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CABra: A NOVEL LARGE-SAMPLE DATASET FOR BRAZILIAN CATCHMENTS

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ABSTRACT - In this paper, we present the Catchments Attributes for Brazil (CABra), which is a large-sample dataset for Brazilian catchments that includes long-term data for 735 catchments in eight main catchment attribute classes (climate, streamflow, groundwater, geology, soil, topography, land-cover, and hydrologic disturbance). We have collected and synthesized data from multiple sources. To prepare the dataset, we delineated all the catchments using the MERIT-DEM and the coordinates of the streamflow stations provided by the Brazilian Water Agency, where only the stations with 30 years (1980-2010) of data and less than 10% of missing records were included. Catchment areas range from 9 to 4,800,000 km² and the mean daily streamflow varies from 0.02 to 9 mm day⁻¹. Several signatures and indices were calculated based on the climate and streamflow data. Additionally, our dataset includes boundary shapefiles, geographic coordinates, and drainage area for each catchment, aside from more than 100 attributes within the attribute classes. The collection and processing methods are discussed along with the limitations for each of our multiple data sources. The CABra intends to improve the hydrology-related data collection in Brazil and pave the way for a better understanding of different hydrologic drivers related to climate, landscape, and hydrology, which is particularly important in Brazil, having continental-scale river basins and widely heterogeneous landscape characteristics. In addition to benefitting catchment hydrology investigations, CABra will expand the exploration of novel hydrologic hypotheses and thereby advance our understanding of Brazilian catchments' behavior. The dataset is freely available at <https://doi.org/10.5281/zenodo.4070146> and <https://thecabradataset.shinyapps.io/CABra/>.

Keywords – catchment hydrology; hydrologic similarity; large-sample database.

1. Introduction

The integrated assessment of large-sample catchment attributes is fundamental for the description and classification of landscape properties, leading to an improved understanding of similarities (or dissimilarities) between catchments. Large-sample catchment hydrology is essential in terms of hydrological processes understanding (Addor *et al.* 2020; Beven *et al.* 2020). It provides an attractive venue for general inferences that would otherwise be impossible to study based on individual or small

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groups of catchments, aside from allowing the testing of new and existing hypotheses in hydrologic sciences (Wagener *et al.*, 2007; Lyon and Troch, 2010; Gupta *et al.* 2014; Addor *et al.*, 2017).

A classic example of a large catchment-scale dataset is the Model Parameter Estimation Experiment (MOPEX) (Duan *et al.*, 2006; Schaake *et al.*, 2006), with hydrologic time series from 438 catchments located within the continental US (CONUS). The MOPEX dataset has been used in several studies supporting theoretic and modeling advances in hydrologic sciences (Ao *et al.* 2006; Sawicz *et al.*, 2011; Ren *et al.* 2016). A more recent example is the Catchment Attributes and MEteorological for Large-sample Studies (CAMELS, Addor *et al.* (2017)) consisting of a set of daily hydrometeorological time series data for 671 catchments at the CONUS, aside from several landscape and climate related attributes. The CAMELS initiative has been widely used and other large-sample datasets have been recently developed following the CAMELS format, such as CAMELS-GB for Great Britain, CAMELS-CL for Chile, and CAMELS-BR for Brazil.

Brazil is a country with continental dimensions, hosting a wide range of climates, soils, geology, and land-cover types. Despite covering almost 50% of South America and hosting between 12% and 18% of the world's renewable freshwater (Rodrigues *et al.* 2015), Brazil suffers from scarce allocation of funds for hydrological monitoring services, which creates great challenges for the proper monitoring of the quality and quantity of its water resources. While the density of streamflow gauges falls below the standards recommended by the World Meteorological Organization (WMO) of 1 station for each 1,000 km², hydrologic observations are often discontinued and lack proper length (WMO, 2010). An integrated dataset containing multiple levels of environmental information can be of extreme importance to leverage investigations in hydrology and related disciplines within the Brazilian territory.

