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Band planting: a new restoration technique under the multi-criteria analysis of ecological functionality

Plantio em faixas: uma nova técnica sob a análise multicriterial da funcionalidade ecológica

Bruno Santos Francisco[1], *Emerson Viveiros*[1], *Felipe Bueno Dutra*[1], *Paulo Cesar Souza Filho*[2], *Rafael Paranhos Martins*[3], *Raquel Aparecida Passaretti*[3], *José Mauro Santana da Silva*[1], *Fatima Conceição Márquez Piña-Rodrigues*[1]

ABSTRACT

We evaluated band planting (BP) to assess its efficiency in the early restoring of ecological processes using a multi-criteria protocol known as Framework for the Evaluation of Natural Resource Management Systems Incorporating Sustainability Indicators (MESMIS) to obtain the ecological functionality consolidation index (EFCI). We sampled a 4.3 ha^{-1} plantation, aged 3 years, with BP, 1.5-m space between bands, 2-m space between seedlings, and a 3.5-m band of natural regeneration, ten areas with conventional planting (CP), aged 5 years, in the coverage and diversity models, and ten areas restored by natural regeneration (NR), aged 4 years. Sampling was carried out in 36 10 m x 10 m blocks, totaling 144 plots, 15 blocks for BP, 11 blocks for CP, and 10 blocks for NR. Species richness was similar between the areas; however, there was a significant difference between BP and the other areas (CP and NR) by the Dunn's test ($p < 0.05$). The NR area had the highest diversity (H' = 3.03; J' = 0.76), followed by BP (H' = 2.56; J' = 0.62), and CP (H' = 2.0; J' = 0.48), whereas the BP area (4.348 $ind.ha^{-1}$) had the highest density. The BP had the highest EFCI for diversity (0.100), control, and management (0.067) compared to NR, for diversity (0.022), and similar to CP in soil protection and nutrient cycling (0.047). BP was efficient in recovering early ecological processes under conditions similar to fragments in the initial stage of succession.

Keywords: ecological restoration; functional attributes; indicators; ecological functions.

RESUMO

Avaliamos o plantio em faixas (PF) em relação a sua eficiência na restauração precoce de processos ecológicos utilizando o protocolo multicriterial, para obter o índice de consolidação da funcionalidade ecológica (ICFE). Amostramos um plantio de 4,3 ha^{-1}, com três anos de idade, no modelo de PF com 1,5 m de espaçamento entre faixas, 2 m entre mudas e uma faixa de 3,5 m de condução de regeneração natural, dez áreas com plantio convencional (PC), com cinco anos de idade, no modelo de preenchimento e diversidade e dez áreas restauradas por regeneração natural (RN), com três anos de idade. A amostragem foi realizada em 36 blocos com dimensões de 10 m x 10 m, totalizando 144 parcelas, sendo 15 blocos para PF, 11 blocos para PC e 10 blocos para RN. A riqueza de espécies foi semelhante entre as áreas, mas houve diferença significativa entre o PF e as demais áreas (PC e RN) pelo teste de Dunn ($p < 0,05$). A diversidade foi maior na área RN (H' = 3,03; J' = 0,76), seguida por PF (H' = 2,56; J' = 0,62 e PC (H' = 2,0; J' = 0,48), mas a maior densidade foi registrada para PF (4.348 $ind.ha^{-1}$). PF apresentou o maior ICFE para diversidade (0,100), controle e manejo (0,067) em comparação com RN (0,022) e semelhante ao PC na proteção do solo e ciclagem de nutrientes (0,047). O PF foi eficiente na recuperação de processos ecológicos precoces em condições semelhantes a fragmentos em estágio inicial de sucessão.

Palavras-chave: restauração ecológica; atributos funcionais; indicadores; funções ecológicas.

[1]Universidade Federal de São Carlos – São Carlos (SP), Brazil.

[2]Ceiba Consultoria em Conservação Ambiental – Bragança Paulista (SP), Brazil.

[3]AES Tietê – Bauru (SP), Brazil.

Correspondence address: Bruno Santos Francisco – Rua Frederico Harder, 160 – Jardim Novo Mundo – CEP: 18052-447 – Sorocaba (SP), Brasil. E-mail: brunofrancisco@estudante.ufscar.br

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Introduction

Several global commitments have guided the ecological restoration of degraded areas as a way to address environmental issues (Antoniazzi et al., 2016), especially climate change, identified as the key alternative for the necessary carbon sequestration from the atmosphere (Benini and Adeodato, 2017). Recently, Brazil made international commitments involving the restoration of 12.5 million hectares by 2030 (Calmon, 2021). Thus, to achieve ambitious goals such as restoring 350 million hectares by 2030 (Dave et al., 2019), it is necessary to develop more efficient ecological restoration techniques and means to monitor the success of restorations through the return of ecological processes (Hobbs et al., 2011).

In Brazil, several restoration models have been produced to recover degraded ecosystems, such as the Miyawaki method (1999) and the dense-diverse-functional model, which focus on rapid soil covering, favoring succession and nutrient cycling processes, with a high density of individuals, high levels of species richness, and high diversity of ecological functions in their implantation (Piña-Rodrigues et al., 1997; Schirone et al., 2011; Galetti et al., 2018).

Although restoration by planting seedlings is one of the most used techniques (Schorn et al., 2010), other alternatives can also be used, either combined or isolated, which require less investment of resources, such as conducting regeneration, especially in areas of difficult access (Leal-Filho et al., 2013), nucleation based on the formation of biodiversity nuclei that favor the process of ecological succession (Reis et al., 2003), the use of functional groups as proposed by Gandolfi et al. (2009) with the so-called "covering species", which grow quickly covering the soil, and "species of diversity", which are generally slower in growth and take longer to cover the soil but increase species richness. Combinations between agroecological and agroforestry techniques as a transitional phase at the beginning of forest restoration were also proposed to reconcile ecological restoration with sustainable development. (Vieira et al., 2009).

Despite the various restoration models, it is necessary to assess their efficiency in restoring ecological processes. The restoration of ecological functionality is associated with factors that affect biotic communities expressed in their indicators of community diversity, structure, and similarity (Gatica-Saavedra et al., 2017), and in the presence of biotic interactions interfering with ecosystem functioning and provision of environmental services (Hopper et al., 2004). Thus, the successful restoration of ecological functions is associated with measurement based on indicators that provide information about the ecosystem that is being formed (Ramos Filho et al., 2007).

