification of Seasonality in Drylands: (a) Annual hydrological cycle for Brazilian Northeast; and (b) Methodological steps



t_1: Date when soil moisture exceeds a limit (SM_S) and triggers the dry-rainy transition season; t_2: Date after t_1 with the first significant precipitation (SP) not followed by a dry spell, beginning of the rainy season; t_3: Date before t_4 with the last significant precipitation (SP), beginning of the rainy-dry transition season; t_4: Date when soil moisture reaches a limit (SM_E) that indicates leaf-shedding (b-NDVI), beginning of the dry season

precipitation or no significant precipitation (BENOIT, 1977; RIVOIRE *et al.*, 2019). Thus, the parameterization process, which may vary for other study areas, should define both the significant precipitation (SP, [mm]) and the minimum dry spell duration (DD, [days]). t_2 is the first day after t_1, when there is a SP not immediately followed by a dry spell of duration DD. If the day with SP is followed by a dry spell, the next date with SP is investigated, and so on.

The next step is to identify t_4, the day when the dry season starts. It is the date when soil moisture lowers below a threshold (SM_E). Analogous to what happens at the start of the dry-rainy transition season, SM_E is an indication that the processes related to the rainy season stopped. This indication can be observed with the help of other processes, such as leaf shedding in deciduous forests. Timing of leaf fall can be obtained from their spectral response with vegetation indices, e.g. NDVI, as an indicator of LAI (ALMEIDA *et al.*, 2019). As the hydrological cycle progresses, the spectral response of the (leafless) deciduous vegetation tends to stabilise at a minimum range (b-NDVI) after having started from values of maximum vegetation vigour (higher NDVI values) in the rainy season. The last step is to identify t_3, the day when the rainy-dry transition season began in that year: it corresponds to the last day (between t_2 and t_4) with a significant precipitation.

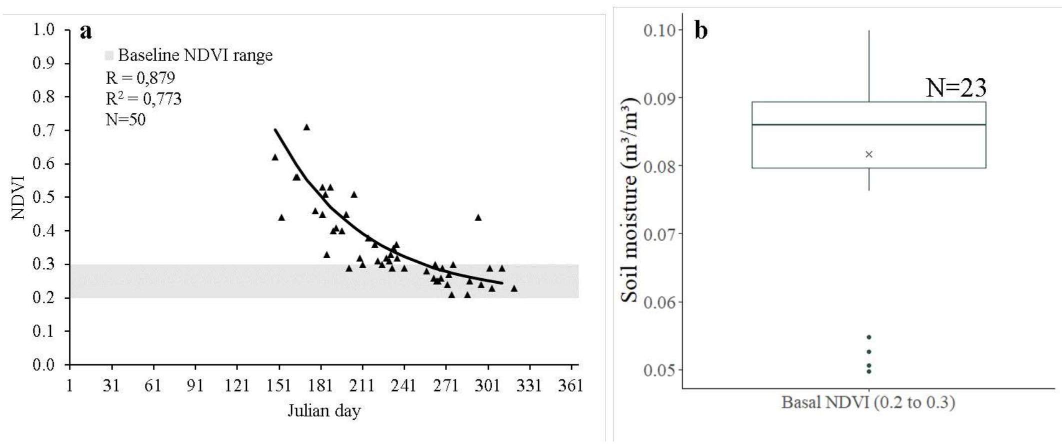
3.4 Assessment of MISD parameters

MISD parameters (SM_S, SP, DD, b-NDVI and SM_E) were adjusted on the basis of historical data derived in the Caatinga Biome (MARENGO; BERNASCONI, 2015) and specifically in AEB (DE ARAÚJO; PIEDRA, 2009; MEDEIROS; DE ARAÚJO, 2014). The values extracted for each parameter are presented in Table 3 together with their description.

Table 3 – MISD parameters for the Aiuaba Experimental Basin (AEB) based on data from Jan 2003 to Dec 2022

Parameters	Acronym	Value
Soil moisture threshold value that indicates the beginning of the dry-rainy transition season, here assumed as equal to the permanent wilting point	SM_S	0.12 m³/m³
Significant precipitation, here assumed as any daily precipitation higher than average actual evapotranspiration	SP	6 mm
Dry spell minimum duration, necessary to identify t_2, the beginning of the rainy season	DD	14 days
Basal NDVI, which corresponds to the vegetational minimum leaf status and, thus, to the beginning of the dry season	b-NDVI	0.20 - 0.30
Soil moisture threshold value, below which b-NDVI is observed, indicating the beginning of the dry season (Figure 10)	SM_E	0.08 m³/m³

Figure 10 – NDVI decay adjustment curve in the analyzed images (a) and distribution of soil moisture values in the baseline NDVI range (0.20 to 0.30) (b)



The use of soil moisture as a proxy of the change between seasons is indicated and described in literature (OCEN *et al.*, 2021; SALACK *et al.*, 2016). In AEB, SM_S corresponds to the value of soil moisture at a tension of -1.5 MPa (0.12 $m^3.m^{-3}$), equivalent to the permanent wilting point (COSTA *et al.*, 2013). The assessment of soil moisture values at different tensions was performed by Costa *et al.* (2013) while analysing spatialized soil moisture under different layers of the soil profile in different AEB areas.

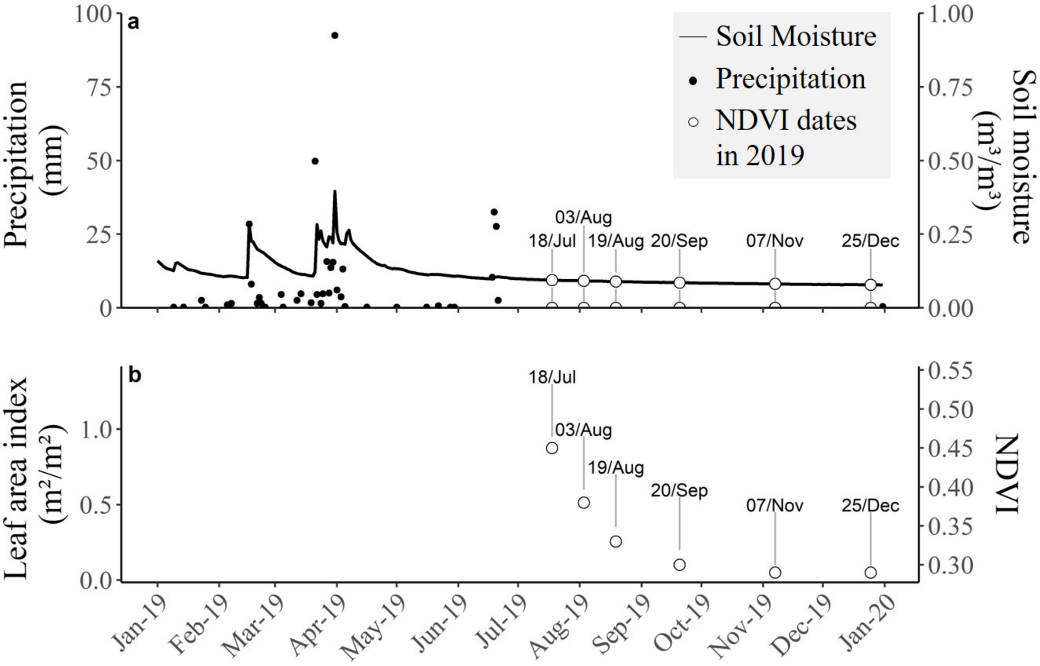
Significant rainfall (SP) is a parameter used both in the beginning (t_2) and end (t_3) of the rainy season, and it is considered to be above or equal to average daily actual evapotranspiration. Evapotranspiration has frequently been used as a threshold for significant precipitation (ADANE *et al.*, 2020; RIVOIRE *et al.*, 2019), and the relationship between precipitation and evapotranspiration has already been employed to determine the beginning and end of the rainy season by authors such as Benoit (1977) and Cochemé Jacques; Cochemé (1967). In AEB, the average actual evapotranspiration during the wettest months is 6 mm (DE ARAÚJO *et al.*, 2022).

DD varies greatly in literature, including in works that study false starts in the rainy season (MUPANGWA *et al.*, 2011; SALACK *et al.*, 2016). The minimum dry spell duration (DD) considered was 14 days, it was called extreme dry spell and used as a false start indicator by Salack *et al.* (2013). In the Brazilian semi-arid region works on dry spells consider events longer than 10 days to be significant (NOGUEIRA *et al.*, 2023), but events of more than 20 days can also occur (ROCHA *et al.*, 2021). Thus, for the beginning of the rainy season we selected the next significant rainfall date (after t_1) that was not immediately followed for a period equal or greater than 14 days without significant rainfall.

A basal value of NDVI (b-NDVI) was used to assess SM_E, the beginning of the dry season. We calculated NDVI values as an average for the representative area where soil moisture data was collected (for more information on data measurements, please refer to section 3.2 and references there). The representative area was the Soil-Vegetation Association (SVA) where soil moisture data was collected. The separation of AEB in SVAs is explained in detail by Almeida *et al.* (2019). Figure 11 shows an example of intra-annual variation of precipitation, soil moisture, NDVI and LAI during the calendar year of 2019, while spatial variation can be observed in Figure 8. We can see that the values of NDVI and LAI drop when precipitation diminishes (ALMEIDA *et al.*, 2019).

When considering all data (57 images in 18 years) and observing the average values of NDVI over the year, there is an asymptotic pattern of decay (Figure 10). When NDVI stabilises

Figure 11 – Values of precipitation, soil moisture, and LAI associated with NDVI in Aiuaba Experimental Basin (AEB) in the year of 2019, highlighting the imaging dates



at a basal range (b-NDVI), the values vary between 0.20 and 0.30; they were also identified as exposed soil values (BENHADJ *et al.*, 2007; JIN *et al.*, 2018). Since the spectral response of leafless Caatinga vegetation can resemble exposed soil when b-NDVI is reached, this indicates that most of the vegetation has lost its leaves. More detailed information on this analysis can be found in Lima (2021).

We selected the dates when the average NDVI was in the basal range (0.2 to 0.3) and compared with soil moisture data (Figure 10b). The median value of soil moisture associated to those dates was 0.087 $m^3.m^{-3}$, with an average of 0.081 $m^3.m^{-3}$. We used a more conservative approach and took 0.08 $m^3.m^{-3}$ as value for SM_E.

3.5 Statistical analysis

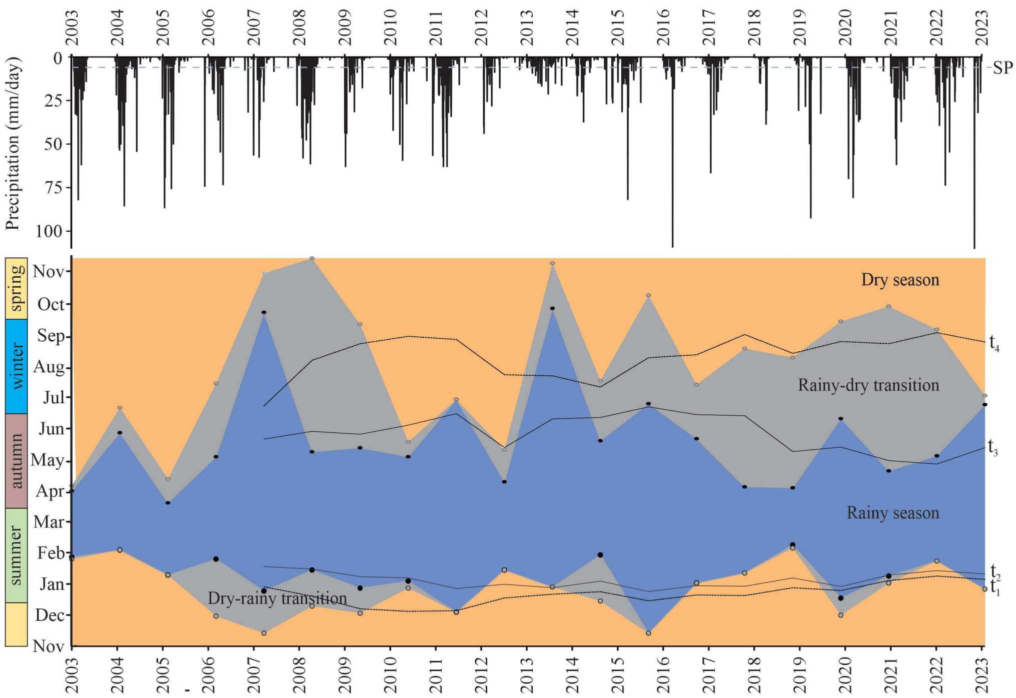
Due to the nature of seasonality, it is difficult to test the result accuracy of our proposed method. However, we can still assess the characterisation of each season and general seasonality. This is valuable information on the hydrological regime of a region, and it can be compared to other observed characteristics. In order to do that we analyse in this work the average and frequency of season start dates, as well as duration, precipitation and number of rainy days in each season.

Statistical trend analysis was performed by using the Mann-Kendall method, as well as Sen's slope (KENDALL, 1975; MANN, 1945). The nonparametric Mann-Kendall test is widely used for hydrological trend analysis as it is robust against outliers, free from assumptions on distributions and has low sensitivity to abrupt breaks in time series (SALMAN *et al.*, 2017; THAPA *et al.*, 2020; ZAMANI *et al.*, 2017). We studied trends on the start date, length of seasons and sum of precipitation to try to observe possible indications of change in some of the main seasonality indicators (KORMANN *et al.*, 2015).

3.6 Observed seasonality at the Aiuaba Experimental Basin (2003 – 2022)

The dates for season partitioning into the four hydrological seasons for each analysed year are shown in Figure 12. Considering the beginning dates of each season (t_{1-4}), we see both the values for each year (points), as well as the 5-year moving average (lines). The distribution of daily rainfall in the Aiuaba Experimental Basin (AEB) is shown in the upper part of Figure 12. The 2022 isolated events (extreme right of the graph) compose the hydrological year of 2023, which is not within the analysis period. In Table 4 we see the summary of the main characteristics of the four analysed seasons.

Figure 12 – Dates for hydrological season partitioning into rainy, dry and transition seasons for each analyzed year (points), with a moving average (n=5) for the different dates (lines).



t_1: start of dry-rainy transition season; t_2: start of rainy season; t_3: start of rainy-dry transition season; t_4: start of dry season

Table 4 – MISD average results for the Aiuaba Experimental Basin (AEB) based on data from Jan 2003 to Dec 2022

	Dry-rainy transition season	Rainy season	Rainy-dry transition season	Dry season	Annual cycle
Mean start dates	31/Dec	31/Jan	31/Jun	15/Aug	
Rainfall	14 mm (CV 145%)	438 mm (CV 93%)	6 mm (CV 40%)	71 mm (CV 167%)	528 mm (CV 37/%)
Rainy days	1 day (CV 76 %)	18 days (CV 36 %)	0	3 days (CV 151%)	21 days (CV 33 %)
Duration	13 days (CV 148%)	140 days (CV 47%)	73 days (CV 79%)	132 days (CV 57%)	336 days (CV 28%)

Due to missing values in soil moisture data, season identification was determined on the basis of precipitation only in two occasions: at the end of 2011 and at the beginning of 2013. Thus, the first rainfall event of SP in 2013 was considered the beginning of the rainy season. The last event with SP in 2011 was the end of the respective rainy season. For this reason, there is no information about the rainy-dry transition season of 2011 and the dry-rain transition season of 2013.

The starting date of the 2021 rainy season occurred in the same week as the beginning of the leaf development stage as determined by research on evapotranspiration in the same study area (DE ARAÚJO *et al.*, 2022). In a work developed in a preserved Caatinga area, the beginning of throughfall rainfall events in 2017 also occurred in the same week as the start of the rainy season determined by MISD (BRASIL *et al.*, 2020).

Regarding the end of the rainy season, Almeida *et al.* (2019) analysed the leaf area index in the AEB through estimates based on litter collection and observed that the period of greatest litter deposition occurs between the months of May and June (2014 to 2016). The MISD rainy-dry transition season happened in similar periods in 2014 and 2016 (May to July), while it differed in 2015 (July to October). Brasil *et al.* (2020) suggested that the leaf fall period started at the end of April and occurred until June for 2017. For the same year, the MISD rainy-dry transition season began in April, and it went on until August. Thus, the rainy-dry transition season determined by the MISD could be an indication of leaf fall period for those years. This observation is important because the t_4, the start of dry season, marks the period that the majority of Caatinga deciduous vegetation would have lost most leaves, which the mentioned works also help to confirm.

The total precipitation amount for each annual hydrological cycle is 528 mm on average, with a coefficient of variation (CV) of 37%. In terms of the distribution of precipitation over the seasons we can observe that it is concentrated in the rainy season, which accounts for 83% of total precipitation. The dry-rainy transition season accounts for 3%, and during the rainy-dry transition occurs only 1% of annual precipitation. On average 13% of annual rainfall happens in the dry season, but variability is greater in comparison to the other seasons. This percentage of annual precipitation in the rainy season is similar to the results of Marques *et al.* (2020) in another area of preserved Caatinga vegetation. The authors identified 82% of annual rainfall within the rainy season. The strong seasonality of precipitation in Caatinga was also addressed by Sparacino *et al.* (2021), who observed an average of 90% of rainfall occurring in the rainy season. The rainfall high standard deviation reveals a meaningful intermittency of precipitation in the region, as well as a low number of rainy days (days with precipitation equal or above SP). The even higher variability during the dry and dry-rainy transition seasons accounts for the occurrence of very isolated (and quite rare) events of precipitation.

The annual hydrological cycle, that is the total duration of all four hydrological seasons, consisted on average of 336 days during our sample period with a CV of 28%. We identified annual hydrological cycles that lasted from 121 to 415 days. It can be seen that seasons are not distributed evenly throughout the year, the rainy and dry season being the two longest (42% and 39% of the annual hydrological cycle, respectively)), approximately 4 months each. The rainy-dry transition represents 22% of the annual cycle, and dry-rainy transition is the shortest (4%).

There is a great variability in duration of both the transitional seasons. In the years of 2014, 2015 and 2019, the annual hydrological cycle had seasons with approximate length. In the other hand, the years of 2003, 2010 and 2011 show very short transition seasons. The comparison between the dry-rainy and rainy-dry transition seasons can also be interesting. There were years when they were similar in length (2003, 2010, 2012, 2019, and 2022), but in about 60% of the years, the rainy-dry transition was longer than the dry-rainy.

The duration of the rainy season and its high variability from year to year is similar to what Mupangwa *et al.* (2011) observed in semi-arid southern Zimbabwe, with a rainy season of 4 months in average and standard deviation of 30 days. Sparacino *et al.* (2021) observed longer rainy seasons, with an average duration of 5 months in another region of Caatinga. The high variability of season duration was also observed by the authors, confirming our observation.

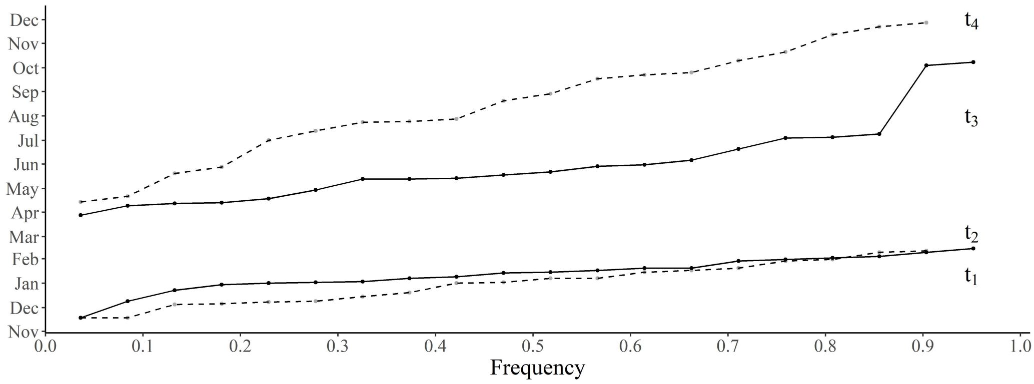
There is a great variability in the duration of both the transitional seasons. During 2014, 2015 and 2019, the annual hydrological cycle had approximately equal seasons. 2003, 2010 and 2011, on the other hand, show noticeably short transition seasons. A comparison between the dry-rainy and rainy-dry transition seasons can also be interesting: There were years when they were similar in length (2003, 2010, 2012, 2019, and 2022), but in about 60% of the years, the rainy-dry transition was longer than the dry-rainy one.

The shorter dry-rainy transition season corresponds to the fast leaf development of Caatinga vegetation according to studies in two Caatinga preserved areas (AEB: DE ARAÚJO *et al.* (2022); Iguatu Experimental Catchment: Brasil *et al.* (2020)). DE ARAÚJO *et al.* (2022) observed that the period of leaf development lasts about two weeks, from the beginning of an increase to a stabilisation of the leaf area index (LAI). Brasil *et al.* (2020) observed equivalent results: Their investigation detected a quick response of vegetation to the triggering effects that lead to the start of the rainy season. These studies were carried out on an experimental scale (only one year each), but they give a broad idea of vegetation dynamics in the Caatinga.

The initiation or transition process set in motion by first precipitation events (even isolated ones) increases soil moisture and already triggers a vegetation response. This quick response could also constitute adaptation mechanisms of the Caatinga vegetation to the occurrence of concentrated precipitation.

Cumulative frequency curves are presented in Figure 13 and exhibit the beginning dates of each season. The dry-rainy transition started in 80% of the time before 31/Jan, and in 55% it happened before or in the second week of January. The rainy season initiated before 01/Jan in 20% of times. This is important because 01/Jan is usually the date considered in scientific analyses the start of the rainy season (DE ARAÚJO; PIEDRA, 2009; COSTA *et al.*, 2021; MEDEIROS; DE ARAÚJO, 2014).

Figure 13 – Cumulative frequency curves considering the starting date for each of the analysed seasons (t_{1-4}).



t_1: start of dry-rainy transition season; t_2: start of rainy season; t_3: start of rainy-dry transition season; t_4: start of dry season

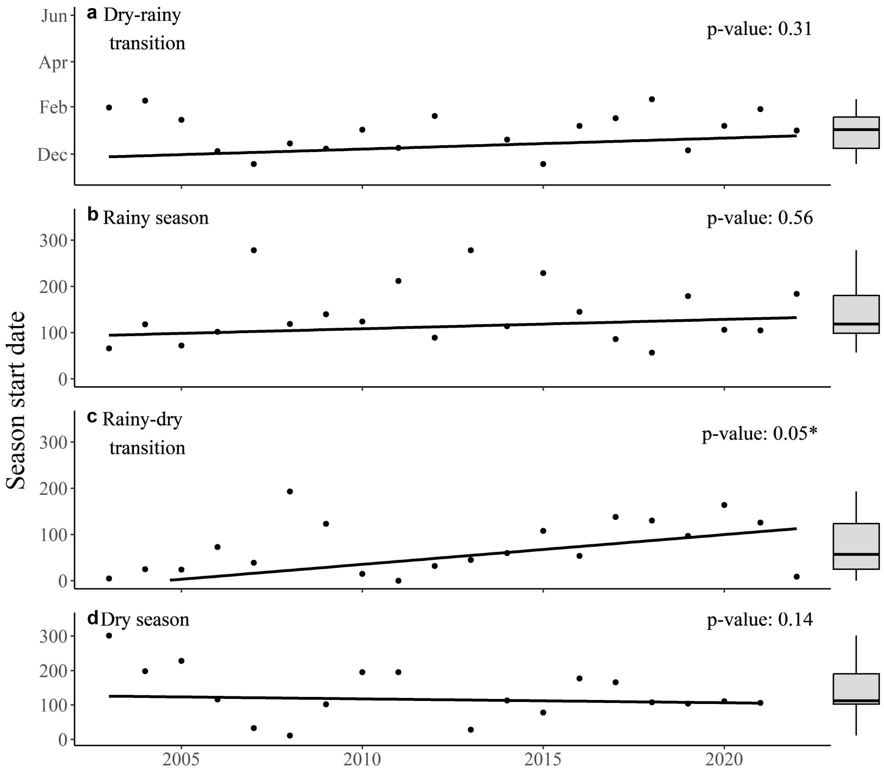
The rainy-dry transition, i.e. the end of the rainy season, begins before 31/May in 65% of the years, and in 90% it happens before 09/Jul. This corresponds well to the fact that most hydrological works about the Brazilian semi-arid region regard either the end of May or of

June as termination of the rainy season (DE ARAÚJO; PIEDRA, 2009; COSTA *et al.*, 2021; MEDEIROS; DE ARAÚJO, 2014). Finally, looking at the dry season, it was found out that in 90% of the cases it begins after 21/Apr.

