Are Brazilian Catchments Gaining or Losing Water? The Effective Area of Tropical Catchments

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Abstract

Similar to most countries, the Brazilian water resources management considers topographically delineated catchment as a territorial unit for policy implementation. Yet, previous studies have shown that catchments are not hydrologically isolated, and topographic limits often neglect the groundwater boundaries. Thus, studies on effective catchment area are promising for shedding light on inter-catchment groundwater flow. Here, we investigated the deviation between the topographic and effective areas across Brazil. We applied the Effective Catchment Area index (ECI) to 733 Brazilian catchments and identified the most influencing attributes on the ECI by using Principal Component and Random Forest Analyses (PCA and RFA, respectively). Further analysis of consistency was carried out by contrasting the ECI values against the expected range of the Budyko curve considering both topographic and effective catchment areas (classic and adjusted framework). Considering the studied catchments, 15% and 16% of their effective areas were respectively smaller than half (strong losing water condition) and larger than double (strong gaining water condition) of their corresponding topographic areas. The aridity index was the main driving factor and negatively correlated with ECI followed by mean slope, precipitation seasonality, and mean elevation. In general, the more arid biomes in Brazil — the Cerrado and Caatinga — are prone to have smaller effective areas while larger effective areas were mostly found in the Atlantic Forest biome, a humid tropical region with a higher mean elevation. We highlight the potential of adopting a *pooling of catchments* based on their interconnectivity to minimize management costs while maximizing synergies and lessening trade-offs of water transfer processes. Our results contribute to a better country-scale understanding of hydrological connectivity among catchments and highlight the need to consider the effective catchment area to overcome water-food-energy security challenges on multiple scales.

Keywords: hydrological connectivity, physiographic parameters, water resources management.

Do Brazilian Catchments Gain or Lose Water?

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INTRODUCTION

Brazil has one of the largest world's freshwater reserves (ANA, 2019); however, water availability across the country is poorly distributed leading to regions with scarcity and others with relative abundance (Oliveira, Lucas, Godoi, & Wendland, 2021). Due to its continental proportions, Brazil has different climatic conditions that affect water availability. In addition, the availability is highly affected by prolonged droughts, increasing irrigated areas, agricultural expansion, industrial demand, and population growth (Gesualdo *et al.* , 2021; Mello *et al.* , 2020). That critical situation is expected to deteriorate once Brazilian water consumption is expected to increase by 24% in the next 30 years (Val *et al.* , 2019). In turn, agriculture will require more water to meet the projected increase in food demand of 40% (OECD/FAO, 2015). Therefore, there is an urgent need to expand water supply capacity (Mello *et al.* , 2020) since Brazil plays an important role in the world's food supply and the sector represents 80% of the total water consumption in the country (Gesualdo *et al.,* 2021).

The topographic catchment area is the unit for implementation of the Brazilian water resources policy as most of the world's water resources management systems. Over this territorial unit, environmental, social, and economic studies are carried out to develop a relevant and consistent management plan for present and future interests. The national Water Law (from Portuguese Lei das Águas No. 9,433/97) provides orientations for committees composition and the development of water resources management plans, lists the responsibility of public authorities, and standardizes fines and penalties following international guidelines (Veiga & Magrini, 2013; Araújo et al., 2015). Nevertheless, there is still a long journey to completely implement all the instruments (e.g., classification of water bodies, issue of water permits, and charge for the use of water to grant the multiple uses of water). Nonetheless, are topographic catchments isolated in a way to be defined as a single management unit?

Hydrological connectivity studies investigate water-mediated transfer of matter, energy, and/or organisms and have become popular since water is vital for the functioning of ecosystems (Reid, Reid, & Thoms, 2016; Cui et al., 2020). Given the importance of surface and groundwater, previous studies proposed hydrological connectivity indicators and investigated how catchments are inter-connected (Bracken *et al.* , 2013). These indices are based on integral connectivity scale lengths (ICSL) (Western, Blöschl, & Grayson, 2001), a variation of conductivity in a geologic medium (Knudby & Carrera, 2005), landscape's information (Borselli, Cassi, & Torri, 2008), relative surface connection function (Antoine, Javaux, & Bielders, 2009), and effective contributing area (Ali & Roy, 2010). Moreover, Liu, Wagener, Beck, & Hartmann (2020) recently proposed the effective catchment index (ECI), which improves the discharge/recharge ratio introduced by Fan & Schaller (2009) by detecting and quantifying the deviation between topographic and effective catchment areas. While most indices cited use soil moisture and topography as input data, the ECI is calculated by the logarithmic ratio between streamflow and the difference of precipitation and evapotranspiration. Although most of the effective boundaries of a catchment are unknown, the ECI provides a quantification of the effective contributing area.

The concept and use of the effective catchment area are of paramount importance for understanding hydrological connectivity, contributing to a more effective intervention on catchment processes than just adopting the topographic catchment area (Bracken *et al.* , 2013). The effective area considers the inter-catchment groundwater flow, and they are usually significantly smaller or larger than the area given by its topographic boundaries (Aryal, Mein, & O'Loughlin, 2003). Underground water connectivity is even more important from the water management perspective, in which surface water channels are commonly considered to be independent channels that become a unit only and through a topographic encounter (Liu *et al.* , 2020). Although there is still little research dedicated to the subject, most hydrological models assume no hydrological connectivity between catchments for simulating water flow. This assumption leads to a misunderstanding about the actual hydrological potential of a catchment (Bouaziz *et al.* , 2018). Therefore, users tend to force hydrological models on isolated catchments during calibration/evaluation while the truth is that those catchments are truly connected.

There are many factors associated with the hydrological connectivity of a catchment such as land cover (Ludwig, Wilcox, Breshears, Tongway, & Imeson, 2005), topography (Poesen, 1984; Hopp & McDonnell, 2009), climate (Bracken, Cox, & Shannon, 2008), and geology (Ali, Tetzlaff, Soulsby, & McDonnell, 2012). In this context, Liu *et al.* (2020) identified the catchments with the potential to transfer water beyond topographic limits and correlated them with different physiographic factors in the Americas, Europe, and Oceania. Nevertheless, there is still the need for regional studies that consider local characteristics to improve the understanding on multiple scales. Therefore, we used the novel Brazilian dataset of catchment attributes comprising a greater number of catchments and attributes than that analyzed by Liu *et al.* (2020). Our objective was to investigate the deviation between effective and topographic areas and to assess potential climatic and physiographic attributes explaining that deviation. Additionally, we discussed the implication of our results on the catchments' potential to lose or gain water and how it affects hydrological connectivity by inferring inter-catchment groundwater flow. Our findings contribute to improving water resources management and allocation mainly in water-scarce environments, which we started to unveil.