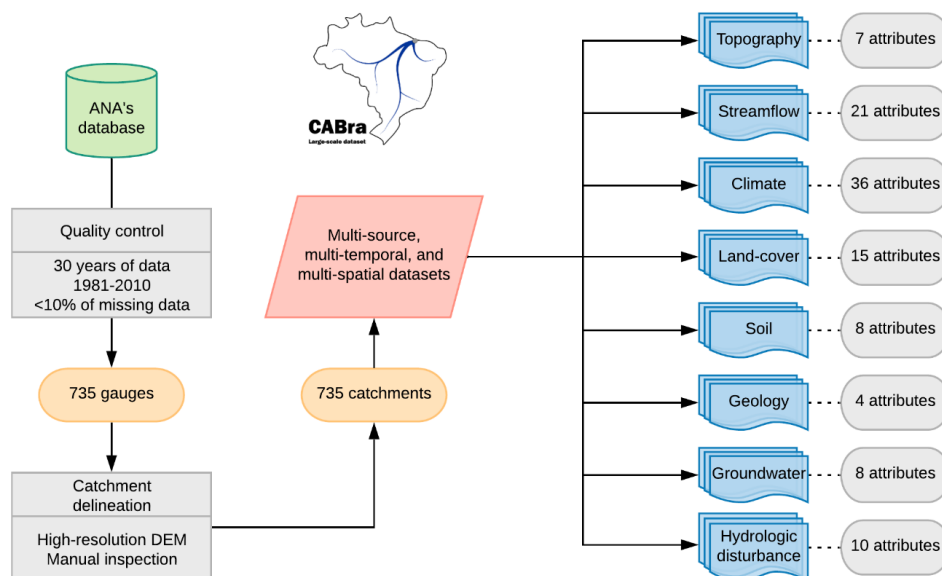
In this paper, we present the CABra dataset, which is a comprehensive, large-sample dataset for catchment attributes in Brazil. We have synthesized several multi-source data from eight main attribute classes (topography, climate, streamflow, groundwater, soil, geology, land-use and land-cover, and hydrologic disturbance) for 735 catchments in Brazil. Our dataset covers all hydrographic regions as well as its biomes. We have delimited all the catchments using an error-corrected digital elevation model employing automatic drainage area delineation methods. A hydrologic disturbance index was created to indicate the most human-impacted catchments. Finally, we discuss the spatial variabilities of the attributes and their limitations of application.

2. The CABra dataset

2.1. Overview

The CABra dataset is a multi-source, multi-temporal, and multi-spatial resolution large-sample dataset for catchment attributes for Brazilian catchments. Using an extensive local/global high-quality data collection, we developed CABra considering eight main classes of attributes: topography, climate, streamflow, groundwater, soil, geology, land-cover, and hydrological disturbance. Gridded datasets of various kinds were averaged onto the selected catchments located over Brazil and neighboring countries, in the case of transboundary catchments. Moreover, we provide daily time series from climate and streamflow variables for a 30-year period, covering the hydrological years from 1980 to 2010, as described in Figure 1. The CABra dataset is recommended for a wide range of users for decision-making at multiple scales – local, national, or regional – covering all Brazilian biomes. CABra was created to ensure easy access to its information and provide high-quality data, with attributes useful for a variety of hydrometeorological modeling and assessments. Moreover, we made available all the geospatial data (shapefile of the boundaries) for the users.

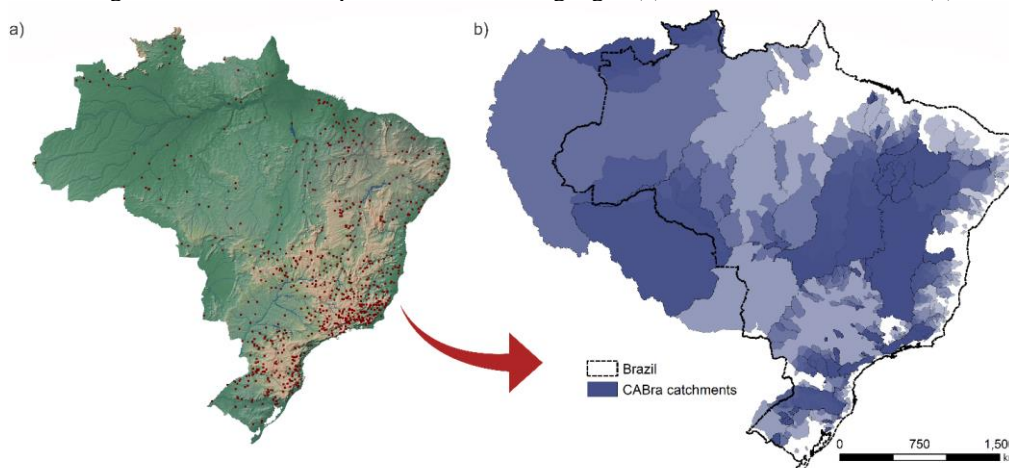
Figure 1 – Study delineation for the CABra dataset organization. From ANA's database, 735 were selected to integrate our dataset due to its high consistency and long-time series of streamflow.



