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IMPLICATIONS OF LCA CHOICES ON INTERPRETATION OF RESULTS AND ON DECISION SUPPORT

Water scarcity in Brazil: part 1—regionalization of the AWARE model characterization factors

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Abstract

Purpose This paper presents the regionalized water scarcity characterization factors (CFs) of the available water remaining (AWARE) model, which was found by a previous study, on the water scarcity in Brazil, to be the most indicative characterization model for the water-scarce regions in Brazil. We used the national database and hydrographic delimitations defined by the National Water Agency (Agência Nacional de Águas — ANA) to generate the regionalized AWARE BR CFs.

Methods The CFs were regionalized by hydrographic delimitations used by ANA: (i) State Hydrographic Units (SHU) and (ii) Hydrographic Regions (HR). These AWARE BR CFs were compared with the factors originally proposed by WULCA (2018) and with the Scarcity Index used by ANA to identify the scarcest regions in the country. Finally, the AWARE and AWARE BR factors were applied to a case study of Brazilian melons, evaluating the regionalization effects on the results of water scarcity analysis.

Results and discussion The AWARE BR CFs demonstrate most consistency with the regions recognized by ANA to have water scarcity problems, such as the semiarid region. Approximately 12% of the SHUs exhibited maximum water scarcity (CF = 100) during the entire year, while 11% presented minimum scarcity factors (CF = 0.1). The comparison of hydrologic data from ANA with those from WaterGAP indicated that water availability was overestimated in WaterGAP, while demand was underestimated in different basins. The comparison of AWARE BR CFs with ANA Scarcity Index values indicated more similarity (smaller residual error) than the comparison of AWARE BR CFs with AWARE. The case study regarding the impact of water scarcity on melons showed a significant difference between characterization factors and, consequently, in the values of impact.

Conclusions AWARE BR factors generated with national characterization data are adapted to the different regions of Brazil, exhibiting higher sensitivity to the semiarid region. This regionalization provided a more accurate representation of the scarcity in smaller basins located in larger basins, characterized by large climate variation.

Keywords Brazilian semiarid · Characterization factors · Hydrographic regions · State hydrographic units · Water scarcity

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1 Introduction

Water scarcity became a global concern due to increasing water demand by the human population especially for irrigated agriculture and urban areas. Irrigated agriculture represents the largest water user in the world, being responsible for 70% of global water abstraction, whereas water demands for industry represent about 20% and for municipal use, 10% (Ashley and Cadilhon 2018). According to Mekonnen and Hoekstra (2016), two thirds of the world's population, comprising approximately four billion people, live under severe water scarcity conditions for at least 1 month of the year. Additionally, half a billion people around the world face severe water scarcity during the entire year.

In addition to posing an environmental problem in different regions of the world, water scarcity can also become a commercial concern for exporting countries or regions when the product is dependent on water supply. This is because of the growing consumer demand for environmental certification of products.

In 2014, the water footprint norm, ISO 14046:2014 (ISO 2014), was published, which requires consideration of the life cycle in the calculation of a product water footprint. The water footprint, according to this norm, includes different impact categories related to water, such as freshwater and marine eutrophication, as well as water scarcity. However, this norm also supports the conduction of studies considering only one associated water-related impact category, for example, water scarcity. In this case, the study is named the water scarcity footprint.

According to ISO 14046, water scarcity is defined as water consumption that approaches or exceeds the natural regeneration capacity of a water body (ISO 2014). The consumption should consider human demand as well as the demands of the ecosystems (Kounina et al. 2013). The regeneration capacity is associated with annual water availability in regions that should be capable of meeting the total water demand in that region. Therefore, to evaluate the water scarcity of a region, variables related to the demand, availability, and area of the hydrographic region are considered.

Studies on the water scarcity footprint evaluate the impact of water consumption on the water availability of a region. Because many production processes are related to the product life cycle, these studies consider water scarcity in the different regions that provide water for each process in the product life cycle.

Thus, the evaluation of the impact of a product on water scarcity requires the investigation of water consumption in the different processes related to the product life cycle (inventory data), as well as the generation of characterization factors (CF) that depict the scarcity level in each region. Many models are available where the scarcity factors are calculated in a hydrographic basin, country, or continent.

Almeida Castro et al. (2018) evaluated 12 models to identify the most adequate for the Brazilian context according to criteria related to the scope of the indicator, scientific robustness, and availability of CFs for Brazil. The monthly water stress integral (WSI) (Pfister and Bayer 2014; Pfister et al. 2009) and AWARE (WULCA 2018) models were most efficiently evaluated by these criteria. Both models are based on hydrologic data generated by the WaterGAP global model at the scale of 0.5° × 0.5°, aggregated in large hydrographic basins. However, Almeida Castro et al. (2018) observed that the demand and availability data from WaterGAP are not very sensitive to the low water availability and high water demand historically present in one part of the São Francisco basin located in the semiarid region of Brazil. Furthermore, the WaterGAP basins scale is large, and future CFs regionalization studies for Brazil should adopt a smaller scale, following the state hydrographic divisions of Brazil according to the National Water Agency (Agência Nacional de Águas — ANA). In Almeida Castro et al. (2018), the authors identified the availability of hydrographic data in national databases from ANA and suggested that this data should replace the data generated by WaterGAP in a future regionalization study, aiming to increase the sensitivity of the CFs in Brazilian watersheds, especially of those located in scarce regions.

In the last few years, studies regarding the regionalization of water scarcity models have been performed in many countries, aiming to obtain results with greater spatial differentiation. Studies of this kind were performed in Mexico (Farell 2013), Chile (Peña and Huijbregts 2014), and Spain (Núñez et al. 2015). The latter performed the regionalization of CFs for the WSI model (Pfister et al. 2009; Pfister and Bayer 2014) using databases and spatial delimitations of national hydrographic basins. This study concluded that the regionalization of CFs improved the evaluation of impact factors related to water scarcity, thus promoting regionalization also in other countries.

This study performs the regionalization of CFs from the AWARE model (WULCA 2018) for Brazilian basins with data and delimitations from ANA. The AWARE model was selected because of its positive evaluation by Almeida Castro et al. (2018), in addition to being the model indicated by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) for the evaluation of product water scarcity footprint.

The basins adopted in the WaterGAP and AWARE comprise large areas, hindering the distinction of regions and their differentiation in terms of water availability and demand. The main contribution of this study is the improvement of the CFs sensitivity in climatically and demographically non-homogeneous areas located inside large water basins.

2 Methods

2.1 Selected model

The AWARE model (WULCA 2018) has an indicator depicting the inverse of the difference between water availability and demand, $1/AMD_i$. AMD_i denotes the monthly remaining water volume available for use in basin i per area unit (m^3/m^2 month), once human and water ecosystem demands are met. The remaining flow rate is obtained by the difference between water availability (natural flow rate) and water demand in the basin (Eq. (1)).

The natural flow rate is the flow rate that would occur in a section of the river in the absence of anthropic actions in the basin upstream, such as the regulation of reservoir flow rate, transpositions, and the collections for different purposes (Álcamo et al. 2003).

$$AMD_i = \frac{(Availability\text{–}Human\ Demand\text{–}Ecosystem\ demand\ )}{\text{Area}} \quad (1)$$

The normalized CF, used to depict the scarcity of a basin in relation to the world's average scarcity, is obtained by the $AMD_{world\ ave}$ to AMD_i ratio calculated for the basin (Eq. (2)).

$$CF = \frac{AMD_{world\ ave}}{AMD_i} \quad (2)$$

Lower and upper limit rules are applied to the CFs after normalization. When the basin's demand exceeds water availability, the upper limit is adjusted to 100 (maximum value), while when the AMD_i is lower than ten times the value of $AMD_{world\ ave}$, the minimum value of 0.1 is applied to the CF.

AWARE characterization factors were calculated using monthly estimations of human consumption in specified sectors and the natural flow rate of the WaterGAP global hydrology model (Álcamo et al. 2003). In the same way, to determine ecosystem demand, monthly ecological flow rates proposed by Pastor et al. (2013) were used. This model quantifies ecosystem requirements as a fraction of the total flow rate available in the water body.

The AWARE model CFs are available at different temporal and spatial resolutions. The highest resolution is per month and per hydrographic basin. Annual and monthly factors are likewise available for different hydrographic and political divisions (country and continent), considering agricultural (*Agri CF*) activities, other non-agricultural (*Non-Agri CF*) and generic (*Generic CF*) activities.

The aggregation of monthly factors into annual estimates, as well as estimates gathering basins in countries and continents, occur through a weighted average, weighting the factors according to the water consumption: (i) agricultural consumption for agricultural aggregates (Agri CF); (ii) non-agricultural consumption (industrial and domestic) for aggregated non-agricultural factors (non-Agri CF); and (iii) total consumption for generic aggregated factors (default CF).

2.2 Study area

The adopted study area comprised the 12 Hydrographic Regions (HR) of Brazil and the 449 State Hydrographic Units (SHU) that compose these HRs (Fig. 1), defined by ANA for Brazil (ANA 2005).

The regionalization of the factors was performed gradually, with the SHUs as the highest spatial resolution depicting the smaller geographical areas to be considered for the calculation of the CFs of Brazil, hereinafter named AWARE BR CFs. Thus, monthly and annual generic AWARE BR CFs (*Generic* CFs), annual agricultural AWARE BR CFs (*Agri*), and annual non-agricultural AWARE BR CFs (*Non-Agri*) were determined. The CFs of the SHUs were aggregated for the HRs, calculating the monthly and annual "*Generic*," "*Agri*," and "*Non-Agri*" AWARE BR CFs.