3.7 Trends in the characteristics of seasons

The starting dates of the rainy season, dry season and transition season are shown in Figure 14 for each year. . In the right part of the figure, we can also see boxplots for each season showing the variability of season start during our analysed period (20 years). The p-values of the Mann-Kendall trend analysis reveal that no trends were observed. The mean values for each analysed variable are shown in Table 2. Sparacino *et al.* (2021) also observed high variability of the start of rainy and dry seasons without any tendencies during their analysed period (35 years).

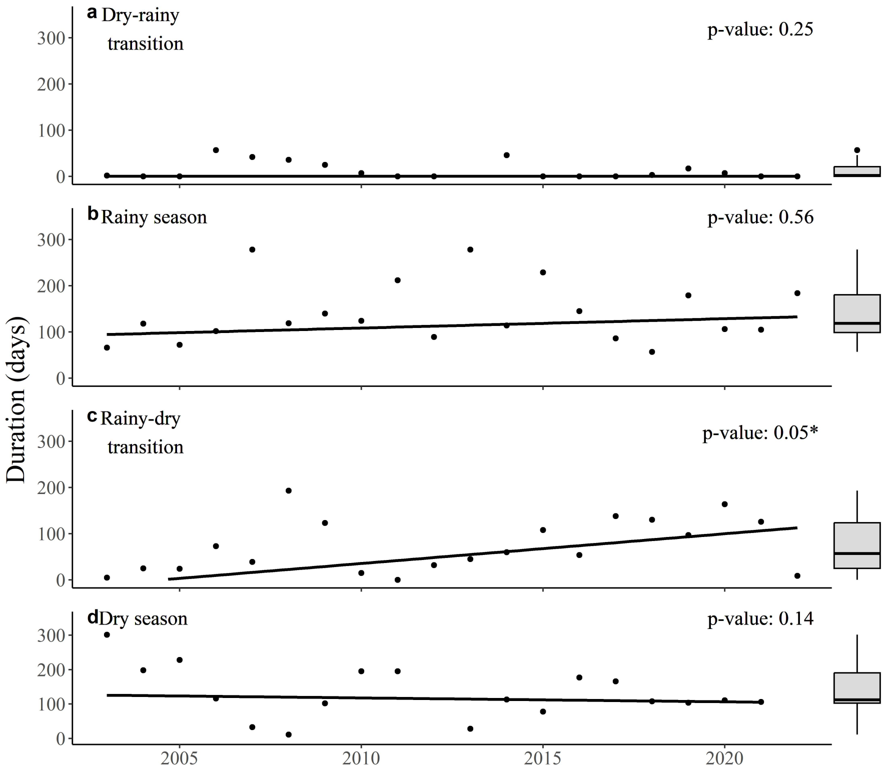
Figure 14 – Start date of the dry-rainy transition (a), rainy season (b), rainy-dry transition (c) and dry season (d). Lines refer to Sen's slope and p-value refers to the Mann-Kendall trend analysis.



The duration of the hydrological seasons in days is displayed in Figure 15for each year. The result of the Mann-Kendall test presented in Figure 15c exposes a significant trend ($p < 0.05$) for an increase in the duration of the rainy-dry transition season. Figure 15 also shows the temporal distribution of data from the other seasons, which did not manifest significant trends.

An increase in the duration of the rainy-dry transition season leads to a reduction of the other seasons. However, the reduction in duration is not following a simple linear trend in any of the other seasons.

Figure 15 – Duration of the dry-rainy transition (a), rainy season (b), rainy-dry transition (c) and dry season (d). Lines refer to Sen's slope and p-value refers to the Mann-Kendall trend analysis.

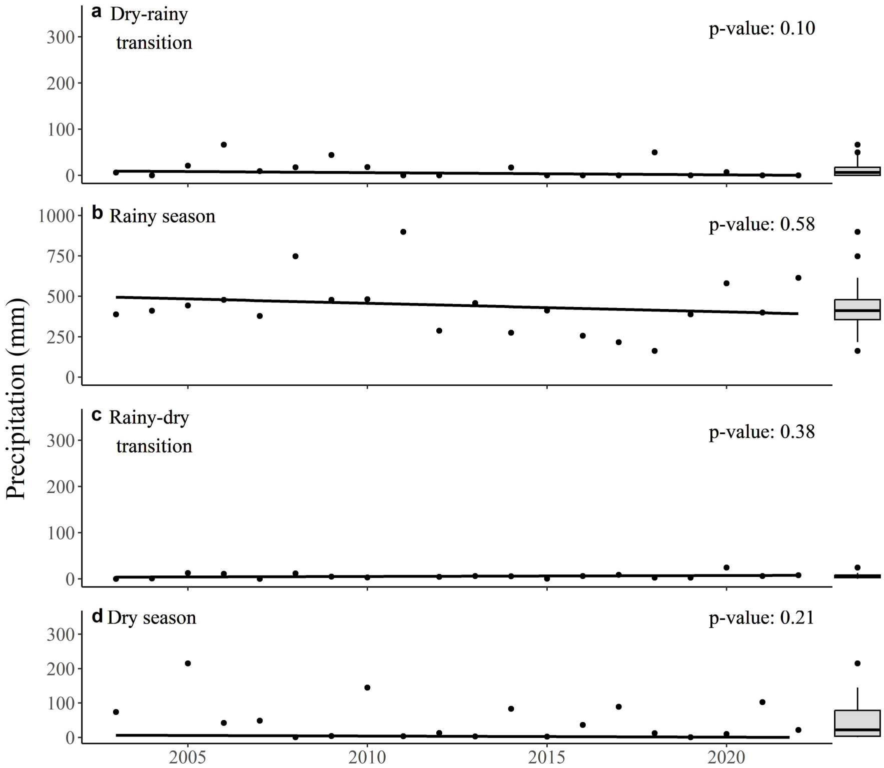


We can observe the precipitation distributions of each season in Figure 16. None of them produced a significant trend in the Mann-Kendall test. Here, for better visualisation a different y-axis limit was used for the rainy season. Sparacino *et al.* (2021) observed a tendency of decrease of precipitation and number of rainy days in their analysed period. However, the authors highlight that the drought that occurred from 2012 to 2017 may have influenced the trend.

No events with significant precipitation (SP) can occur in the rainy-dry transition season per definition, since it begins on t_3, i.e. the last day between t_2 and t_4 with precipitation above or equal SP. Therefore, to observe a possible occurrence of isolated events, we computed the number of days with rainfall above zero, yet no trend was identified in any season (Figure 17). Since we observed only three years with rainy days during the dry season, no trend analysis was computed for that season.

This way, we see that the tendency of an increased duration of a rainy-dry transition

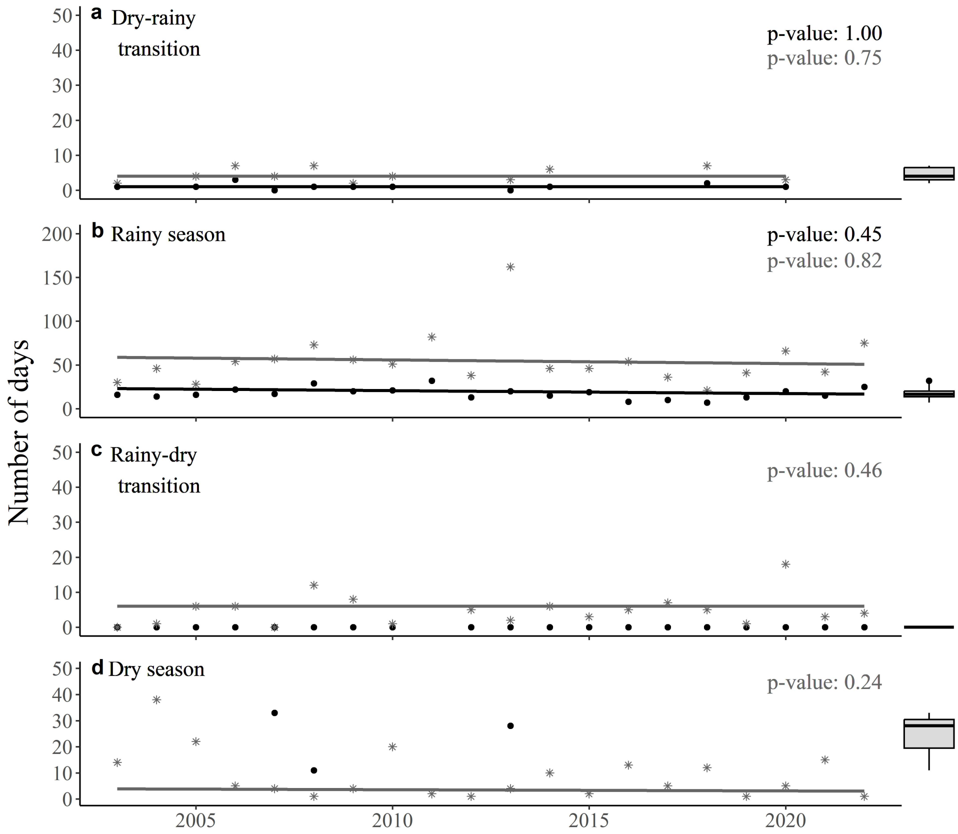
Figure 16 – Precipitation sums during the dry-rainy transition (a), rainy season (b), rainy-dry transition (c) and dry season (d). Lines refer to Sen's slope and p-value refers to the Mann-Kendall trend analysis.



season means a longer period since the last significant precipitation event, and this longer period until the start of the dry season does not produce more small isolated precipitation events, given that no trend was identified in the number of isolated events (Figure 17).

The significant positive trend in the duration of the rainy-dry transition season may indicate that vegetation needs a longer time to lose all its leaves. This observation will need to be confirmed, e.g. by means of a specific analysis of leaf senescence. It could be inferred by the delay of soil moisture reaching SM_E, since SM_E is an indication of leafless vegetation. The present analysis points to a possible shift in the hydrological regime of the studied region, an indication that corroborates with the observations of Werner and Gerstengarbe (2003) and Gerstengarbe and Werner (2003) about the delay in the onset of the dry season in this region.

Figure 17 – Number of days with rainfall above zero or above significant precipitation (SP) during the dry-rainy transition (a), rainy season (b), rainy-dry transition (c) and dry season (d). Lines refer to Sen's slope and p-value refers to the Mann-Kendall trend analysis.



3.8 Conclusions

The proposal and application of the novel MISD (Method for Identification of Seasonality in Drylands) method for a hydrological season identification allowed the characterization of seasons in the Brazilian semi-arid region using criteria based on precipitation, soil moisture and vegetation. Hydrologically relevant criteria to identify seasonality in the data-scarce Semiarid is a novelty and can be helpful in many investigative aspects related to hydrological processes in these regions.

The application of the method to 20 years of monitoring data in the experimental basin of Aiuaba allowed a very detailed observation of the seasonal behaviour of hydrological characteristics in the region. Precipitation-driven processes could be observed in regard to the particularities of the different seasons with a large inter-annual variability. This variability contributes to the annual precipitation intermittence that is characteristic of the Brazilian dryland. In addition, the short dry-rainy transition seasons can be an indication of a quick vegetation response to first rainfall events.

The application of the MISD method allowed the study of seasonal trends; we observed, for instance, the trend of a longer rainy-dry transition season. No trend was observed neither regarding the amount of precipitation and number of rainy days in any season, nor concerning the starting date of seasons. Since there was no observed effect on those variables, the changes that are taking place could be related to a more general shift in the time frame of hydrological processes in the Caatinga biome.

Water resources management and planning in the Caatinga Biome can benefit from the identified hydrological seasons and their potential changes. Our research contributes empirical insights about seasonality that can guide informed decisions for sustainable water resource management. This is of particular importance in semi-arid regions where efficient water allocation is vital for both human consumption and agricultural sustenance.

One limitation of our study was the size of our representative area. Since our goal was to model the hydrological seasons for the entire Caatinga forest, our experimental basin is relatively small and may not represent the whole complexity of Caatinga biome. In future research, we plan to address this issue by incorporating other areas in different regions of the Caatinga Biome. Incorporating soil moisture in the season delineation increases their informative power, as soil moisture is, without doubt, a direct prerequisite for vegetation development. However, related measurements are much less common than rainfall measurements. Thus, developing a respective proxy from meteorological and soil data would increase the applicability of MISD in future.

4 CHAPTER III - RIVER INTERMITTENCY: MAPPING WET AND DRY PATTERNS WITH UNMANNED AERIAL VEHICLE-DRIVEN DATA AND MODELLING WITH RANDOM FOREST AND REMOTE SENSING

Abstract: Although intermittent rivers exist naturally, climate change can have a direct influence on the them. Models and measurements in temporary rivers are still scarce, but it is essential for future scarcity scenarios. Thus, this work aims to map and model the spatial and temporal dynamics of an intermittent river. The specific objectives are: (i) to acquire field data; (ii) to identify the most important variables in intermittency dynamic; and (iii) to model river intermittency using remote sensing-driven data. A modelling framework (River Intermittency modelling - RivInt) was applied to the Brazilian Semiarid Umbuzeiro River that forms the main river of the Benguê catchment ($\sim$1000 km²). This is an ephemeral river and spatially coherent streamflow occurs exclusively in the wettest months during rainy season. Monthly UAV surveys were conducted between March and June 2022, and in November 2022 in selected reaches of the river. River reaches were classified into "Wet","Partially wet", "Dry"or not determined ("NotDet") with visual inspection of 1-m reaches. For explaining the observed patterns, 40 candidate predictors based on static and dynamic landscape attributes were analysed. Among these, altitude, drainage area, distance from dams and one different dynamic predictor proved to be most informative in Random Forest models. The models differ in the source and type of dynamic variable used to capture the temporal dynamics: (a) series of Sentinel MNDWI; (b) series of Planetscope NDVI; and (c) accumulated precipitation (30 days). All model variants successfully modelled the intermittency of the river with an accuracy greater than 80%. Models (a) and (b) captured the temporal dynamics in model extrapolation to the whole river. When analysing the spatial distribution of intermittency, models (a) and (c) identified areas more prone to wet or partially wet conditions. The results provide insight into the hydrological diversity of semi-arid rivers which is important to understand their ecological role and habitat.

Keywords: Temporary rivers. Random Forests. UAV. Ephemeral rivers

4.1 Introduction

The presence of intermittent and ephemeral rivers are increasingly prevalent in drainage networks around the world. According to recent research, predicted changes in temperature and precipitation may increase the irregularity of spatio-temporal characteristics in rivers, making them more intermittent (MESSAGER *et al.*, 2021). Although intermittent rivers exist naturally, climate change increase demand for water and human activities resulting in changes in land use and occupation influence the permanence of runoff. In this context, the study of naturally intermittent rivers in the semi-arid region is essential for understanding scarcity scenarios.

Intermittent and ephemeral rivers are characterised by periods of drying and rewetting. The dominant factors controlling the flow of a river are: (i) the interaction between the structure of the river basin and the climate; (ii) anthropogenic activities; (iii) climate change (COSTIGAN *et al.*, 2017). In semi-arid regions, surface runoff is largely controlled by low annual precipitation, as well as intense rainfall events that occur only during short periods of time (FIGUEIREDO *et al.*, 2016). Furthermore, water courses are influenced by high evapotranspiration rates and given these conditions, the prevalence of intermittent rivers is common (PEREIRA *et al.*, 2019).

The duration of the drying phase is very important in the assessment of the ecological status in temporary rivers (MAZOR *et al.*, 2014). In addition, metacommunity assembly mechanisms can have a seasonal response to changes in hydrological conditions of intermittent rivers (SARREMEJANE *et al.*, 2017). The possibility to model the temporary condition in small reaches throughout the river gives a possibility to incorporate the temporal dimension into studies that need a detailed assessment of water occurrence in intermittent rivers.

The extrapolation of point data from fluviometric stations to characterize patterns throughout the drainage network is difficult when it comes to intermittent rivers due to the high variability of spatial characteristics (BEAUFORT *et al.*, 2019; SNELDER *et al.*, 2013). However, in these cases, data collection and characterization of local conditions can be used to evaluate flow dynamics in unmonitored parts of the drainage network. Therefore, it is necessary to investigate ways of extrapolating available measurements in space and time, particularly for unmonitored areas.

Unmanned aerial vehicles (UAVs) represent an accurate approach to the study of water resources at a detailed scale (ACHARYA *et al.*, 2021). UAVs have been used as a tool to observe water surface areas and river stages (NIEDZIELSKI *et al.*, 2016). Due to the high spatial resolution of most UAV-acquired images, it is possible to detect even small changes in water surface area using multitemporal surveys.

Random Forest models have been applied to forecast the spatial distribution of both intermittent and perennial rivers (BEAUFORT *et al.*, 2019; PRICE *et al.*, 2021; SNELDER *et al.*, 2013). However, these studies usually focus on flow/non-flowing classification. Only a few attempts were made to classify different spatial-temporal dynamics and drying patterns in intermittent rivers (EASTMAN *et al.*, 2021).

The aim of this work is to model the spatial and temporal dynamics of an intermittent river in the Brazilian semi-arid region. The specific objectives are: (i) to acquire suitable field data; (ii) to identify the most important variables affecting intermittency; and (ii) to model river intermittency using remote sensing-driven data.

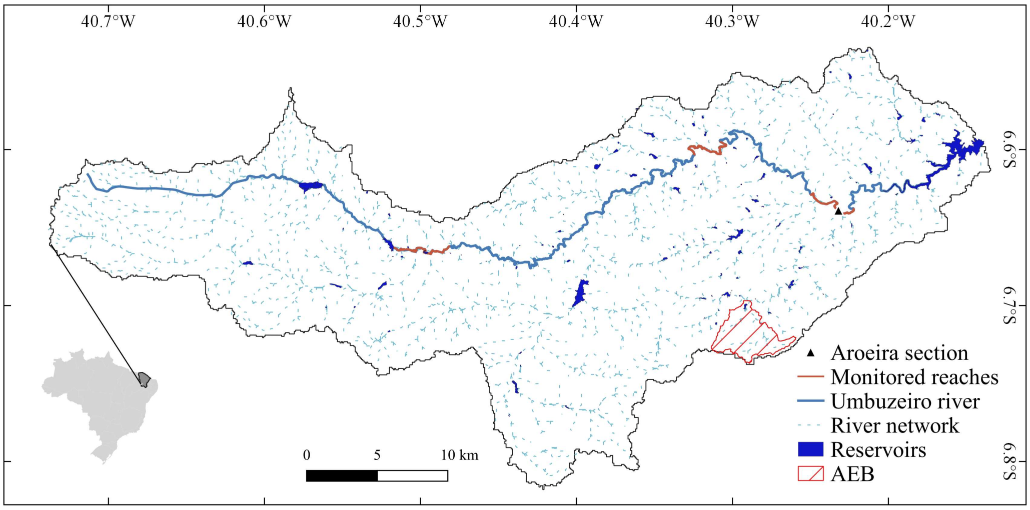
4.2 Material and methods

4.2.1 Study area

The Benguê catchment comprises an area of approximately 1000 km^2. The Benguê Reservoir (18 hm³) is located at its outlet and was built in 2000 to supply water to part of the district of Aiuaba. The area of Benguê catchment is located in one of the driest parts of the Brazilian Semiarid (Figure 18). The mean annual potential evaporation is approximately 2500 mm and mean annual rainfall is around 560 mm with high temporal variability (MEDEIROS; DE ARAÚJO, 2014). The predominant vegetation in Bengue catchment is Caatinga, a dry forest endemic to Brazil (COSTA *et al.*, 2023). Another particularity is that this area is covered by a large number of reservoirs. According to Mamede *et al.* (2018), 114 reservoirs were present in the catchment, with most of them damming the Umbuzeiro River, the catchment's main river.

The finest resolution available for the river network is derived from flow accumulation from a 30 m resolution DEM from Shuttle Radar Topography Mission (SRTM; USGS (2009)). Since this is relatively coarse considering an average river width of 5-15 m, the mapping of the course of the Umbuzeiro River was done manually using Planetscope images with approximately 3 m resolution. Google Earth Explorer was also used to supplement information. The resulting main branch had a river length of 105 km after this mapping (Figure 18). Monitoring of streamflow is present in the Aroeira section since 2011. According to measured data during 10 years, the average streamflow occured 40 days/year, considering only the years with any streamflow (7 out of 10 years), with average discharge of 0.63 m^{3}s^{-1} (LIMA *et al.*, 2022).

Figure 18 – Bengue catchment and Umbuzeiro River with the river reaches monitored with UAV surveys. Aiuaba Experimental Basin (AEB) can also be observed



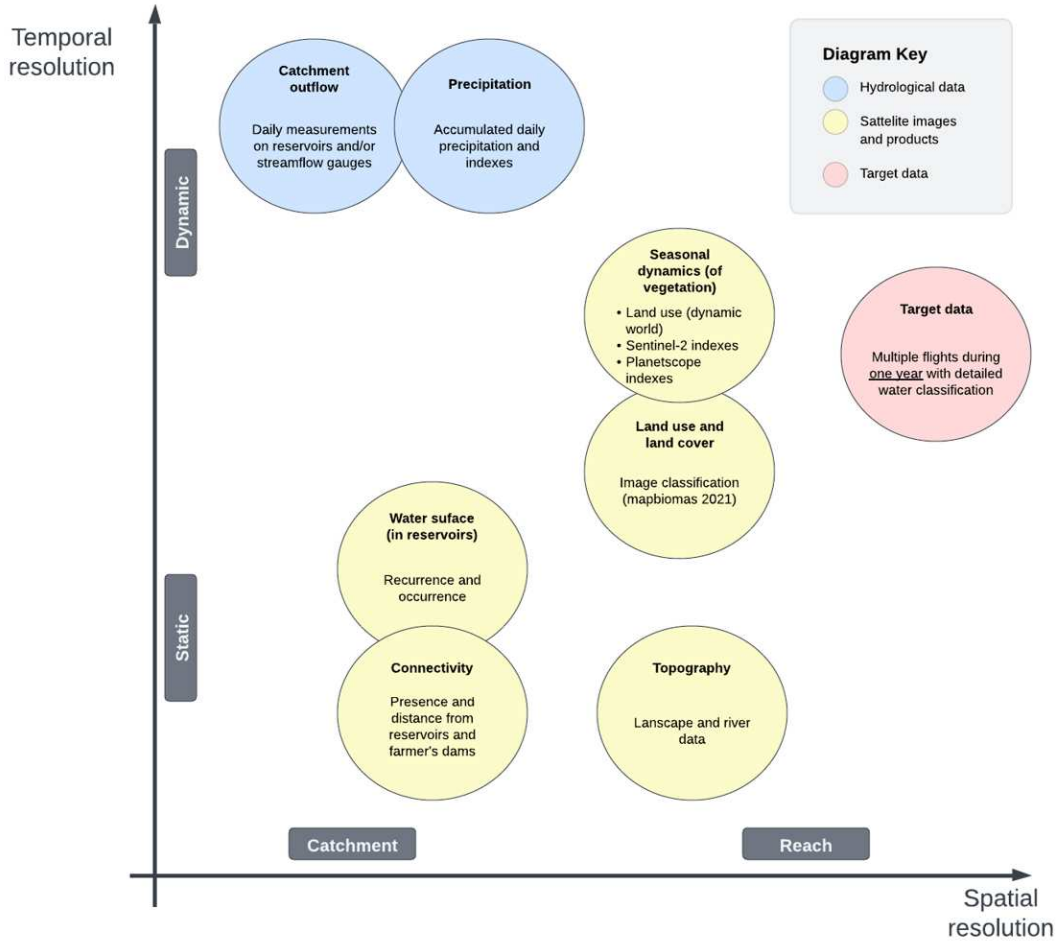
4.2.2 Data collection and preprocessing

The groups of data used on the modelling approach is presented in Figure 19, and can be classified with regard in terms of temporal and spatial resolution. Target data (i.e. "response variable") is the result of the classification of river reaches in terms of water occurrence, and it has the most detailed spatial resolution. Among the predictors, in terms of temporal resolution, the daily hydrological data (rainfall, streamflow, reservoir levels) is the most detailed. Data regarding the connectivity and water surface in reservoirs on the river network are the coarsest spatial resolution since its related to the places where there is a damming structure. Since changes in the presence of these structures were not considered, this is a static data. Physiography data is also static, but it is distributed in each modelling unit. Land use and land cover data is yearly available and distributed in each unit. Last, seasonal dynamic of water and vegetation is accessed with satellite indices and products (Sentinel with Dynamic World product and Planetscope). Those are dynamic data since they would be available every time there is a cloud-free image.