DATA AND METHODS

Study Area and Data

We investigated the relationship between the effective and the topographic area of 733 catchments in Brazil (Figure 1). The country comprises six biomes with a climate that varies from semiarid to subtropical with annual precipitation ranging from about 400 to 4,000 mm. Elevation ranges from sea level up to 2,900 m. In this study, we used the Catchment Attributes for Brazil dataset (CABra) (Almagro, Oliveira, Meira Neto, Roy, & Troch, 2020) for the analysis detailed throughout the next sections. CABra is a large-scale dataset for catchment attributes, comprising a set of several multi-scale attributes for 735 Brazilian catchments. Moreover, the dataset provides daily time series of climate and streamflow for a 30-year period (1980-2010). The dataset allows for multiple uses and scales supporting the decision-making process by providing eight main classes of catchment attributes: topography, climate, streamflow, groundwater, soil, geology, land cover, and hydrological disturbance. We excluded from our analyses two catchments; one presented inconsistency between precipitation and evapotranspiration data while the other was highly disturbed by human activities such as inter-catchment water transfer.

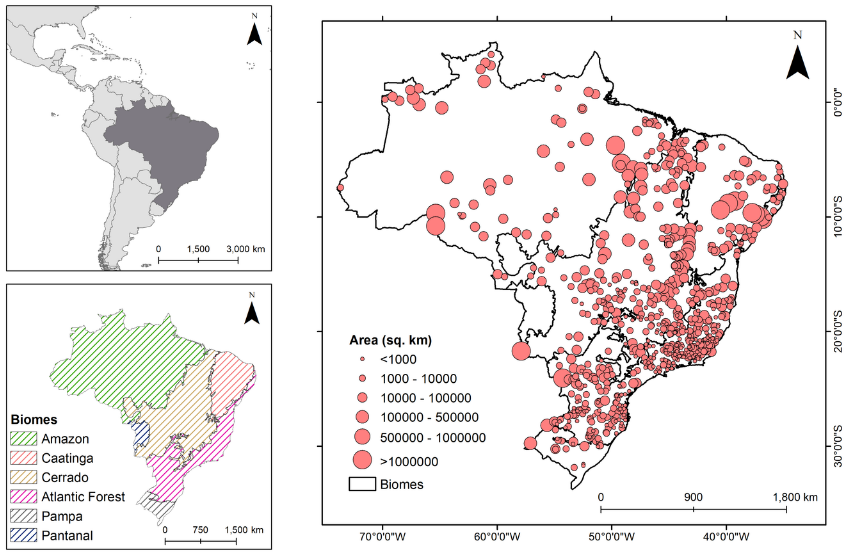

Figure 1: Figure 1 – Study area location in South America, the Brazilian biomes and the 733 catchments from Catchments Attributes for Brazil dataset (CABra).

The Effective Catchment Index

To obtain the effective catchment area, we used the effective catchment index (ECI) proposed by Liu *et al.* (2020). The ECI indicates the occurrence and the strength of inter-catchment groundwater flow (IGF), improving previous studies (e.g. Schaller and Fan (2009)) regarding water gain or loss by catchments. The ECI describes the deviation of the effective catchment area from the topographic area counting for IGF in the water balance. The assumption of a closed water balance without IGF in topographic catchments may lead to a misunderstanding of hydrological data (Liu *et al.* , 2020). The index is calculated as follows:

$$ECI = log \left[\frac{Q}{(P-ET)}\right](1)$$

where P (mm d^{-1}), ET (mm d^{-1}), and Q (mm d^{-1}) are the long-term estimates of precipitation, actual evapotranspiration, and streamflow at the catchment outlet, respectively. Catchments have their effective area larger than their topographic area when ECI $>$ 0 (gaining water condition). On the other hand, catchments with an effective area smaller than the topographic area present ECI $<$ 0 (losing water condition).

If any IGF occurrence affects the observed water flow (Q) at each catchment outlet, direct response of Q to the effective catchment area (A_{eff}) is established whereas the response to the topographic catchment area (A_{topo}) is derived from the difference between the catchment precipitation (P) and actual evapotranspiration (ET) (Liu *et al.* , 2020). Therefore, the ratio of the effective to the topographic catchment area is defined as:

$$\frac{A_{\mathrm{eff}}}{A_{\mathrm{topo}}} = \frac{Q}{(P-ET)}(2)$$

The effective and topographic area is related to ECI by combining the previous equations, as shown in the equation below (Equation 3). We adopted the same definition of substantial deviation between the topographic and effective areas as (1) effective area larger than double or (2) smaller or losing water (ECI $>$ -0.15) conditions. ECI values that fall between these extreme ranges indicate either a small gain or a small loss condition.

$$\frac{A_{\mathrm{eff}}}{A_{\mathrm{topo}}} = 10^{\mathrm{ECI}}\ (3)$$

We evaluated the ECI estimates by contrasting our results against the expected range of the Budyko curve (Budyko, 1974) considering both topographic and effective catchment areas. We adopted the Fu curve (Fu, 1981), which is widely used and represents the Budyko curve with w = 2.6 (Beck *et al.* , 2020). For evaluation and discussion, we define the Budyko framework considering the topographic area as a classic framework whilst the one considering the effective area as an adjusted framework. For both, we plotted the relationship between the long-term aridity index — PET/P — and the long-term evaporative index — (P-Q)/P. We have used P and PET from the climatology of the CABra dataset (calculated over the 1980-2010 period). As described in Almagro et al. (2020), P is derived from a reference dataset obtained from ~4,000 rain gauges that cover the Brazilian area. Nonetheless, as there are catchments with area beyond borders of the Brazilian territory, Almagro*et al.* (2020) developed an ensemble dataset (reference + ERA5) that we used in the present study. The PET, in turn, is also a climatology from daily estimation by the Priestley and Taylor method (see Almagro et al., 2020). Finally, the Q is only based on streamflow gauge observations over the Brazilian catchments. We also expected to diminish the uncertainties by not adopting another different dataset for the AET calculation. Considering the water and energy limits in the Budyko framework (Bouaziz *et al.* , 2018; Liu *et al.* , 2020), a catchment with Q > P gains water (ECI > 0) whereas those with P-Q > PET lose water (ECI < 0).