The CFs of the SHUs were also aggregated for the calculation of the monthly and annual "*Generic*," "*Agri*," and "*Non-Agri*" CFs of Brazil. The same aggregation rules of the AWARE model were applied in the calculation of the AWARE BR CFs at HR and country level.

2.3 Calculation of the water availability

ANA has developed a georeferenced database which provides information (flow rate, drainage section, area of hydrographic contribution, drainage point, water course, hydronym, dam, and water body) for river sections. This database is provided in a shapefile which is available online and can be obtained at ANA Geonetwork.

Each SHU has a main river composed for several sections, and one of these sections is the mouth of the river, the point of a water course where the entire superficial flow generated inside the hydrographic basin converges. The mouth of each SHU was located, and the monthly flow rate was identified in the georeferenced files provided by ANA. However, for many SHUs, only the annual flow rate was available. In this case, the daily data from Brazilian gauging stations were used to calculate the monthly water flow. The station located closer to the mouth of the main river within the SHU, which contained at least 30 years of gauging data, whenever possible, was selected. The flow rates from all Brazilian gauging stations are available on the ANA HidroWeb database (ANA 2005).

The calculation of average water availability was performed considering time series of natural flow rates, from 1901 to 2018. For each flow rate acquired via gauging station, the value of the total demand in a

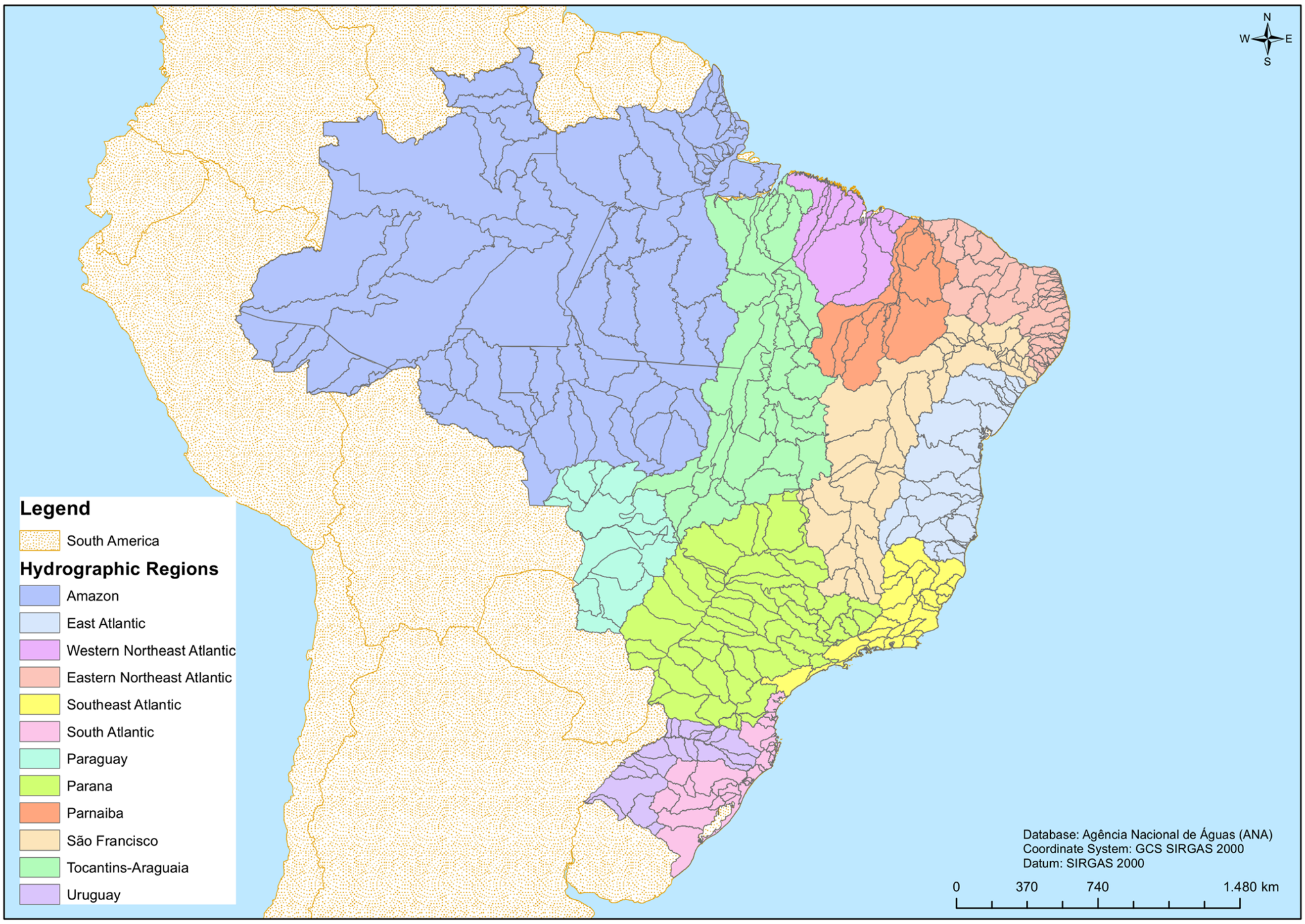

Fig. 1 Map of the hydrographic Regions (HR) of Brazil and the state hydrographic units (SHU)

SHU was added to obtain the value of the natural basin flow rate.

2.4 Calculation of the agricultural and non-agricultural demands

The data related to agricultural and non-agricultural water demands were provided by ANA through personal communication, since it was a big database not available online. This data contains water demands in 2013, which was the last update made by ANA. These included georeferenced data whose detailing level features microbasins (areas ranging between 1.6 m^2 and 8720.5 km^2, with an average of 16.6 km^2). The SHUs are on average 20,601 km^2, while the HRs, 770,000 km^2.

To calculate the CFs at SHUs level, the demands of each microbasin inserted in the SHU limit were added. Only agricultural demand (irrigation data) included monthly data. For the others, the value proposed by ANA as annual demand in each microbasin was repeated from January to December as monthly non-agricultural demands, assuming these demands are constant along the year.

2.5 Calculation of the ecosystem demand

Pastor et al. (2013) provided the ecosystem demand percentage (environmental flow requirements — EFRs) in the form of a raster map — at a scale of 0.5° × 0.5° — for the entire globe. With the ArcGIS trial version, it was possible to determine the fraction of the ecosystem demand for all 449 Brazilian SHUs.

The ecosystem demand flow rate was obtained with the product of the natural availability flow rate of the basin and the demand fraction obtained by Pastor et al. (2013).

2.6 Cases studies

2.6.1 The impact of melon production applying both AWARE and AWARE BR CFs

To compare the impact of water scarcity, both the original factors indicated by the AWARE (AWARE CF) and the regionalized factors obtained in this study (AWARE BR CF) are used to evaluate the impact of melon production on water scarcity. Melon culture was selected due to its importance for the Brazilian international trade and the semiarid region. Over

233,652 t of melon was exported in 2017, according to MDIC (2018). The main melon producers are located in the States of Ceará, Rio Grande do Norte and Bahia that accounted for over 86% of the national melon production in 2016 (IBGE 2018).

The studies by Figueirêdo et al. (2014) and Santos et al. (2018) were selected to obtain the consumed water volume in the production of yellow melons. These studies contemplate the melon culture in the relevant regions of Lower Jaguaribe and Açu (located in the States of Ceará and Rio Grande do Norte), and region of São Francisco (State of Bahia), respectively. Water consumption for irrigation in these studies was provided by farmers located in each region.

Although Figueirêdo et al. (2014) and Santos et al. (2018) provided irrigation water values for the whole melon production season (from July to December), only monthly values for one production cycle, from July to September, were used. The driest period in the Brazilian semiarid region occurs in these months (Marengo et al. 2011).

The water scarcity footprint was calculated by the sum of the products of the amount of water consumed in the production of 1 kg of fruit multiplied by the proposed monthly factors for the studied regions.

2.6.2 Effect of a short period of water crisis in regionalized CFs

A second case study was performed to evaluate if regionalization shows scarcity in regions subject to atypical period of water shortage. Characterization factors are usually calculated using a large period of data (30 years) to derive mean values for availability water. In this case study, the AWARE BR CFs of three SHUs in São Paulo State, subject to atypical water shortages, were compared to AWARE CFs. Furthermore, the regionalized CFs for these SHUs were also calculated considering shorter time series, accounting only the years with water shortage.

In 2014, the state of São Paulo started to experience a water crisis. This crisis resulted from a combination of the lack of rainfall and high human consumption (Marengo et al. 2015).