2.2. Catchment delineation and topography

We freshly generated all the CABra catchments boundaries used in this study. Digital Elevation Model (DEM) quality and resolution are crucial at this stage since all the post-analysis with the multi-source information utilized in the CABra dataset are area-averaged. For example, is well-known that errors in topographic indices, e.g., slope and catchment area and boundary, are dependent on and highly sensitive to DEM resolution and accuracy, and it is suggested that, if available, a high-resolution DEM should be used instead of a low-resolution DEM due the negative effects of terrain generalization caused by them (Wechsler 2007; Vaze *et al.*, 2010; Mukherjee *et al.*, 2012). We delineated the CABra catchments following the procedure described in Maidment (2002), using streamflow gauges location information from the ANA's database and a high-resolution elevation product, i.e., the Multi-Error-Removed Improved-Terrain Digital Elevation Model with a 90-m spatial resolution at Equator (Yamazaki *et al.*, 2017) (Fig. 2). Once the catchment boundaries were delimited, we calculated seven attributes related to the topography of each catchment: area, slope, maximum, minimum, and mean elevation, streamflow gauge elevation, and catchment order. The catchment boundaries and drainage network are also provided in CABra dataset.

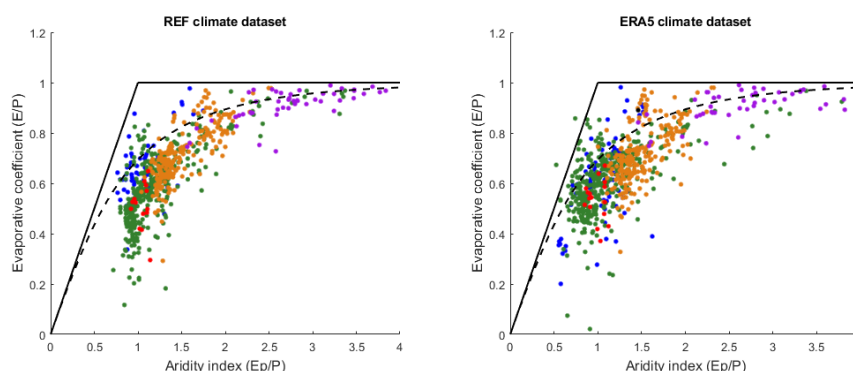
Figure 2 – Location map of the streamflow gauges (a) and CABra catchments (b).



2.3. Climate

We present daily time series of area-averaged precipitation, minimum, maximum, and mean temperatures, solar radiation, relative humidity, wind speed, evapotranspiration, and potential evapotranspiration (calculated by Penman-Monteith, Priestley-Taylor, and Hargreaves methods). Moreover, we calculated several core climate indices, defined by the Climate and Ocean: Variability, Predictability, and Change project from the World Climate Research Programme (WCRP). Two main climate datasets were used in CABra. The first one, a high-resolution meteorological gridded dataset ($0.25^\circ \times 0.25^\circ$), developed by Xavier *et al.* (2016) (here referred to as “REF”) is based on data from ~4,000 rain gauges in Brazil. The second is the ERA5, the most recent version of climate reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) and provides hourly, daily, and monthly data on several atmospheric, sea, and land variables in a $0.25^\circ \times 0.25^\circ$ spatial resolution grid, from 1950 to the present. From the climatic variables and attributes, we carried out an analysis of the annual water balance in the Budyko space (Budyko, 1948; 1974) which considers that the ratio between the long-term annual actual evapotranspiration (ET) and precipitation (P) is a function of the ratio between the long-term potential evapotranspiration (PET) and precipitation (P). Results show that half of CABra catchments are water-limited, and the other half are energy limited (Fig. 3). The lowest aridity index values are found in the Amazon and the Atlantic Forest, while the warmer and drier climate can be found in the Cerrado and Caatinga biomes. Furthermore, we can note that the main climate features are captured by all the datasets, with catchments in Caatinga being more arid, followed by the Cerrado.