4.2.2.1 Target data: UAV imagery

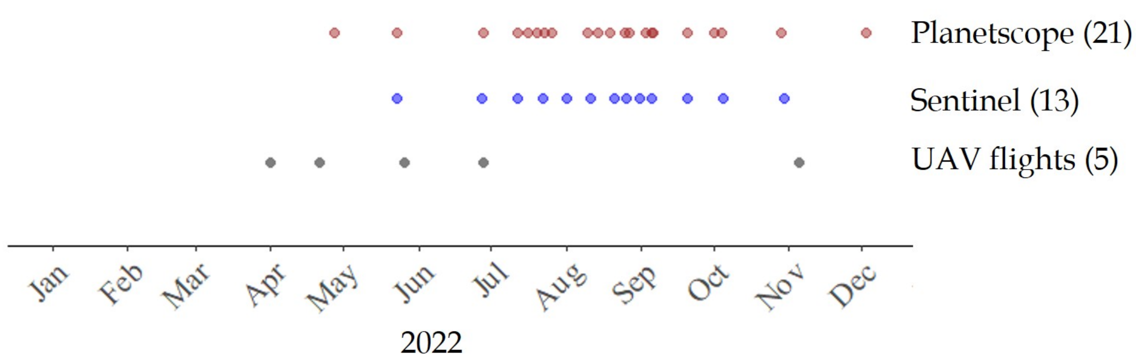
Data were acquired for three reaches of the Umbuzeiro River at different dates, with two UAV systems. UAV surveys were performed every month during the rainy season (Apr - Jul), and on November of 2022 (Figure 20). Since the rainy season usually occurs during the first months of the year, it is common to not have available satellite images during this period due the high cloudiness. The equipment used were the copter-system Phantom 4 pro (DJI Ltd.,

Figure 19 – Spatial and temporal distribution of data used in the model with temporal scale going from static to dynamic data and spatial scale going from catchment to reach scale



China) and the glider-system eBee SQ (senseFly SA, Switzerland). The eBee SQ was equipped with multi-spectral cameras while the Phantom had a RGB camera. The post-processing of the images was performed in Agisoft Metashape following the default configurations recommended by each type of images (i.e. multi-spectral or RGB).

Figure 20 – Date of available imagery for 2022 with the number of images available for each sensor



The UAVs images was done visually identifying the water occurrence in each mapped reach. The intermittency was manually classified in 1 m reaches into three classes: "Wet", "Partially wet"or "Dry", and also not determined ("NotDet") when it was not possible to discern the riverbed, e.g. because being obscured by canopy. The differentiation between the "Wet"and "Partially wet"classes is based on how clearly it was possible to see the water. When it was not possible to see clearly the presence of water (i.e. due to the presence of herbaceous vegetation), the 1-m reach was classified as "Partially wet". In cases when it was possible to observe the dry riverbed, the "Dry"class was used.

4.2.2.2 Satellite images and products

Sentinel-2 MSI images were used as dynamic data, and it will be referred to as 'Sentinel' from now on. The images are freely available, with temporal resolution of 5 days. Spatial resolution change depending on the bands: for blue, green, red, and near infrared (NIR) bands, the resolution is 10 m, while for shortwave infrared (SWIR) and red edge bands, the resolution is 20 m. The processing level used here was 2A after corrections and conversion of top of atmospheric reflectance to surface reflectance (for more information on Sentinel images, please refers to https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi). Sentinel images were obtained and processed in Google Earth Engine (GEE).

Planetscope images were also used as dynamic data from proprietary access. Images are available daily, under cloud-free conditions and have spatial resolution of 3.0 m to 4.1 m, with final resolution of approximately 3 m. The product used was analytic surface reflectance (level 4b), also already corrected and converted. Images were downloaded from Planet website as a "composite"(a mosaic of available images for that date). If there were missing portions, the gaps were filled with the image from the previous or the following day. Images were processed in QGIS 3.14 and R 4.1.

Both Sentinel and Planetscope images were used to calculate different spectral indices commonly used in water detection. A summary of these indices used are presented in Table 5. Most indices are related directly to water or moisture detection, with exception of Normalized Difference Vegetation Index (NDVI). Normalized Difference Water Index (NDWI), Modified Normalized Difference Water Index (MNDWI), and Sentinel Water Index (SWI) have been used for detection of surface water (MCFEETERS, 1996; XU, 2006; JIANG *et al.*, 2021). Normalized Difference Moisture Index (NDMI) is used to compute moisture present in leaves of vegetation, and it is calculated with either Near Infrared ($NDMI_{NIR}$) or Red Edge bands ($NDMI_{RE}$) (JR; ROCK, 1989; LASTOVICKA *et al.*, 2020). To compute these indices in each area, zonal statistics were performed in QGIS 3.14 considering the mean value per area. For Sentinel indices, the ones with SWIR2 or Red Edge bands (20-m resolution bands) were resampled to 10 m resolution.

Table 5 – Spectral indices obtained from Sentinel-2 and Planetscope images and equations with the band numbers

Spectral Index	**Equation**	**Sentinel-2 bands**	**Planetscope bands**	**Reference**
Normalized Difference Vegetation Index	$NDVI = \frac{\rho NIR - \rho Red}{\rho NIR + \rho Red}$	Band 8; Band 4	Band 4; Band 3	Townshend and Justice (1986)
Normalized Difference Water Index	$NDWI = \frac{\rho Green - \rho NIR}{\rho Green + \rho NIR}$	Band 3; Band 8	Band 2; Band 4	McFeeters (1996)
Modified Normalized Difference Water Index	$MNDWI = \frac{\rho Green - \rho SWIR2}{\rho Green + \rho SWIR2}$	Band 3; Band 11		Xu (2006)
Normalized Difference Moisture Index (Using NIR band)	$NDMI_{NIR} = \frac{\rho NIR - \rho SWIR2}{\rho NIR + \rho SWIR2}$	Band 8; Band 11		Jr e Rock (1989)
Normalized Difference Moisture Index (Using Red Edge 4 band)	$NDMI_{RE} = \frac{\rho RE4 - \rho SWIR2}{\rho RE4 + \rho SWIR2}$	Band 8A; Band 11		Lastovicka *et al.* (2020)
Sentinel Water index	$SWI = \frac{\rho RE1 - \rho SWIR2}{\rho RE1 + \rho SWIR2}$	Band 5; Band 11		Jiang *et al.* (2021)

Dynamic World is a near real-time land use land cover (LULC) classification product based on Sentinel-2 images with less than 35% cloud cover (BROWN *et al.*, 2022). The product is delivered as new Sentinel-2 scenes become available (every 5 days). Each image has a band with a discrete classification of LULC, and nine probability bands featuring class-specific probability scores, derived from the deep learning model's analysis of the pixel's spatial context (VENTER *et al.*, 2022). For modelling purposes, the discrete classification of LULC for each pixel and the unit's major class and the frequency of each class in that area were used.

4.2.2.3 Hydrological data

Daily hydrological data was used to take into account changes in precipitation and in the reservoir located at the outlet of the catchment. For precipitation data, accumulated precipitation in the last 30 days, and Antecedent Precipitation Index (API) also considering the last 30 days and a k coefficient equal to 0.90 (HEGGEN, 2001). Only the last 30 days were used, based on the results of Beaufort *et al.* (2019) that showed the importance of this predictor in intermittence modelling with Random Forest. Regarding reservoir data, the daily Benguê reservoir water level, volume and volume variation from previous day. The Benguê Reservoir has been monitored by the Water Resources Management Company of Ceará (COGERH), with data available since 2004.

Precipitation data were provided by a data collection on Aiuaba Experimental Basin (AEB), located in the Southern part of the Benguê catchment. Hydrological data has been collected there by HIDROSED research group since Jan 2003 and precipitation data has been used as representative for the Benguê catchment (FIGUEIREDO *et al.*, 2016).

4.2.2.4 Physiography

Static data were used in order to take into account the catchment static landscape characteristics. To obtain data on basin physical attributes, SRTM DEM survey data with 30 m resolution were used, downloaded from the USGS portal (https://earthexplorer.usgs.gov/). Due to the different resolution (i.e. compared to the river mapped with 3-m resolution), the river location derived with flow accumulation deviated significantly in some areas. Thus, the corresponding river reaches were mapped: the main river obtained from the flow accumulation with SRTM data was divided by the number of modelling units obtained manually dividing the Umbuzeiro River (see Section 4.2.3). Since the river from flow accumulation is slightly shorter than the one mapped using a finer resolution, the modelling units spacing was shorter (44 m). Having the same number of units, the data could be related sequentially to the river network used in the model.

The data used to characterise the physical attributes of the basin and modelling unit included “mean altitude”, “max drainage area”, “mean hill slope” and “number of river cells”. Every predictor was calculated per modelling unit, using zonal statistics. The presence of stream cells consisted in the sum of cells that was classified as river in the flow accumulation algorithm.

4.2.2.5 Land use and land cover

MapBiomas (https://brasil.mapbiomas.org/en/) is a project created by a collaborative network of NGOs, universities, and technology startups focused on using science to track changes in the Brazilian landscape. The project has annually created maps of LULC with data since 1985 using Landsat images, with a spatial resolution of 30 m. MapBiomas data is freely available and was downloaded and processed in Google Earth Engine (GEE). In the modelling, the classification of LULC was used for each pixel. Then, the unit’s most frequent class and the frequency of each class in that area were calculated.

4.2.2.6 Connectivity: damming structures and water surface in reservoirs

The damming structures were taken into account as static predictors. Dams were mapped throughout the Umbuzeiro River using Planetscope images to visually locate each dam. The mapping also took into consideration previous knowledge about the presence and location of damming structures on the river, including actual barrages for water storage and smaller dams for river crossing. In total, 45 structures were mapped, of which 15 structures had been known (ground truth) and 30 were detected on the images.

The presence of dams was marked on modelling units with 1 (dam present) or 0 (no dam). The distance to the next downstream dam and the distance from the last last upstream dam structure were calculated in QGIS 3.14, considering one reach between two dams at a time. The position of each dam in the river, relative to other dams, was measured along the river flowline (FENCL *et al.*, 2015).

Global Water Surface is a dataset developed by the European Commission's Joint Research Centre in the framework of the Copernicus Programme (PEKEL *et al.*, 2017). The dataset maps the location and temporal distribution of water surfaces at the global scale based on Landsat data since 1985, providing statistics on their extent and change to support water resources assessment. In the modelling, the maximum extent of water bodies was used, and both recurrence and occurrence of water in that pixel. For more information on how those statistics are calculated, please refer to their material in https://global-surface-water.appspot.com/.

A summary of all the candidate predictors used in the modelling are presented in Table 6. It holds the type of variable, as well as the spatial distribution and frequency.

4.2.3 RivInt modelling units

The River Intermittency modelling (RivInt) approach was carried out in the Umbuzeiro River. For modelling purposes, the river was divided into areas of equal size constituting spatial modelling units. Circular areas were chosen to better follow the river's sinuosity. The modelling units had 50% overlap, so that adjacent conditions were considered when determining the water occurrence of that area. Analyses of stream habitat are usually measured by wetted width, where a sampling reach has a length of 20 times the maximum mean wetted width, with a recommended minimum of 50 m (DATRY *et al.*, 2021; FENCL *et al.*, 2015). Since this is an important aspect for future application of this modelling approach, the length of 50 m was used.

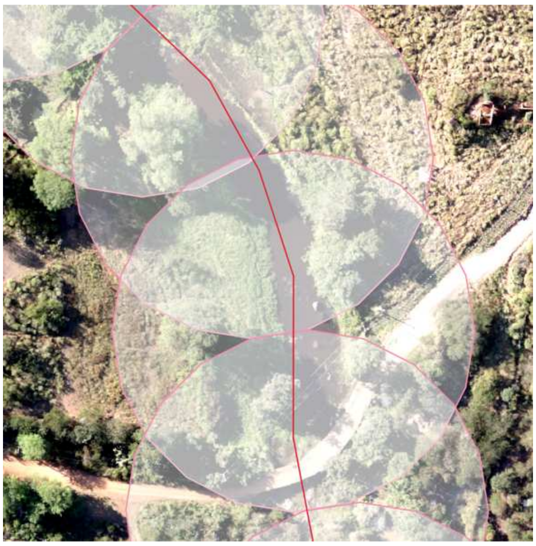
Table 6 – List of predictors, indicating in which models they were used: (a) Model using Sentinel predictors to capture temporal dynamics; (b) Model using Planetscope indices as dynamic predictors; and (c) Model using hydrological data as the only source of temporal dynamics

Type	Predictors	Frequency*	Spatial aggregation	Used by model:
Sentinel	Dynamic world - most frequent class and percentage of each class of land cover (8 classes)	5 days	Distributed	a
	NDVI	5 days	Distributed	a
	NDWI	5 days	Distributed	a
	MNDWI	5 days	Distributed	a
	NDMI with Red-Edge	5 days	Distributed	a
	NDMI with Near Infrared	5 days	Distributed	a
	SWI	5 days	Distributed	a
Planetscope	NDVI	Daily	Distributed	b
	NDWI	Daily	Distributed	b
Hydrology and climate	Rainfall accumulation over the last 30 days	Daily	Aggregating values for catchment	a,b,c
	Antecedent precipitation index from last 30 days	Daily	Aggregating values for catchment	a,b,c
	Reservoir at the outlet of catchment: water level (m)	Daily	Aggregating values for catchment	a,b,c
	Reservoir at the outlet of catchment: water volume (m^3)	Daily	Aggregating values for catchment	a,b,c
	Reservoir at the outlet of catchment: water volume variation form previous day (m^3)	Daily	Aggregating values for catchment	a,b,c
Basin physical attributes	Mean altitude at each modelling unit (m)	Constant	Distributed	a,b,c
	Max drainage area at each modelling unit (km^2)	Constant	Distributed	a,b,c
	Mean hill slope at each modelling unit ($m\ km^{-1}$)	Constant	Distributed	a,b,c
	Stream presence (0 or 1)	Constant	Distributed	a,b,c
Land use and land cover	Mapbiomas - most frequent class and percentage of each class of land cover (7 classes)	Constant	Distributed	b,c
Connectivity	Presence of dams (0 or 1)	Constant	Distributed	a,b,c
	Distance from last dam (km)	Constant	Distributed	a,b,c
	Distance to next dam (km)	Constant	Distributed	a,b,c
Water surface	Maximum extent (presence of cell)	Constant	Distributed	a,b,c
	Recurrence (%)	Constant	Distributed	a,b,c
	Occurrence (%)	Constant	Distributed	a,b,c

* Satellite images frequency refers to availability under cloud-free conditions

Thus, modelling units were equally spaced every 50 m and had 100 m of diameter (Figure 21).

Figure 21 – Example of modelling spatial units: areas from which data will be evaluated in the modelling of the reach. Image from eBee flight. Line in red is the Umbuzeiro River talweg.

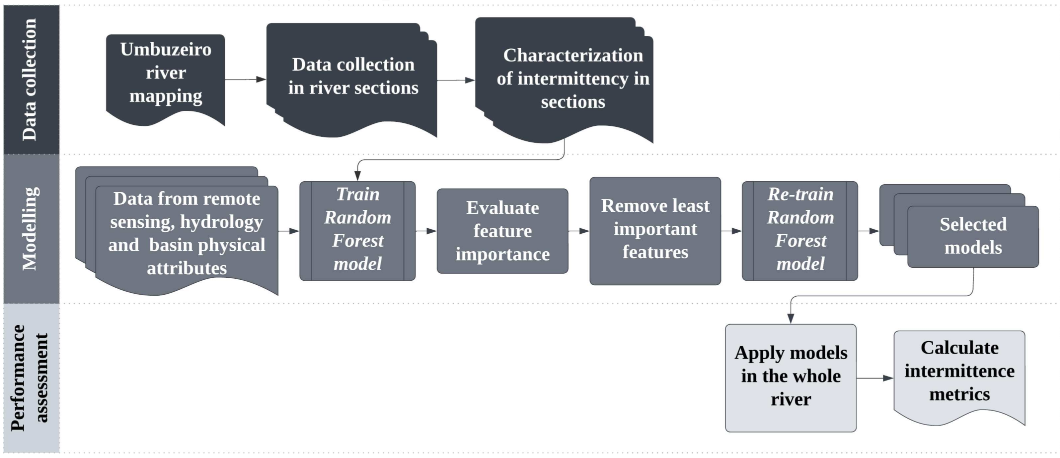


4.2.4 RivInt modelling framework

The workflow was carried out according to the flowchart shown in Figure 22. Initially, data was collected in river reaches and characterised in terms of intermittence and that made the target data (see Section 4.2.2). These observations were used in the training of Random Forest classification models in order to obtain the same class as in the observed data. In a recursive process of variable selection, the importance of the predictors (a.k.a. “features”) was observed and the least important ones were removed. The Random Forest models were re-trained with the selected predictors, and this way, the best models were obtained. In the approach presented here, three models based on subgroups of the predictors were tested and the best predictors in each one were selected. The finalised models were applied to the whole river and intermittence metrics were calculated.

The Random Forest classification model was implemented using the R package "randomForest"(LIAW *et al.*, 2002; BREIMAN, 2001). The importance of predictors is quantified as “variable importance”, which assesses the increase in mean square errors during prediction when a predictor is randomly permuted within the tree. In order to perform the selection of the most suitable predictors, the "rfe"function in the R package "caret"was used. This function performs a Recursive Feature Elimination (RFE), an algorithm that applies a backward selection process to find the optimal combination of features, thus selecting the most relevant predictors

Figure 22 – Flowchart showing steps taken in the modelling process



(GREGORUTTI *et al.*, 2017).

It was also tested whether it was possible to use fewer dynamic data to predict intermittence. For this, models with different data source were tested in three groups: (a) Model using Sentinel variables to capture temporal dynamics; (b) Model using Planetscope indices as dynamic predictors; and (c) Model using hydrological data as the only source of temporal dynamics. This way, each of this predictor subgroups resulted in a model.

4.2.5 Performance assessment and comparison

4.2.5.1 Cross-validation

A cross-validation procedure was carried out with data partitioning into training and testing data sets. The training set is created from selecting randomly 75% of the observations. The test set consists of the remaining 25%. After the training, the evaluation criteria were calculated on the test set. This was repeated 20 times in order to consider uncertainties on the data set partitioning (BEAUFORT *et al.*, 2019).

The tested models used different number of observation data. Since satellite images are needed in the case of the models a and b, images in concomitant dates (more or less one week from flight date) were considered in the training process. In Figure 20, for the Sentinel images (model a), there are three concomitant dates; and for Planetscope (model b), there are four. In the case of the last model (c), since satellite images are not needed, all five UAV surveys could be used.

4.2.5.2 Evaluation criteria

Several validation criteria are calculated to compare the performance of the models. For a general assessment of modelling performance, out-of-bag error estimates (OOB) from Random Forest models training were used. The error estimates from trained models were compared to a benchmark classifier that simply estimates dominant class from the overall dataset. Probability of detection was calculated on test dataset (BEAUFORT *et al.*, 2019; EASTMAN *et al.*, 2021).

4.2.5.3 Spatio-temporal extrapolation evaluation

In order to assess the extrapolation ability of the models, they were calibrated over river reaches during the period with available overlapping data (different for each model, see Figure 20) and they were applied to the whole river in the remaining dates of 2022. For the Sentinel and Planetscope models, the images are available almost exclusively on the dry season. For the third model, the application was carried out for the whole year.

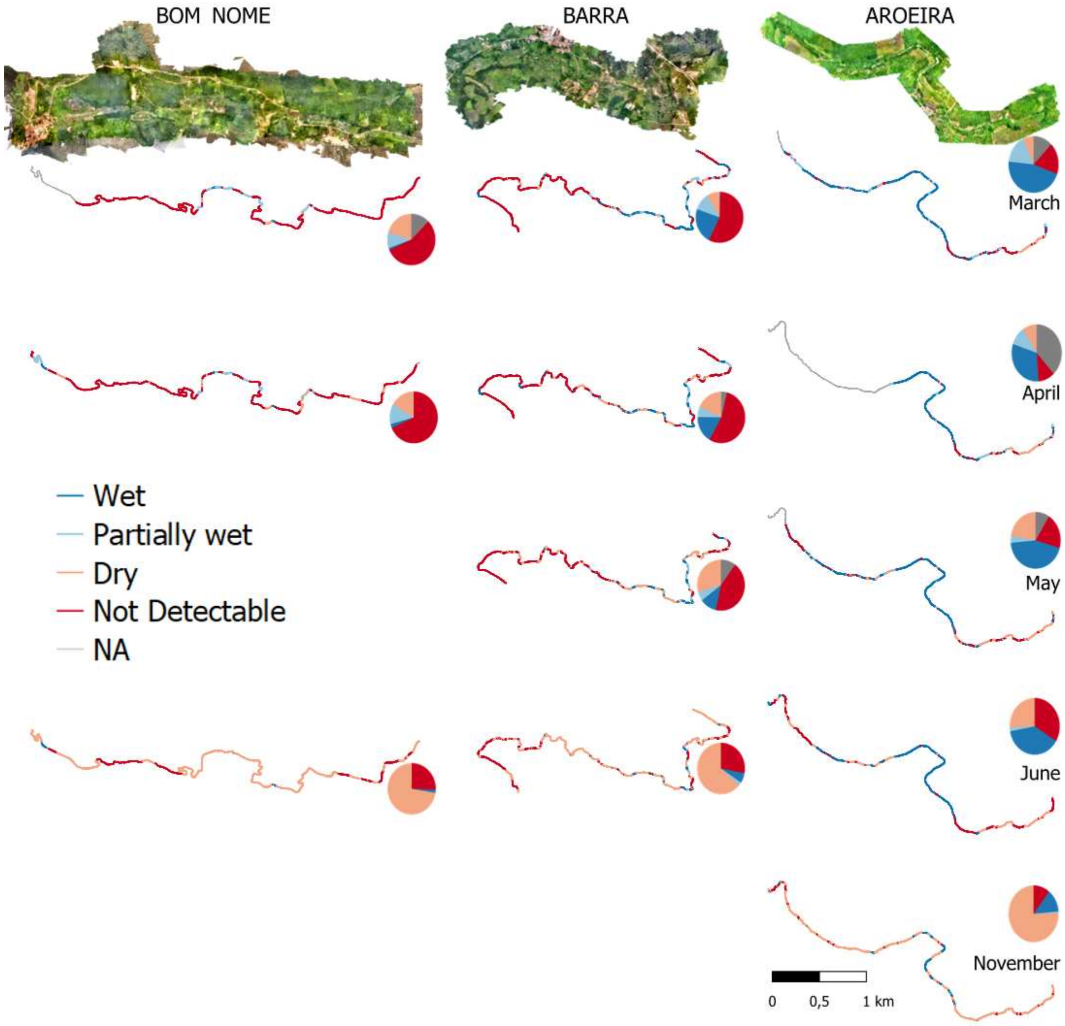
The results were evaluated in terms of temporal and spatial distribution. For the temporal evaluation,the proportion of each class in the river was calculated at each date. For spatial extrapolation, the number of days that each modelling unit had either a wet or partially wet condition were analysed and assessed for plausibility.