São Paulo is in the HRs of Paraná (with 18 SHUs) and Southeast Atlantic (with 4 SHUs). Two of these SHUs were reported by Marengo et al. (2015) to present water shortages

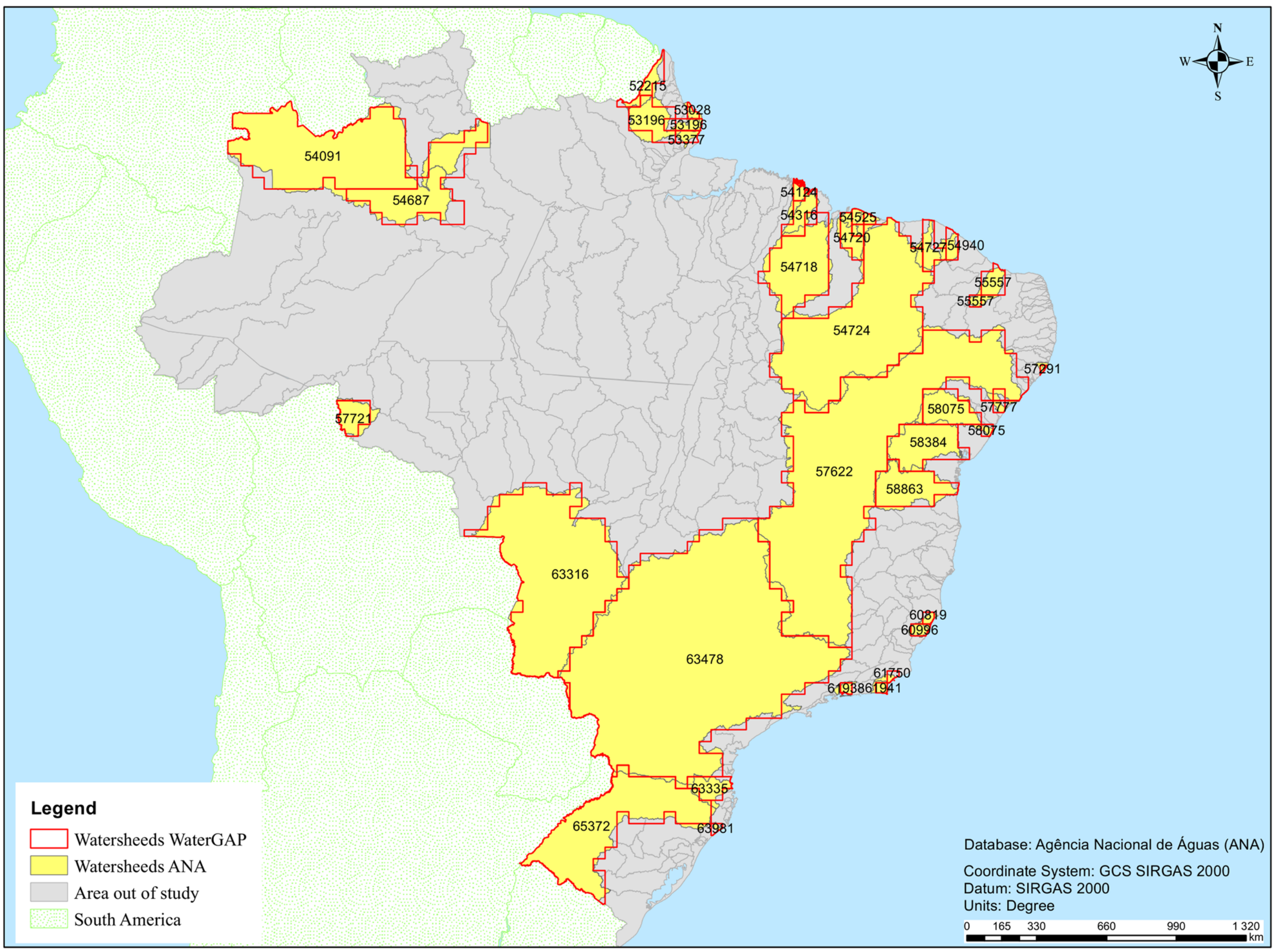

Fig. 2 Watersheds for the comparison between WaterGAP and ANA

Table 1 Regionalized CFs (AWARE BR CF) for the hydrographic regions of Brazil

HR	CF Jan	CF Feb	CF Mar	CF Apr	CF May	CF Jun	CF Jul	CF Aug	CF Sep	CF Oct	CF Nov	CF Dec	CF annual default	CF annual agri	CF annual non-agri
Eastern Northeast Atlantic	91.7	79.7	63.0	48.9	46.4	56.6	69.5	72.2	82.2	97.2	99.5	97.0	81.3	86.6	74.3
Parnaiba	38.2	13.8	12.2	12.9	29.4	46.1	49.8	50.8	52.0	54.0	53.2	47.9	42.9	51.5	34.0
Western Northeast Atlantic	25.7	21.2	20.0	19.6	18.8	24.5	50.2	57.4	57.9	68.8	69.2	45.1	42.9	54.0	40.4
South Atlantic	48.0	60.1	46.9	2.0	1.2	0.8	0.5	0.6	0.5	0.6	1.8	27.4	39.2	46.3	6.7
São Francisco	23.5	22.8	16.0	21.7	22.7	25.8	30.4	37.9	47.9	37.7	46.9	37.7	32.2	38.9	18.7
East Atlantic	30.1	19.6	20.9	23.2	27.7	28.7	28.6	41.5	50.3	32.6	23.6	25.5	30.4	35.3	27.2
Southeast Atlantic	10.4	18.6	20.6	18.4	20.3	27.3	32.0	30.6	30.5	26.7	26.1	23.5	24.1	29.5	5.6
Uruguay	19.3	19.3	1.4	0.6	0.5	0.5	0.5	0.6	0.5	0.4	0.5	1.4	12.3	14.0	1.5
Paraná	16.0	15.6	13.4	8.5	8.6	8.6	10.3	15.2	13.3	9.4	12.2	15.9	11.8	4.4	17.6
Tocantins-Araguaia	2.4	0.9	0.8	0.5	0.6	1.0	11.6	13.9	8.0	9.0	6.4	5.2	5.7	8.6	3.1
Amazon	3.4	2.1	1.5	1.1	1.2	2.0	3.5	4.8	6.1	6.1	5.6	4.9	3.6	4.7	3.3
Paraguay	1.1	0.9	0.9	0.8	1.0	1.6	2.4	3.2	3.7	3.5	2.5	1.7	2.1	2.0	2.2

and were selected to be analyzed: Pardo SP and the Mogi-Guaçu and Pardo Rivers. Gauging stations were used for the calculation of the water availability in these SHUs, considering stations with time series of at least 10 years of water availability data, which included the years of intense water scarcity (2014 and 2015).

2.7 Strategy for the comparison of CFs

The spatial resolution of the basins from the WaterGAP model, employed by AWARE, and of the SHUs, employed by ANA, is different. While WaterGAP defines large basins formed by the combination of cells with 0.5° latitude × 0.5° longitude, the SHUs were defined by ANA according to the main rivers in each region, while observing the political limits of the states of Brazil.

The decision was made to not recalculate the CFs through spatial aggregations to avoid accumulation of errors in the CFs. However, some WaterGap basins were identified with spatial delimitations similar to those of the SHUs from ANA. The WaterGAP Hydrologic Model for Brazil contained 34 of the total 171 basins that were defined by presented limits similar to the SHUs or HRs from ANA (Fig. 2). These basins were in all Brazilian regions. Thus, a comparison between annual and monthly AWARE CFs with AWARE BR CFs was performed, for these 34 basins.

Table 2 Regionalized factors (AWARE BR CFs) for Brazil

	CF AWARE BR			CF AWARE original		
	CF agri	CF non-agri	CF default	CF agri	CF non-agri	CF default
January	43.1	20.1	32.0	1.47	2.09	1.75
February	44.4	19.3	33.7	1.35	1.39	1.36
March	29.2	19.0	21.8	1.30	1.01	1.21
April	10.8	17.4	13.5	1.19	0.91	1.09
May	12.0	17.6	14.6	2.09	1.18	1.73
June	13.6	19.7	16.6	4.77	1.61	2.62
July	18.8	23.2	22.2	4.43	1.81	2.49
August	25.9	27.9	29.2	4.60	2.24	2.94
September	33.7	30.1	30.8	5.80	2.54	3.69
October	38.1	28.4	30.7	8.04	2.70	4.60
November	48.3	26.4	30.2	5.73	2.63	3.70
December	42.5	24.3	28.6	1.60	2.44	2.09
Annual CF	31.6	22.8	26.1	2.45	1.88	2.17

Furthermore, the annual default AWARE CFs and AWARE BR CFs were likewise compared with the annual Scarcity Index generated by ANA. The values for this Scarcity Index were obtained from the quotient between the total annual removal and the average long-period annual flow rate in the SHUs, with values higher than zero (ANA 2013).

Because the Scarcity Index does not have minimum or maximum values, the same delimitations used by AWARE were adopted, applying 0.1 for the minimum delimitation and 100 for the maximum delimitation. The minimum delimitation of 0.1 was applied to avoid very small values such as 0.001. The maximum value (100) was applied when a value higher than 0.4 was found, since this criterion is applied by ANA to identify highly critical situations. For instance, the Curu SHU (Eastern Northeast Atlantic HR) presents a Scarcity Index of 42.4 and the Mid North Coast SHU (Southeast Atlantic HR), of 2394.9, both of which are considered by ANA to be in a highly critical situation (values higher than 40).

In these comparisons, the residual error (RE) was calculated (Eq. (3) to determine the geometric standard deviation ($GSD^2 = 10^2RE$, according to WULCA 2018). The interpretation states that the smaller the value of GSD^2, the higher the similarity between the results of the different CFs sets.

$$RE = \sqrt{\frac{\sum_{t=1}^{n}\left(\log x_{1,t} - \log x_{2,t}\right)^2}{n}} \quad (3)$$

Here, RE depicts the residual error; n is the total number of factors used in the calculation; t is each pair of factors compared; x_1 denotes the AWARE BR CF; x_2 denotes the AWARE CF or the Scarcity Index.

3 Results

Monthly generic factors (CF) were generated for 448 SHUs (Electronic Supplementary Material). These factors were aggregated, according to Boulay et al. (2018), and specified for the 12 Brazilian HRs (Table 1) and for Brazil (Table 2).