Influence of Catchment Attributes on ECI

To identify relevant catchment attributes and hydrological signatures explaining the variability of ECI, we used a combination of Principal Component and Random Forest analyses (PCA and RFA, respectively) (Figure 2). The PCA is a dimension reduction technique and was used to evaluate which of the 15 attributes from the CABra dataset (available in S1) are responsible for the most variation in the ECI results. This first step allowed us to remove features that do not hold any predictive value, dealing with the overfitting problem on the classification of decision trees. A random forest is an ensemble of decision trees (Denisko & Hoffman, 2018), in which a single decision tree can exhibit high variance and overfit, but a random forest can reduce the variance by combining several trees.

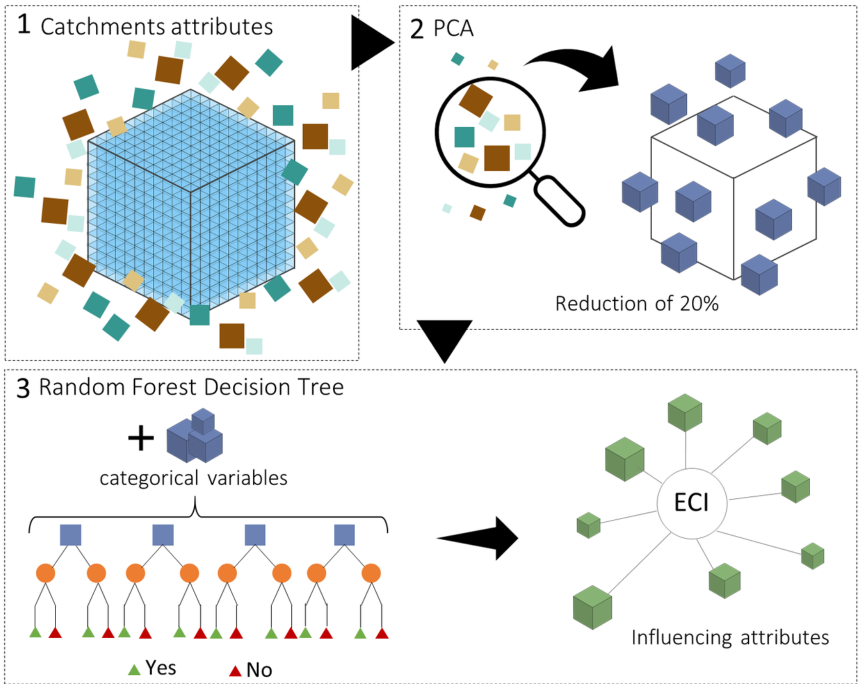

Figure 2: Figure 2 – Scheme of the analysis carried out for identifying the most relevant influencing factors.

After performing the PCA, we selected attributes that showed the highest variance among all principal components as input for RFA, totalizing 12 attributes: aridity index, precipitation seasonality, water table depth (WTD), height above the nearest drainage (HAND), reservoir area, hydrological disturbance index, streamflow elasticity, porosity, permeability, hydraulic conductivity, mean elevation, and mean slope. The precipitation seasonality indicates the timing between the precipitation seasonal cycle and the temperature seasonal cycle. Values of this attribute close to +1 indicate the occurrence of summer precipitation while values close to -1 indicate winter precipitation (Almagro et al., 2020). Additionally, we added the Brazilian biomes — Amazon, Cerrado, Caatinga, Atlantic Forest, Pantanal, and Pampa — and soil texture — clay, clay loam, loam, sandy clay, sandy loam, and sandy clay-loam — as categorical variables to the analysis by using the One-Hot encoding method (Pedregosa *et al.* , 2011). This method converted these variables into numerical ones by treating them with equal order.

We applied the classifier and regressor classes of the Random Forest algorithm (Pedregosa *et al.* , 2011) to a total of 24 attributes. The classifier class correlated the 12 attributes to ECI values by the majority vote across the decision trees while the regressor considered the average correlation in the ensemble of the decision trees. We also applied 10-fold cross-validation and tested different hyper-parameters, such as numbers of ensembles and the maximum depth of the trees to control the quality of the forest. All analyses were carried out by using a Python script available at http://doi.org/10.5281/zenodo.4247710.

RESULTS

The effective area of about 16% of the studied catchments was larger than double (dark blue circles on the coast) of their corresponding topographic areas. On the other hand, 13% of the effective catchment areas were smaller than half (dark red circles in the northeast) of their topographic areas (Figure 3, the histogram is available in S2). A clear pattern was noted in Caatinga, Cerrado, and Atlantic Forest although we did not observe a clear tendency of an ECI sign in the Amazon, Pampa, and Pantanal biomes. In the Caatinga (predominantly semiarid region) and the Cerrado biomes, our analysis demonstrated that catchments have their effective area smaller than the topographic area whilst most catchments presented the effective area larger than the topographic area in the Atlantic Forest biome.