Figure 3 – Distribution of the CABra catchments in the Budyko space from the three different climate datasets of CABra: REF, ERA5 and ENS. Values of E were estimated from the relation $P = E + Q$, considering long-term means.

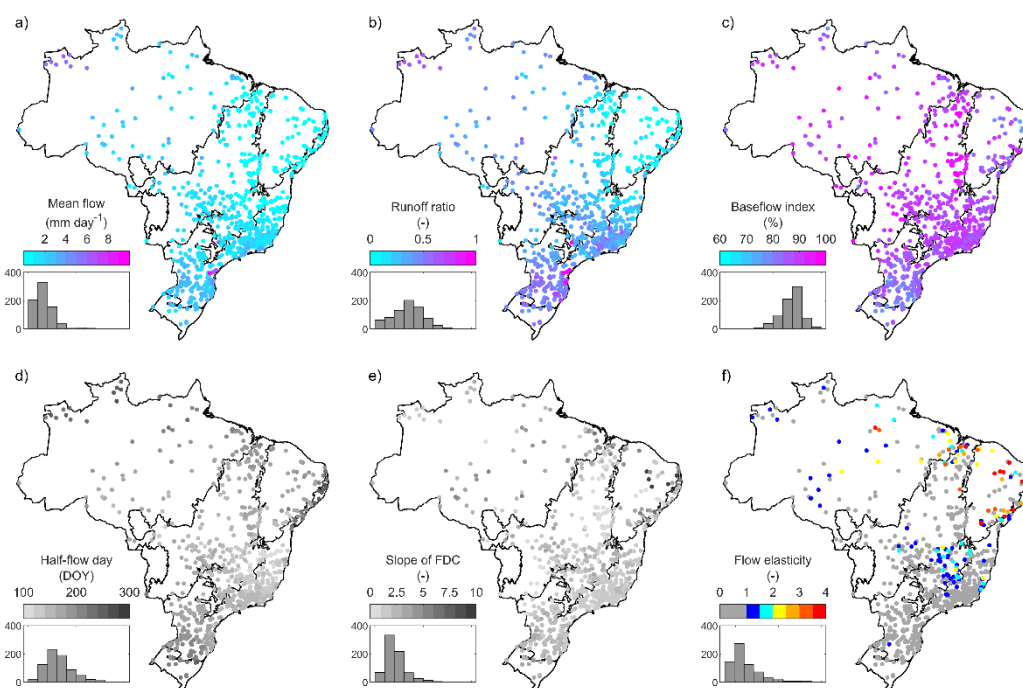


2.4. Streamflow and hydrologic signatures

The CABra dataset provides daily streamflow records for 735 catchments in Brazil. We used data from streamflow gauges of ANA, where each gauge is related to one of the abovementioned catchments. This dataset is available in the HIDROWEB database. ANA’s database contains raw time series of dozens of thousands of gauges of streamflow, precipitation, water quality, and sediment discharge, with a consistency level for each observation. Due to the inconsistencies and missing records in the streamflow data provided by ANA, we implemented filters to consider only the reliable data for the CABra dataset. After the employment of filters to ensure data consistency, we calculated for the 735 selected catchments, a variety of hydrological signatures, which can provide a better understanding of the patterns of functionality and behavior of the catchments. From the quantification of hydrological characteristics, it is possible to explain the variability in responses to climate forcings. We selected hydrological signatures obtained from widely available hydrological series, as well as Sawicz *et al.* (2011) and Westerberg and McMillan (2015). All the hydrological signatures were calculated considering the hydrological years (October 1st – September 30th) from 1980 to 2010, as

adopted by the ANA. Our results show (Fig. 4) that the mean daily flow for the Brazilian catchments ranges from less than 1 mm day⁻¹ to up to 9 mm day⁻¹, with an overall mean of 2 mm day⁻¹. The highest values were found in the extreme north of Amazon, and the lowest was found in the Caatinga. Most of the CABra catchments presented a runoff coefficient up to 0.5 and are mainly dependent on the baseflow since all of it presented a baseflow index greater than 70%. Non-perennial rivers were found in the Caatinga biome, which indicates mainly dependence on direct runoff of rainfall. Most CABra catchments present high flows up to 10 mm day⁻¹, but in some catchments, this value can reach 30 mm day⁻¹. As seen in the low flow analyses, the mean frequency of high flow does not exceed 50 days per year for most of the catchments. The frequency, instead, lasts for lower time, up to 10 days.