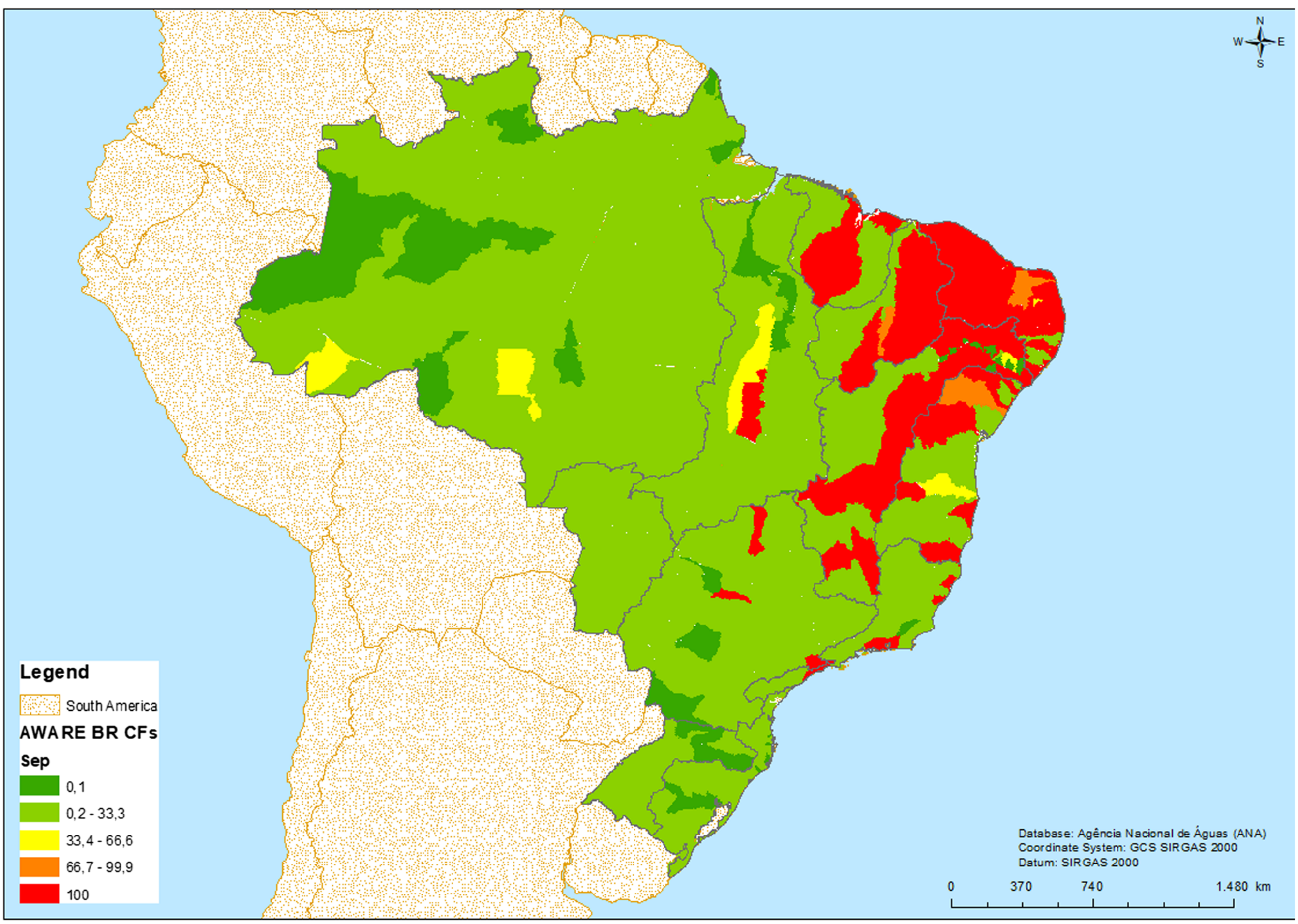

Fig. 3 Monthly CFs for SHUs in the month of September for the Brazilian HRs

3.1 Characterization factors for SHUs

Approximately 12% of the SHUs exhibit maximum water scarcity (CF = 100) in all months of the year. A similar percentage of basins, 11%, exhibit factors with minimum scarcity (CF = 0.01) in all months. Hence, most Brazilian basins are in an intermediary situation with high scarcity factors in some months of the year, and lower scarcity in the other months. The link to access the AWARE-BR CFs, at SHU, HR, and country level is provided in the Electronic Supplementary Material.

The scarcest months vary between the SHUs in each HR, especially due to the rainfall regime in the different regions that affect the natural flow and water availability. According to the CFs calculated for the SHUs in each HR, the months of November and October are the scarcest (the highest CF value) for the SHUs located in the HRs of Eastern Northeast Atlantic, Western Northeast Atlantic, Parnaíba and Amazon. In the HRs of São Francisco, East Atlantic, and Paraguay, September is the scarcest month for all SHUs. August is the month with the highest CF value in the SHUs of Tocantins-Araguaia. For the SHUs in Southeast Atlantic, it is July, in South Atlantic, February, and in Uruguay and Paraná, January.

Considering the monthly factors (CF) of the SHUs, the majority with maximum scarcity (CF = 100) are located in the Eastern Northeast Atlantic (33 SHUs), São Francisco (8), and East Atlantic (5) HRs (Fig. 3 and Electronic Supplementary Material). On the other hand, the monthly and annual factors with minimum values (0.01) are predominant in the SHUs located in the Amazon (9 SHUs), São Francisco (9), and Tocantins-Araguaia (5) HRs.

According to the analysis of the annual generic CF (*Default* CF), 87% of the SHUs with maximum water scarcity are located in the northeast region of Brazil, 33 SHUs in the Eastern Northeast Atlantic, 8 in the São Francisco, and 5 in the East Atlantic HR (Fig. 4). The 48 SHUs that exhibit minimum water scarcity are in the north and southeast regions (31% in the Amazon, 19% in the São Francisco and 15% in the Paraná HR).

In relation to the annual Agricultural CF (*Agri* CF), 47 SHUs in the different regions of the country exhibited maximum water scarcity, 28 in the Eastern Northeast Atlantic, 8 in the São Francisco, and one in the Paraná HR. The minimum CF also appeared in the different regions of Brazil, in 46 SHUs, 14 located in the Amazon HR, nine in the São Francisco HR, six in the Tocantins-Araguaia and Paraná

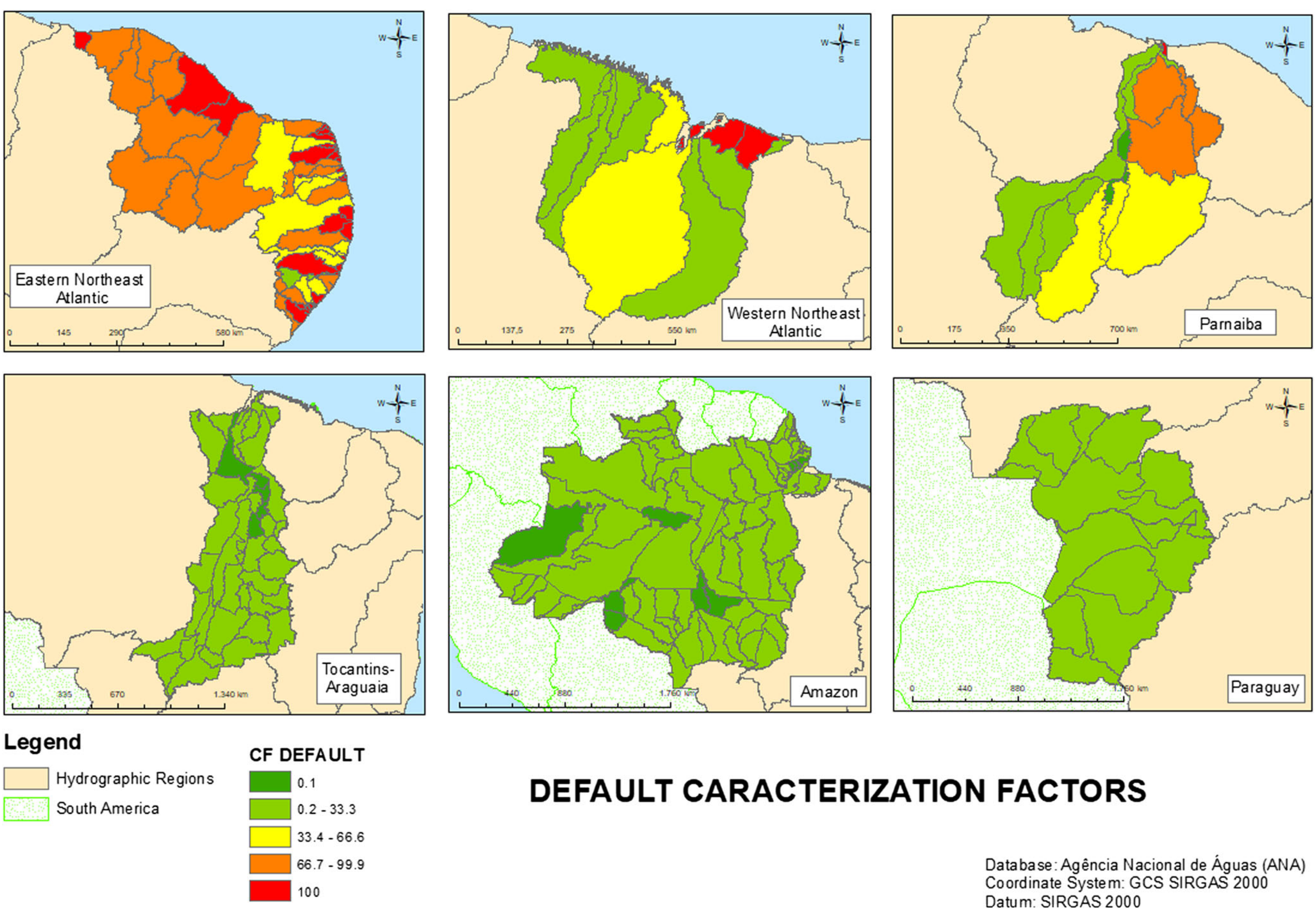

Fig. 4 HRs with the highest (top row) and smallest (bottom row) Generic CFs

HRs, five in the South Atlantic, three in the Uruguay, two in the Southeast Atlantic, and one in the East Atlantic HR (Fig. 5).