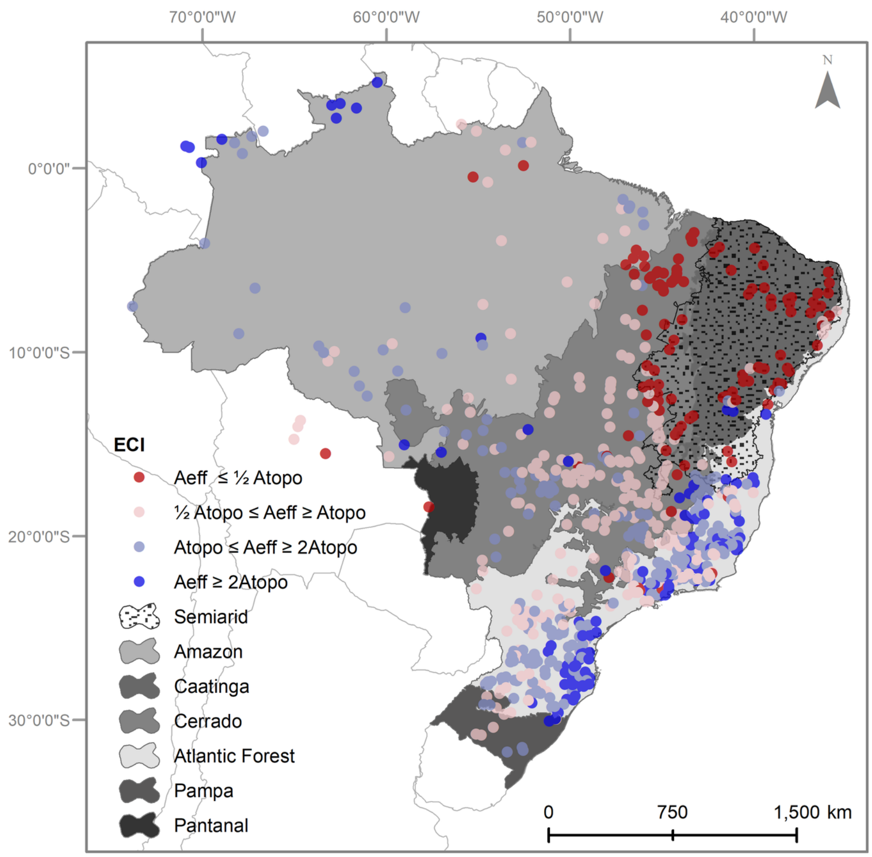

Figure 3: Figure 3 – Distribution of the Effective Catchment Index (ECI) over Brazil highlighting the ratio of the effective to the topographic area, where Aeff and Atopo are respectively the effective and topographic catchment areas. The dark blue and dark red dots respectively represent catchments with the effective area that is more than double and smaller than half of the topographic area. The light blue and red dots indicate smaller deviation between the topographic and effective areas.

Most catchments were between the theoretical water and energy limits in the Budyko space (dashed blue and red lines) for both classic and adjusted Budyko framework as expected for natural catchments (Bouaziz *et al.* , 2018) (Figure 4). In the energy limit zone (above red dashed line), actual evapotranspiration (ET) is greater than potential evapotranspiration (PET), and water discharge (Q) becomes negative in the upper water limit (above blue dashed line). Considering the topographic area (the classic Budyko framework, Figure 4a), we noted that catchments with effective areas smaller than half of their topographic areas (dark red circles) were placed near those limits, remaining within the assumption of a closed water balance. In addition, most of the others with effective areas larger than their topographic areas (light and dark blue circles) distanced themselves from the Budyko curve. Four catchments were located outside the Budyko space with specific streamflow (Q) larger than precipitation (P). In turn, Q cannot be larger than P assuming a closed water balance, which corroborates our findings that these catchments have effective areas larger than the topographic area.

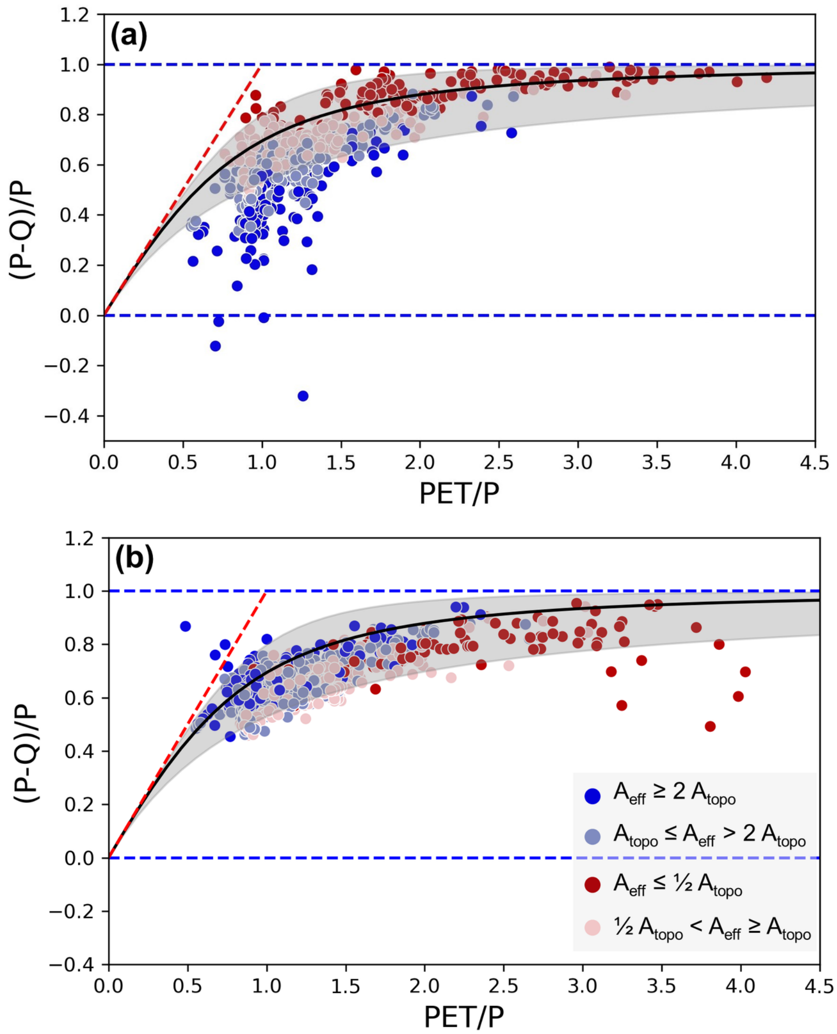

Figure 4: Figure 4 – Consistency evaluation of the Effective Catchment Index (ECI) by using the Budyko framework. The blue dashed lines show the upper (Q = 0) and lower (Q = P) water limits while the red dashed line indicates the energy limit. The black line is the Fu curve w = 2.6, and the gray shade covers the feasible range around the Budyko curve with 90% of confidence of the w parameter.