The method known as MESMIS (Framework for the Evaluation of Natural Resource Management Systems Incorporating Sustainability Indicators) has wide applicability in different activities around the world (Loureiro et al., 2020) and is classified as flexible and adaptable as it reflects the specificities of the contexts being assessed (Cândido et al., 2015). Despite being widely used in agroecology due to its versatility, it can also be used to assess the recovery of ecological functions in different restoration models (Galetti et al., 2018). The method is based on stability indicators, which would be the system's ability to maintain a stable balance, or resilience, which is the ability to return to equilibrium or maintain its productive potential after disturbances, and system reliability, defined as the ability to maintain productivity at levels close to its equilibrium over time (López-Ridaura et al., 2002; Theodoro et al., 2011; Pinã-Rodrigues et al., 2015; Galetti et al., 2018).

In this context, given the demands for restoration methods that efficiently recover the ecological functions of an ecosystem, since the use of pre-established restoration models based on adjustments to each condition has been identified as one of the causes of failure in restoration plantations (Durigan et al., 2010), we evaluated a new ecological restoration technique called band planting through its ecological functionality proposed by Piña-Rodrigues et al. (2015). Considering the above, this work intends to answer the following questions:

- Is the band planting restoration technique efficient in restoring stability and resilience, reliability, and ecological processes compared to conventional planting of seedlings and natural regeneration?
- What conditions or processes have affected the establishment of ecological functionality in the restoration models assessed?

Material and Methods

Study areas

The survey was conducted in 21 areas, totaling 31.7 hectares, located in the municipalities of Borborema, between 384-387 m altitude, and Itapira, at 954 m altitude, both in the state of São Paulo, Brazil (Figure 1). The areas before expropriation had been used as cattle pasture with grass (*Paspalum notatum* Flüggé).

The regions are characterized with a predominance of Seasonal Semideciduous Forest, with a tropical climate and little rain in the winter, classified by Köeppen as Aw (Alvares et al., 2014). The average temperature is 22.2°C and the average annual rainfall is 1.231 mm. August is the driest month, with 19 mm. The highest precipitation occurs in January, with an average of 234 mm. January is the warmest month of the year, with an average temperature of 24.8°C. The average temperature in June is 18.5°C (Climate-Data.org, 2019).

In the surroundings of the study areas, we observed fragments of seasonal semideciduous forest, with secondary vegetation, with herbaceous, shrub, and tree strata. The canopy is approximately 12 meters high, with emerging species. The canopy is occasionally discontinued, with exotic shrub and grass species in the openings.

The first treatment was performed by BP, aged three years, where 8,600 seedlings of 97 shrub and tree species were distributed in an area of 4.3 hectares. The second one comprised ten areas with CP, aged five

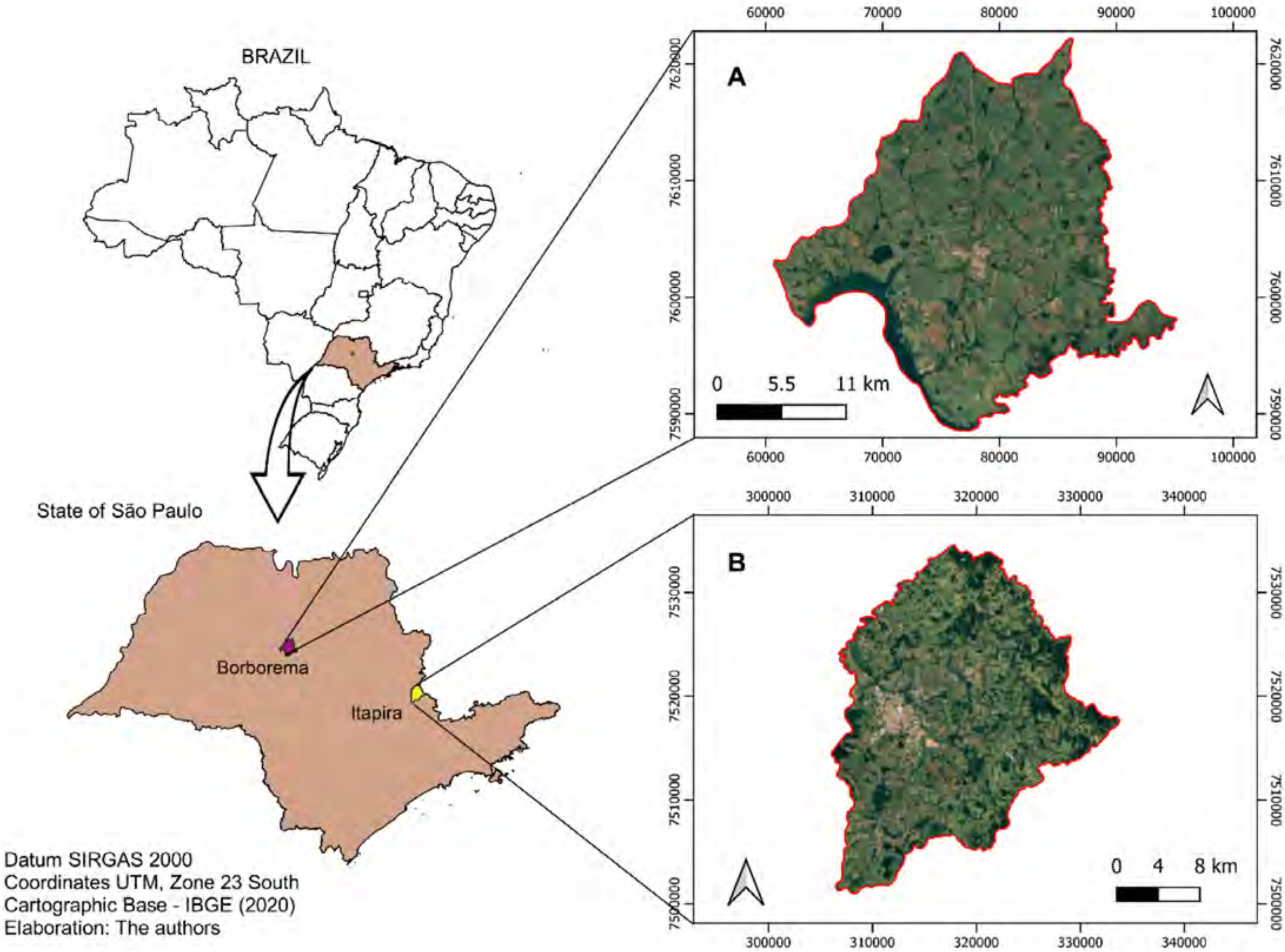

Figure 1 – Location of the study areas. (A) municipality of Borborema and (B) municipality of Itapira.

years, where 22,455 seedlings of 97 shrub and tree species were planted on 13.47 hectares. The third treatment consisted of ten areas with the conduction of natural regeneration (NR), aged 4 years, totaling about 14 hectares (Figure 2).