The annual Agricultural CFs (*Agri* CF) could not be determined in 23 SHUs due to the lack of irrigation demand in these SHUs or due to unavailable data. This includes 15 SHUs in the Amazon HR, 5 SHUs in the Eastern Northeast Atlantic HR and 1 SHU in the Western Northeast Atlantic, South Atlantic, and São Francisco HRs.

According to the evaluation of the values of the annual non-agricultural factor (*Non-Agri* CF), 52 SHUs presented maximum water scarcity. Most of these SHUs are in the Eastern Northeast Atlantic (63%), São Francisco (15%), and East Atlantic HR (10%). On the other hand, 51 SHUs presented minimum *Non-Agri* CF, being located especially in the Amazon (31%), Paraná (18%), and São Francisco HR (18%) (Fig. 6).

3.2 Characterization factors for the HRs

The HRs that presented the highest *Generic CFs* (monthly and annual) and annual *Agri CFs* are located in the northeast (Eastern Northeast Atlantic) and north (Western Northeast Atlantic) regions (Fig. 4). Eastern Northeast Atlantic and Parnaíba regions are within the Brazilian Semiarid, which also comprises part of the East Atlantic and São Francisco HRs.

The HRs with the lowest scarcity factors are in the midwest (Paraguay and Tocantins-Araguaia) and north (Amazon) of Brazil (Fig. 5). These HRs are found in historically rich regions in terms of water availability, and they still present low water demands.

For annual *Non-Agri CFs*, the scarcest HR was the Eastern Northeast Atlantic. The lowest scarcity occurred in Tocantins-Araguaia and Uruguay.

The HR that exhibited the greatest variation in terms of water scarcity during the year was the South Atlantic HR, presenting minimum CF of 0.5 in September and maximum CF of 60.1 in February. Least variation was found in the Paraguay HR, with CFs ranging from 0.8 in April to 3.7 in September.

3.3 Characterization factors for Brazil

New CFs were generated for Brazil through the aggregation of SHU CFs, according to Boulay et al. (2018) (Table 2). These

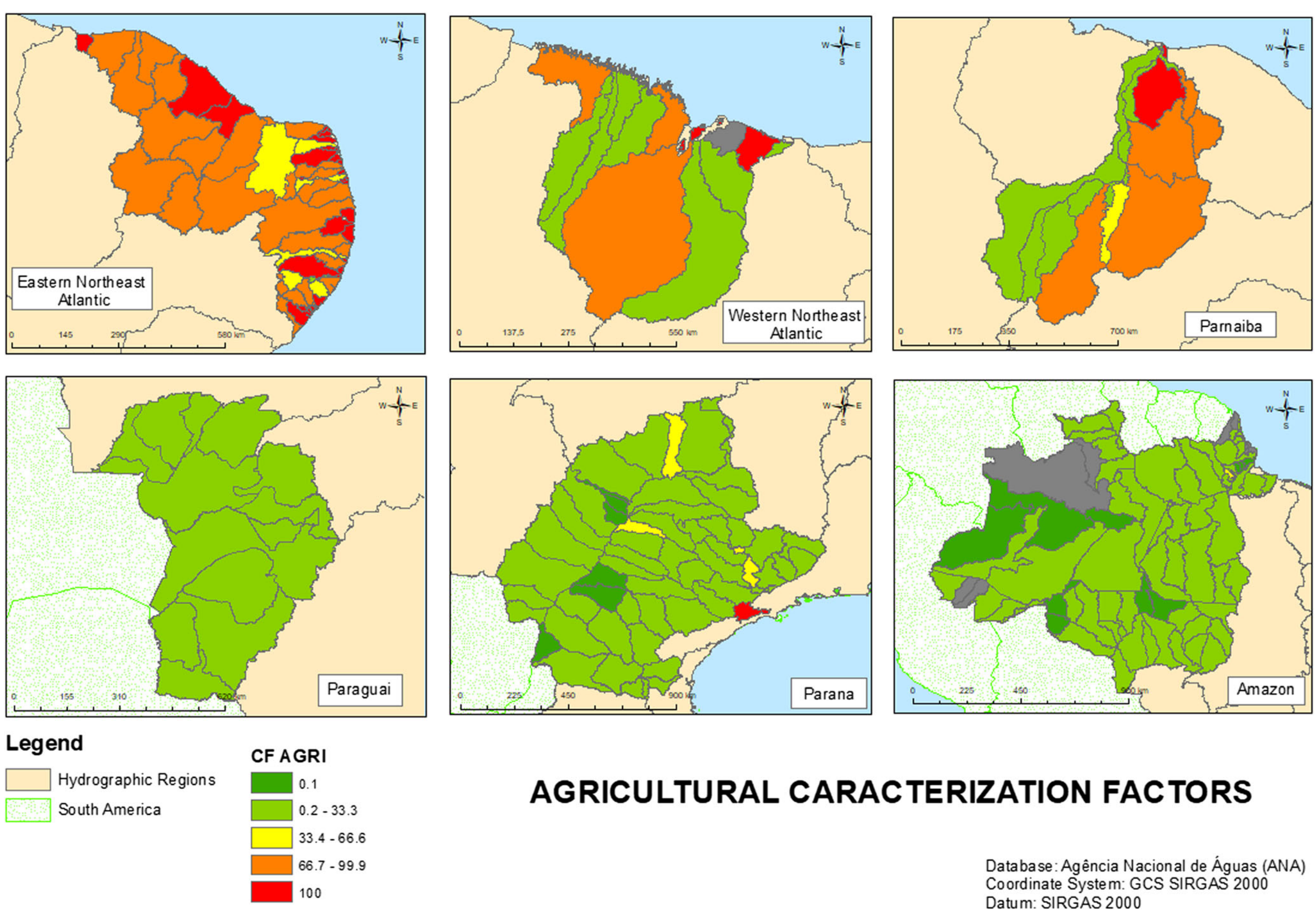

Fig. 5 HRs with the highest (top row) and smallest (bottom row) Agricultural CFs

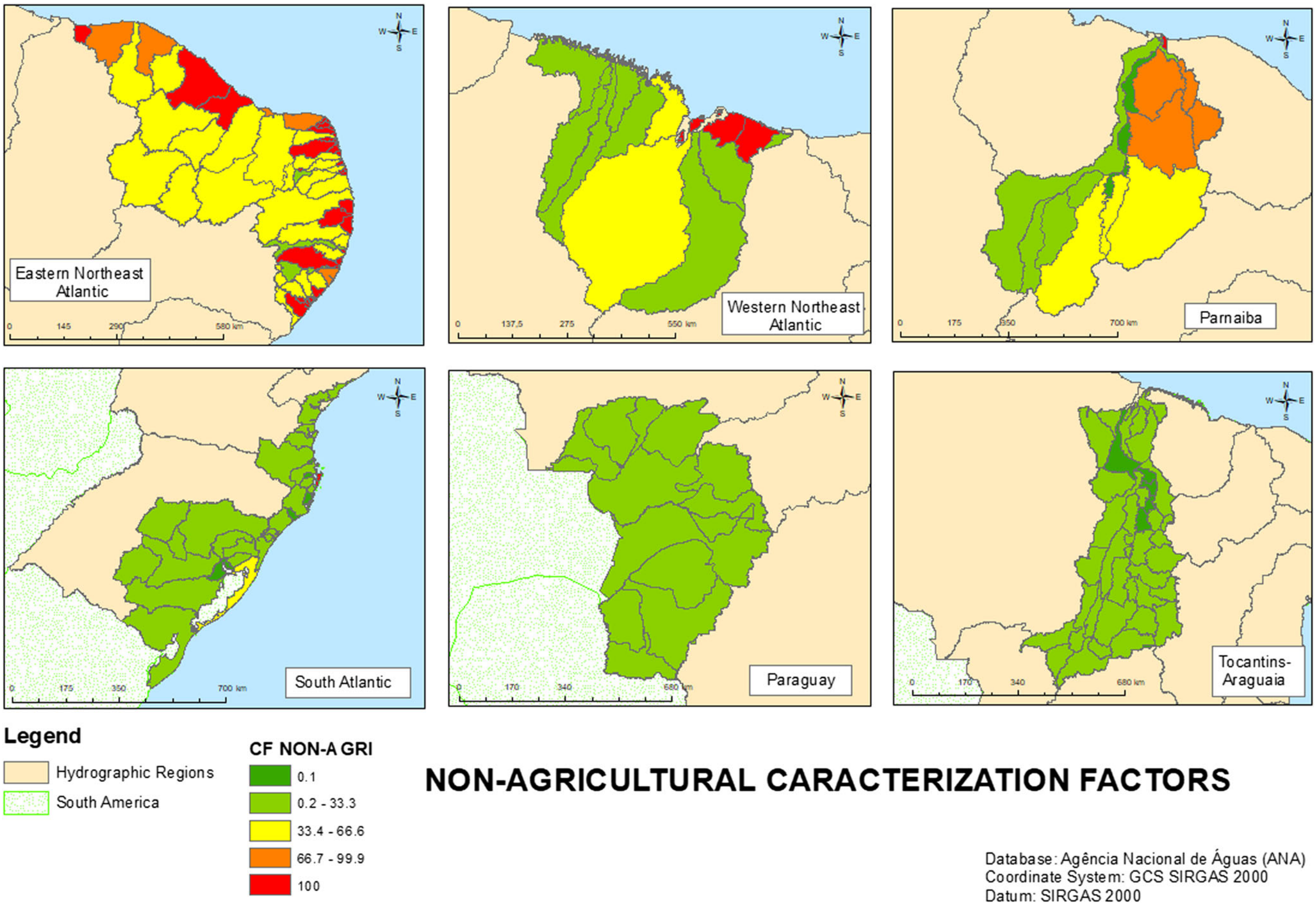

Fig. 6 HRs with the highest (top row) and smallest (bottom row) non-agricultural CFs

AWARE BR CFs indicated higher scarcity than those of AWARE, with differences between the factors greater than 65%.