4.3 Results

4.3.1 Observed water intermittency: UAV surveys

Figure 23 shows the spatio-temporal evolution of the four classes in the three reaches where the UAV surveys were carried out. As expected, the wet class is more present in the most downstream reach (Aroeira) and its share diminishes towards the dry season. Since the vegetation is deciduous and during the dry season, most of Caatinga vegetation is leafless, the "not determined"(NotDet) class tends to be smaller. Conversely, the dry class is more present in the dry season, since it is easier to discern the riverbed with leafless vegetation.

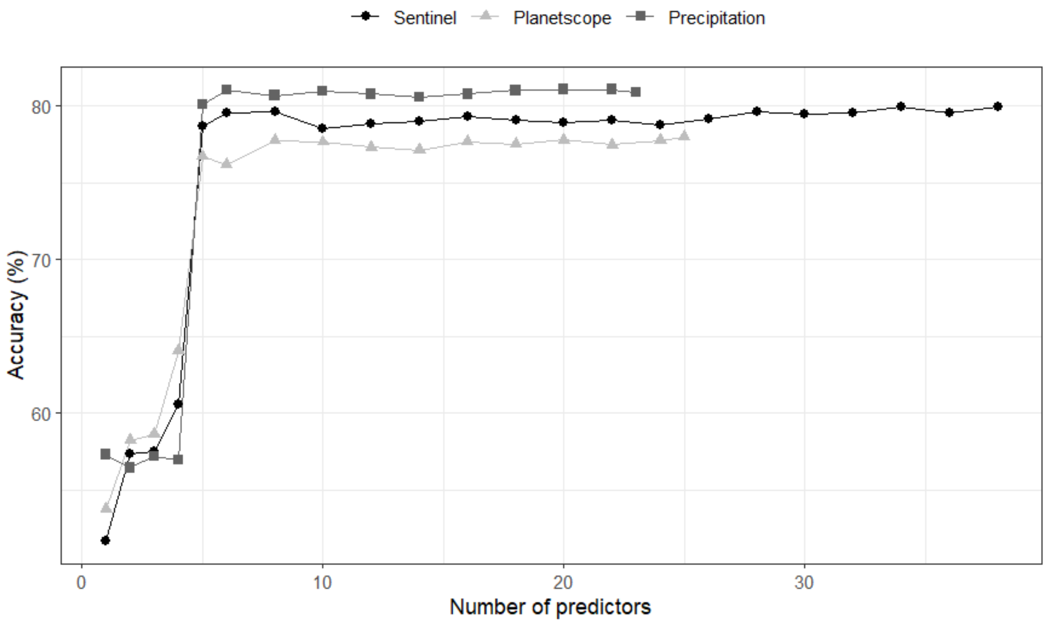
Figure 23 – Observed data on the four classes (Wet, Partially wet, Dry, and Not Detectable) during the UAV surveys carried out on the three reaches of Umbuzeiro River (river flowing from left to right)



4.3.2 Identification of most relevant predictors

Model accuracy in relation to the number of predictors is shown in Figure 24. For all three models, five predictors were enough to reach saturation in accuracy. Using the Recursive Feature Elimination tool (RFE), it was possible to observe almost no gain in using all predictors (GREGORUTTI *et al.*, 2017). The same four predictors were selected for all three models: mean altitude, drainage area, distance from last dam, and distance to next dam (Table 7). The difference for each model was only one dynamic predictor. One normalised index for each of the remote sensing models a and b (Sentinel and Planetscope), and accumulated precipitation (30 days) for the precipitation model (model c).

Figure 24 – Acquired accuracy in relation to the number of predictors



The final models with the selected predictor are shown in Table 7. Similarities in the importance value of predictors in models Planetscope and Precipitation were observed. In both of them, the dynamic predictor was the most relevant. For the Sentinel model, the most important was drainage area and the Sentinel index had the smallest value.

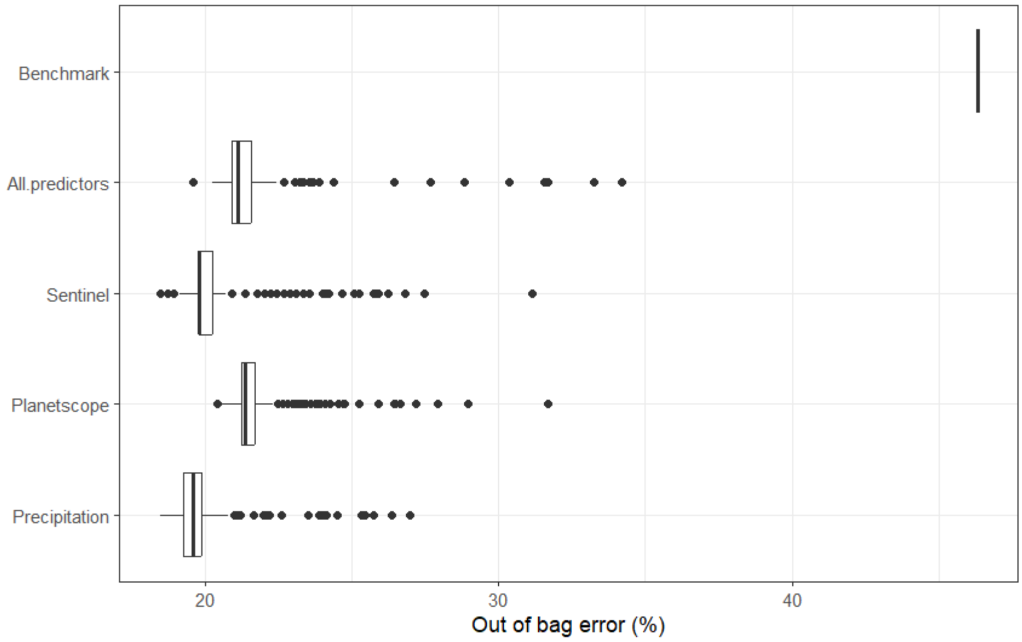
Table 7 – Selected predictors and their importance (%) in their respective model after re-training

Variables	**Sentinel (Model a)**	**Planescope (Model b)**	**Precipitation (Model c)**
	Importance (%)		
Mean altitude	0.14	0.13	0.13
Drainage area	**0.28**	0.21	0.24
Distance from last dam	0.21	0.20	0.19
Distance to next dam	0.24	0.18	0.17
Sentinel MNDWI	0.13		
Planetscope NDVI		**0.29**	
Acummulated precipitation (30 days)			**0.28**

4.3.3 Model performance evaluation

The model using all the predictors available and the three models with selected predictors outperformed benchmark. The out of bag error (OOB) for all models are shown in Figure 25. The models Sentinel, Planetscope and Precipitation were trained only with the selected variables shown in Table 7. Among the three models with selected predictors, the Planetscope model performed slightly worse. Both Sentinel and Precipitation models performed slightly better than the model with all predictors.

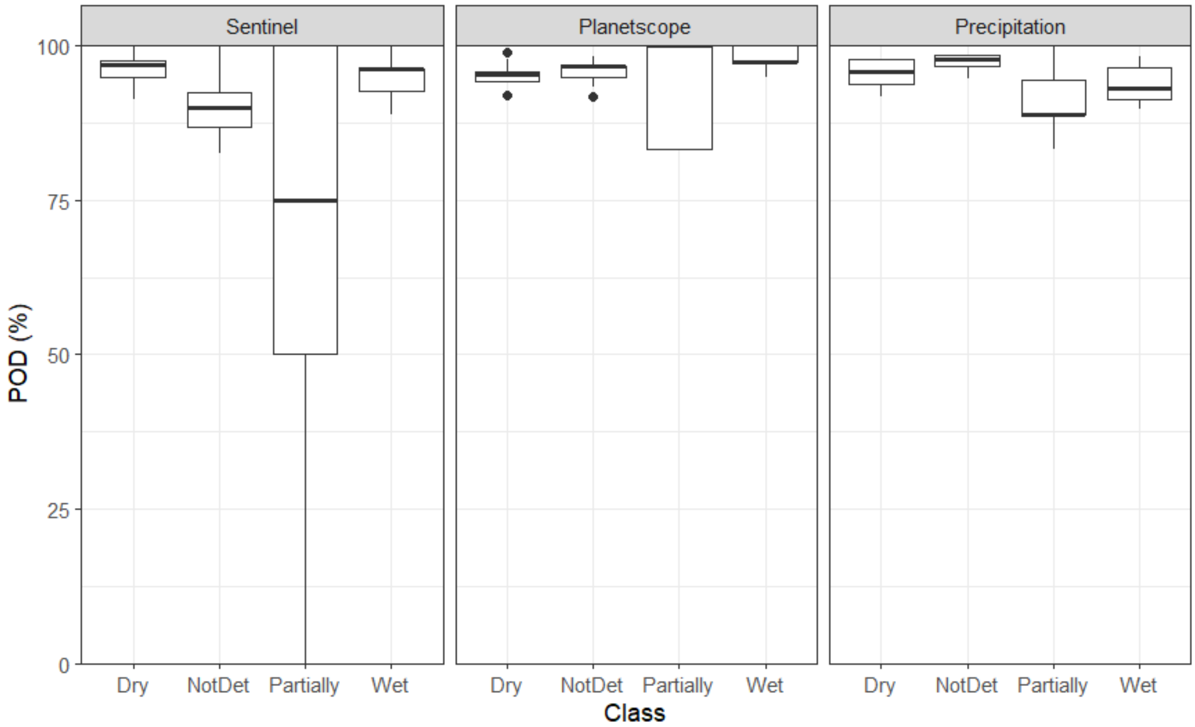
Figure 25 – Comparison between models with all predictors and models with selected predictors on full dataset



Similar results were obtained by the three models regarding test data (Figure 26). The classes had different probability of detection (POD) rates. For all models, "Partially wet"was the class most difficult to predict. The classes "Dry"and "Wet"had very similar detection rates, and for "NotDet"it was slightly lower. For the "Partially wet"class, this result is expected since it had the smallest number of observations. The overall performance of "Dry"and "Wet"classes can be explained by their probably more homogeneous classification, whereas a higher heterogeneous classification can be expected from the "NotDet"class.

Model performance can be observed in detail in Figure 27. An example is shown to better capture the comparison between observed and predicted classes at each modelling unit. Training and test data sets are separated also for a better observation. In this example, model accuracy was 77% for the test data.

Figure 26 – Performance of models: Probability of Detection (POD) based on test data
(a)



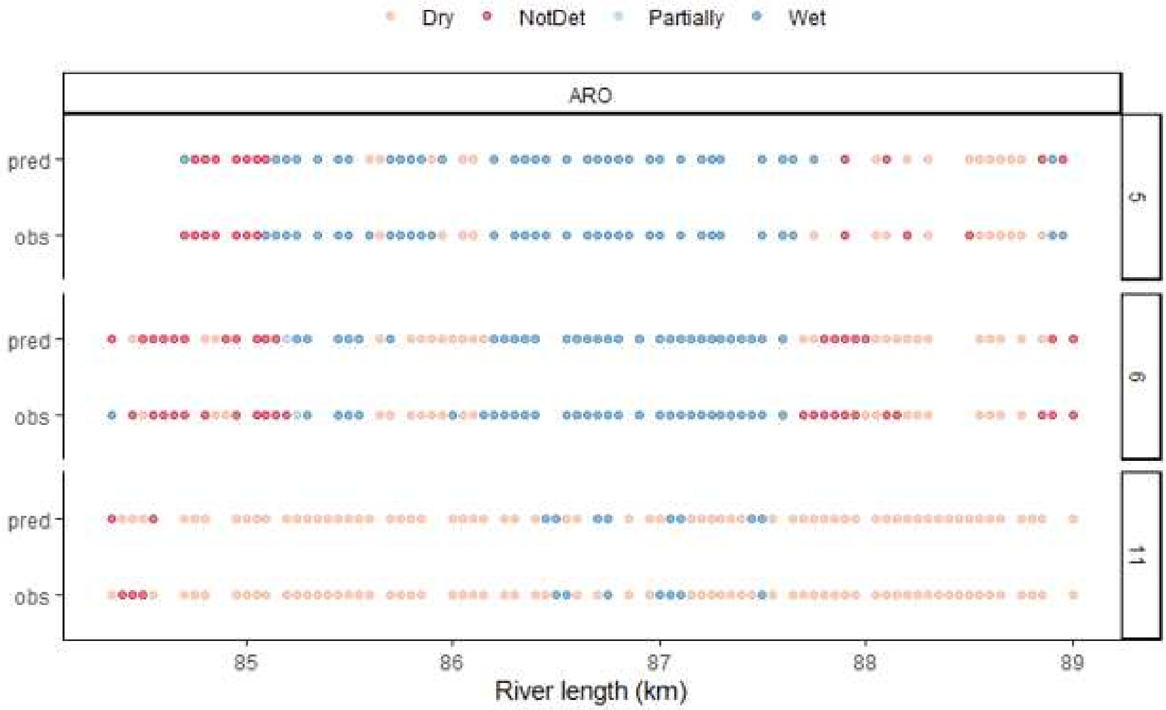
4.3.4 Umbuzeiro River: extrapolation with models

The proportion of each class in the whole river is shown in Figure 28 for each model. The models were applied with all available data in 2022 and the temporal distribution is shown for each class. The Precipitation model is the one least sensitive to temporal variation specially in the "Wet"class. For both Sentinel and Planetscope models, there is a gradual decrease of "Wet"and "NotDet"classes as the dry season progresses.

With the model extrapolation applied to the whole river, the number of days with either "Wet"or "Partially wet"classes were calculated for each spatial unit, indicating “water in the riverbed” (WIR). In Figure 29, the number of WIR-days varies differently depending on the model. For the models Sentinel and Planetscope, it varies from 0 to 12 days and for the Precipitation model the value varies from 0 to 365 days with either condition. Although with different scales, it is possible to observe similar areas in all three models that are prone to wetter conditions. However, it is shown in the extreme right that only the models Sentinel and Precipitation identified the Benguê reservoir as a place with frequently wet or partially wet.

Figure 27 – Modelling results comparing predicted (pred) and observation (obs) classes considering training (a) and testing data sets (b). Example shows the results in Aroeira reach (ARO), with Sentinel model for the months of May (05), June (06) and November (11)

(a) Training data set (75%)



(b) Testing data set (25%)

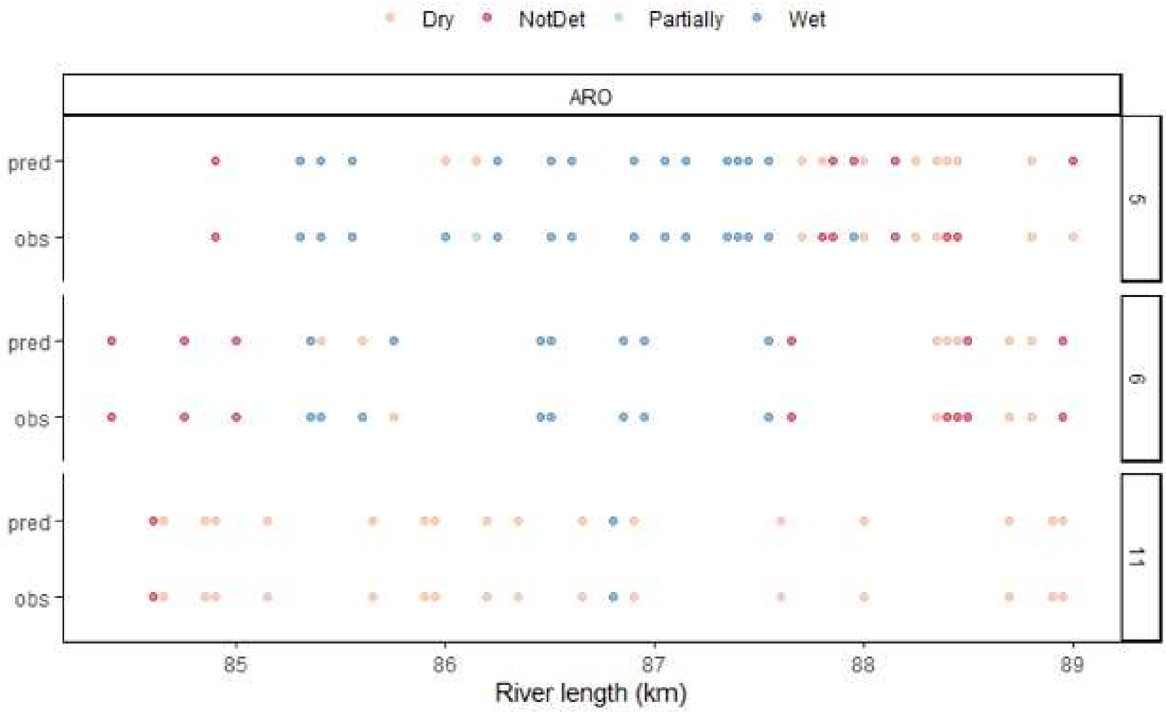
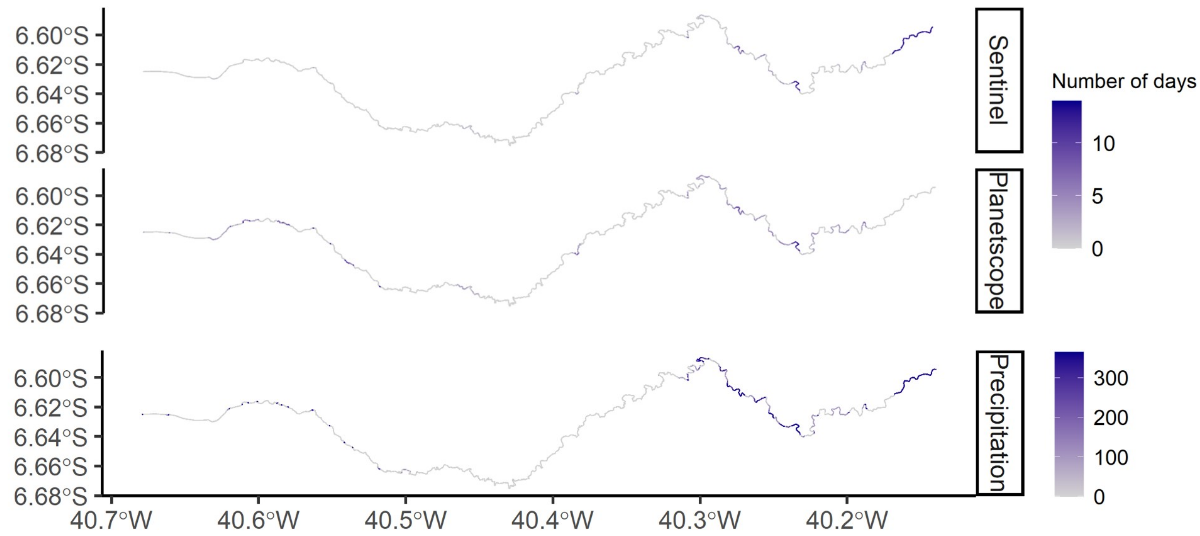


Figure 28 – Application of models with all available data for 2022

Figure 29 – Number of days with wet or partially wet classes



4.4 Discussion

The importance of the predictors was similar for all the Random Forest models. Basin physical attributes predictors were among the selected predictors: mean altitude and maximum drainage area of the modelling unit. Catchment area or drainage area was identified as a very important variable to classify streams as temporary or perennial (GONZÁLEZ-FERRERAS; BARQUÍN, 2017; SNELDER *et al.*, 2013). Altitude is also a relevant variable to identify intermittent streams (D'AMBROSIO *et al.*, 2017; SNELDER *et al.*, 2013). Heterogeneity of physiographic characteristics also helps. When studying intermittency, Beaufort *et al.* (2019) analysed homogeneous catchments and it was difficult to correlate physical attributes to water occurrence.

Regarding connectivity, the distance from dams was an important static predictor. This shows that even small dams can impact river intermittency. Small dams individually and cumulatively are shown to alter lotic ecosystems (FENCL *et al.*, 2015). The impact on water accumulation upstream and the lack of water downstream a dam are the most clear effect of dams when identifying water occurrence in river reaches.

Dynamic predictors were important to observe temporal variation within a hydrological year. The models differ in which dynamic variable they use to predict intermittency. The simplest model (model c), although it had satisfactory performance in test data, did not show good temporal extrapolation of river drying dynamic. The better plausibility of Sentinel (model a) and Planetscope (model b) models is due to the more detailed and distributed information that they add to the application of the models. The use of Sentinel MNDWI in the study of open-surface water was done in large water bodies and perennial rivers (JIANG *et al.*, 2021; LI *et al.*, 2020). With the findings presented here, it is emphasised the possibility to use this index even in narrow temporary rivers. Planetscope NDVI was used successfully to access LULC change detection, including detection in water classes (WANG *et al.*, 2022).

Regarding spatial distribution of intermittency, the Precipitation model outperformed the Planetscope model, when it identified important reservoirs as areas prone to pounding. The Sentinel model also showed important benefits in this aspect, indicating mainly areas in the lowest part of the basin. The identification of those areas is very important event in the smallest of scales because it could be key areas to river ecology. The mapping of intermittency of wet and dry conditions throughout the river in temporary rivers is essential to analyse the migration and resilience of species, to understand their habitat and to conduct studies on river metabolism.

4.5 Conclusion

First contribution of this chapter refers to the selection of predictors as the main drivers of intermittency in the study area. Consistent static variables were identified in the three models (mean altitude, drainage area, distance from last dam, and distance to next dam), and dynamic predictors that differ for each model: (a) Sentinel MNDWI; (b) Planetscope NDVI; and (c) accumulated precipitation (30 days). Different dynamic predictors can be used depending on data availability with the possibility to increase detailed information depending on the detailed input available.

River intermittency was modelled for the Umbuzeiro River, capturing temporal and spatial dynamics. Sentinel and Planetscope models captured the temporal dynamics in model extrapolation to the whole river, whereas the precipitation model showed small ability to model the drying of the river as the dry season advanced. Regarding spatial distribution of intermittency, Planetscope performed worst, not being able to map important spots of water accumulation. This way, the Sentinel model was the best with good temporal and spatial response based on its ability to extrapolate.