Figure 4 – Distribution of the hydrological signatures of the CABra catchments. a. Mean daily streamflow; b. Runoff ratio; c. Baseflow index; d. half-flow day; e. The slope of the flow duration curve; f. Elasticity of daily streamflow.



2.5. Groundwater

The CABra dataset presents eight attributes regarding the groundwater at the catchments. They are related to the water table (water table depth and height above the nearest drainage) and to the aquifer where the catchment is within (aquifer name and rock type). Data were extracted from Fan *et al.* (2013), which is a global water table depth map generated using a climate-sea-terrain coupled model, and Height Above Nearest the Drainage (HAND), also related to the water table but is an indirect way to infer the water table depth, as defined by Nobre *et al.* (2011). We also present the aquifer in which the catchment is within (most of the area) and the most common type of rock of the aquifer. This information was provided by the ANA database and it is important to the knowledge of the aquifer geology and its implication to the groundwater storage and recharge. We also have included data from experimental wells on the CABra catchments, when available. The data was provided by the Integrated Groundwater Monitoring Network (RIMAS) from the Geological Survey of Brazil (CPRM) and includes the location of each well and its levels. Our analyses showed a close relationship between the water table depth from Fan *et al.* (2013) and the HAND. In the northern portion of Brazil, especially in the Amazon, we can find shallow water table depths, while in the south-eastern, especially in the Atlantic Forest, we noted the deepest values for the water table depths. Values of water table depth and HAND are also in accordance with the experimental wells for

catchments where this analysis was possible to carry. Despite this, the low density of experimental wells shows the lack of field data about groundwater in Brazil. We also found that most of the CABra catchments are dominated by fractured and porous rocks.

2.6. Soil

The CABra dataset has eight attributes related to the soil type, properties, and texture. The soil type of the catchment presented here is the most common type for each catchment derived from the Brazilian soil map developed by the Brazilian Agricultural Research Corporation (Santos *et al.* 2011). Due to the high importance of the knowledge of the soil depth, density, texture, and organic matter to the understanding of soil-water dynamics and root grow (Dexter, 2004; Saxton and Rawls, 2006), we also present the mean areal attributes for them. These fields were taken from the SoilGrids250m, a global high-resolution gridded soil information based on field measurements, data assimilation, and machine learning. The catchments presented 12 main soil classes, with the Ferrasols, Acrisols, and Nitisols being the most common soil types in more than 90% of them. Most of the catchments present soil texture dominated by sand and clay. South-eastern, northern, and central regions of Brazil are dominated by sandy clay loam soils, while the southern portion is dominated by clay, which can reach up to 80%, making this region one of the most productive in terms of agriculture in Brazil. The soils presenting a clay and clay loam texture are in the southern portion, especially where the Nitisols occur. There is a spatial correlation between the soil organic carbon, bulk density, and the distance to the bedrock.

2.7. Geology

The CABra dataset presents four attributes related to the geology of the catchments, being the predominant lithology class, the porosity, the saturated permeability, and the saturated hydraulic conductivity, derived from the Global Lithologic Map (GLiM) (Hartmann and Moosdorf 2012), and the GLobal HYdrogeology MaPS (GLHYMPS), developed by Gleeson *et al.* (2014). Considering the saturated hydraulic conductivity as one of the most important physical properties on the quantitative and qualitative assessment of the water movement in the soil, we presented its values in the CABra dataset. Following the assumption that the hydraulic conductivity is separable into the contributions of the porous matrix of the soil, and the density and viscosity of the fluid, we also estimated the saturated hydraulic conductivity of the CABra catchments using its relation to the permeability, as described in Grant (2005). Catchments present 10 different classes. We found that 35% of the catchments have the metamorphic rocks as the most common lithologic class, 39% are formed by sedimentary rocks, and 25% presents igneous rocks (plutonic and volcanic) as the most common lithology class. In respect to the porosity, most CABra catchments presented values lower than 20%, with a mean value of 10%. Catchments in the Atlantic Forest presented the lowest values of the catchments set. Results regarding the saturated permeability and hydraulic conductivity reinforce the heterogeneity and random occurrence of these soil properties. Saturated permeability ranges from -14 to -12 m² in log scale, with a mean of -13.4 m², while the saturated hydraulic conductivity presented a mean value of -6.4 m s⁻¹, vary between -10 to -4 m s⁻¹.