According to the comparison of the *Agri CFs*, the largest difference was verified between the months of January and February, which presented a 97% increase in the AWARE BR CFs. When compared to the *Non-Agri CFs*, the months of March and April presented a 95% increase in the AWARE BR CFs. Among the *Generic CFs* the largest difference was in the month of February, with a 96% increase in the AWARE BR CF.

3.4 Cases studies

3.4.1 The impact of melon production in water scarcity applying both AWARE and AWARE BR CFs

The impact of melon production in the Low Jaguaribe/Açu and São Francisco regions on water scarcity was evaluated using the monthly AWARE CFs and the monthly AWARE BR CFs (Table 3). There was a significant difference between the factors in the studied basins and, consequently, in the resulting impact values.

The AWARE BR CFs are higher in all the months of plantation (July, August, and September), implying the higher impact of melon production on water scarcity. This result presents higher conformity with the very critical scarcity reality (demand/availability greater than 40%) in these basins, according to the national observations by the Ministry of Environment and ANA (MMA 2006a, b).

When applying the AWARE factors for the Low Jaguaribe/Açu region, there was a progressive increase in the impact over the months because of the increase in factors with the intensification of dry weather in the region. With regionalization and use of AWARE BR CFs, the impact of the Low Jaguaribe and Apodi-Mossoró SHUs did not vary over the months since they already exhibited maximum monthly factors (CF = 100).

Although larger water volumes were used to produce 1 kg of melon in the São Francisco region, this region still presented the smallest water scarcity footprint with the AWARE model. This result is due to the indication of high water availability in the region, according to WaterGap observations, which implies less impact on water scarcity (see Table 3). In contrast, when the AWARE BR CFs were applied, the impact of the Salitre SHU, where most of melon production area is located, became the

Table 3 Water scarcity applying AWARE CFs and AWARE BR CFs, considering the water consumption by the field melon production

Region		Lower Jaguaribe and Açu (Figueirêdo et al. 2014)						São Francisco (Santos et al. 2018)		
Water consumption (m^3/kg month)		0.06						0.09		
Period		JUL	AUG	SEP	JUL	AUG	SEP	JUL	AUG	SEP
Yield in 3 months (kg/ha)		23,000			23,000			33,711.21		
WATERGAP	Cell	55,365			55,557			57,622		
	Water demand irrigation (m^3/month)	36,798,308	29,928,132	35,171,120	10,696,130	7,366,264	9,568,804	6,101,891	12,157,413	15,756,557
	Water availability (km^3/month)	0.344	0.284	0.214	0.103	0.064	0.035	768,366	480.934	264.579
AWARE	Watershed	9280			9309			9692		
	CF	8.20	10.70	16.00	4.90	9.30	20.10	5.30	5.30	5.00
	Result 1	0.507	0.662	0.990	0.303	0.575	1.243	0.472	0.472	0.445
	Water scarcity footprint 1 (m^3/kg)	2.159			2.122			1.388		
ANA	Water demand irrigation (m^3/s)	11.8	17.1	20.8	5.8	8.7	10.5	1.8	1.2	2.5
	Water availability (m^3/s)	0.211	0.211	0.211	10.140	3.391	2.025	0.802	0.739	0.668
Regionalization Brazil	SHU	Low Jaguaribe			Apodi-Mossoró			Salitre		
	CF	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	Result 2	6.185	6.185	6.185	6.185	6.185	6.185	8.899	8.899	8.899
	Water scarcity footprint 2 (m^3/kg)	18.556			18.556			26.697		

highest among the SHUs evaluated in this case study, since regionalization best expresses the scarcity reality in this region.

3.4.2 Effect of a short period of water crisis in regionalized CFs

From 2014 to 2015, the population in São Paulo State started to deal with water shortages, especially in the SHU of Pardo SP and the Mogi-Guaçu and Pardo Rivers. The comparison between AWARE BR and AWARE CFs shows that no significant change was observed with the regionalization of SHU Pardo SP CFs (Table 4). Both original and regionalized monthly CFs ranged from 0.2 to 1.9, denoting a low scarcity in these SHUs along the year.

For Mogi-Guaçu and Pardo Rivers, after regionalization, the CFs increased, including CF 100 for August. However, it was necessary to evaluate if this water scarcity was due to the water crisis in 2014/2015 or it was an intrinsic situation in the watershed. Thus, comparisons were made between AWARE BR CFs for these SHUs, considering the full at least 10 years) and partial (years 2014–2015) historical series of "water availability" (Table 4).

In this case, the average annual flow rate was 52% higher than the atypical flow rate in the Pardo SHU, reaching 68% difference in the month of October. For the Mogi-Guaçu and Pardo SHUs, the difference between the total average flow rates and those of the year 2014/2015 was 69%, reaching 77% in the month of March (Table 4). In this former SHU, CFs of the maximum value (100) were found for 6 months of the year.

This case study highlights the need for using smaller historical series of water availability, instead of large periods of 10 to 30 years, when the purpose is to reveal recent scarcity events in a region.

4 Discussion

Considering the case study, regionalization led to major modifications in the water scarcity footprint of melon production. In this context, the following issues should be discussed: what is the residual error between the AWARE CFs and the AWARE BR CFs? Which Brazilian regions presented the largest variations? Are the regions indicated by ANA in its reports as the scarcest in Brazil the same as the ones identified by the AWARE BR CFs?

4.1 Comparison between the original and regionalized CFs

The residual error (GSD^2) of the comparison between the AWARE CF and AWARE BR CF sets was evaluated, considering 29 SHUs and 5 HRs with similar areas (Electronic Supplementary Material). Although it was not possible to compare the 449 SHU, these 34 watersheds are representative,

Table 4 Comparison of the data during the years of drought in São Paulo in the Pardo SP and Mogi-Guaçu Rivers SHU

Watersheds data			Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Pardo SP	Natural availability	Total	345.3	345.6	320.1	274.0	210.3	188.1	164.9	160.1	159.1	168.1	162.9	227.1
		Exclusion period of drought	365.2	367.6	336.9	285.3	218.7	196.1	171.0	166.4	165.6	177.4	168.3	232.0
		2014/2015	146.3	126.2	151.4	160.8	126.5	108.2	103.5	96.7	97.3	75.2	109.4	178.0
	CF	AWAREBR	0.2	0.2	0.2	0.4	0.6	0.8	1.7	1.9	1.2	0.7	0.6	0.3
		Exclusion period of drought	0.2	0.2	0.2	0.3	0.6	0.8	1.6	1.7	1.1	0.6	0.6	0.3
		2014/2015	0.6	0.7	0.6	0.7	1.3	2.4	11.9	100.0	5.1	3.1	1.0	0.4
		AWARE	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.9	0.9	0.7	0.7	0.7
Mogi-Guaçu and Pardo Rivers	Natural availability	Total	35.0	35.5	32.4	29.7	22.8	21.6	19.9	19.8	18.8	18.8	19.7	27.2
		Exclusion period of drought	31.8	32.3	28.3	22.3	16.5	14.7	12.4	10.3	10.7	12.4	15.0	23.7
		2014	8.7	4.9	6.4	6.3	4.9	4.7	4.3	3.7	3.4	3.0	5.6	14.9
	CF	AWAREBR	1.7	1.7	1.9	3.3	5.7	8.1	64.8	100.0	18.2	7.5	4.7	2.3
		Exclusion period of drought	1.7	1.6	1.9	3.3	5.6	8.0	59.1	100	17.6	7.3	4.6	2.3
		2014	7.1	15.2	11.4	38.3	100.0	100.0	100.0	100.0	100.0	100.0	20.2	3.8
		AWARE	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.9	0.9	0.7	0.7	0.7

once they are distributed in all over Brazil, not in one specific area (Fig. 2).

As observed, a GSD^2 value of 88.96 was obtained. This value of GSD^2 is higher than the result found by WULCA 2018) when comparing AWARE-DTAx ($GSD^2 = 11.43$), AWARE-WSI Pfister ($GSD^2 = 24.44$), AWARE-HDI Berger ($GSD^2 = 34.43$), and AWARE-WSI Boulay ($GSD^2 = 63.25$). This higher value is partially related to the smaller sample of basins analyzed in this study (34) when compared to the number of basins used in the study of basins at a global level, performed by WULCA (2018): (i) the AWARE -HDI Berger, AWARE-WSI Boulay, and AWARE-WSI Pfister factors were compared in 212 basins; and (ii) AWARE-DTAx in 11,050 basins.

For the SHU Rio Negro, SHU Oiapoque, SHU Gurijuba, SHU Ilha do Maraca, and SHU Urussunga, the regionalization decreased the yearly CFs (Agri, Non-Agri and Default). For the other 29 watersheds, the regionalization increased the yearly CFs (Electronic Supplementary Material).