The application of the results presented here is relevant to both ecological and hydrologycal studies to understand and evaluate river dynamics, but also pool formation. For hydrological studies, the dry and wet patterns can be used to better understand streamflow formation, drying and wetting frequency, and impacts of damming structure on river connectivity. For ecology, the mapping of intermittency of wet and dry conditions throughout the river in temporary rivers is essential to analyse the migration and resilience of species, to understand their habitat and to conduct studies on river metabolism.

5 GENERAL CONCLUSIONS

The organisation and cataloguing of data acquired over the last 20 years in Aiuaba Experimental Basin (AEB) was important to consolidate the work carried out in the experimental basin. This way, it is possible to preserve data acquired in the high-density monitoring scheme in preserved Caatinga conditions in AEB, and facilitate access and reusability. The new data organisation proposal can contribute a lot to current and future work developed in the region. This documentation will be useful for future users of the database, but also for current and continuous work, facilitating the updating of new data collected in coming campaigns.

The proposal and application of the novel MISD (Method for Identification of Seasonality in Drylands) method for hydrological seasons identification allowed the the reproducible characterisation of seasons in the Brazilian semi-arid region using objective criteria based on precipitation, soil moisture and vegetation. The application of the method to AEB allowed a more detailed observation of the seasonal behaviour of hydrological characteristics in the region and the study of possible trends. We observed, for instance, the trend of a longer rainy-dry transition season. No trend was observed neither regarding the amount of precipitation and number of rainy days in any season, nor concerning the starting date of seasons. Since there was no observed effect on those variables, the changes that are taking place could be related to a more general shift in the time frame of hydrological processes in the Caatinga biome.

The modelling of intermittency in the study area identified consistent static variables (mean altitude, drainage area, distance from last dam, and distance to next dam), and dynamic predictors that differ for each model: (a) Sentinel MNDWI; (b) Planetscope NDVI; and (c) accumulated precipitation (30 days). Regarding temporal and spatial distribution of intermittency in Umbuzeiro river, models (a) and (b) models captured the temporal dynamics in model extrapolation to the whole river, whereas model (c) showed small ability to model the drying of the river as the dry season advanced. This way, model (a) had both good temporal and spatial response based on its ability to extrapolate.

The application of the results presented here is relevant to both ecological and hydrological studies to understand and evaluate river dynamics, but also pool formation. For hydrological studies, the dry and wet patterns can be used to better understand streamflow formation, drying and wetting frequency, and impacts of damming structure on river connectivity. For ecology, the mapping of intermittency of wet and dry conditions throughout the river in temporary rivers is essential to understand their habitat.

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APPENDIX A – AIUABA EXPERIMENTAL BASIN DATABASE

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DEPARTAMENTO DE ENGENHARIA AGRÍCOLA
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA AGRÍCOLA

GRUPO DE ESTUDOS HIDROSEDIMENTOLÓGICOS NO SEMIÁRIDO (HIDROSED)

BANCO DE DADOS DA BACIA EXPERIMENTAL DE AIUABA - BDBEA

FORTALEZA
2022

SUMÁRIO

1 INTRODUÇÃO

A essência metodológica do uso de bacias experimentais consiste em examinar o comportamento temporal dos processos hidrológicos em uma determinada resolução temporal (dias, tempestades, estação, anos) e a partir disso concluir quanto a hidrologia da área de estudo.

A bacia experimental de Aiuaba (BEA) é uma bacia de monitoramento contínuo que foi implementada em 2003 e é desde então monitorada pelo Grupo de Pesquisa Hidrossedimentológica no Semiárido (HIDROSED). Entre as variáveis hidrológicas estudadas no local e mensuradas pelo grupo estão: precipitação, interceptação evaporação, evapotranspiração, escoamento superficial, erosão etc.

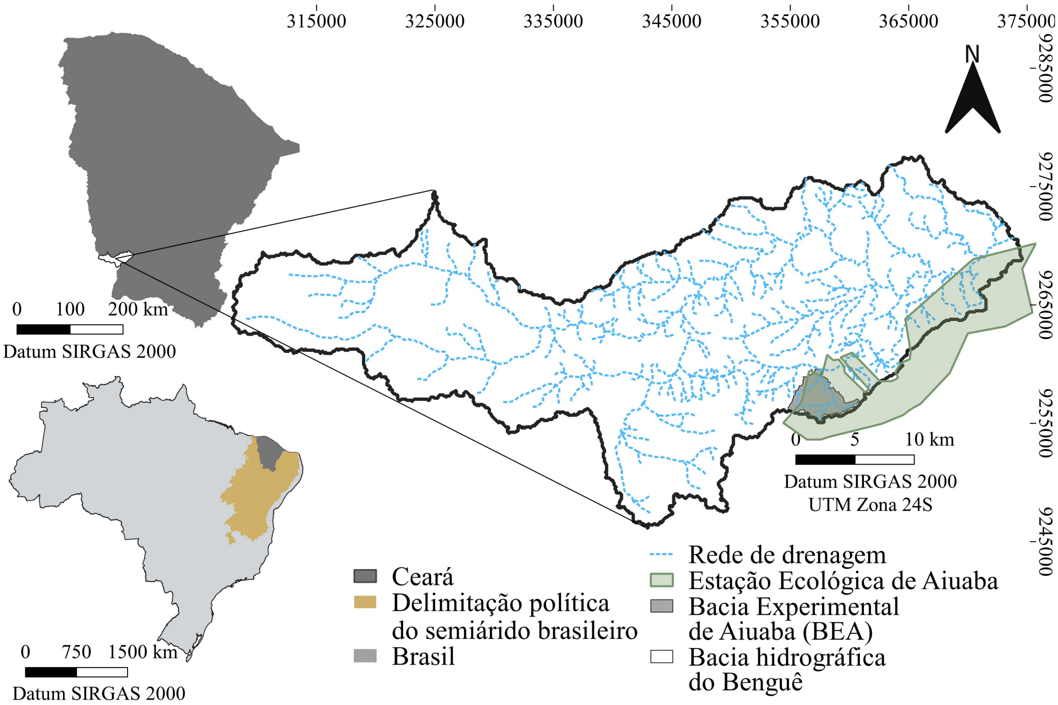
Um renascimento está ocorrendo entre os estudos de bacias experimentais, em resposta às questões políticas e científicas contemporâneas, às novas tecnologias e ao valor reconhecido de locais com forte histórico de pesquisa e contextos temporais e geográficos úteis (ALMEIDA *et al.*, 2019; PEREIRA *et al.*, 2017; ARAÚJO FILHO *et al.*, 2018).

O Banco de dados da Bacia Experimental de Aiuaba (BDBEA) consolida e organiza os dados presentes na BEA. O presente documento consiste em um arquivo único para instruir o usos dos dados presentes no BDBEA, contendo referências de trabalhos que possam ser úteis ou que iniciaram a coleta de um determinado dado.

2 BACIA EXPERIMENTAL DE AIUABA

A bacia experimental de Aiuaba (BEA) está localizada na bacia hidrográfica do Benguê e tem área de aproximadamente 12 km^2 (Figura 1). A bacia é uma área preservada e é coberta integralmente com floresta de caatinga-arbórea densa, sendo controlada pelo reservatório Boqueirão (60 mil m^3) em seu exutório. Situada dentro da Estação Ecológica de Aiuaba (ESEC de Aiuaba), é a maior unidade de conservação federal do bioma Caatinga administrada pelo IBAMA (DE ARAÚJO; PIEDRA, 2009). Assim, essa área representa um importante papel para o ciclo hidrológico da região devido, principalmente, à sua cobertura florestal densa, estando associada à manutenção da biodiversidade florística e faunística do bioma Caatinga (ALMEIDA *et al.*, 2019).

Figura 1 – Mapa de localização da área de estudo, mostrando a Bacia Experimental de Aiuaba (BEA) localizada no município de Aiuaba, CE em relação à Bacia hidrográfica do Açude Benguê e à Estação Ecológica de Aiuaba

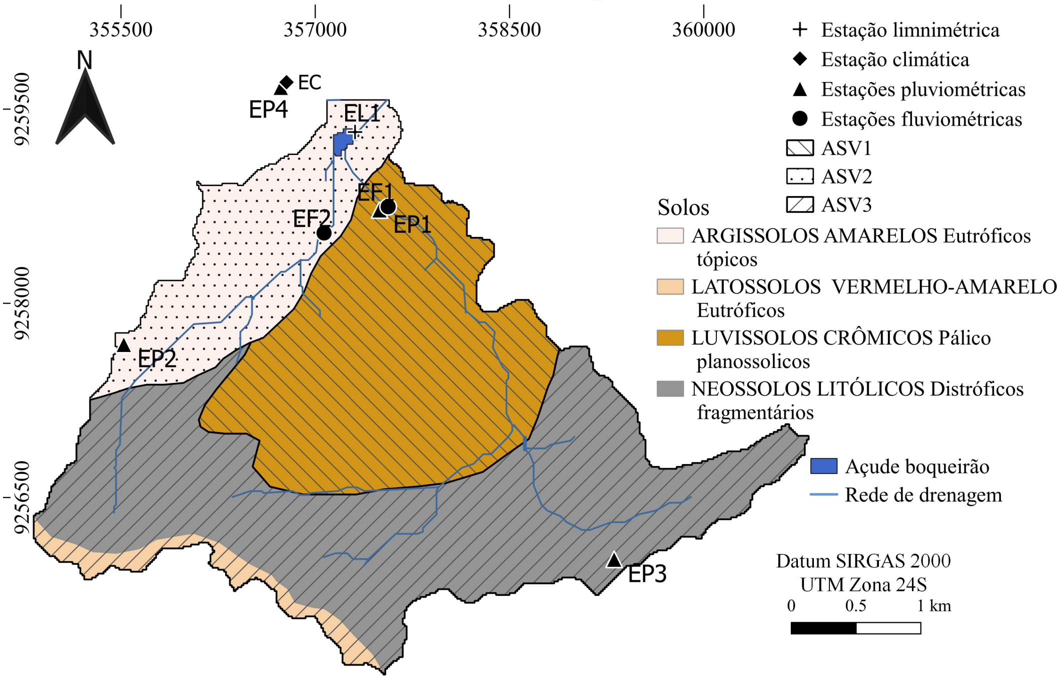


2.1 ASVs e tipos de solos

Na perspectiva de estudos hidrológicos realizados em escalas de bacias hidrográficas em áreas preservadas, é comum adotar a associação principal entre solo e vegetação a fim de melhor representar a variabilidade espacial. Na BEA, adotaram-se associações solo-vegetação

(ASV), que são unidades relativamente homogêneas para estudos das variáveis ambientais (COSTA *et al.*, 2013; PINHEIRO *et al.*, 2013). Almeida (2016) utilizou a definição de ASV para a BEA adotando a classificação de solos realizada por Araújo (2012) (Figura 2).

Figura 2 – Estações de monitoramento na Bacia Experimental de Aiuaba (BEA)



O mapa de solos elaborado por Araújo (2012), a partir de levantamento in situ, mostra quatro classes distintas de solos na BEA, sendo elas: ARGISSOLOS AMARELOS Eutróficos típicos; LATOSSOLOS VERMELHO-AMARELO Distróficos típicos; LUVISSOLOS CRÔMICOS Pálico planossólicos e NEOSSOLOS LITÓLICOS Distróficos fragmentários (Figura 2). Observa-se na Tabela 1 o tipo de solo predominante e a área de ocupação de cada ASV.

Tabela 1 – Distribuição das classes de solos predominantes na Bacia Experimental de Aiuaba (BEA)

ASV	Classe de solo predominante	Ocupação na BEA (km²/%)
ASV1	LUVISSOLOS CRÔMICOS	2,40/20
ASV2	ARGISSOLOS VERMELHO - AMARELO	4,08/34
ASV3	NEOSSOLOS LITÓLICOS	5,52/46

Fonte: Pinheiro *et al.* (2016)

A espécie Caesalpinia pyramidalis Tul E. Gagnon G. P. Lewis conhecida como catingueira é a planta de porte arbóreo de maior ocorrência na ASV1 (ALMEIDA, 2016; CARVALHO et al., 2016; COSTA, 2012; FIGUEIREDO, 2018; TILLESSE, 2017). Podendo chegar a 10 m de altura e 0,5 m de diâmetro, tem ocorrência e ampla dispersão na região. A catingueira é uma espécie decídua com período de rebrotamento rápido, que em aproximadamente 30 dias após o início da estação chuvosa está em vegetação plena.

Na ASV2 a espécie de maior ocorrência é a Piptadenia obliqua (Pers.) Brenan, o Angelim (ALMEIDA, 2016; CARVALHO et al., 2016; COSTA, 2012; PINHEIRO et al., 2016). O Angelim apresenta uma altura média de 4 a 5 m e tem ocorrência em toda a bacia, com perda de todas suas folhas na estação seca. Enquanto que na ASV3 a espécie Mimosa tenuiflora (Willd.) Poir, popularmente chamada de Jurema-preta (ALMEIDA, 2016; CARVALHO et al., 2016; COSTA, 2012; PINHEIRO et al., 2016). Com altura de 3 a 7 m e caule ereto, a Jurema-preta tem boa parte de sua folhagem perdida ao fim do período chuvoso. Além disso, essa espécie possui raízes com alta capacidade de penetração nos terrenos compactos (MAIA, 2004).

2.2 Levantamento de trabalhos realizados na BEA

A BEA tem sido monitorada pelo Grupo de Pesquisa Hidrossedimentológica no Semiárido (HIDROSED) desde sua implantação em 2003, pela atuação do projeto FINEP/IBESA, com objetivo principal de fazer a medição de variáveis hidrológicas no semiárido brasileiro (COSTA, 2012b). Estudos realizados na área incluem a análise de processos hidrológicos como precipitação (MEDEIROS; ARAÚJO, 2014; DE ARAÚJO; PIEDRA, 2009; RODRIGUES; ARAÚJO, 2019; BARBOSA *et al.*, 2018), evapotranspiração (COSTA *et al.*, 2021; SOARES, 2019; TEIXEIRA, 2018), evaporação (COSTA, 2007), transpiração (FIGUEIREDO, 2018), interceptação (MEDEIROS *et al.*, 2009), relação solo-planta-atmosfera (ALMEIDA *et al.*, 2019; PINHEIRO *et al.*, 2016; PINHEIRO *et al.*, 2017) e escoamento superficial (FIGUEIREDO *et al.*, 2016), assim como estudos sedimentológicos (ARAÚJO, 2012; FARIAS *et al.*, 2019) e hidrogeológicos (COSTA *et al.*, 2013). A Tabela 2 mostra os trabalhos realizados na região e os dados utilizados.

2.3 Coleta de dados na BEA: dados primários e secundários

Os dados coletados pelo grupo Grupo de Pesquisa Hidrossedimentológica no Semiárido (HIDROSED) na Bacia Experimental de Aiuaba (BEA) formam prioritariamente o BDBEA. Medições de variáveis climáticas, hidrológicas e de produção de sedimentos são realizadas desde 2003 em diferentes pontos da bacia. O monitoramento na BEA acontece principalmente com

Tabela 2 – Trabalhos realizados na Bacia Experimental de Aiuaba (BEA) pelo Grupo de Pesquisa Hidrossedimentológica no Semiárido (HIDROSED)

Citação dos trabalhos	Processos hidrológico estudados	Dados utilizados
Costa (2007)	Principais processos hidrológicos	Precipitação, nível do açude, escoamento, evaporação
De Araújo e Piedra (2009)	Hidrologia comparada	Precipitação, nível do açude, escoamento
Medeiros *et al.* (2009)	Cálculo da interceptação	Precipitação
Araújo (2012)	Estimativa de assoreamento	Solos, sedimentos, uso e ocupação
Costa *et al.* (2013)	Umidade do solo na zona das raízes	Umidade do solo, tipo de solo, dados meteorológicos, topografia
Pinheiro *et al.* (2013)	Profundidade efetiva das raízes	Tipo de solo
Medeiros e Araújo (2014)	Variabilidade temporal da chuva	Precipitação, nível do açude, sedimento
Carvalho *et al.* (2016)	Relação entre NDVI e IAF	Índice de área foliar, imagens landsat
Figueiredo *et al.* (2016)	Iniciação do escoamento	Precipitação, umidade do solo
Pinheiro *et al.* (2016)	Modelagem relação solo-água-planta	Umidade do solo, tipo de solo, dados meteorológicos, topografia
Pinheiro *et al.* (2018)	Disponibilidade hídrica para as plantas	Umidade do solo, tipo de solo, dados meteorológicos, topografia
Lourenço *et al.* (2017)	Separação de classes de solos com sensor	Uso de sensor próximo no solo
Tilesse *et al.* (2021)	Potencial de armazenamento de água nas plantas	Levantamento fitossociológico, turgência dos troncos
Pinheiro *et al.* (2017)	Cenários de mudanças climáticas	
Teixeira (2018)	ETP e balanço hídrico	Imagens Rapideye, precipitação, umidade do solo, dados meteorológicos
Barbosa *et al.* (2018)	Padrão de precipitação sub-horário	
Almeida *et al.* (2019)	Relação entre IAF e variáveis espectrais e hidrológicas	Índice de área foliar, imagens landsat, umidade do solo, precipitação, ETP
Rodrigues e Araújo (2019)	Curvas IDF	Precipitação
Morais (2019)	Sucessão vegetacional	Levantamento fitossociológico
Soares (2019)	ETP modelada	Umidade do solo, tipo de solo, dados meteorológicos, topografia
Farias *et al.* (2019)	Estradas Rurais não Pavimentadas Como Fonte de Sedimentos	Precipitação, erosão
Costa *et al.* (2021)	Evapotranspiração real por imagens de satélite	Dados climatológicos e imagens Landsat

o uso das estações pluviométricas: EP1, EP2 e EP3 (até 2009), as quais registram dados de precipitação a cada 5 min, 1 hora e 6 horas. Além disso, a umidade horária é captada por um sensor TDR (*Time Domain Reflectometry*) instalado na camada de 0 – 20 cm do solo, camada em que estão presentes cerca de 50% das raízes (PINHEIRO *et al.*, 2013). A Figura 2 apresenta a localização de todas as estações.

No exutório da bacia, o açude Boqueirão é monitorado com medições diárias de nível. As vazões afluentes ao açude Boqueirão são monitoradas nos dois riachos principais por meio do uso das estações fluviométricas, o que ocorreu durante alguns períodos. A Tabela 4 apresenta a lista das estações em funcionamento, além das variáveis monitoradas e dos intervalos de medição.

Tabela 3 – Estações de monitoramento operadas pelo Grupo de Pesquisa HIDROSED em Aiuaba, Ceará

Estação	Localização	Instrumento	Variável	Intervalo de medida	Período de observação
EP1	ASV1	Pluviômetro TDR Tanque Classe A Sensor de fluxo de seiva Sensor de umidade do caule Sensor de umidade do solo Sensor de temperatura do solo	Chuva Umidade do solo Evaporação Transpiração	5 min 1 hora 1 hora 1 hora	Desde 2003 Desde 2003 2003 a 2006 2016 a 2018
		Anemômetro Termo-higrometro Sensor de radiação Sesor de temperatura do dossel Lisimetro de pesagem	Evapotranspiração real	10 min	Desde 2021
EP2	ASV2	Pluviômetro TDR	Chuva Umidade do solo	5 min 1 hora	Desde 2003 Desde 2003
EP3	ASV3	Pluviômetro TDR	Chuva Umidade do solo	5 min 1 hora	2003 a 2010 2003 a 2010
EP4	Próximo à bacia experimental	Pluviômetro TDR Tanque Classe A Sensor automático	Chuva Umidade do solo Evaporação Nível de água	5 min 1 hora 1 dia 15 min	2004 a 2005 2004 a 2005 Desde 2003 2003 - 2017
EP5	Próximo à bacia experimental		Chuva Temperatura Umidade relativa do ar Velocidade do vento Radiação solar	1 hora 1 hora 1 hora 1 hora 1 hora	Desde 2021
EL1	Reservatório Boqueirão	Régua linimétrica Sensor automático	Nível de água Nível de água	1 dia 15 min	Desde 2003 2003 - 2017
EF1	Riacho Boqueirão	Calha Parshall	Vazão	30 min	2003 a 2013
EF2	Riacho secundário	Seção triangular	Vazão	30 min	2007 a 2010

Tabela 4 – Estações de monitoramento operadas pelo Grupo de Pesquisa HIDROSED em Aiuaba, Ceará (continuação)

Estação	Localização	Instrumento	Variável	Intervalo de medida	Período de observação
EC1	Sede da ESEC de AIUABA		Chuva	1 hora	2005 a 2008
			Temperatura	1 hora	
			Umidade relativa do ar	1 hora	
			Velocidade do vento	1 hora	
			Direção do vento	1 hora	
			Pressão atmosférica	1 hora	
			Radiação de onda curta	1 hora	

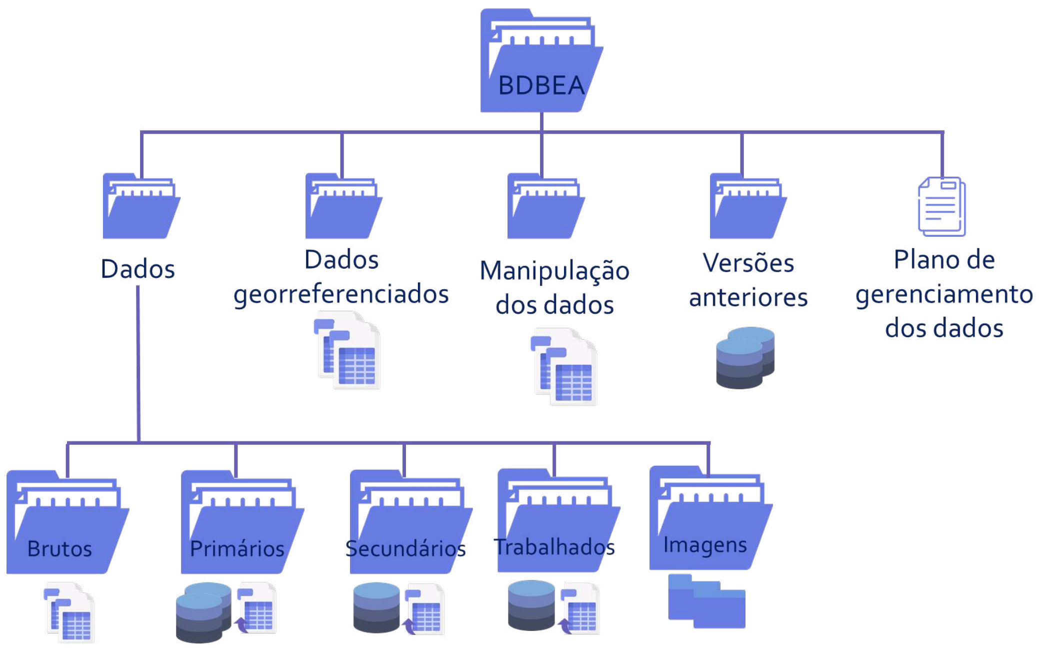
Além dos dados monitorados pelo HIDROSED na BEA, há disponibilidade de dados secundários. Um exemplo é a estação climática monitorada pela Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) localizada nas proximidades da BEA (ver Estação Climática na Figura 2). A FUNCEME e o Instituto Nacional de Meteorologia (INMET) dispõe ainda de séries de dados climáticos em outras estações nas proximidades do município de Aiuaba que foram incluídas como dados secundários. As estações climáticas obtém dados de velocidade do vento, saldo de radiação, temperatura e precipitação. Além desses dados, estações pluviométricas desses e de outros órgãos governamentais também foram incluídas no BDBEA. Maiores informações podem ser adquiridas na Seção 3.1.3.