The collections were carried out between June and July 2020, in 36 blocks totaling 144 plots, 15 blocks for the band planting method, 11 blocks for conventional planting, and 10 blocks for the natural regeneration conduction method. For the diversity descriptors and functional parameters of the community, all arboreal individuals were identified, and their total height (cm) and circumference at breast height (CBH) were measured.

Each species was classified by successional group (pioneer and non-pioneer), using the same criteria as in SMA Resolution No. 08 (São Paulo, 2008) and Barbosa et al. (2015). The observed tree specimens were evaluated regarding the presence of vines and vascular epiphytes. In the control and management descriptor, soil cover per canopy was estimated, calculated according to the indications of SMA Resolution No. 32/2014 (São Paulo, 2014).

Canopy cover (%), cover with exotic grasses (%), and impacts caused by human presence, both positive (management, weeding, and absence of fires) and negative (trails, paths, and fires), were assessed through visual inspection of the 100 m² blocks. Regarding soil protection and litter input, the following descriptors were estimated: soil cover with herbaceous plants (%), soil cover with regenerating individuals (%), mulch (%), and litter height (cm).

The indicators of soil cover with litter, mulch, soil cover with herbaceous plants, cover with regenerating individuals, and cover with exotic grasses were obtained using a 0.50 x 0.50-m table, subdivided into 4 squares of 0.25 x 0.25 meters, launched in 3 points of each plot. Each grid filled in more than half of its area, representing 25% cover. Subsequently, the average percentage of the cover was calculated for each indicator.

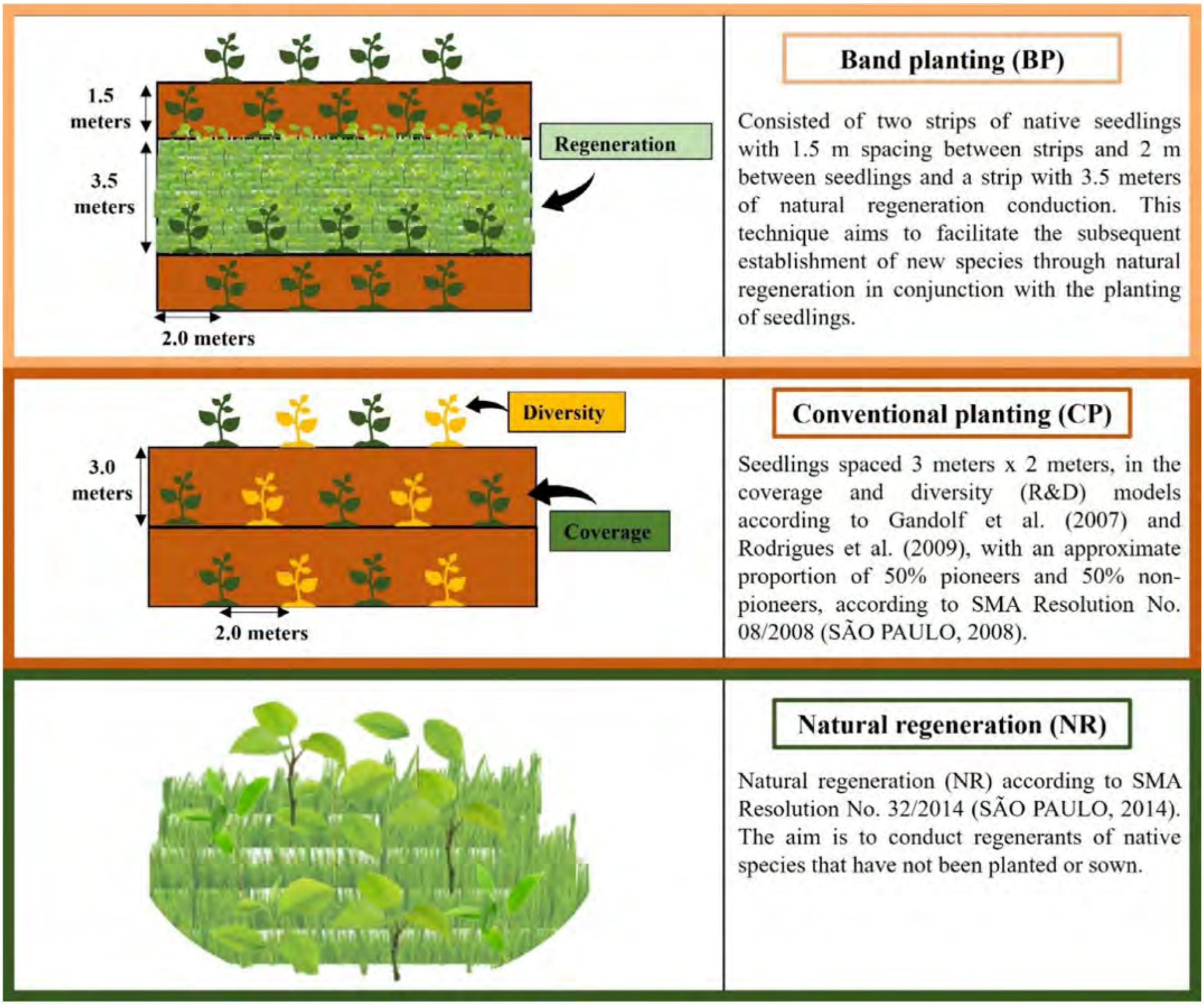

Figure 2 – Description of the treatments (restoration models) studied.

Analysis of ecological functionality

Since interactions in restored systems or the restoration process follow trajectories at different levels, the multicriterial selection of indicators using the MESMIS provides for protocols for the selection and application of indicators, making it possible to combine temporal and spatial variations to assess ecological processes (Masera et al., 1999; Priego-Castillo et al., 2009; Cândido et al., 2015). Thus, the MESMIS protocol (Masera et al., 1999), adapted by Piña-Rodrigues et al. (2015), was used to evaluate the different restoration methods, for which the attributes of stability, resilience and reliability, descriptors, and referential scenarios were defined and evaluated through indicators and their parameters (Galetti et al., 2018). For each indicator, positive and negative scenarios and references were proposed, based on a bibliographic review (Table 1).

Following the method by Galetti et al. (2018), scores ranging from 0-3 were assigned as follow: 0-1 = critical: bad, nonexistent, or distinct from the positive scenario; 2 = acceptable degree; and 3 = desired degree of sustainability, similar to the positive scenario. From this analysis, radar charts were elaborated, contemplating the indicators of stability and resilience, and reliability. In the graph, each radius represents one of the indicators, the length of which is proportional to the score of the indicator (0-3).