The largest variation between the annual *Default CFs* of the AWARE and AWARE BR (calculated by the modulus of the difference of these CFs) occurred in the Lagos de São João SHU (Southeast Atlantic HR), while the smallest variation occurred in the Mamoré SHU (Amazon HR) and the Itajaí SHU (South Atlantic HR) (Fig. 7).

In the analysis of the five HRs, which were compared with the AWARE basins, the Paraguay HR presented the smallest difference in annual *Default CFs* and the São Francisco HR the largest.

Comparison of the calculation strategies used by WaterGAP and ANA for the determination of the water demand and availability reveals that they diverge (Table 5). The calculation of the availability water flow presented a larger divergence, which was performed by ANA through the monitoring of gauging stations, and by WaterGAP through hydrologic modeling. As observed, WaterGAP overestimated the availability flow values, obtaining almost three times the value calculated by ANA in some months of the year in the São Francisco region (Table 6). This overestimation is one cause for different CF calculated, comparing CF AWARE BR to the originals CFs proposed for Boulay et al. (2018).

Regarding water demand, both ANA and WaterGAP based their values on estimations. Nevertheless, different strategies were applied. WaterGAP used older area and irrigated culture references, resulting in underestimation of the irrigation demand, especially in areas with irrigated agricultural perimeters, such as in the HRs located in the semiarid region of Brazil (São Francisco and Eastern Northeast Atlantic).

Analyzing the general panorama for the country, it was possible to verify many areas that were shown as not scarce by the original values, but with the regionalization they became scarce, especially in São Francisco HR, Parnaiba HR, and East Northeast Atlantic HR, located in the Brazilian semiarid region.

4.1.1 Analysis of the AWARE BR CFs for the semiarid region

Four HRs (Eastern Northeast Atlantic, East Atlantic, São Francisco, and Parnaiba) and 80 SHUs are located, in their totality or large part of their territory, in the semiarid region of Brazil (Fig. 8). A CF of 100 was found in 84% of the SHUs within this semiarid region (Electronic Supplementary Material).

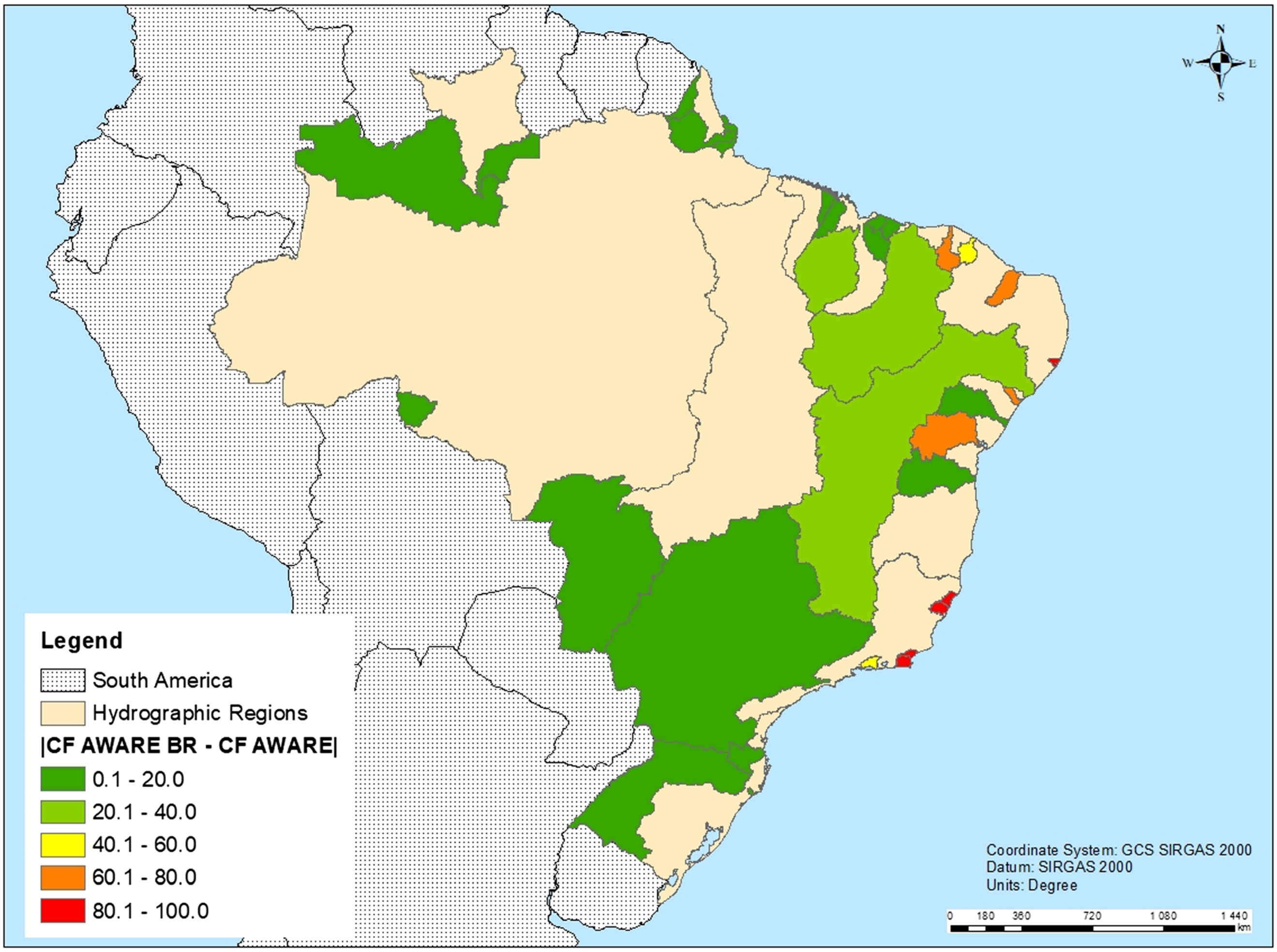

Fig. 7 Differences in the modulus between AWARE BR CFs and AWARE in the compared basins

According to ANA and the Brazilian Ministry of Environment (MMA), all the SHUs in the Eastern Northeast Atlantic HR experience some type of scarcity. SHUs such as the North Coast AL, North Coast PB, AL Paraíba, PB Paraíba, Goiana, and Potengi are presented with a highly critical situation (MMA 2006a). This scarcity situation is reflected in the AWARE BR CFs of these SHUs, where the lowest CF was 54.7 in the SHU PB Paraíba. However, according to AWARE CFs, these SHUs do not present scarcity. The maximum AWARE CF found in these SHUs was 17.7 for SHU Paraiba PB, that is shorter than the lowest CF AWARE BR (54.7).

In the case of the São Francisco HR, the WaterGAP values predicted no variation with the increase in demand over the driest months, due to the premise that agricultural production would halt in the absence of rainfall (Table 6). However, the agricultural production continues throughout the year in Brazil, especially in the semiarid region, where production is based on irrigation, as is reflected in the calculation of the irrigation demand by the ANA. In AWARE, the original CFs to São Francisco HR ranged from 1.13 to 7.21; AWARE BR from 16.05 to 47.85, increasing the CFs in this RH.

A study by MMA and ANA indicated that in the São Francisco HR, the SHUs of Verde Grande, Salitre, Verde and Jacaré, Paramirim and Santo Onofre, Carnaíba de Dentro, Pontal, Garças, Macururé, and Curaçá and Terra Nova are in a critical water scarcity situation and require intensive management and investment (MMA 2006b). Among these SHUs, only Paramirim and Santo Onofre, and Macururé and Curaçá did not exhibited AWARE BR CFs equal to 100 for all months. However, according to AWARE CFs, Verde Grande, Salitre, Verde e Jacaré, Paramirim and Santo Onofre, Carnaíba de Dentro, Pontal, Garças, Macururé and Curaçá and Terra Nova do not present scarcity.

Regarding the rainfall distribution in the semiarid region, the summer rainy period dominates the months of December to April (de Moura et al. 2006). In some HRs, this rainy season could be shorter and weaker (Eastern Northeast Atlantic), while in others, it could be longer and more intense (East Atlantic).

During the rainy period, there is a reduction of water scarcity events in the HRs located at the semiarid region, since the demand does not vary much throughout the months (Graph 1a — ESM). Hence, from December (beginning of the rainy

Table 5 Comparison between the WaterGAP and ANA databases

	National Water Agency		WATERGAP	
Water Availability (ANA 2016)	Data from the monitoring acquired by the state Water Companies		- Calculated through a series of water storage equations (storage change over time is equal the output subtracted with the input flow rates), the WaterGAP Hydrologic Global Model calculates daily water flow rates and storages in a 0.5° × 0.5° spatial resolution (55 km by 55 km at the Equator) for the whole terrestrial area of the Earth, except for Antarctica. - WaterGAP 2.2 is calibrated with the average annual river discharge in 1319 gauging stations and the calibration factor is adjusted and regionalized for the grid cells outside the calibration basins.	
Water Demand (ANA 2015)	Urban	- ATLAS – Water Supply - IBGE	Domestic	The development of domestic use over time is calculated by the product of the intensity of water use per capita and the population
	Rural	- 2010 Census (IBGE 2011) in the estimated population for 2013. -Values of rural per capita use established by State groups		
	Industrial	-Conceded by the states and by ANA until July, 2014. -Data spatialization was performed according to the localization of the industrial concessions	- The development of the manufacturing use over time is calculated by the product of the industrial production unit (considering structural and technological changes over time) multiplied by the motive force of the national industrial production (as gross aggregated value, which is one of the gross domestic product variables), or national thermal power production. - The national industrial demand is allocated to the grid cells as a function of the urban population	
	Animal	- Updated information from the Municipal Livestock Research - 2013 (IBGE). - The spatialization was performed according to soil use (pasture)	- The consumptive water use by cattle is calculated with the number of animals per grid cell and the water requirements per capita for 10 types of different animals. - The values of the national production and water consumption are regionalized for the grid cells using the population density	
	Irrigation	-Irrigated area incorporating the results from the Water Resources Plans and the mapping of center-pivot irrigations 2014 (ANA & EMBRAPA partnership). - 2006 Agricultural and Livestock Census and surveys by Conab - The data spatialization was performed by the mapping of pivots (Embrapa) and other available irrigated areas	- The irrigation water consumption is calculated in daily time steps for each grid cell based on the grid area equipped for irrigation and climate such as the total irrigation of rice with husk and other cultures, based on modeled culture standards. - The Global Irrigation Model is updated, and it computes liquid and gross requirements for the sector	