Catchments better fitted the Budyko curve when considering the effective area (the adjusted Budyko Framework, Figure 4b). Moreover, we noted a different behavior of those catchments regarding the long-term evaporative index (P-Q)/P. Catchments that gain water are closer to the upper water limit while catchments that lose water are mostly concentrated below the Fu curve by comparing the classic and adjusted framework. The increase in the evaporative index of catchments with larger effective areas reflects the correction of Q (i.e., the difference between P and Q increases as Q is corrected by an effective area larger than the topographic area). Conversely, lower evaporative indices were observed in catchments that lose water as P-Q decreases. Furthermore, three catchments that gain water exceeded the energy limit probably due to errors in the ET estimation. These catchments are geographically close to each other and both belong to a mountainous region. Most catchments that deviated from the Budyko curve range are those which lose water. These deviations may be attributed to the framework limitations regarding the assumption of a closed water balance and the climate aridity control of catchment hydrological processes (e.g., the long-term partitioning of precipitation into streamflow (Budyko, 1951) and evapotranspiration).

Identifying Influencing Attributes

From the subsequent PCA phase, three attributes — distance to coast, baseflow index, and the Strahler order — were excluded from the Random Forest analysis. Most catchments studied are more densely distributed along the Brazilian coast (Figure 3) and share similar branching complexity. Thus, those attributes may not contribute to the variance of the entire dataset (Supplement S2). Based on the RFA, the aridity index was the most influencing factor and negatively correlated with ECI (Pearson coefficient of -0.6 and p-value < 0.05). The global study of Liu *et al.* (2020) (Figure 5a) also showed a strong correlation between the ECI and the aridity index. Most catchments with effective areas smaller than half of their topographic areas are located in the aridest biomes: the Cerrado and Caatinga. On the contrary, larger effective areas were mostly found in the Amazon and Atlantic Forest biomes, which are characterized by lower aridity indices.

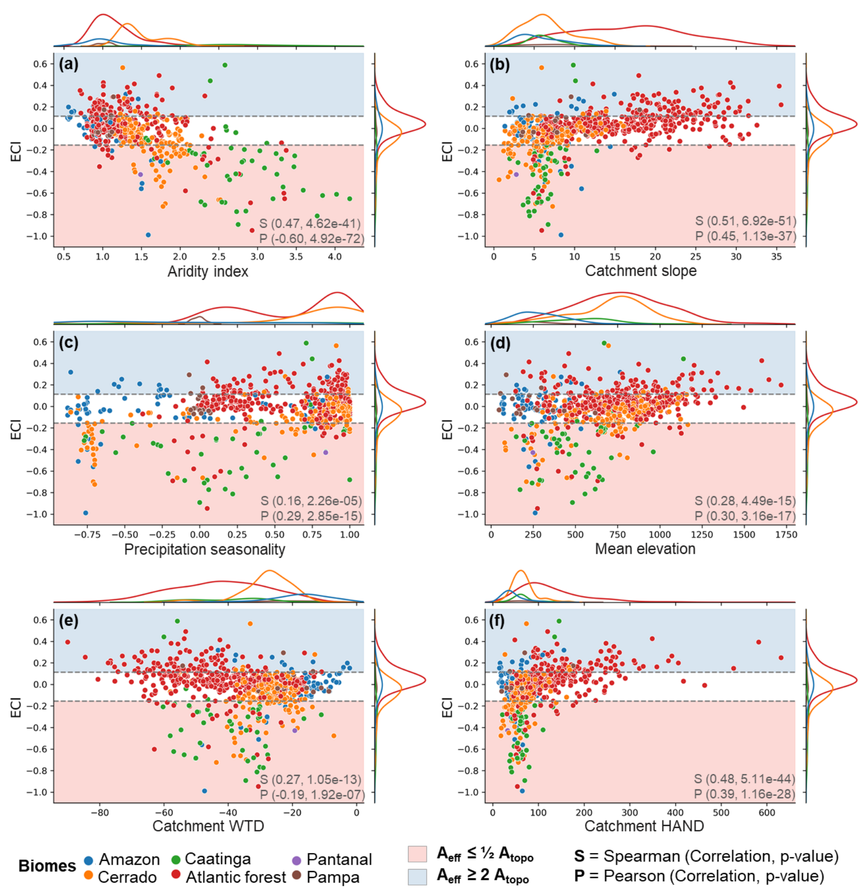

Figure 5: Figure 5 – Relationship between the Effective Catchment Index (ECI) and the six most relevant influencing factors: (a) Aridity Index, (b) Catchment slope (Catch Slope), (c) Precipitation seasonality (P seasonality), (d) Mean elevation, (e) Water table Depth (Catch WTD), and (f) Height above the nearest drainage (Catch HAND).

Mean slope, precipitation seasonality, and mean elevation were also significantly correlated with the deviation between the topographic and effective areas of the Brazilian catchments (Figure 5, the other influencing factors based on RFA are available in Supplement S3). Our ECI results were positively correlated with mean slope and did not vary with decreasing slope contrasting the results of Liu *et al.*(2020), who observed positive and negative ECI in lower slope degrees. On the contrary, a clear pattern shows a tendency of flat areas to lose water ($A_{eff} < A_{topo}$) and hilly areas to gain water ($A_{eff} > A_{topo}$). The ECI variability decreased with increasing elevation, showing that elevated areas tend to gain water ($A_{eff} > A_{topo}$). Furthermore, the catchments with summer precipitation (P seasonality close to +1, Figure 5c) are prone to have effective areas larger than their corresponding topographic areas. We found positive ECI in areas with a well-defined precipitation seasonality, mainly in the Cerrado and Atlantic Forest biomes, while the northeast region — Caatinga biome — endures long drought spells leading to an unbalanced timing between temperature seasonal dynamics, seasonality close to 0 (negative ECI). We provide further detail about the relationship between those most influencing attributes and ECI in section 4.1 (i.e., aridity index, mean slope, mean elevation, and precipitation seasonality).

It is important to mention that, besides the four most relevant attributes, WTD and HAND also explain the variance in the attribute's dataset according to PCA (variance-based test). A significant non-linear correlation (Spearman's p-value < 0.05) corroborates the results from PCA (Figure 5e and f). Nevertheless, they showed less influence on the ECI than the previously mentioned attributes after the RFA (Supplement S3). The fact that HAND is closely related to slope and mean elevation may have contributed to its lower score after the machine learning process in the RFA.