Data analysis

To calculate diversity, the Shannon-Weaver Index (H') and Pielou's Evenness Index (J') were used according to Martins and Santos (1999). Density, species richness, and abundance of successional groups were calculated according to Barbosa et al. (2015).

Table 1 – Protocol for assessing the ecological functionality of restoration areas based on the MESMIS system.

Attribute	Keywords	Indicators	Scenarios and References	Parameters
Stability and Resilience	**Community diversity**	Diversity of tree species (H')	Shannon-Weaver index close to expected for Seasonal Forest fragments according to Galleti *et al.*, 2018	H' > 3.0 = 3 1.0 < H' < 2.9 = 2 H' < 0.9 = 1
		Richness of native species (S)	Undesirable: lower than expected according to SMA Resolution No. 08/08. Regular: low diversity impairs the establishment of a future community. Desirable: according to SMA Resolution No. 08/08.	Number of species > 30 = 3 10 > Number of species < 30 = 2 Number of species < 10 = 1
		Density of arboreal individuals (Number of ha^{-1}) (d)	Undesirable: high mortality, considering the density of plants recommended by SMA Resolution No. 08/08. Regular: average density values based on SMA Resolution No. 08/08. Desirable: values close to those recommended by SMA Resolution No. 08/08.	> 1.200 = 3 > 800 and < 1.200 = 2 > 400 and < 800 = 1 < 400 = 0
		Evenness (J')	Pielou's index (J') close to that expected for fragments of seasonal forest according to Galleti *et al.*, 2018	J' ≥ 1 – high = 3 0.5 < J' < 0.9 – average = 2 J' < 0.5 – low = 1
		Number of successional individuals/group (IND/Ge)	Undesirable: does not meet SMA Resolution No. 08/08. Desirable: meets SMA Resolution No. 08/08.	> 40% and < 60% of species/group = 3 IND < 40% and IND > 60% of species/group = 1
Stability and Resilience	**Functional Diversity**	Number of species per group of successional tree species D(GE)	Higher number of non-pioneer species present in the system.	P < NP= 3 P ± NP = 2 P > NP = 1
		Average basal area – AB (m^2)	Close to the expected for Seasonal Forest fragments according to Galleti *et al.*, 2018	AB > AR = 3 AB ≈ AR = 2 AB < AR = 1
		Diversity of ecological functions – F (eco)	The main functions of the forest were considered: (a) presence of manure or fertilizer species (with interaction with microorganisms for nitrogen fixation); (b) contribution of biomass (deciduous species); (c) attraction of fauna (zoochoric species); (d) ground cover (wide and dense crowns).	F (eco) > 4 = 3 1 > F (eco) < 4 = 2 1 F (eco) = 1 No role = 0
		Vascular epiphytes (EPI)	Undesirable: absent. Desirable: present, predominance of position in the upper (TS) and middle (TM) thirds of tree individuals. Reference: Resolution No. 04/1994 (BRASIL, 1994).	Abundant = 3 Regular/present = 2 Few = 1 Absent = 0
		Creepers (CIP)	Undesirable: dominating the canopy of trees, especially the upper and middle thirds.	Absent =3 Few = 2 Regular, present = 1 Abundant = 0
		Canopy cover – CC (m) (%)	3 years > 15%. 5 years > 30%. Reference: SMA Resolution No. 32/14 (São Paulo, 2014).	CC > 80 = 3 30% < CC < 80 = 2 15% < CC < 30 = 1 CC < 15% = 0
Reliability	**Control and management**	Canopy closure – L (%)	Undesirable: open areas, without canopy cover, with brightness greater than 50%. Desirable: closed areas with less light (< 50%).	0 < L < 25% = 3 25% < L < 50% = 2 50% < L < 75% = 1 75% < L < 100% = 0
		Ground cover with exotic grasses - GRAM (%)	Undesirable: SMA Resolution No. 08/08 provides for initial control of competitors. Desirable: low invasive density is favorable to the development of native species.	Absent to 10% = 3 > 10 to 25% = 2 25 to 50% = 1 > 50% of coverage = 0

Continue...

Table 1 – Continuation.

Attribute	Keywords	Indicators	Scenarios and References	Parameters
Reliability	**Control and management**	Human presence positive - Phum (+) (positive impacts)	Periodic visits and management of the area.	Recent management = 3 Old management = 2 Unmanaged = 1
		Human presence negative - Phum (-) (negative impacts)	Presence of traces of fires in the area, trails, paths and trash.	Not visited = 3 Little visited = 2 Very visited = 1
		Ground cover with regenerating species (herbaceous) – %herb	Undesirable: absence of regenerating species. Regular: presence of some regenerating species in the area. Desirable: presence of regenerating species.	75 to 100% = 3 50 to 75% = 2 25 to 50% = 1 1 to 25% = 0
	Soil protection and Litter input	% of regenerating cover - %reg	% litter close to that found in the reference area (75 to 100%).	75% to 100% = 3 50% to 75% = 2 25% to 50% = 1 1% to 25% = 0
		% of dead matter cover in the soil - %mmo	% litter close to that found in the reference area (75 to 100%).	75% to 100% = 3 50% to 75% = 2 25% to 50% = 1 1% to 25% = 0
		% Litter covering the soil -% s.e.r.	% litter close to that found in the reference area (75 to 100%).	75 to 100% = 3 50 to 75% = 2 25 to 50% = 1 1 to 25% = 0
		Litter height (cm) – H-Ser	Litter covering the soil with values close to that expected for fragments of Seasonal Forest according to Galleti et al., 2018	Bigger than AR = 3 Similar to AR = 2 Smaller than AR = 1

Source: MESMIS (Masera et al., 1999); descriptors, indicators, scenarios and references and parameters adapted by Piña-Rodrigues et al. (2015).

Data concerning the height of tree individuals, species richness, density of individuals, litter height, and basal area of individuals in each of the restoration techniques were assessed for normality, using the Shapiro-Wilk test, and homoscedasticity through the Levene's and Kruskal-Wallis tests. Based on the results, the restoration models were compared by Dunn's post-test ($p < 0.05$). All analyses were performed using the R program (R Core Team, 2020).

For the set of indicators of community and functional diversity, control and management, soil protection, and litter input, the EFCI was calculated, using the Equation 1:

$$EFCI \; \frac{\sum scores\ of\ the\ indicators - number\ of\ indicators}{(number\ of\ indicators) \times (\sum No.of\ parameters\ per\ indicator)} \qquad (1)$$

Results and Discussion

we found that the species richness among the restoration techniques was close, ranging from 47 to 55 species sampled. However, the Kruskal-Wallis analysis evidenced that there was a difference in richness among the techniques ($p < 0.01$), and Dunn's post-test showed that the BP restoration technique differed ($p < 0.05$) from CP (Figure 3). We observed that there was a loss in the richness of 42 species both for CP and BP since 97 species were planted at the beginning of the restoration.