Table 6 Comparison between WaterGAP and ANA data for water availability and demand, regarding the São Francisco hydrographic region

	Water availability (m^3/s)		Agricultural demand (m^3/s)		CF default	
	WaterGAP	ANA	WaterGAP	ANA	AWARE	AWARE BR
January	2055.6	1033.6	58.4	88.5	1.5	23.6
February	3710.9	1105.7	110.5	122.6	1.1	22.8
March	4949.4	1117.1	105.5	86.6	1.2	16.1
April	5007.9	961.2	119.0	235.5	1.4	21.7
May	4424.7	701.9	106.5	332.5	4.3	22.7
June	3714.6	567.9	51.9	325.5	7.2	25.8
July	2950.5	526.5	38.9	340.1	5.3	30.4
August	1846.8	511.5	33.8	402.2	5.3	37.9
September	1016.0	506.7	40.0	411.5	5	47.9
October	598.5	516.9	36.0	331.5	4.5	37.9
November	479.0	598.1	26.4	161.9	3.7	46.9
December	669.1	802.0	30.4	113.3	2.6	37.7

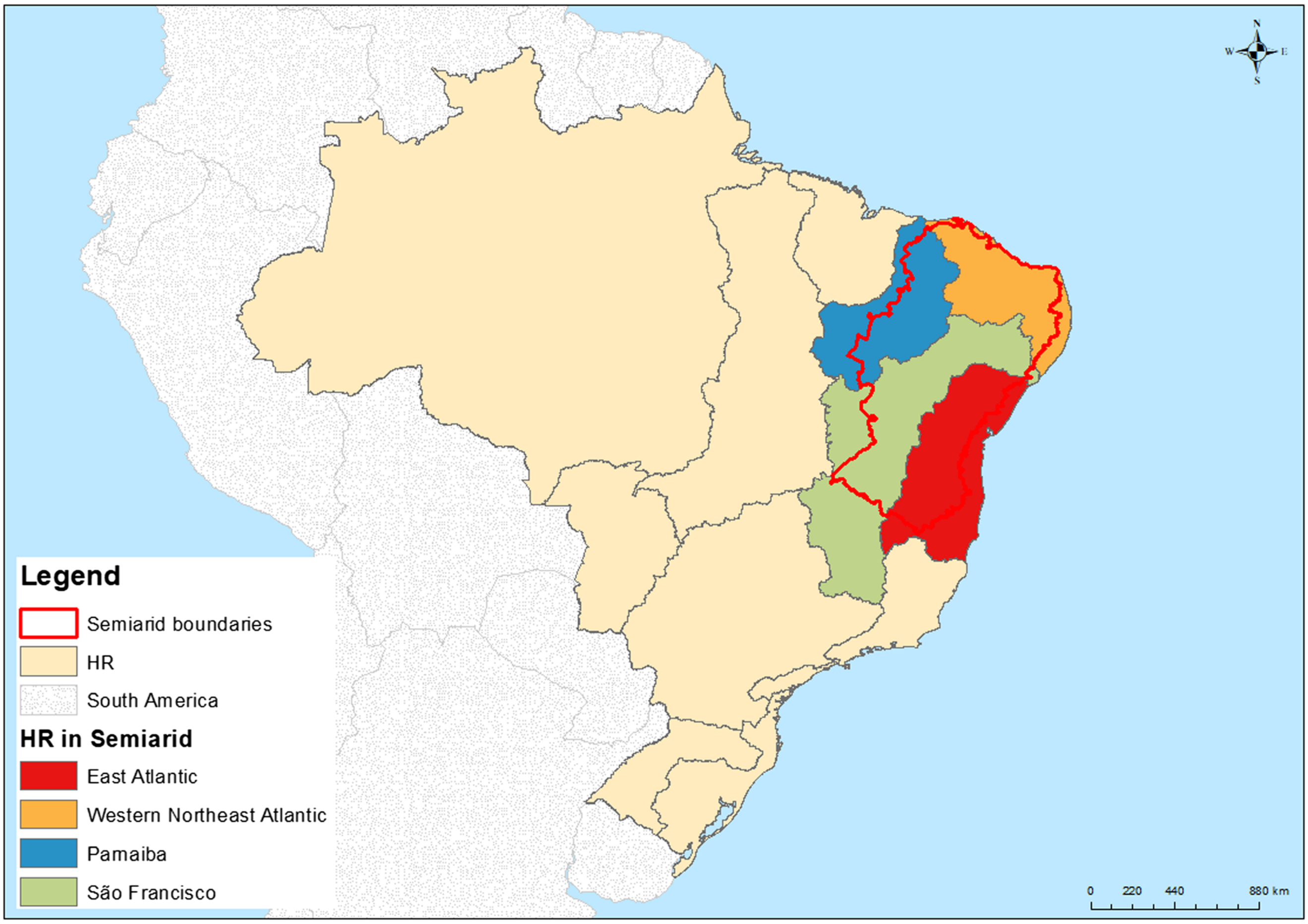

Fig. 8 HRs in semiarid region of Brazil

period) to April (end of the rainy period) there is a decrease in the values of the CFs in all HRs located in this region.

AWARE CFs in Semiarid HRs did not always present a similar variation during the year. However, when this variation is verified, the CF AWARE did not show water scarcity in the HR (Graph 1b—ESM). For São Francisco HR, the lowest CFs are from December to April; Parnaíba, from March to June. Apodi-Mossoró SHU represented Eastern Northeast Atlantic HR, once this HR did not have a similarity in WaterGAP basins, and the lowest CFs are from March to July. De Contas SHU represented East Atlantic HR, once this HR did not have a similarity in WaterGAP basins, and the lowest CFs are from November to April.

4.2 Comparison between the regionalized AWARE BR CFs and ANA scarcity index

The AWARE CFs were compared to the Scarcity Index applied by ANA, considering 29 SHUs, while The AWARE BR CFs were compared to the Scarcity Index, considering 29 SHUs. The latter comparison presented the smallest residual error (GSD^2 of 138.61), while the former, the highest (GSD^2 of 149.96).

5 Conclusions

The use of regionalized water scarcity factors is important to evaluate the impact that simulates reality to the largest degree due to the water consumption in LCA studies. Without regionalization, the water scarcity in small basins is difficult to identify. Big water basins show average scarcity values, making difficult to differentiate areas with low and high scarcity inside them. Furthermore, characterization factors based on global hydrological models, such as WaterGAP, are based on water and availability data that diverge from national monitoring and statistical data. These facts affect the quality of LCA studies, making results less sensitive to reality, more uncertain, and less useful.

This study generated regionalized CFs for Brazilian basins that improved the identification of known scarce areas by governmental reports that were not shown in AWARE factors, such as those in the semiarid region. Furthermore, it showed that the consideration of smaller basins also reduced scarcity in some basins, such as in Gurijuba SHU (Amazonica HR), Oiapoque SHU (Amazonica HR), Ilha do Maraca SHU (Amazonica HR).

The main divergence between regionalized and AWARE factors was found in the Eastern Northeast Atlantic region. According to the analysis of the state hydrographic units, Lagos São João in the Southeast Atlantic region presented the largest divergence. The following hydrographic units also presented a large difference between these methods: São Francisco HR, Parnaíba HR, Paraná HR, Periá SHU (Eastern Northeast Atlantic HR), Preguiças SHU (Eastern Northeast Atlantic HR), Acarau SHU (Western Northeast Atlantic HR), Curu SHU (Western Northeast Atlantic HR), Apodi — Mossoró SHU (Western Northeast Atlantic HR), Litoral SHU (Western Northeast Atlantic HR), Sergipe SHU (Southeast Atlantic HR) and Paraguaçu SHU (East Atlantic HR).

The AWARE BR factors showed that the least scarce hydrographic regions in Brazil are the Amazon (33% of the AWARE BR CFs with minimum value) and Paraguay (Annual Generic CF = 2.1). The scarcest region is the Eastern Northeast Atlantic, with 87% of the AWARE BR CFs in this region presenting maximum value. Regarding the dispersion of the monthly factors, the highest dispersion occurs in the South Atlantic region, and the lowest in Paraguay.

The case study carried out for melon-producing in Brazil showed that there were significant changes in results when applying the regionalized factors compared to the original ones. Furthermore, the case study carried out for São Paulo region, showed that atypical years of drought in a medium time series (at least 10 years of data) did not have any impact in regionalized CF. It is necessary to use water availability data for the period corresponding for the water shortages to the scarcity appears in regionalized CFs.

The residual error analysis indicated that the AWARE BR CFs present smaller error in comparison to ANA Scarcity index than the comparison of AWARE CFs to Ana index. It is important to highlight that whether the watershed limits were more similar, the comparison would be better done, once we were not able to quantitatively compare the CFs of the 449 SHU but only 34. Nonetheless, the comparison of the scarcity levels in AWARE BR CFs with government reports showed consistency in results, with agreement between basins with high and low level of water shortages.

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