2.8. Land-cover

The CABra dataset presents 15 attributes regarding the land-cover and land-use of the Brazilian catchments. They are related to the area-averaged land-cover and land-use itself (dominant cover type, and the cover fractions of 9 main classes of use: bare soil, forest, grass, shrub, moss, crops, urban, snow, and water) and to the area-averaged intra-annual variability of the vegetation biomass, here represented by the Normalized Difference Vegetation Index. The land-cover and land-use map used in the CABra dataset is derived from the PROBA-V satellite observations of the year 2015, which has 100-m spatial resolution, available at <https://land.copernicus.eu/global/lcviewer>. As an indicator for the vegetation biomass of the land-cover through the year, we are using the seasonal

NDVI for each CABra catchment. We adopted a product derived from the Long Term Statistics (LTS) based on the Normalized Difference Vegetation Index (NDVI) from the Copernicus Global Land services. This dataset is an NDVI mean for each month of the year during the 1999-2017 period, obtained from the SPOT-VGT and PROBA-V sensors in a 1-km spatial resolution, available at <https://land.copernicus.eu/global/products/ndvi>.

We observed that most of the Brazilian catchments are covered by forest and grassland. The shrub is the dominant cover for most of Caatinga catchments, while the grass is the dominant one in the Cerrado (tropical savannah). The forest cover is dominant especially in the Amazon and Atlantic Forest, as these two biomes are known by tropical forest occurrence, but even though the forest cover is not the most common for all the CABra catchments, ~85% of them present at least 20% of it. The grass cover fraction presented values up to 40% of the area for most of the catchments but reached 60% in some cases. A few numbers of catchments present the crops as the dominant cover type, mostly in the central and southern region. Likewise, there are only a few cases of urban catchments, within or close to major Brazilian cities that present this type of cover, showing that the CABra dataset is mainly composed of either natural or minimally (hydrologically) modified catchments.

2.9. Hydrologic disturbance

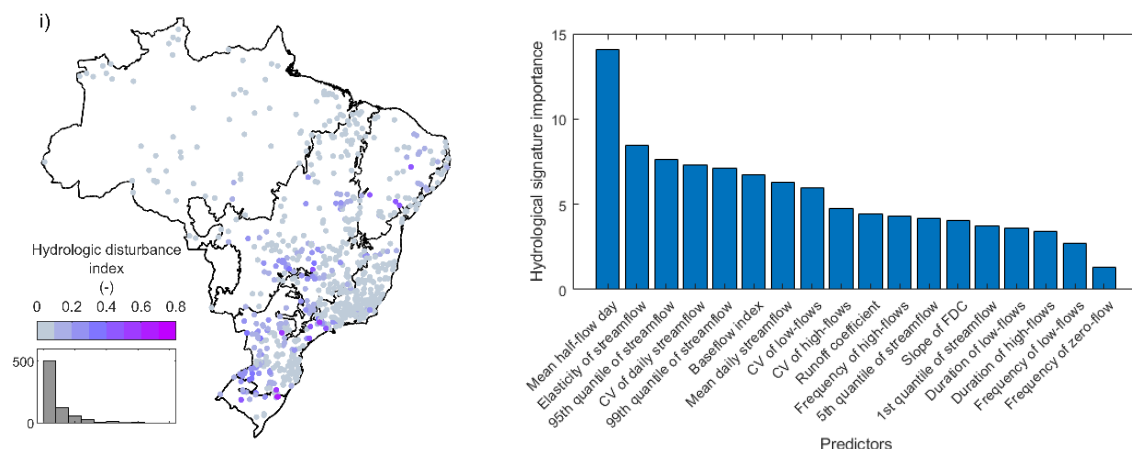
The CABra dataset presents 10 attributes related to the hydrologic disturbances on catchments water fluxes. Natural conditions of catchments are constantly modified by human interactions such as land-cover and land-use changes, flow regulation, water abstractions, soil impermeabilization, and many others, which can drastically alter the way hydrologic fluxes in the catchments respond. Then, our goal was to create a simple index, with easily accessible inputs, that is capable to measure how much disturbed a catchment is in relation to its hydrology. In the development of this index, we have considered fraction of urban cover, the distance to the nearest urban area of each catchment, the number and total volume of reservoirs (ANA, 2020), and its flow regulation capacity, the fraction of reservoir area of each catchment area (ANA, 2020), and the annual water demand (ANA, 2019). The equation related to the hydrologic disturbance index can be found in the following Equation 1:

$$HD_{index} = 0.4([U_C \cdot U_D] + CR_C) + 0.05R_N + 0.05R_{\%A} + 0.4R_R + 0.1W_D \quad 1$$

where HD_{index} is the hydrologic disturbance index, dimensionless; U_C is the normalized fraction of urban cover; U_D is the normalized distance to the nearest urban area; CR_C is the normalized fraction of crops cover; R_N is the normalized number of reservoirs; $R_{\%A}$ is the normalized percentage of catchment's area covered by reservoirs; R_R is the normalized reservoirs' regulation capacity of catchment's mean annual flow; and W_D is the normalized catchment's annual water demand.

The result is the hydrologic disturbance index (HDI), in Figure 5, which provides for users the degree of human interactions that can modify water fluxes in each catchment. Most of the catchments present $HDI < 0.2$, indicating a low anthropic interference on water fluxes. Higher values, > 0.4 , indicate catchments with some significant interference on water fluxes. High values of the hydrological disturbance index in the central and southern portion of Brazil may be related to agriculture development, while in the south-eastern part, they may be related to urbanization, and in the north-eastern part, they may be related to the presence of numerous voluminous reservoirs. 25% of the variance of the HDI is explained by the Half-flow day and the Streamflow Elasticity, which are two signatures sensitive to streamflow regulation and to the generation of runoff in the catchment. Our results show us that the index is capable to capture what it was intended to: catchments with higher values presents a large number or high regulation capacity of reservoirs, or a great percentage of non-natural areas. Medium values present some level of non-natural areas (pasture or crops), but there is not a high hydrological disturbance. Finally, lower values of HDI indicates minimally human-impacted catchments.

Figure 5 – Distribution of the hydrologic disturbance attributes of CABra catchments and the hydrological signatures as predictors of it. The HDI is a weighted relationship between all the anthropogenic factors of the catchments.



4. Conclusions

In this study, we have collected, synthesized, organized, and made available more than 100 topography, climate, streamflow, groundwater, soil, geology, land-use, and land cover, and hydrologic disturbance attributes for 735 catchments in Brazil. To do so, we have used several sources, such as observed time series, gridded data, remote sensing data, and reanalysis data. Moreover, we have calculated attributes for providing more accurate data than those available in the literature, and providing inexistent data, such as the hydrological disturbance index. As this dataset deals with catchment-scale averaged attributes, we have paid particular attention to DEM resolution, catchment delineation, while also manually inspecting each of the CABra catchments.

The development of the CABra dataset opens several opportunities to test and develop hypothesis in a unique environment like Brazil, with its vast and rich diversity in hydrology and landscapes. Finding relationships between the catchments' attributes will enable hydrologists to identify the drivers of the water fluxes. We hope our dataset will aid catchment classification efforts that will ultimately unravel the underlying dominant controls of Brazilian regional hydrology across space and time. At the same time, the CABra dataset covers fundamentally different hydroclimatologic and ecologic regions than those covered by other similar large-sample datasets (United States, Great Britain, Chile, etc.), being a complement for global assessments and expanding the possibility of the use of our dataset for multiple scientific areas, such as geology, agronomy, ecohydrology.

We intend to expand the CABra dataset in the future. Information and attributes related to relevant fields of work, such as soil erosion, ecology, biology, and chemistry, as well as climate change projections, will be added to the CABra dataset in future updates release. Thus, CABra represents a robust multi-source data collection effort for Brazil and is intended to play a key role in advancing the scientific understanding of climate-landscape-hydrology interactions. As such, we hope it will guide large-sample hydrology investigations and pave the way for testing novel hypotheses by both the Brazilian and the international scientific community.

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