3 BANCO DE DADOS DA BACIA EXPERIMENTAL DE AIUABA

Os dados coletados na BEA pelo grupo HIDROSED e dados secundários coletados nas imediações da bacia foram estruturados ao decorrer dos anos em único arquivo, organizado no *Microsoft Access* (.accbd), que foi modificado e alterado por diversos membros do grupo. Neste arquivo, os dados são organizados em diversas planilhas diferenciando-se pelo tipo de dado medido e/ou da localização da estação. No entanto, outros dados vieram se acumulando com o decorrer dos anos. Como por exemplo imagens de satélites, dados oriundos delas, voos de veículo aéreo não tripulado ou a manipulação de dados de chuva que possam ter sido explorados em um trabalho e os dados não foram incorporados ao banco de dados (BDBEA). O tamanho dos arquivos e a grande variedade de dados que foram criados de acordo com os trabalho que vinham sendo realizados fez com que a organização e compilação desse material fosse dificultada.

Nesse contexto, uma nova proposta de organização dos dados foi criada pra incorporar diferentes aspectos do banco de dados (Figura 3). Na nova proposta, os dados ficam organizados em diferentes pastas e subpastas juntamente com um arquivo com instruções e informações gerais sobre o banco de dados.

Figura 3 – Esquema geral da organização do Banco de Dados da Bacia Experimental de Aiuaba (BDBEA)



De maneira geral, a estrutura o banco de dados consiste de quatro diretórios, sendo eles: Dados, Ferramentas para manipulação dos dados, Dados georreferenciados e Versões anteriores. Em "Dados"são colocados os principais materiais do banco de dados como dados brutos, dados primários de coleta contínua e descontínua, dados secundários, dados trabalhados, além de imagens de satélite e de voos de veículo aéreo não tripulado. O diretório “Ferramentas para manipulação dos dados” consiste em local para inserir arquivos utilizados na organização do banco de dados e instruções para coleta dos dados dos *dataloggers* instalados no campo, por exemplo. Em “Dados georreferenciados”, os diversos arquivos referentes as informações georreferenciadas da BEA são organizados. Em "Versões anteriores"estão alocadas as versões que não estão mais em uso do banco de dados.

3.1 Dados coletados

Nesse diretório serão encontrados os principais componentes do banco de dados. Como observado na Figura 3, estão presentes os dados brutos, primários, secundários, além dos dados que já foram trabalhados em projetos mais delimitados. As imagens também estão nessa pasta.

3.1.1 Dados brutos

Os dados brutos são aqueles coletados em campanhas e que ainda não foram organizados, nem minimamente processados. Portanto, aqui há uma pasta chamada "Campanhas"com subpastas organizadas de acordo com a data de realização da campanha. O nome de cada subpasta é do tipo "ANO-mês"(por exemplo, "2015-05"). Todos os arquivos referente as campanhas são adicionados em cada uma dessas pastas. Os dados provenientes de um dos *dataloggers* das estações pluviométricas, por exemplo, são adicionados aqui como arquivo .dat, do modo como é baixado.

Em algumas campanhas, múltiplas localidades do município de Aiuaba foram visitadas e os dados são subdivididos de acordo com isso. A localidade de Aroeira, por exemplo, ou a Barra são os locais visitados em algumas campanhas.

Nesta seção, também foram adicionados alguns atalhos para outros arquivos que podem ser interessantes na realização de campanhas e que estão localizados em "Ferramentas para manipulação dos dados"(Seção 3.3). Exemplo disso são os *softwares* que precisam ser instalados para conseguir acesso aos *dataloggers* das estações pluviométricas.

3.1.2 Dados Primários

Os dados coletados na BEA pelo próprio grupo HIDROSED no decorrer dos anos de monitoramento estão presentes principalmente nesta seção. Isso faz dela uma das mais importantes. Os principais arquivos aqui presentes são: "Dados primários de coleta contínua (plurianual).accdb"e "Dados primários de coleta restrita.accdb". Ambos são arquivos organizados no *Microsoft Access* (.accbd).

Há também algumas subpastas, como a que contem os arquivos do tipo .hobo que foram coletados ao longo do tempo na BEA ou em localidades circunvizinhas. Os arquivos não chegaram a ser processados. Portanto, a organização foi feita de acordo com a localização das coletas e com a data em que foram realizadas.

A subpasta "Erosão - Pinos encosta"contém dados referentes a diversas medidas (2008 a 2021) dos pinos de erosão localizados em um a encosta na BEA. Maiores informações podem ser acessadas no trabalho de Pinheiro (2013).

Há também uma subpasta contendo eventos de escoamento ao longo do tempo (Eventos de escoamento (EF1 e EF2)).

A subpasta "Ksat - Pontos medidos"contém diversos dados sobre medições realizadas no âmbito da tese de Costa (2012a).

Além dessas, recentemente foi incluída a subpasta "Disdrômetro"para armazenar os dados coletados pelo equipamento instalado na EP5 em abril de 2022.

3.1.2.1 Dados Contínuos

O arquivo "Dados primários de coleta contínua (plurianual).accdb"compila os dados continuamente coletados na BEA. Um exemplo de como está o arquivo é apresentado na Figura 4. Como pode ser observado, o idioma escolhido para as planilhas e para a disposição das variáveis foi o inglês. Assim também, os dados foram inseridos nas planilhas utilizando o ponto como separador decimal. Em cada planilha, há uma curta descrição em "propriedades da tabela"(acessada por clique com o botão direito na planilha) contendo informações específicas sobre aquelas medições e/ou onde encontrar maiores informações.

Na primeira planilha "#Coordinates"estão descritas as coordenadas geográficas de cada uma das estações presentes na BEA (ver Figura 2). A planilha "Air pressure and temperature"são dados de 2012 que podem ter sido retirados na estação climática da FUNCEME

Figura 4 – Planilhas presentes no arquivo "Dados primários de coleta contínua (plurianual).accdb"

- #Coordinates
- Air pressure and temperature
- Class A pan - hourly (automatic)
- Class A pan evaporation - daily (manual)
- Climate station Aiuaba EC1 WAVES
- Discharge Boqueirao reservoir daily
- Discharge Boqueirao reservoir events
- EF1 station - Discharge
- EF2 station - Discharge
- EL1 water level station - daily lymnimetric ruler
- EL1 water level station - sub-daily automatic
- EP1 gauge - rainfall (5-min)
- EP1 gauge - rainfall (6h)
- EP1 gauge - rainfall (daily)
- EP1 gauge - sap flow sensor
- EP1 gauge - soil moisture
- EP1 gauge - transpiration (daily)
- EP2 gauge - rainfall (5-min)
- EP2 gauge - rainfall (6-hour)
- EP2 gauge - rainfall (daily)
- EP2 gauge - soil moisture
- EP3 gauge - rainfall (5-min)
- EP3 gauge - rainfall (6-hour)
- EP3 gauge - rainfall (daily)
- EP3 gauge - soil moisture
- EP4 gauge - rainfall (5-min)
- EP4 gauge - rainfall (6-hour)
- EP4 gauge - rainfall (daily)
- EP4 gauge - soil moisture
- Interception losses
- Runoff events when ppt >10mm
- Sediment - Boqueirao
- Sediment - EF1 station
- Sediment - EF2 station

da região (ver Estação Climática na Figura 2).

3.1.2.1.1 Meteorologia

A planilha "Climate station Aiuaba EC1 WAVES"diz respeito aos dados de uma estação climatológica que operou de 2005 a 2008 (Figura 4). A estação operou no âmbito do projeto WAVES e para maiores informações, os seguintes documentos podem ser consultados: DE ARAÚJO (2002), Gaiser *et al.* (2003) e Hauschild e Döll (2000). A localização da estação pode ser consultada na planilha "#Coordinates"como "Estação Climatologica 1 - EC1", na sede da ESEC de Aiuaba.

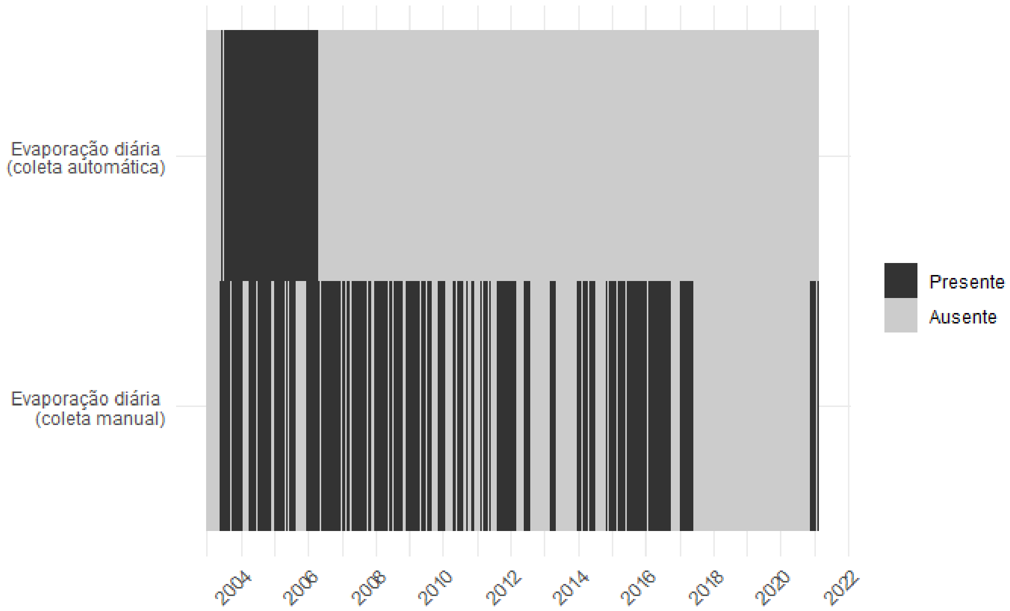
A EP5 se trata de uma estação de medição de variáveis climáticas. No local apresentado na Figura 2, são realizadas medições a cada 5 minutos das seguinte variáveis: Velocidade do vento (m/s), Radiação Solar (W/m²), Chuva (mm), Temperatura (°C) e Umidade Relativa do ar (%).

3.1.2.1.2 Evaporação

O banco de dados conta com duas medidas de evaporação: "Class A pan - hourly (automatic)"e "Class A pan evaporation - daily (manual)". As medidas automáticas horárias foram realizadas de 2003 a 2006 (Tabela 4).

A mensurações manuais da evaporação diária foram realizadas desde 2003 até os dias atuais, apesar de conter falhas durante alguns anos (2018 e 2019, por exemplo). A Figura 5 mostra a falha nos dados dessas duas medições entre 2003 e 2020.

Figura 5 – Dados faltantes de evaporação diária com coleta automática horária e evaporação diária com coleta manual presentes no BDBEA (arquivo "Dados primários de coleta contínua (plurianual).accdb")



Ainda sobre a planilha de evaporação manual, os dados são coletados pela leitura do nível da água. Se houver reposição ou precipitação, isso também é anotado. No recebimento dessas planilhas, é necessário processar os dados para fazer a conversão de unidades e calcular a diferença entre as leituras, diferença essa que vem a ser a evaporação. Nessa planilha, também foi incluída a evaporação média nos últimos sete dias. Todo esse processo é feito conjuntamente e para mais informações sobre o detalhamento das planilhas utilizadas nessa etapa de manipulação dos dados, ver Seção 3.3, onde esse processo será melhor explorado.

Para essa versão do banco de dados, foram realizadas algumas medidas para auxiliar na verificação e melhora da consistência dos dados. Inicialmente, valores de evaporação iguais a zero foram retirados. Assim, quando houve falha nos dados ficaram espaços vazios ao invés de zeros. Em seguida, valores destoantes (mais que 5 vezes maiores que a média) foram desconsiderados.

Foi incluída também uma medida para dirimir os efeitos das constantes faltas de dados. Como é necessário que haja dado no dia atual e o no anterior para ter-se medidas de evaporação, a continuidade é comprometida pelas falhas nos dados. Para contornar esse problema, começou-se a utilizar a diferença entre os dados de dois dias nos casos em que há dado no dia atual e no penúltimo dia. Essa diferença é encontrada e dividida por dois. Ou seja, assume-se que a evaporação é a mesma nesse dia e no dia que não há medida.

3.1.2.1.3 Nível do açude Boqueirão e eventos de escoamento

A seguir, observa-se duas planilhas referentes a descargas no reservatório Boqueirão: "Discharge Boqueirao reservoir daily"e "Discharge Boqueirao reservoir events"(Figura 4). A planilha com os dados diários é um planilha de balanço hídrico, na qual se utilizam os dados da medida de nível do açude, de precipitação, evaporação e retiradas para calcular a descarga no reservatório. Os dados nessa planilha vão de 2003 a 2008, com períodos de falhas. Esses dados foram utilizados no trabalho de Medeiros (2009) e lá podem ser encontradas maiores informações. Uma forma análoga dessa planilha foi utilizada por Figueiredo *et al.* (2016) na determinação de eventos de escoamento.

A planilha de descarga no reservatório por eventos possui poucos dados, apenas do dia 01/01/2007. As duas planilhas seguintes também são de eventos de escoamento ("EF1 station - Discharge"e "EF2 station - Discharge"). Esses são eventos de escoamento que foram registrados em uma das duas estações fluviométricas (Figura 2).

De acordo com os registros de Costa (2007), a medição do deflúvio superficial na BEA iniciou-se sistematicamente a partir de novembro de 2006 com a instalação de um medidor de nível de água automático na calha Parshall, denominados conjuntamente de Estação Fluviométrica 1 (EF1) (Figura 2 e Tabela 4). Essa estação controla uma sub-bacia na BEA de $7,54\ km^2$, localizando-se no riacho principal.

Os dados foram coletados na EF1 utilizando alguns sensores e também leituras manuais. A Figura 6 mostra a calha Parshall com sensor de nível de água instalada no Riacho Boqueirão, com registros de vazão em intervalos de 30 minutos. Maiores informações sobre essa seção podem ser obtidas nos trabalhos de Costa (2007) e também no de Medeiros (2009).

Quanto à Estação Fluviométrica 2 (EF2), um vertedouro triangular foi implementado

Figura 6 – Calha Parshall e amostrador de sedimentos no Riacho Boqueirão, Bacia Experimental de Aiuaba

Fonte: Medeiros (2009)

no riacho secundário da BEA. As medidas também foram feitas em períodos descontínuos, mas relativamente numerosos. Na Figura 7 pode ser observada a seção triangular com sensor de nível de água instalado no riacho secundário da BEA, ajustado para medir em intervalos de 30 minutos. Infelizmente, não há dados com medidas simultâneas nas Estações Fluviométricas 1 e 2.

As planilhas seguintes fazem referência a Estação Linimétrica 1 (EL1) localizada no açude Boqueirão (Figura 2): "EL1 water level station - daily lymnimetric ruler"e "EL1 water level station - sub-daily automatic". A leitura diária do nível do reservatório é realizada desde 2003. As medidas automáticas foram realizadas com um sensor do tipo obo, que mensurava o nível por diferença de pressão entre 2003 e 2008. A coleta de dados automáticos foi descontinuada por problema técnicos nas leituras dos dados. A coleta manual dos dados foi mantida mesmo durante o período de coleta automática.

Ao receber os dados de leitura de nível, além de preencher as colunas referentes ao número da régua e ao valor da leitura, alguns processamentos devem ser considerados. Um deles é a conversão do valor lido na régua em nível do açude. Outros cálculos são os valores de área, volume e diferença de volume calculados de acordo com os valores da CAV do reservatório. Para informações mais detalhadas sobre esse passo a passo, ver Seção 3.3.

Figura 7 – Estação fluviométrica EF2 no riacho secundário da Bacia Experimental de Aiuaba

Fonte: Medeiros (2009)

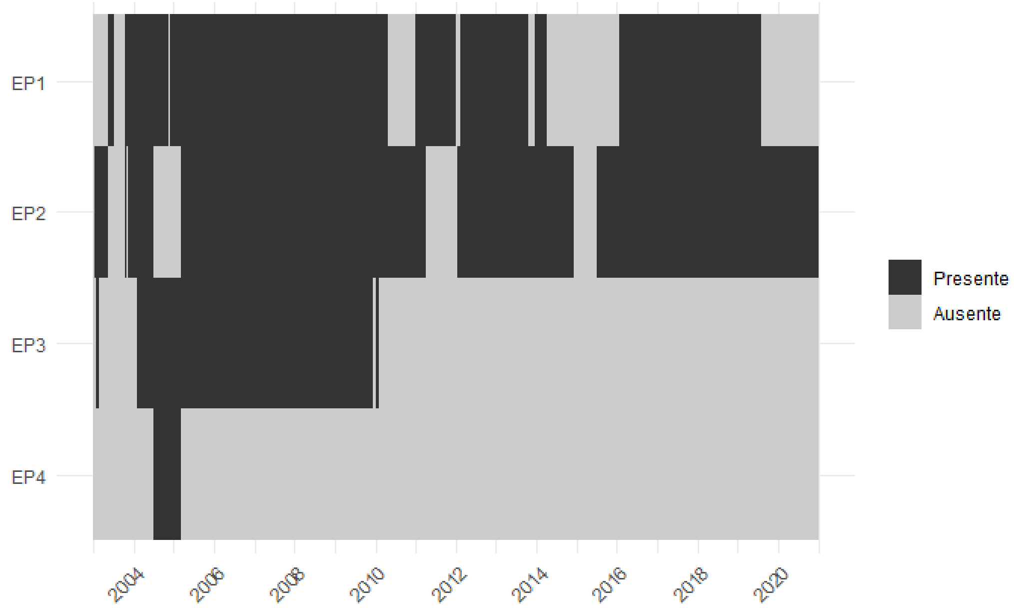
3.1.2.1.4 Precipitação e umidade do solo

As estações pluviométricas possuem a divisão de planilhas bem semelhante. As três estações principais (EP1, EP2 e EP3) foram instaladas em 2003 com dispositivos TB4 (*Tipping Bucket rainfall gauge*), os quais fazem a leitura a cada minuto e armazena o somatório de 5 minutos. No banco de dados, a precipitação de 5 minutos é armazenada quando há valores acima de zero. Ou seja, os valores são recebidos de um dos *dataloggers*, filtrados para dados acima de zero e armazenados. A precipitação a cada 6h e diária é resultado do somatório da precipitação de 5 minutos.

A estação pluviométrica 3 (EP3) foi desativada em 2009 devido a depredação. No seu período de funcionamento, diversas interrupções ocorreram pelo mesmo motivo. A estação pluviométrica 4 (EP4) operou de 2004 a 2005 na localização mostrada na Figura 2. Nesse período, a EP2 necessitou ser recolhida e foi instalada nessa localização próxima à BEA. A localização da EP4 é cerca de 4 km distante do ponto onde as demais medições foram realizadas. Quando a situação foi normalizada, a estação retornou para a localização original. Assim, atualmente, as estações que continuam em funcionamento são as EP1 e EP2 (Figura 8).

A fim de conseguir gerar uma série de dados completa, tomou-se como base a EP2,

Figura 8 – Dados faltantes de precipitação diária presentes no BDBEA (arquivo "Dados primários de coleta contínua (plurianual).accdb")



por ser a estação com menor percentual de dados faltosos e foram utilizados dados das outras estações pluviométricas localizadas na BEA fazendo o preenchimento direto. Durante o período de 2004 a 2005 em que EP2 ficou longe do ponto original e os dados foram armazenados como EP4. Para períodos com dados na EP1, esses foram utilizados para o preenchimento.

Para os períodos que continuaram com falhas, os dados secundários das estações circunvizinhas foram usados na análise de consistência da série histórica, que foi obtida através do Método da Dupla Massa desenvolvido pelo Serviço Geológico dos Estados Unidos (SEARCY; HARDISON, 1960), explorado por Villela e Mattos (1975). Essa análise será melhor explorada na Seção 3.1.3.

Os dados de umidade do solo são mensurados por sensores de umidade do tipo TDR (*Time Domain Reflectometry*) instalados na camada de 0 – 20 cm do solo. A determinação do conteúdo de água do solo é obtida a partir da estimativa da constante dielétrica determinada, usando-se a técnica da reflectometria no domínio do tempo. Os modelos utilizados são do tipo *CS616 Water Content Reflectometer* fabricados pela *Campbell Scientific*. Os dados são armazenados em escala horária.

A unidade padrão de armazenamento é aquela obtida pelo sensor, em microssegundos (μs). Todos os dados armazenados pela EP3 foram armazenados nessa unidade. A conversão para outras unidades referentes à umidade do solo é feita por curvas de calibração disponibilizadas pelo fabricante ou realizadas com medidas em campo. Durante o período de 09/03/2016 a 2019 na EP1 e de 13/11/2013 a 2021 na EP2, os dados passaram a ser armazenados apenas em medida volumétrica ($m^3.m^{-3}$). Ou seja, os dados foram armazenados depois de feita a conversão para umidade do solo nessa unidade. Foi utilizada uma das equações disponibilizada pelo fabricante (Equação 1), que relaciona a umidade volumétrica (volumetric water content - VW) e às medidas do TDR:

$$VW_{m^3.m^{-3}} = 0.0007TDR^2_{\mu s} - 0.0063TDR_{\mu s} - 0.0663 \tag{1}$$

No entanto, essa não é a melhor equação para relacionar a constante dielétrica do solo em umidade do solo volumétrica, como visto no trabalho de Costa (2012b). A melhor relação encontrada entre as medidas realizadas em campo e os valores obtidos do sensor foram regressões lineares em cada estação pluviométrica na BEA. Ainda assim, como a conversão desses dados foi feita na própria programação do *datalogger*, então não se teve acesso aos dados originais obtidos pelo sensor TDR.

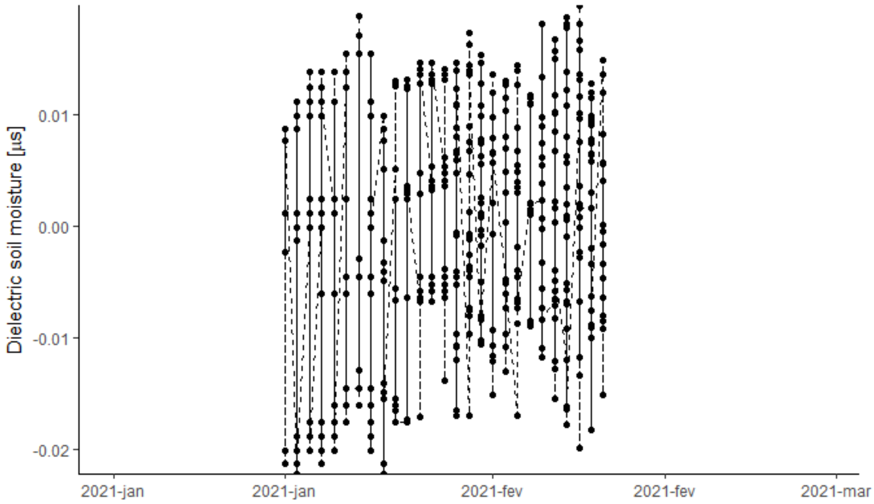
Análise de consistência: umidade do solo

A fim de padronizar os dados em uma mesma unidade de medida e obter valores mais próximos aos mensurados pelo TDR, utilizou-se os dados armazenados em medida volumétrica para resolver a equação para cada medida horária. Observou-se se há mudanças significativas nos dados obtidos dessa maneira e àqueles mensurados pelo TDR utilizando o período de janeiro e fevereiro de 2021, em que os valores foram armazenados pelo *datalogger* em (μs) e ($m^3.m^{-3}$). Então pudemos resolver a equação com os dados volumétricos e comparar com os dados originalmente obtidos. O resultado mostrou que a diferença varia entre -0.02 a 0.1μs (Figura 9).