DISCUSSION

The distribution of water losses and gains across Brazil follows climatic domains (Cherlet *et al.* , 2018) and is consistently supported by the Budyko framework. The Amazon and Pampa biomes presented both losing and gaining water conditions without a clear tendency for each condition due to the low density of catchments with observed hydrometeorological monitoring data in these biomes (Figure 3). It reveals the heterogeneous distribution of gauged catchments among the Brazilian regions and biomes (ANA, 2019) and the lack of basic observed data systematically collected over time and space (Marengo, 2006). Especially in the Amazon biome, the sparse monitoring network is due to the difficulty in access for local operations.

Most arid catchments located in the Caatinga and Cerrado biomes presented effective areas smaller than half of their topographic boundaries, indicating a losing water condition (dark red circles in Figure 4). We observed that these catchments have higher evaporative and aridity indices when all catchments were plotted on the classic Budyko framework (Figure 4a), i.e., the framework which considers the topographic area. In fact, topographic catchments with a strong deviation from their effective areas ($A_{efftopo}$ or $A_{efftopo}$) were closer to theoretical water and energy limits. Catchments that are close or exceed these limits support the hypothesis of inter-catchment connectivity (e.g., groundwater fluxes) (Bouaziz *et al.* , 2018). Therefore, considering a closed water balance in those Brazilian catchments with larger deviation possibly increases uncertainty in hydrological studies, leading to inconsistent results.

The effective area represents the subsurface fluxes and processes (Figure 4b) by estimating possible gains or losses from the relationship between Q and P-ET. The effective catchment area provided a better fit of catchments in the adjusted Budyko framework as expected. Nonetheless, the arid catchments with effective areas smaller than half of their topographic areas were outside the Budyko range (dark red circles, Figure 4b). This scenario suggests other hydrological processes not captured by the use of the effective area. Those arid catchments are located along the northeast coast of Brazil (Caatinga and Atlantic Forest biomes) and share particular characteristics that influence the surface and subsurface hydrological processes. They have a complex network of reservoirs (Nascimento & Neto, 2017; ANA, 2021), which alters the local water cycle by reducing flow downstream and increasing ET losses. In the ECI estimation, this disturbance exacerbates the deviation of the effective area from its corresponding topographic area. Consequently, even small deviations can represent a large offset between streamflow change and aridity, primarily in arid regions (Berghuijs, Gnann, &Woods, 2020). The hydrological disturbances caused by a series of reservoirs may violate the hypothesis of Budyko about the climate aridity control over the precipitation partitioning. Furthermore, considering heavy hydrological disturbances in approaches that investigate catchments effective areas and inter-catchment connectivity.

Inadequate measures of P, ET, and Q can also be considered as sources of uncertainty not only in the Budyko framework but also in the ECI estimation. We made use of the best database available in order to make our findings reliable, but there are still some uncertainties such as low density of precipitation monitoring stations, mathematical limitations to represent the ET processes, and possible non-representative rating curves for discharge estimations. Despite the uncertainties associated with the ECI estimate, we achieved a better adjustment of the catchments using the effective area within the Budyko framework (Figure 4b). Therefore, we can assume that these uncertainties in the ECI estimates are lower than those associated with studies using the topographic area. Nonetheless, hydrological disturbances should be carefully investigated. Overall, the Budyko framework corroborates the water losing and gaining conditions assumed from ECI as an alternative to comply with the assumptions of a closed water balance.

The ECI most influencing attributes

The climatic and physiographic attributes found in the Brazilian biomes support the effective area indices found and contribute to a better country-scale understanding of hydrological processes and inter-catchment connectivity. Liu *et al.* (2020) significantly contributed to understanding how physiographic factors and some catchment location aspects could explain the deviation between topographic and effective areas at a global scale. Our study takes further steps towards downscaling their global study and investigating other factors that, in turn, were relevant influencing the variability of ECI in Brazil. Furthermore, we bring some practical implications of our findings to water resources management in Brazil.

The strong negative correlation between the aridity index and ECI found in the semiarid region is closely related to its hydrological characteristic of intermittent rivers and ephemeral streams. This region is characterized by shallow soils formed on crystalline bedrock with a minimum contribution of baseflow from deeper groundwater to the surface flow. Moreover, the semiarid has great spatiotemporal variability of precipitation, with a mean annual amount of less than 600 mm (Silva, Santos, and Santos, 2018; Toledo & Alcantara, 2019). The effective precipitation (P-ET) is larger than the surface runoff in losing water catchments (negative ECI) and therefore contributes to the subsurface flow, which may not return as baseflow in the same draining catchment (Figure 6). The absence of rainfall precipitation in most part of the year limits the ET losses, which corroborates the correlation between aridity and the losing water condition (negative ECI) in the semiarid when combined with intermittent flow.