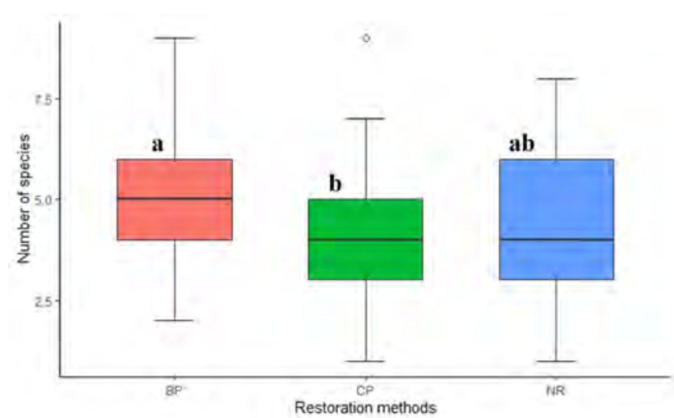

Figure 3 – Boxplot of the median and quartiles of the number of species among the different ecological restoration techniques*.
BP: number of species by the band planting technique; CP: number of species by the conventional planting technique; NR: number of species by the natural regeneration conduction technique; *same letters do not differ by Dunn's post-test with $p < 0.05$.

The Shannon-Weaver diversity index (H' = 3.03) and the Pielou's evenness index (J' = 0.76) were higher for the technique of NR (Table 2), and lower for CP of seedlings (H' = 2; J' = 0.48). The BP technique had intermediate values (H' = 2.56; J' = 0.62), as it is a technique

Table 2 – Values obtained for the indicators of the attributes of stability, resilience, and reliability of the restoration areas studied.

Attributes	Indicators	CP	NR	BP
Stability and resilience	**Species diversity**			
	H' (bits.ind^{1})	2.00	3.03	2.56
	Richness	55	47	55
	Density	4164	4300	4348
	J	0.48	0.76	0.62
	Ind/GE (%) - NP	55	33	51
	Ind/GE (%) – P	45	67	49
	Functional diversity			
	D(GE)(No. P)	25	31	27
	D(GE)(No. NP)	30	16	28
	IMA(m/ano)	-	-	-
	AB (m²) ha	7.72	0.22	5.06
	F (eco)	4	4	4
	EPI	0	0	0
	CIP	1	1	1
Reliability	**Control and Management**			
	CC (%)	88	38	65
	L (%)	-	-	-
	GRAM (%)	5	45	5.9
	Phum (+)	2	2	3
	Phum (-)	2	2	3
	Soil protection and Litter input			
	%herb	18	54	20.9
	%rege	37	10	23.75
	%mmort	58	58	76.3
	%ser	96	92	96.9
	H-ser	1.9	1.7	4.2

CP: conventional planting; BP: band planting; NR: area with the conduction of natural regeneration; H': Shannon's diversity index; S: species richness; d: density of individuals; Ind/GE: percentage of individuals/ecological group; J: Pielou's evenness index; D (Ge): diversity of ecological groups; AB: basal area; F (eco): diversity of ecological functions; Epi: epiphytes; CIP: creepers; CC: canopy cover; L: incidence of light; GRAM (%): presence of exotic grasses; Phum (-): negative human presence; Phum (+): positive human presence; % herb: percentage of herbaceous plants; % ser: percentage of litter; H-ser: litter height.

that mixes the planting of seedlings with the conduction of natural regeneration (Table 2).

Comparing these results with the indexes observed in a seasonal forest in the same state, in which the Shannon-Weaver index (H') was 2.66 and the Pielou's Evenness (J') index was 0.904 (Galetti et al., 2018), we found that the technique of conducting natural regeneration had the highest Shannon-Weaver index. Our results were lower than those found in recent studies on the diversity in seasonal forests, conducted in the states of Minas Gerais (Brazil), with H' = 3.94 (Torres et al., 2017) and Paraná, with H' = 3.35 (Souza et al., 2017); states adjacent to ours.

The density of individuals was close among the techniques; however, CP had the lowest density ($p < 0.05$) (Figure 4). BP had the highest density with approximately 4,348 individuals per hectare. Galetti et al. (2018) compared different restoration techniques with a seasonal forest area and observed that the techniques had higher diversity than the natural area. All the techniques evaluated in our study showed higher density than the seasonal forest area sampled by Galetti et al. (2018). Pinheiro et al. (2002) found a density of 7,488 individuals per hectare in a seasonal forest in the municipality of Bauru (86.4 km away from the study areas); however, the study area chosen by the authors had not been disturbed for more than 30 years, being a very well-preserved area.

Despite the diversity and evenness indices among the techniques are different, the densities were very close, so we realized that analyzing the parameters of richness, diversity, evenness, and density individually could mask the results of ecological restoration, through the inspection agencies that use these parameters as references (Fernandes et al., 2017).

Regarding functional diversity for the basal area indicator in the different techniques evaluated, we observed that all of them differed ($p < 0.01$), with BP being the technique that had the largest basal area, followed by CP, and the NR technique had the smallest basal area (Figure 5).

This fact can be attributed to the age of the conventional planting of seedlings, which is already five years old and has larger trees.

BP, although newer, had a basal area close to that of CP, whereas the area subjected to NR, despite being four years old, still does not have an arboreal structure forming a continuous canopy. The results for the basal area are still a long way from being similar to the ones found in preserved seasonal forest areas in the state of São Paulo, where values of 20.93 $m^2.ha^{-1}$ were found (Galetti et al., 2018) and Minas Gerais, with 20.019 $m^2.ha^{-1}$ (Torres et al., 2017), and some reforestation plantations in the same state, with a value of 15.05 $m^2.ha^{-1}$ (Melo and Durigan, 2007).

There were no significant differences in height between BP and the other techniques (Figure 6). However, there were differences between the CP and NR areas ($p > 0.01$), which had the lowest heights in the vertical stratum (Figure 6). Both the basal area and the height influence the shading of the community, since larger basal areas and greater heights can be correlated to larger individuals in the community (Francisco, 2020). Thus, we expected that both the CP of seedlings and BP would show greater canopy cover when compared to NR, corroborating our results.

Like height and basal area, canopy cover is related to shading, preventing exotic grasses from establishing themselves in the community, as they need a lot of light, thus favoring the process of restoration and ecological succession (Melo and Durigan, 2007; Galetti et al. 2018).