Após feita a conversão e a padronização de toda a série disponível em μs, utilizaram-se as equações propostas por Costa (2012b), obtendo as medidas em $m^3.m^{-3}$ com equações que melhor representam a região. Assim, após essas alterações, os dados de umidade do solo são armazenados com os valores originalmente mesurados pelo TDR em μs e convertidos para $m^3.m^{-3}$ em armazenados em paralelo.

A umidade do solo já convertida para $m^3.m^{-3}$ é apresentada na Figura 10 com destaque para a umidade residual em cada uma das três estações pluviométricas. Como pode ser visto, há muitos pontos em que a medição chega a próximo de zero. No decorrer das coletas de campo, foi verificado que quando há falhas na bateria ou ela não consegue manter carga por

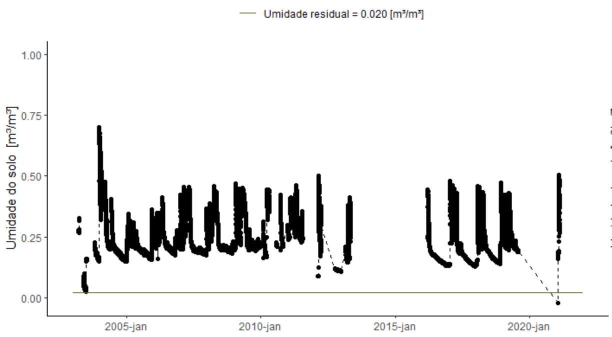
Figura 9 – Diferença entre os valores da constante dielétrica do solo calculados com a Equação 1 e àqueles armazenados e obtidos originalmente pelo TDR



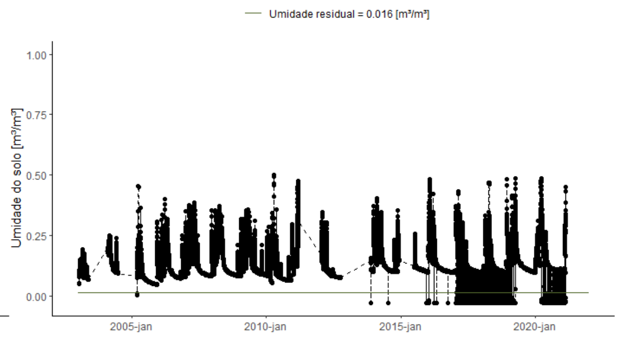
muito tempo, há esses pontos de medida que variam muito dos demais em um curto espaço de tempo. Para desconsiderar esses dados, foram descartados os valores menores que a umidade residual (EP1: 0.020 $m^3.m^{-3}$; EP2: 0.016 $m^3.m^{-3}$; EP3: 0.009 $m^3.m^{-3}$) de acordo com os dados de Costa (2012b).

O resultado do processo de retirada dos pontos que estavam abaixo dos valores de umidade residual é apresentado na Figura 11. Nela, vê-se que os principais pontos problemáticos foram solucionados para a EP1 e EP3. No entanto, observando os dados da EP2 (Figura 11b), verifica-se que ainda há muitos dados que destoam dos demais, ou seja, dados que são *outliers* e que dificultam o entendimento do processo que está sendo estudado.

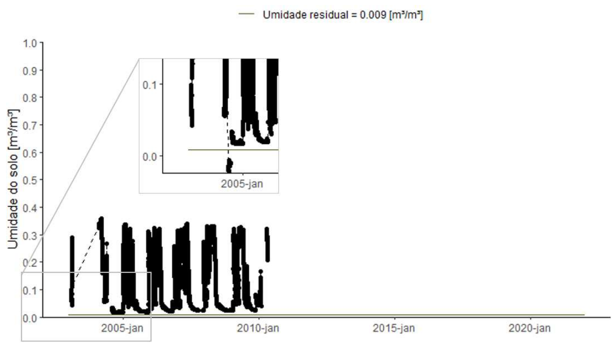
Figura 10 – Umidade do solo para as três estações pluviométricas na Bacia Experimental de Aiuaba (BEA) com destaque para os valores de umidade residual em cada estação



(a) EP1



(b) EP2



(c) EP3

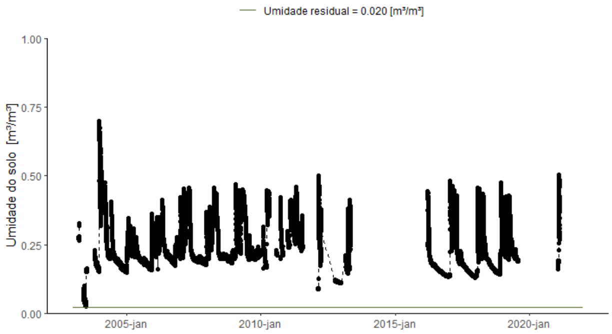
Para auxiliar na resolução desse problema, fez-se uma análise de comparação entre o primeiro valor do dia (onde geralmente está o valor destoante) e a média da umidade do solo de todo o dia e a média da umidade do solo do dia anterior. Quando a diferença entre o valor mensurado e as médias for maior que 50% em pelo menos uma das médias, o valor foi descartado.

O resultado da retirada dos *outliers* é apresentado na Figura 12. Como pode ser observado na Figura 12a, apenas um *outlier* foi mantido. Nesse caso, o dado mensurado com erro foi o segundo do dia. Após notada essa peculiaridade, o *outlier* foi retirado manualmente. A Figura 12b traz a organização final dos dados de umidade do solo para a EP2.

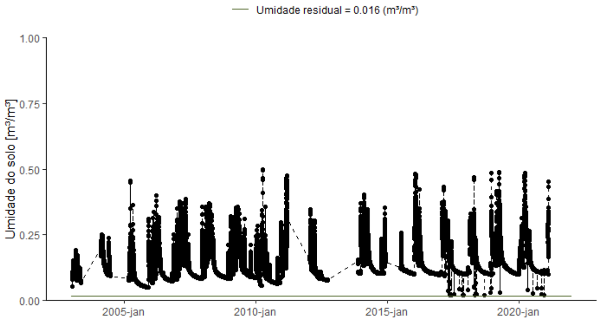
Análise de consistência: precipitação

A verificação da consistência dos dados de precipitação levou em consideração a precipitação nas estações pluviométricas dentro da bacia experimental. Assim como também foram considerados os dados auxiliares obtidos de estação pluviométricas do entorno da BEA. Além disso, outro fator preponderante foi a observação das medições de umidade no local.

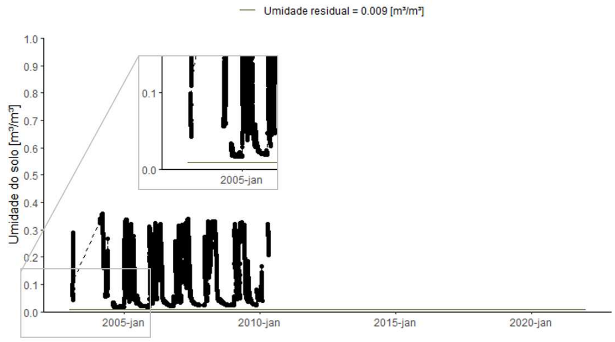
Figura 11 – Umidade do solo para as três estações pluviométricas na Bacia Experimental de Aiuaba (BEA) após a retirada dos pontos abaixo da umidade residual



(a) EP1



(b) EP2



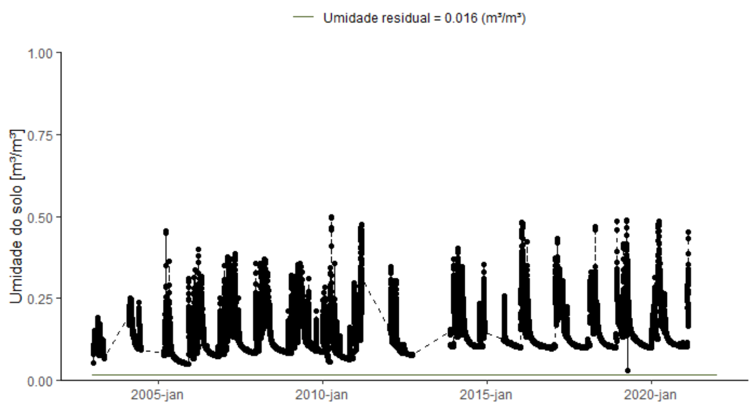
(c) EP3

A verificação da consistência dos dados de precipitação levou em consideração a precipitação nas estações pluviométricas dentro da bacia experimental. Assim como também foram considerados os dados auxiliares obtidos de estação pluviométricas do entorno da BEA. Além disso, outro fator preponderante foi a observação das medições de umidade no local. Dados extremos de precipitação foram avaliados quanto a sua consistência, utilizando os dados de umidade do solo. Quando o equipamento mostrou medidas extremas em meses que geralmente não ocorre precipitação significativa (julho a dezembro), a umidade do solo foi averiguada. Quando não houve aumento significativo na umidade do solo concomitante com os eventos registrados, outras estações da região foram consultadas. Se o resultado da umidade do solo corroborar com a ausência de registro de qualquer precipitação na região, os dados da estação avaliada foram descartados.

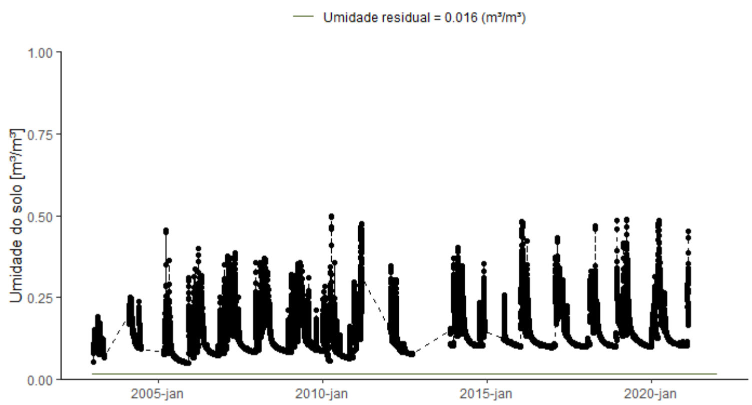
Será utilizada a análise do ano de 2019 para exemplificar esse procedimento. Nesse caso, a EP2 apresentou precipitação muito elevada no período seco, principalmente nos meses de junho a outubro. A Tabela 5 mostra os valores da precipitação mensal da EP2 em comparação aos valores da EP1 e das estações pluviométricas de órgãos governamentais que ficam no entorno

Figura 12 – Umidade do solo para a estação pluviométrica 2 (EP2) na Bacia Experimental de Aiuaba (BEA) após a retirada dos pontos abaixo da umidade residual

(a) Situação após a retirada dos pontos com apenas 1 *outlier* restante



(b) Após a retirada de todos os *outlier*



da BEA. No exemplo são mostradas as estações que ficam na sede do município e na localidade de Bom Nome. Não há disponibilidade de dados para a EP1 após o mês de junho.

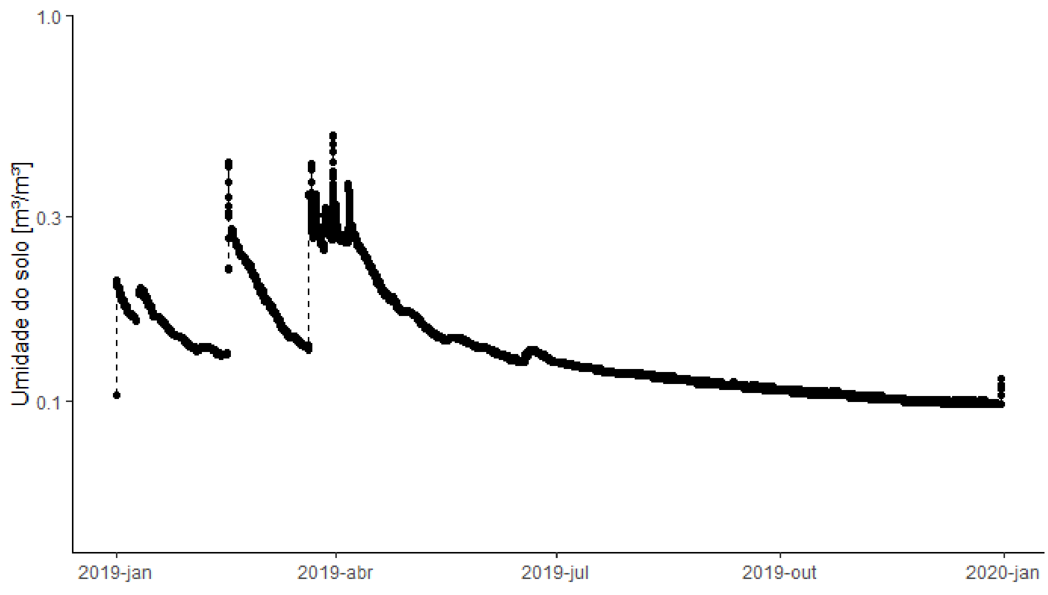
Como não há precipitação registrada de julho a outubro nas demais estações e a precipitação do mês de junho é quase dez vezes maior que todas as outras estações, a umidade do solo na EP2 foi utilizada para verificar possíveis alterações que indicassem precipitação. A Figura 13 mostra a variação da umidade do solo horária na EP2 para o ano de 2019. Como pode ser observado, não indícios de precipitação da magnitude que foi registrada, visto que não há aumento na umidade do solo em todo o período seco. No entanto, há um aumento da umidade do solo no mês de junho dos dias 17 a 21. Assim, a precipitação para esses dias foi mantida.

Para observar melhor o comportamento da umidade do solo ao longo do tempo, pode ser utilizada a diferença entre as medidas horárias subsequentes (Figura 14). Assim como observado na distribuição da medidas de umidade do solo, não há variação positiva no período

Tabela 5 – Precipitação mensal para o ano de 2019 nas estações pluviométricas localizadas na BEA (EP1 e EP2) e nas estações pluviométricas circunvizinhas (Bom nome e Sede), exemplo da análise de consistência realizada dos dados presentes no banco de dados

	EP1	**EP2**	**Bom nome**	**Sede município**
2019-01	48.8	3.3	75.6	57.0
2019-02	99.0	46.5	119.8	107.4
2019-03	162.2	242.3	226.4	197.0
2019-04	66.6	23.9	148.4	62.4
2019-05	24.2	1.8	20.2	7.0
2019-06	20.2	146.3	15.0	10.0
2019-07	2.2	765.3	0.0	0.0
2019-08	NA	587.0	0.0	0.0
2019-09	NA	219.7	0.0	0.0
2019-10	NA	166.9	9.0	2.2
2019-11	NA	11.9	12.0	0.0
2019-12	NA	8.4	0.0	1.2
Total ano:	**423.2**	**2223.3**	**626.4**	**444.2**

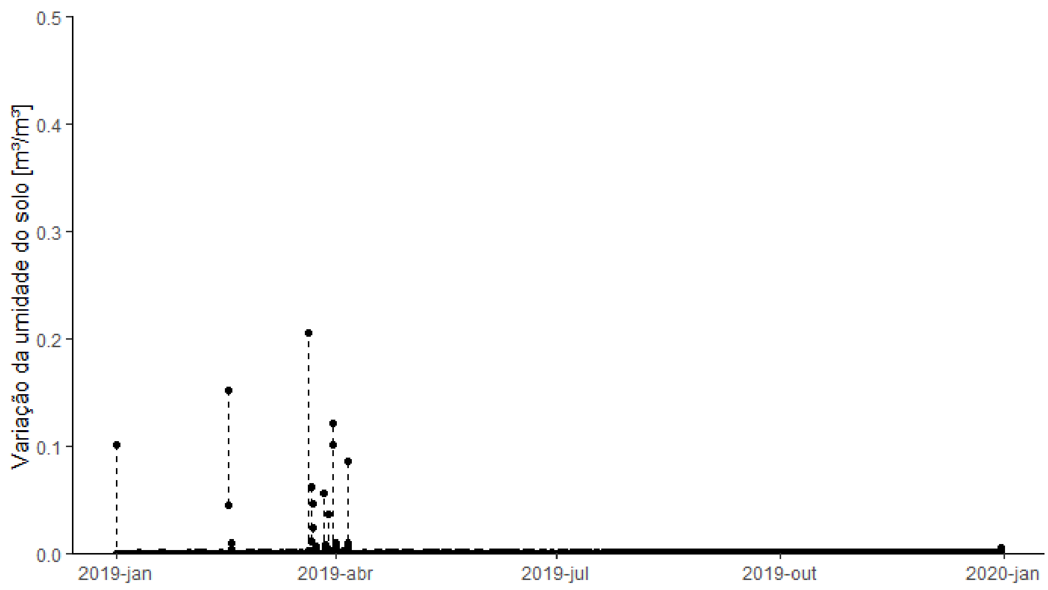
Figura 13 – Distribuição temporal da umidade do solo horária na Bacia Experimental de Aiuaba (BEA) na estação pluviométrica 2 (EP2) para o ano de 2019



Fonte: elaborada pelos autores.

seco como observamos no período chuvoso. Não havendo dados que indiquem que essas medidas de precipitação estão consistentes com a realidade, os valores foram descartados sendo mantidos alguns registros em junho.

Figura 14 – Diferenças entre as medidas subsequentes de umidade do solo horária na Bacia Experimental de Aiuaba (BEA) na estação pluviométrica 2 (EP2) para o ano de 2019



3.1.2.1.5 Outras variáveis

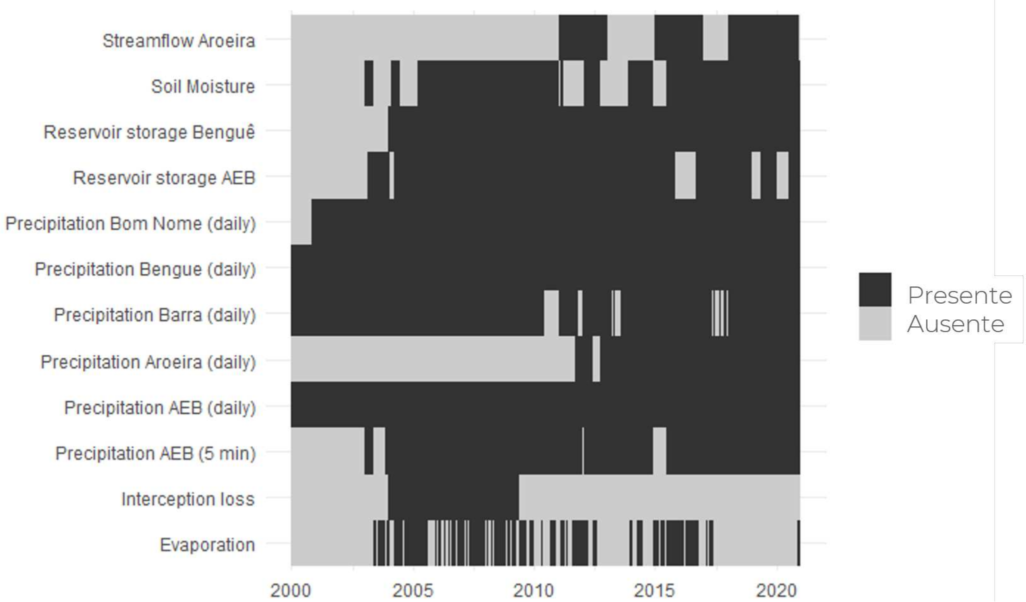
Além dos processos mencionados, outros experimentos foram realizados e coletaram dados por períodos extensos na BEA. A medida de transpiração é um desses experimentos. Duas planilhas contém esses dados: "EP1 gauge - sap flow sensor"e "EP1 gauge - transpiration daily". Esses dados foram coletados no âmbito da tese de Figueiredo (2018), a qual avaliou os dados brutos do sensor de fluxo de seiva e processou esses dados ao nível de transpiração. Os dados contemplam os anos de 2016 a 2018. Maiores detalhamentos quanto ao método e calibração utilizada podem ser obtidos na tese.

Os dados da planilha "Interception losses"foram obtidos no âmbito dos trabalhos de Medeiros (2005) e Medeiros *et al.* (2009). Os dados foram coletados de 2003 a 2008 no experimento que contemplou diversas classes de diâmetros de troncos e diferentes espécies. Para detalhamento da metodologia e acesso aos demais parâmetros de interceptação estimados para a Caatinga, recomenda-se o acesso aos trabalhos originais.

A planilha "Runoff events when ppt > 10mm"contem os dados de escoamento modelados por Figueiredo *et al.* (2016). Como já mencionado, o trabalho utilizou uma metodologia análoga ao apresentado na planilha "Discharge Boqueirão reservoir daily". Como um dos resultados do trabalho, os autores apresentaram a tabela presente nessa planilha com os valores de precipitação e escoamento para cada um dos eventos modelados, assim como outras métricas. A metodologia e o detalhamento é apresentado no artigo Figueiredo *et al.* (2016) e também nos trabalhos de dissertação e tese do autor (FIGUEIREDO, 2018).

As três planilhas referentes a medidas de sedimentos foram abordados no âmbitos dos trabalhos de Farias (2008) e Medeiros (2009). Maiores informações sobre as curvas-chave e as medidas realizadas para a obtenção desses dados podem ser encontradas nesses trabalhos.

Figura 15 – Esquema geral de organização do BDBEA com as medições das principais variáveis

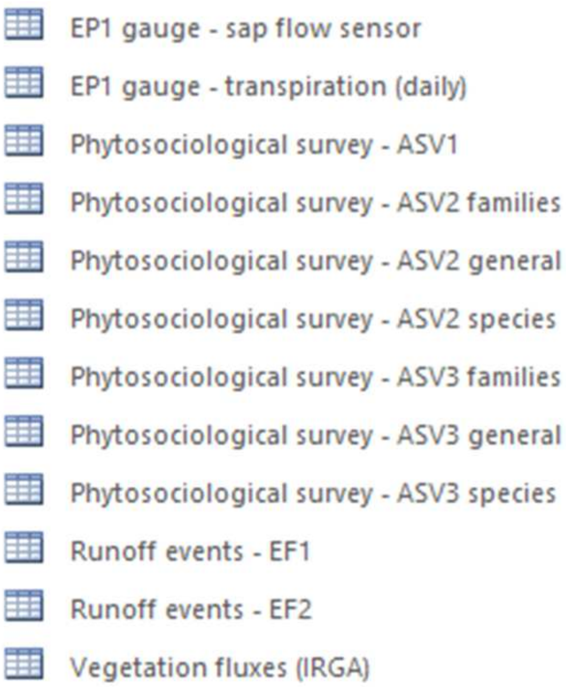


3.1.2.2 Dados Pontuais

O arquivo "Dados primários de coleta restrita.accdb"possui as planilhas apresentadas na Figura 16. Estão contidas nesse arquivo planilhas referentes a levantamentos pontuais e que não tiveram continuidade no tempo. Como pode ser observado, o idioma escolhido para as planilhas e para a disposição das variáveis foi o inglês. Assim também, os dados foram inseridos nas planilhas utilizando o ponto como separador decimal.