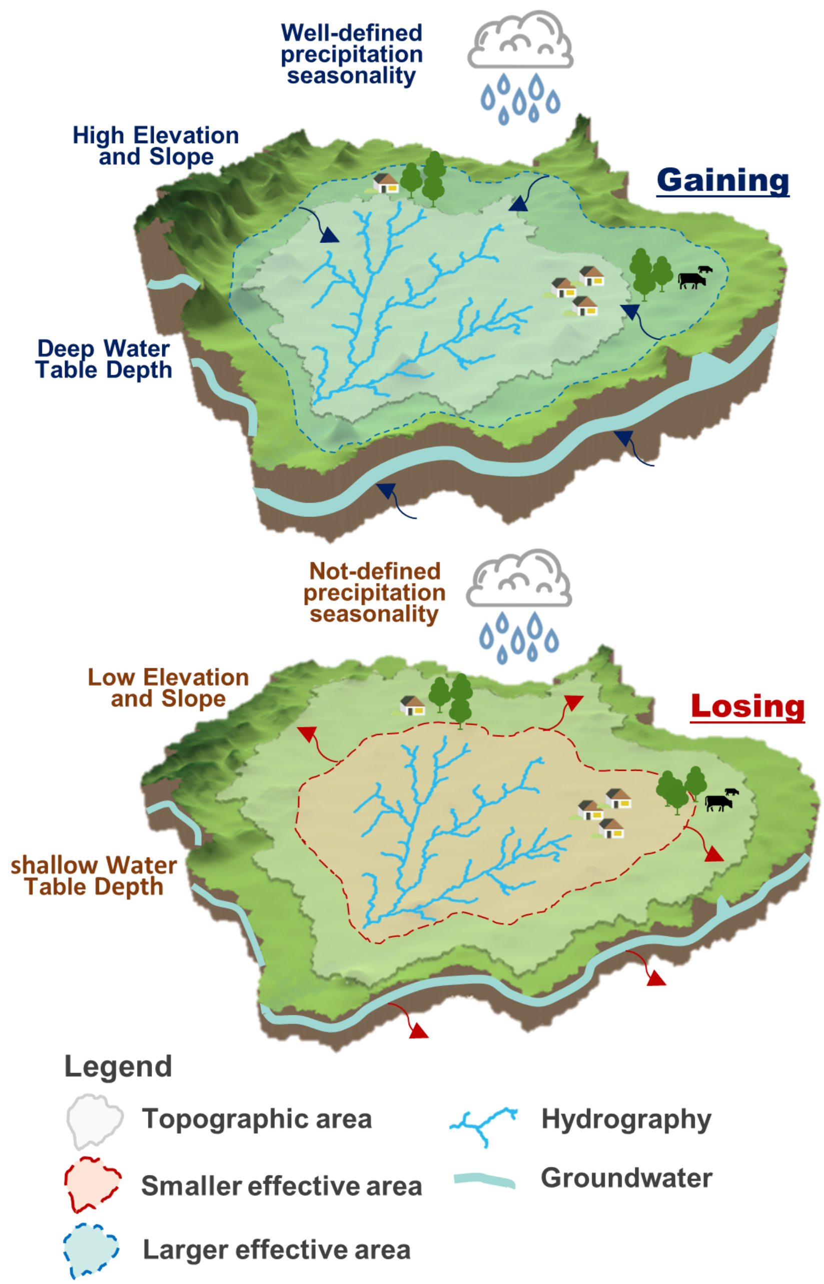

Figure 6: Figure 6: Main features of gaining and losing water cacthments.

Catchments in the Cerrado e Caatinga — more arid biomes — were prone to present a losing water condition that deteriorates the imbalance between water availability and demand in these regions (Gesualdo *et al.* , 2021). This situation is exacerbated by the long-term conversion of natural vegetation to different agricultural land uses (e.g., sugarcane, soybean, and corn), which have been responsible for more than half of the national grain production (Spera, 2017) mainly in the Cerrado. Furthermore, the increase in irrigated areas for food production in the Cerrado and Caatinga biomes has been recently related to an increase in evapotranspiration and baseflow reduction in these regions (Oliveira *et al* ., 2020; Lucas *et al* ., 2021). Therefore, quantifying the effective catchment area is key to better understand synergies and trade-offs of land use changes and the increase in irrigated areas. The observed losing water condition suggests a strong inter-catchment hydrological dependency among the catchments in these biomes as a substantial part of precipitation contributes to the subsurface flow.

Our ECI results were positively correlated with mean slope and mean elevation corroborating the gaining water condition found in 72% of the catchments located in the Atlantic Forest biome, which presents the highest mean elevation and slope (Almagro et al., 2020). Indeed, low and high slopes were associated with smaller and larger effective areas, respectively (Figure 5b). Different from Liu *et al.* (2020), we did not note high variability of the effective area — i.e., either positive or negative ECI — in flatter regions (Figure 5d). On the other hand, ECI only presented low variability with increasing elevation. For instance, the catchment in the Pantanal biome, characterized by a complex hydrological dynamic, presented a substantial deviation between its effective and topographic area, indicating a losing water condition. Thus, the observed losing water condition corroborates the characteristics of a flat lowland area, where rivers flood the plains and feed an intricate seasonal drainage system (Ivory, McGlue, Spera, Silva, & Bergier, 2019). Additionally, the topographical catchment delineation is more susceptible to errors in complex topographies since the effect of Digital Elevation Models accuracy is not well understood, leading to a mismatch between topographic and effective areas (Zandbergen et al., 2011).

Catchments with a well-defined precipitation seasonality were associated with gaining water conditions as in the southern part of the Cerrado and the entire Atlantic Forest biome. Nonetheless, the precipitation seasonality index has some limitations when applied in Brazil due to its climate characteristics. Low thermal amplitude characterizes the climate in the north and northeast regions so that it is difficult to determine whether precipitation occurs during the summer, the winter, or throughout the year. The WTD and HAND had little influence on ECI probably due to the low spatial resolution of the available data. Carrying out large-scale studies involving groundwater is still challenging since high-resolution products at large scales are scarce (Gleeson, Cuthbert, Ferguson, & Perrone, 2020). Besides, monitoring the groundwater table is associated with high levels of uncertainties, frequently limited to developed regions (Fan, Li, & Miguez-Macho, 2013). Similarly, the soil texture data used in this study also have a low spatial resolution (250 m), which may have compromised the RFA performance in identifying its influence on ECI estimates (Supplement S3). Even though this attribute presents the lowest influence, it plays an important role in the catchment's water cycle and groundwater flow in terms of soil water storage and percolation.

Implications for the understanding of hydrological connectivity and potential advances in water resources management

In this paper, we assessed the concept of interconnected catchments through the investigation of their effective areas. The hydrological connectivity was inferred from the flow-process perspective, defined by Bracken *et al.* (2013) as the understanding of runoff patterns and processes on hillslopes. From this perspective, we spatially assumed the connection between catchments and their influencing attributes. Based on the ECI results, we can state that catchments are sub-superficially interconnected. Although the scientific community agrees on inter-catchment connectivity, this is still a recent concept and little explored by water management decision-makers.

Incorporating the knowledge of the effective area and its influencing factors in the water resources management, the groundwater boundaries and processes may be reasonably considered. These processes are often neglected when the topographic area is solely used as a management unit. Therefore, the inclusion of the magnitude of the effective area would improve the comprehension of more reliable hydrological processes on a catchment scale. Besides, understanding the deviation between topographic and effective areas copes with the lack of clear and detailed information about aquifer properties and limits (Hirata, Kirchheim, & Manganelli, 2020), which are important to have integrated water management (Samani, 2021).