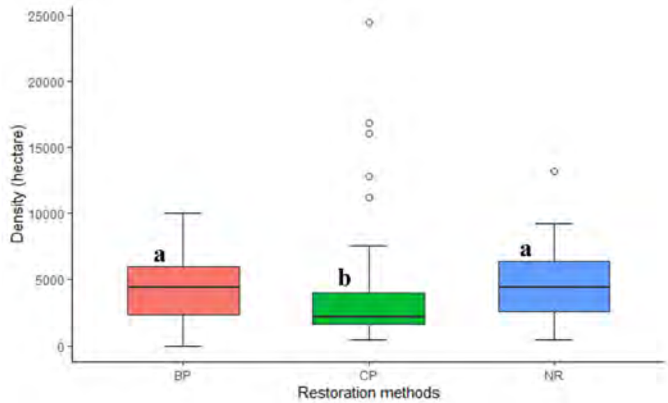

Figure 4 – Boxplot of the median and quartiles of the density of individuals among the different ecological restoration techniques*.
BP: number of species by the band planting technique; CP: number of species by the conventional planting technique; NR: number of species by the natural regeneration conduction technique; *same letters do not differ by Dunn's post-test with $p < 0.05$.

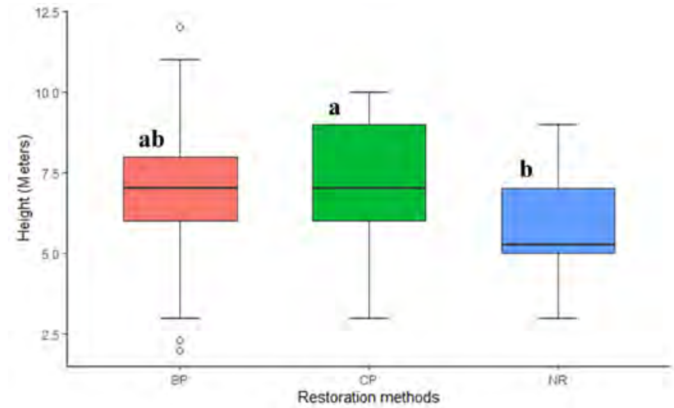

Figure 6 – Boxplot of median and quartiles of tree height between different ecological restoration techniques*.
BP: number of species by the band planting technique; CP: number of species by the conventional planting technique; NR: number of species by the natural regeneration conduction technique; *same letters do not differ by Dunn's post-test with $p < 0.05$.

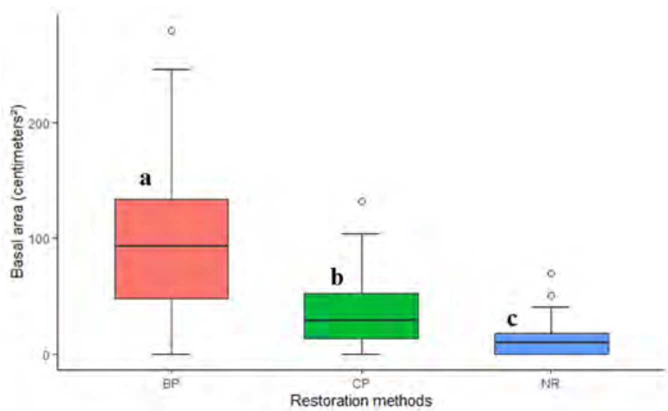

Figure 5 – Boxplot of the median and quartiles of the basal area between the different ecological restoration techniques*.
BP: number of species by the band planting technique; CP: number of species by the conventional planting technique; NR: number of species by the natural regeneration conduction technique; *same letters do not differ by Dunn's post-test with $p < 0.05$.

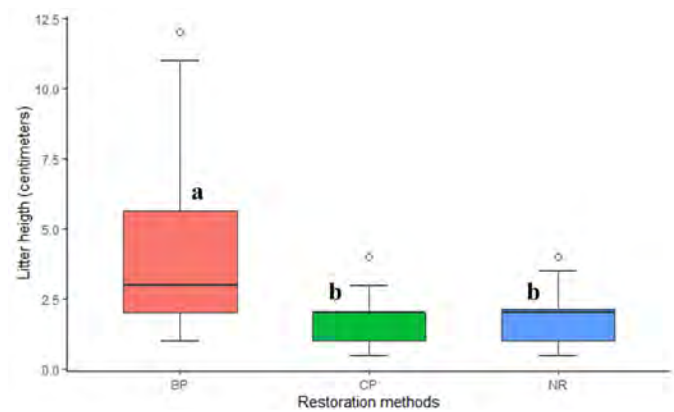

Figure 7 – Boxplot of median and quartiles of litter height among the different ecological restoration techniques*.
BP: number of species by the band planting technique; CP: number of species by the conventional planting technique; NR: number of species by the natural regeneration conduction technique; *same letters do not differ by Dunn's post-test with $p < 0.05$.

This may have contributed to the fact that the values for the cover indicator of exotic grasses in the control and management descriptor were much lower in the CP of seedlings (5% of exotic grasses) and BP (5.9% of exotic grasses). For NR, it was 45% of exotic grasses.

Regarding the soil protection and litter input descriptors, the BP technique showed better results concerning the number of indicators evaluated. There was a significant difference between litter height in BP ($p < 0.01$). This may be due to the presence of herbaceous, shrub, and tree species whose leaves and branches fall in the less favorable season or end up dying for being annual, as this technique mixes NR with planting seedlings (Figure 7).

Litter cover in restoration areas is very important because it plays several roles in the balance and dynamics of ecosystems, especially in tropical regions where most soils have low natural fertility, favoring nutrient cycling and the maintenance of tropical forests (Caldeira et al., 2020; Silva and Brandão, 2020).

The results of the stability and resilience and reliability indicators (Figures 8 and 9) showed that the BP restoration technique promoted similar and even superior conditions compared to the other restoration techniques evaluated in this study (Figure 8). There was a higher abundance and richness of pioneer species in NR. For BP (51% non-pioneer; 49% pioneer) and CP of seedlings (55% non-pioneer; 45% pioneer), there was a higher abundance of non-pioneer species as a result of the proportion used for planting (Table 2).