As planilhas referentes aos levantamentos fitossociológicos trazem informações gerais na EP1. Esse levantamento encontra-se detalhado no trabalho de Tillesse (2017), que pode ser consultado para maiores esclarecimentos. Os arquivos referentes aos levantamentos na EP2 e EP3 foram explorados no trabalho de Morais (2019). Essas planilhas contém informações detalhadas divididas em espécies, famílias e uma análise geral. Maiores informações podem ser obtidas no trabalho citado.

Figura 16 – Planilhas presentes no arquivo "Dados primários de coleta restrita.accdb"

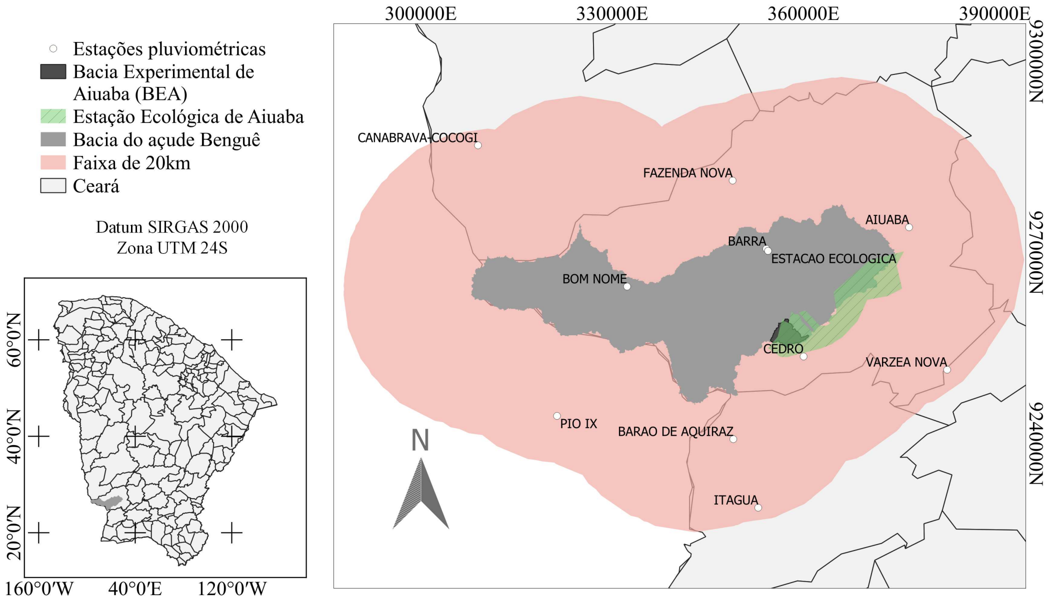


Os dados presentes na planilha "Vegetation fluxes (IRGA)"foram coletados durante 24h com o equipamento IRGA. Uma análise desses dados e um melhor detalhamento metodológico podem ser encontrados no trabalho de Figueiredo (2018).

3.1.3 Dados Secundários

Dados de estações circunvinhas à BEA foram incluídos neste diretório. O critério para a inclusão dos dados foi uma faixa de 20 km a partir da bacia do Benguê, da qual a BEA faz parte (Figura 17). As estações ativas sob monitoramento do órgão governamental (http://funceme.br/app-calendario/postos) foram incluídas no banco de dados.

Figura 17 – Estações pluviométricas secundárias incluídas no BDBEA (arquivo "Dados secundários.accdb")



Fonte: Funceme (2019)

O arquivo principal é o "Dados secundários.accdb"(Figura 18). Os dados foram inseridos nas planilhas utilizando o ponto como separador decimal. Os dados foram incluídos a partir de 2000 para todas as planilhas. Os períodos sem dados foram deixados em branco.

Nesta seção, também foram adicionados alguns atalhos para outros arquivos que podem ser interessantes na atualização desse arquivo e que se encontram em "Ferramentas para manipulação dos dados"(Seção 3.3).

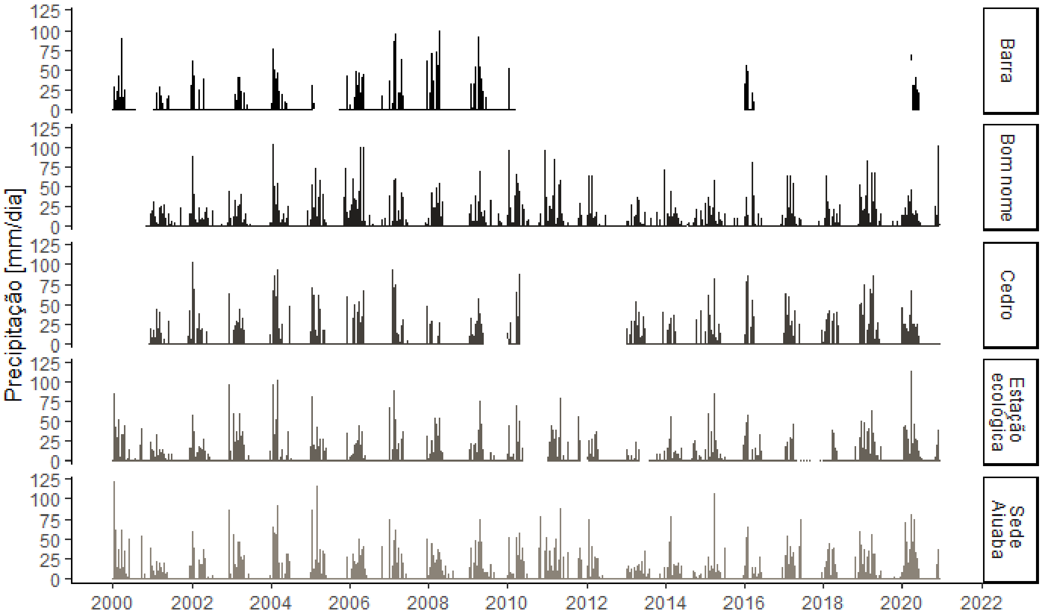
Preenchimento de falhas: precipitação Para gerar uma série de dados completa representativa para a região, os dados que foram inicialmente preenchidos com os valores provenientes das demais estações localizadas na BEA foram submetidos junto aos dados da EP2 (Figura 8) à análise de dupla-massa com as estações circunvizinhas e presentes no município de Aiuaba (Figura 19). Por serem as estações com menos falhas, foram utilizados como comparativos os dados de precipitação diária da estação pluviométrica localizada na sede do

Figura 18 – Planilhas presentes no arquivo "Dados secundários.accdb"

- COORDENADAS E CÓDIGOS - ESTAÇÕES (FUNCEME, INMET e DNOCS
- EP_DNOCS - Pio IX
- EP_FUNCEME - Aiuaba/Aiuaba
- EP_FUNCEME - Aiuaba/Barra
- EP_FUNCEME - Aiuaba/Bom Nome
- EP_FUNCEME - Aiuaba/Cedro
- EP_FUNCEME - Aiuaba/Estação Ecológica
- EP_FUNCEME - Aiuaba/Fazenda Nova
- EP_FUNCEME - Antonina do Norte/Várzea Nova
- EP_FUNCEME - Assaré/Assaré
- EP_FUNCEME - Campos Sales/Barão Aquiraz
- EP_FUNCEME - Campos Sales/Itagua
- EP_FUNCEME - Parambu/Canabrava/Cocogi
- EP_INMET - Taua

município, a estação localizada na localidade de Bom Nome e a média entre essas duas estações.

Figura 19 – Distribuição temporal da precipitação diária nas estações pluviométricas localizadas em Aiuaba incluídas no BDBEA como dados secundários



Fonte: Funceme (2019)

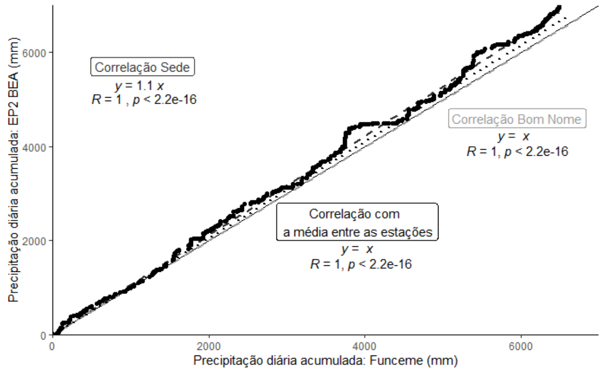
É apresentado na Figura 20 a análise em escala diária na escala padrão (Figura 20a) e na escala logarítmica (Figura 20b). Além disso, também são analisados os dados anuais (Figura 20c). Nos dados diários é observada uma distribuição distinta quando plotados nas diferentes escalas. Isso porque as diferenças em torno do valor de 4000 mm ficaram mais evidentes na primeira situação, já na escala logarítmica as diferenças mais evidentes foram aquelas com os valores mais baixos (abaixo de 1000 mm). No entanto, os valores foram muito semelhantes na comparação das três situações e visto que essa é uma análise acumulativa fica claro que os dados ficam mais semelhantes a medida em que a escala de análise aumenta. De forma que os valores da BEA foram considerados iguais aos da estação de Bom Nome e à média entre as duas estações analisadas nas duas análises diárias. A estação localizada da sede mostrou ter precipitação cerca de 10% maior quando utilizados os valores sem padronizações e igual à precipitação da BEA quando usados os valores padronizados em escala logarítmica.

A análise a nível anual mostrou certa inclinação nas retas correspondentes aos dados da estação do Bom nome e da média entre as estações consideradas (Figura 20c). A estação localizada na sede municipal mostrou dados equivalentes aos da BEA. Isso mostra que embora os dados se assemelhem a medida em que a escala de análise aumenta, pode haver um limite em que a partir dele os dados passam a se diferenciar. É importante salientar que os dados do período para o qual visou-se o preenchimento foram descartados. Assim, o ano de 2015, que teve toda a estação chuvosa sem dados, quase não teve acréscimo de precipitação em relação ao ano de 2014.

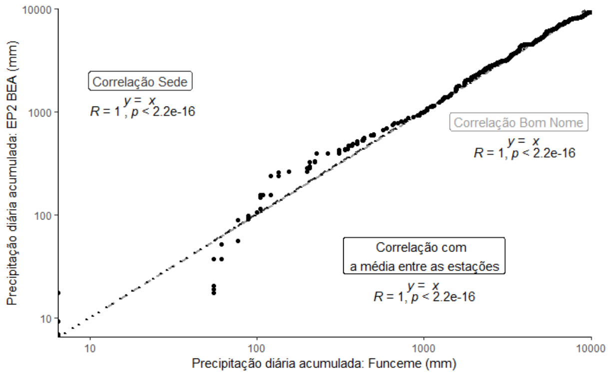
Baseando-se na análise de dupla-massa, realizou-se o preenchimento das falhas na série história da BEA com os dados diários da média entre as estações da sede municipal e Bom nome (Figura 21). Observa-se que o padrão sazonal é semelhante em todas as estações analisadas assim como a marcação de eventos extremos. As maiores diferenças se encontram na concentração da precipitação no período chuvoso, visto que pode ocorrer de ser mais concentrada como na sede municipal ou mais distribuída como nas estações da BEA e do Bom nome.

Figura 20 – Gráficos com precipitação acumulada entre os anos de 2003 e 2020 mostrando a relação entre a estação pluviométrica 2 (EP2) localizada na Bacia Experimental de Aiuaba (BEA) e a as estações pluviométricas localizadas na sede municipal de Aiuaba (Sede), distrito de Bom Nome e a média entre as duas estações (Sede e Bom nome)

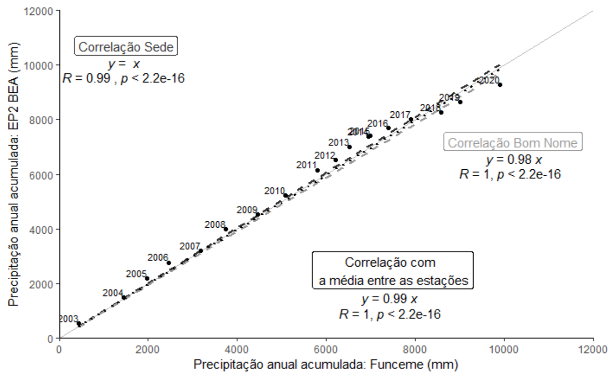
(a) Precipitação acumulada diária



(b) Precipitação acumulada diária: escala logarítmica



(c) Precipitação acumulada anual



3.1.4 *Dados Trabalhados*

Os dados presentes nesta pasta dizem respeito àqueles que foram obtidos através de processamento dos dados primários ou secundários. A subpasta "Planilhas recebidas"contem os dados originais recebidos dos autores dos trabalhos ou que foram publicados.

O arquivo que contem os dados organizados é o "Dados trabalhados (primários e secundários).accdb"(Figura 22). Como pode ser observado, o idioma escolhido para as planilhas e para a disposição das variáveis foi o inglês. Assim também, os dados foram inseridos nas planilhas utilizando o ponto como separador decimal.

Observando a estrutura dos dados, vê-se que são divididos em grupos temáticos. Os dados de evapotranspiração potencial (ETP) foram obtidos no trabalho de Teixeira (2018). Foram usados dados secundários das estações meteorológicas localizadas nas proximidades da BEA (AEB), em Campos Sales, em Tauá e os dados da estação do projeto WAVES (EC1).

Os dados do arquivo "IDF curves"foram resultados do trabalho de Rodrigues e

Figura 21 – Distribuição temporal da precipitação na Bacia Experimental de Aiuaba (BEA) nas três estações pluviométricas consideradas na análise de dupla massa, a média entre as estações localizadas na sede municipal de Aiuaba e no distrito de Bom nome e a série completa com os dados preenchidos com destaque para os períodos de falhas nos dados na BEA

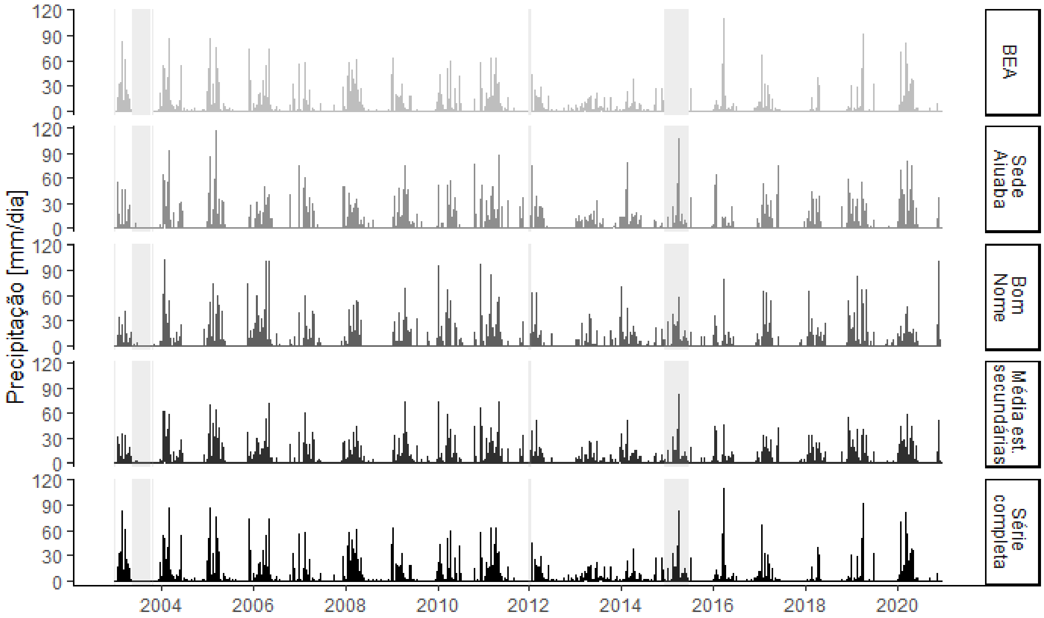


Figura 22 – Planilhas presentes no arquivo "Dados trabalhados (primários e secundários).accdb"

Araújo (2019), que obteve as curvas de intensidade, duração e frequência para a BEA, seguindo metodologia de Pfafstetter (1958). Maiores informações podem ser encontradas no trabalho.

Um outro grupo de planilhas são aquelas relacionadas ao índice de área foliar (LAI, em inglês). Esses dados foram utilizados no trabalho de Almeida *et al.* (2019) e detalhes da forma de obtenção podem ser encontrados nesse trabalho ou em Almeida (2016), Carvalho *et al.* (2016), Carvalho (2016).

3.1.5 Imagens

Este diretório é organizados com subpastas organizadas pelo nome do satélite ou meio como foram obtidas. Maiores informações sobre as imagens estão nos arquivos de metadados em cada subpasta. Um esquema mostrando a organização atual pode ser observado na Figura 23.

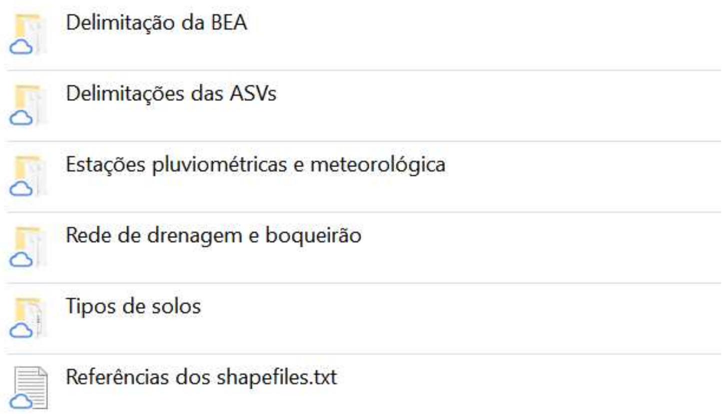
Figura 23 – Subpastas presentes no diretório "Imagens"

Outros dados importantes aqui armazenados são as imagens e resultados de processamento dos vôos realizados com os drones DJI Phantom 4 pro e SenseFly eBee SQ com câmera Sequoia Parrot+.

3.2 Dados georreferenciados

Arquivos que auxiliam a criação de mapa e localização geográfica das estações de monitoramento da BEA estão presentes neste diretório (Figura 24. Na primeira subpasta pode ser observada a delimitação da BEA com o código EPSG em que ela se encontra (Sirgas 2000, zona UTM 24S). O mesmo é encontrado em relação à delimitação das associações solo-vegetação (ASVs) e a rede de drenagem.

Figura 24 – Subpastas presentes no diretório "Dados georreferenciados"



Na subpasta "Estações pluviométricas e meteorológicas) estão os arquivos referentes às estações de coleta de dados primários (Figura 2 e Tabela 4) e também as estações de dados secundários (Figuras 17 e 18). Na subpasta "Tipos de solos", a delimitação dos solos é apresentada com base no trabalho de Araújo (2012). Uma proposta de "Simbologias para mapas pedológicos no QGIS"também foi inserida nessa pasta. Com essas informações é possível utilizar o esquema de cores apresentado no Manual Técnico de Pedologia da EMBRAPA e no Sistema Brasileiro de Classificação de Solos para cada tipo de solo. São apresentados os arquivos e passo-a-passo para o *software* QGIS nas versões 2.X e 3.X.

3.3 Ferramentas para manipulação dos dados

O diretório foi pensado para auxiliar nas atividades de manipulação de dados que antecedem à atualização do banco de dados, principalmente. No entanto, outras ferramentas são disponibilizadas aqui com atalhos em outros locais em que elas seriam interessantes. A esquematização dessa pasta é apresentada na Figura.

A subpasta "Antes da campanha: tutorial e softwares"contém informações que serão úteis na organização de campanhas para a coleta de dados na BEA. Além do tutorial para realizar o *download* dos dados, também estão presentes os *softwares* necessários para conectar-se aos *dataloggers* instalados lá.

Os arquivos da subpasta "Após a campanha: dados organizados"são as planilhas utilizadas para estruturar os dados após o recebimento deles. Dentro dessa subpasta, os arquivos são organizados pelos diferentes tipos de dados.

Os dados de precipitação são divididos entre as duas estações pluviométricas: EP1 ou EP2. Independente da estação, o processo de organização dos dados é bem similar. Primeiramente, é necessário identificar qual foi o último dado inserido. Feita essa identificação, deve-se abrir o arquivo com os dados de precipitação a cada 5 min. Apenas os dados com precipitação acima de zero são copiados e levados para a planilha.

Após a inserção dos dados na aba de precipitação de 5 min, precisa-se inserir os horários e dias que serão atualizados nas demais abas. As fórmulas tanto da aba de 6h como diária podem ser coladas nos dias atualizados. Vale ressaltar que é importante averiguar até qual linha vão os dados de 5 minutos que foram atualizados e corrigir isso nas fórmulas atualizadas.

Para os dados de evaporação manuais, o recebimento dos dados deve ser realizado em papel ou fotografia e devem em seguida serem digitados. Na planilha de atualização além da coluna de data, têm-se as colunas de nível 1 (dado observado), nível 2 (dado depois da leitura, se houver reposição da água no tanque classe A, esse valor será mais alto), evaporação e evaporação média nos últimos sete dias. A evaporação em milímetros é dada pela diferença entre o valor no nível 2 no dia anterior e o valor no nível 1 do dia atual vezes 10 para a conversão de unidades. Em caso de falha dos dados, pode-se considerar um valor médio para os dois últimos dias: diferença entre o dia antes do anterior e o dia atual, dividida por dois. A média dos últimos sete dias é dada pela média aritmética dos últimos dias contanto que haja pelo menos 6 dias com medidas.

A medida das réguas limnimétricas do açude precisa ser incluída na planilha de organização quando for recebida. Os dados com o número da régua e a medida em centímetros é digitado na planilha. O nível da água é dado pela soma do valor quando não se tem medidas na régua (1,6 m) somado ao número da régua e à medida em metros (coluna de medida dividida por 100). Os dados de volume e área são dados pela equação de interpolação utilizada como padrão. Uma equação é utilizada para o período de 2003 a 2009 (DE ARAÚJO; KNIGHT, 2005) e a partir de 2010, a equação é utilizada de Lima (2010). Ambas podem ser observadas no trabalho de Lima (2010).

Os períodos com falha de dados na estação seca ou de poucos dias foram interpolados com interpolação linear. Esse processo ajudou na análise contínua dos dados. Em todos os dados interpolados há um comentário que indica a natureza do dado (*linear interpolation*).

É importante ressaltar que sempre que necessário, utilizar a coluna de comentários para deixar informações que possam ser importantes para outras pessoas que venham ser usuárias desses dados.

3.4 Versões anteriores

Arquivos com versões anteriores do BDBEA foram incluídos nessa pasta para possíveis análises de consistência ou dúvidas que precisarem ser sanadas. Os arquivos foram inseridos no formato que se encontravam e foram inseridos em subpastas com o nome original que utilizavam.

4 POLÍTICAS DE USO

Os dados são de uso restrito para permitir lançamentos de publicações, realizações de doutorado e pós-doutorado, levando em consideração conta a necessidade de equilíbrio entre abertura e proteção da informação científica e direitos de propriedade intelectual (DPI), preocupações com privacidade, segurança, bem como gerenciamento e preservação de dados questões. O uso e acesso dos dados será permitido mediante esclarecimento com o coordenador do grupo HIDROSED, deixando claro o uso que os dados terão e que análises serão realizadas. A depender da necessidade o acesso será permitido somente ao material a ser utilizado.

A atualização e manutenção do BDBEA deverá ser realizada continuamente (pelo menos uma vez logo após cada campanha) por uma pessoa qualificada e devidamente treinada. Deverão ser mantidas cópias do banco de dados seguindo as regras para bom gerenciamento de dados. De maneira a serem três cópias, 2 cópias em um mesmo local (uma para atualização e uma como backup), com uma outra cópia como backup fora do ambiente de trabalho (nuvem ou hard-drive).

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