The ECI is a relevant tool for tackling water vulnerabilities and inequalities in allocating and managing water.

In the semiarid region, Brazilians are exposed to high levels of water insecurity and inequality exacerbated by recurrent and prolonged droughts (Gesualdo *et al.* , 2021). By knowing the magnitude of the deviation between the topographic and effective areas, the influencing climatic and physiographic attributes, and its underlying hydrological processes, decision-makers can assemble groups of nearby connected catchments. Based on this, water resources management would be settled into a *pooling of catchments* — a combination of the interests and needs of a group of catchments — considering their interconnection. The exclusive use of topographic delineation is a limiting factor although the water resources management practice is already designed for a large group of catchments (e.g., as in the São Francisco River Basin (one of the 12 hydrographic units in the country).

Efforts on water-related preservation and conservation have been made in contributing surface areas upstream reservoirs and pumping points even though these are often much smaller or larger than the actual contributing areas. Therefore, advances in understanding and identifying effective areas play a key role in synergistically managing watershed services related to water yield and provision. For instance, it would imply a greater environmental responsibility by water-gaining catchments benefiting from water ecosystem services provided by water-losing catchments. We emphasize the paramount importance of integrating hydrological processes and water ecosystem services relevant for catchment management as alterations in flow processes impact water provision and vice-versa (Grizzetti, Lanzanova, Liquete, Reynaud, & Cardoso, 2016). Thus, managing a *pool of catchments* can increase synergies and lessen trade-offs of water transfer processes. Sustainable inter-basin water transfer is an alternative for addressing the imbalance in water availability and demand mainly in the Caatinga and Cerrado biomes (Gesualdo et al., 2021). Hence, advancing the understanding of hydrological connectivity between semiarid and arid catchments better copes with water scarcity. In this context, the ECI guides possible solutions to a question encompassed by Guswa *et al.* (2014): "What parcel of land is the highest priority for conservation?". The effective area deviation can support decision-makers in identifying catchments with the highest priority for conservation and best management practices implementation.

Considering the inter-catchment connectivity contributes to investigating the extent of groundwater pollution and projecting efficient water use in activities such as agriculture. In the agriculture sector, the quantification of effective catchment areas would allow decision-makers to strategically manage the increase in water-fed irrigation areas in Caatinga and Cerrado biomes and understand how this disturbs the water balance in these regions. Although the land cover was not one of the most important attributes to identifying the effective catchment area, it has a major role in unveiling the mechanisms of movement and storage of water at a catchment scale. Nevertheless, anthropogenic impacts on water fluxes are still poorly understood (Neupane & Kumar, 2015) such as land use and land cover changes and inter-basin transfers.

There are future research opportunities for addressing surface and groundwater integration, such as:

- How water-fed irrigation area disturb the water balance?
- What are the results and uncertainties from adding the variable "land use and land cover changes and inter-basin transfers" to ECI computation?
- The ECI indicates the deviation between the topographic and effective catchment areas, so what are the physical boundaries of the effective area of a catchment?

CONCLUSIONS

In this study, we were driven by the question "are topographic catchments isolated in a way to be defined as a single management unit?". In order to investigate it, we assessed the effective area of 733 Brazilian catchments and the deviation from their respective topographic area by adopting the effective catchment index (ECI). Our findings indicated that 31% of the studied catchments have a significant mismatch between their topographic and effective areas (i.e., effective areas either smaller than half or larger than double of their topographic areas). We also inferred the hydrological connectivity through flow-process to better understand the groundwater flow and runoff patterns.

We evaluated the ECI estimates by contrasting our results against the expected range of the Budyko curve considering both topographic and effective catchment areas (classic and adjusted framework). Most catchments were between the theoretical water and energy limits in the Budyko space for both classic and adjusted Budyko frameworks. We found that catchments better fitted the Budyko curve when considering the effective area (the adjusted Budyko Framework). Additionally, catchments that gain water are closer to the upper water limit while catchments that lose water are mostly concentrated below the Fu curve, and an opposite behavior was observed on the classic framework.

The ECI values are consistent with the biome's climate dynamics as indicated in the classic Budyko framework. We observed a clear signal of water gain (ECI > 0) in catchments located in the Atlantic Forest biome (humid tropical zone) and water loss (ECI < 0) in the Cerrado and Caatinga biomes (Savannah and semi-arid zones), which present higher evaporative index. A lack of a clear pattern in the other biomes may be due to the low density of gauged catchments. We also identified the aridity index, mean slope, seasonality, and mean elevation as the four most influencing catchment attributes on the ECI. The aridity index showed the most influence in the ECI, increasing as the ECI decreases, indicating that smaller effective areas are found in the aridest biomes. Besides, ECI was positively correlated to mean slope and mean elevation supporting the highest presence of catchments with larger effective areas in the Atlantic Forest biome, a region characterized mostly by a mountainous landscape.

The use of the ECI index allows us to infer from catchment connectivity; therefore, it should be considered in future hydrologic studies at a catchment scale, water-related services, and water resources management. Here, we highlight the potential of *pooling of catchments* based on their interconnectivity (gaining or losing water potential given by ECI) and topographic location and extension. According to this concept, catchments can be grouped by their common interests, minimizing management cost while maximizing synergies and lessen trade-offs of water transfer processes.

Our results contribute to a better country-scale understanding of hydrological connectivity among catchments to overcome regional challenges related to unbalanced water availability and demand. Our contributions are the first steps towards more robust water, food, energy, and ecosystem services management for making Brazilian water security more resilient to climate variability.

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DATA SHARING

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDICES

S1 – Description of the 15 attributes used in the Principal Component Analysis (PCA).

S2 – Histogram of (a) the ratio of the effective to the topographic catchment area (A_{eff}/A_{topo}) and of five catchment attributes: (b) Aridity Index, (c) Catchment slope (Catch Slope), (d) Precipitation seasonality (P seasonality), (e) Mean elevation, (f) Distance to coast.

S3 – Results from the Random Forest Analysis (RFA).