The factors that generated stability and resilience in the three restoration techniques evaluated were found based on the values of the

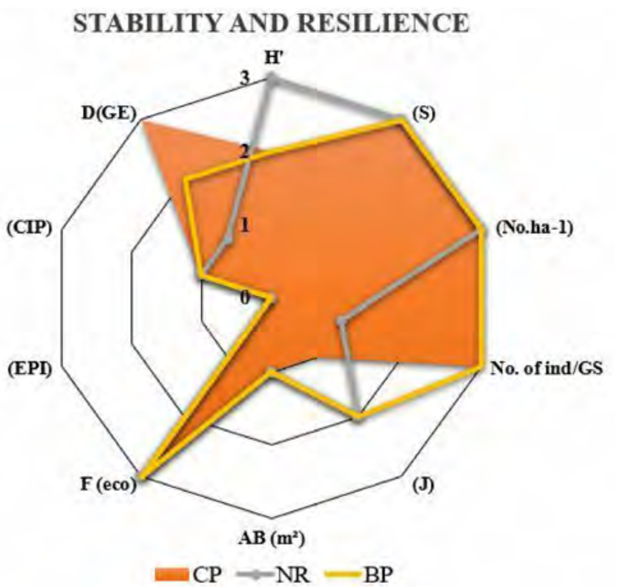

Figure 8 – Radar charts, with radii from 0 to 3, according to the parameters of Table 1, of the indicators of the restoration areas studies. Indicators of community and functional diversity.
CP: conventional planting; BP: band planting; NR: natural regeneration; H': Shannon's diversity index; S: species richness; d: density of individuals; Ind / GE: percentage of individuals / ecological group; J: Pielou's evenness index; D (Ge): diversity of ecological groups; AB: basal area; F (eco): diversity of ecological functions; Epi: epiphytes; CIP: creepers.

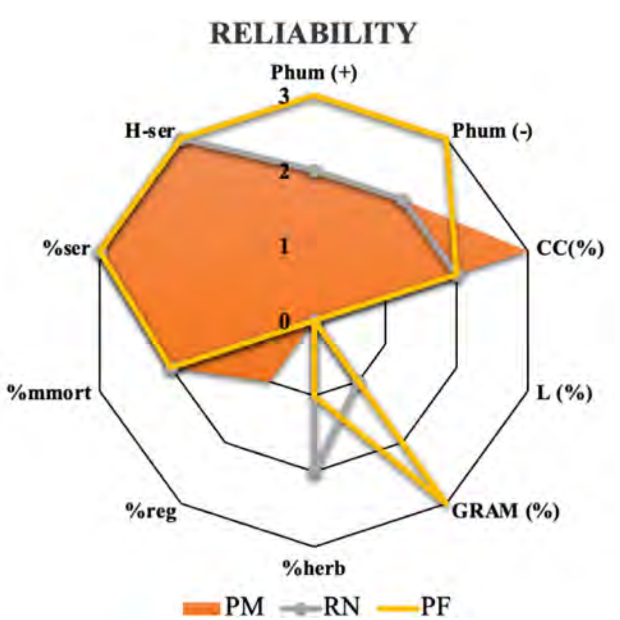

Figure 9 – Radar charts, with radii from 0 to 3, according to the parameters in Table 1, of the indicators of the studied areas of restoration. Indicators of control and management and protection of soil and litter input.
CP: conventional planting; BP: band planting; NR: natural regeneration; CC: canopy cover; L: incidence of light; GRAM (%): presence of exotic grasses; Phum (-): negative human presence; Phum (+): positive human presence; % herb: percentage of herbaceous plants; % ser: percentage of litter; H-ser: Litter height.

indicators diversity of ecological functions (F. (eco)) and development (presence of vines) equivalent (Figure 8). There was no record of the presence of vascular epiphytes in the areas; however, these conditions can be attributed to areas with little age of restoration. On the other hand, the factors associated with environmental sustainability over time (reliability) distinguished BP the most from other areas. (Figure 9).

BP proved to be efficient in recovering ecological functions capable of generating stability and resilience and maintaining ecological processes in conditions similar to fragments in the initial succession stage, with EFCI (Figure 10) higher than CP in the coverage and diversity models and NR conducted in the indicators of community diversity, and control and management.

As BP combines planting seedlings with NR, it uses a restoration approach of assisted natural regeneration, which aims to accelerate ecological succession by removing or reducing barriers to natural forest regeneration such as weed competition, improving favorable microclimatic conditions for native species, and higher seed dispersal by animals (Shono et al., 2007).

BP showed balance in most of the factors that provided ecological functionality, such as community diversity, plant density, as well as the increase in basal area, the number of non-pioneer species or even the density of individuals, which can contribute to ground cover, an important factor for system reliability (Galetti et al., 2018). In this way, BP can be applied in a wide variety of forest types and geographic areas, allowing its adaptation to meet different objectives, such as biodiversity conservation and income generation through a consortium with the production of firewood and timber and even non-timber forest products.

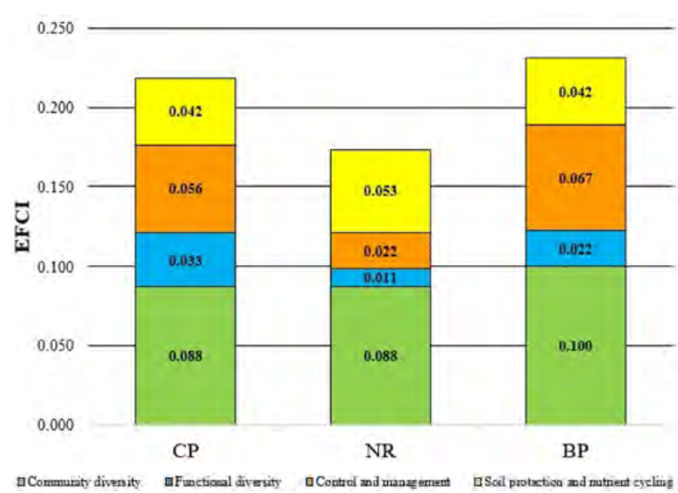

Figure 10 – Ecological functionality consolidation index (EFCI) values obtained for the stability and resilience attributes of the system represented by the diversity of species and functional and reliability, represented by the protection and litter input and the control and management in different techniques restoration.
CP: conventional planting; BP: band planting; NR: conduction of natural regeneration.

Conclusion

All the restoration techniques analyzed in this study had their benefits for ecological restoration and functional diversity in the NR model was strongly affected by the basal area of the community. The MESMIS method proved to be efficient in the evaluation of ecological functions for restoration. Based on the EFCI, we suggest the BP technique as an alternative to the CP of seedlings and NR techniques, as its characteristics derive from the other two techniques.

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Contribution of authors:

FRANCISCO, B. S.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing — original draft; VIVEIROS, E.: Conceptualization; Investigation; Methodology; Supervision; Project Administration. DUTRA, F. B.: Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – revision and editing; SOUZA FILHO, P. C.: Investigation; Methodology; Supervision; Project Administration. MARTINS, R. P.: Investigation; Methodology; Supervision; Project Administration. PASSARETTI, R. A.: Investigation; Methodology; Supervision; Project Administration. SILVA, J. M. S.: Investigation; Methodology; Supervision; Project Administration. PIÑA-RODRIGUES, F. C. M.: Investigation; Methodology; Supervision; Project Administration.

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ABES

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Analysis of the water–energy–greenhouse gas nexus in a water supply system in the Northeast of Brazil

Análise do nexo água-energia-gases de efeito estufa em um sistema de abastecimento de água no Nordeste do Brasil

Isaura Macêdo Alves[1], *Saulo de Tarso Marques Bezerra*[1], *Gilson Lima da Silva*[1], *Armando Dias Duarte*[1], *Henrique Leonardo Maranduba*[2]

ABSTRACT

In recent years, water utilities have been under pressure to increase the efficiency of their processes, mainly due to the decrease in water availability and the need to increase environmental sustainability in their processes. Leak reduction is clearly an important part of sustainable management in the water industry, and its impacts should be assessed with a broader environmental protection objective. This study aimed to present an environmental and energy assessment of the water supply system (WSS) in Caruaru City, northeast of Brazil, for different levels of water loss. This research is one of the first to assess the environmental impacts of a WSS in Latin America. Primary data adopted for preparing the inventory were provided by the water utility, and modeling and analysis were performed with the SimaPro 8.0® program. Cumulative energy demand (CED) was used to track the energy consumption of the system's life cycle. Greenhouse gas (GHG) emissions were calculated through the IPCC GWP 100a method with emissions expressed as CO_2-Eq. The data sets from life-cycle inventories were used from the Ecoinvent 3.1 database. Four scenarios with different levels of water loss were analyzed. Scenario S0 was represented with the real conditions of the system, whereas the others considered hypothetical indices. The percentages proposed for Scenarios S1, S2, and S3 were based on indices that indicate good loss rate in the distribution network for the Brazilian reality (25%), reduction by half of loss rates, and excellent loss rates for the water pipeline system (5%) and distribution network (10%). The analysis of the processes' contributions showed that the electricity consumption

RESUMO

Nos últimos anos, as concessionárias de água têm sofrido pressão para melhorar a eficiência de seus processos, principalmente por causa da diminuição da disponibilidade hídrica e da necessidade de se aumentar a sustentabilidade ambiental de seus processos. A redução de vazamentos é claramente uma parte importante do manejo sustentável no setor de água, e seus impactos devem ser enfrentados com uma visão mais ampla de proteção ambiental. Este estudo tem como objetivo apresentar uma avaliação ambiental e energética do sistema de abastecimento de água da cidade de Caruaru, Nordeste do Brasil, para diferentes níveis de perda de água. Esta pesquisa é uma das primeiras a avaliar os impactos ambientais de um sistema de abastecimento de água na América Latina. Os dados primários adotados para a preparação do inventário foram fornecidos pela concessionária de água, e a modelagem e análise foram realizadas com o programa SimaPro 8.0®. A demanda acumulada de energia (CED) foi usada para rastrear o consumo de energia do ciclo de vida do sistema. As emissões de gases de efeito estufa foram calculadas pelo método IPCC GWP 100ª, com emissões expressas como CO_2–Eq. Os conjuntos de dados dos inventários de ciclo de vida foram usados do banco de dados Ecoinvent 3.1. Analisaram-se quatro cenários com diferentes níveis de perda de água. O cenário S0 representou as condições reais do sistema e os demais consideraram índices hipotéticos. Os percentuais propostos para os cenários S1, S2 e S3 foram baseados em indicadores que apontam: bom índice de perdas na rede de distribuição para a realidade brasileira (25%), redução pela metade dos índices de perdas e excelentes índices de perdas no sistema hidráulico (5%) e rede de distribuição (10%). O consumo de energia

[1]Universidade Federal de Pernambuco – Recife (PE), Brazil.

[2]Flextronics Instituto de Tecnologia – Sorocaba (SP), Brazil.

Correspondence address: Saulo de Tarso Marques Bezerra – *Campus* do Agreste – Avenida Marielle Franco, s/n., km 59 – Nova Caruaru – CEP: 55014-900 – Caruaru (PE), Brazil. E-mail: saulo.tarso@ufpe.br

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of the pumping systems of water mains represented the greatest environmental impact in all scenarios. The most efficient scenario would result in a 52% reduction in the emission of GHGs, demonstrating that the increase in the hydraulic efficiency of the distribution networks represents a significant opportunity to reduce the environmental impacts of the processes.

Keywords: water supply system; environmental impact; water loss; hydraulic efficiency; greenhouse gas emissions.

elétrica dos sistemas de bombeamento das adutoras apresentou o maior impacto ambiental em todos os cenários estudados. O cenário mais eficiente resultaria em redução de 52% na emissão de gases de efeito estufa, demonstrando que o aumento da eficiência hidráulica das redes de distribuição representa uma oportunidade significativa para reduzir os impactos ambientais dos processos.

Palavras-chave: sistema de abastecimento de água; impacto ambiental; perda de água; eficiência hidráulica; emissões de gases de efeito estufa.

Introduction

Water, energy, and greenhouse gas (GHG) emissions are interconnected and have complex interactions (Nair et al., 2014; Thiede et al., 2016; Chhipi-Shrestha et al., 2017). The integration of water and energy interdependence processes in water systems improves the understanding of the trade-offs between these resources in management and politics (Escriva-Bou et al., 2018). Current water and energy resource crises are expected to increase progressively because of population growth and future climate change. Energy efficiency interventions can contribute considerably to reducing water use, reducing GHG emissions, and meeting climate-related mitigation goals. Understanding and modeling the complex nature of the interconnections between water and energy is essential for the efficient use of these resources (Basheer and Elagib, 2018). The energy use and GHG emissions associated with water management are poorly understood and have only partially been considered in water management and planning (Rothausen and Conway, 2011).

The global community is looking for new approaches and solutions for adapting to climate change and the challenges of increased water and energy consumption brought about by development. The nexus between energy and water is dynamic. Actions in one area generally have impacts on both, with profound economic, environmental, and social implications (Rasul and Sharma, 2016). The importance of the interdependence between water and energy is widely recognized. The world's energy security depends on the availability of water, as almost all energy production technologies (e.g., nuclear, thermoelectric, and hydroelectric) require large amounts of water (Nair et al., 2014), whereas water systems need energy for their processes.

Predominantly, water–energy–GHG emissions nexus has been studied regarding political and regulatory challenges and their interaction with food supply, climate change, growth, and the right to water. From a modeling perspective, this nexus has been studied using various technical and economic approaches, mainly considering co-production facilities as the coupling components between water and energy networks (e.g., Chhipi-Shrestha et al., 2017; Escriva-Bou et al., 2018; Oikonomou and Parvania, 2018; Zahraee et al., 2020).

Nair et al. (2014) highlighted the importance of modern thinking in relation to the increase in water supply, emphasizing that the search for water sources must consider measures that contribute to the mitigation of global warming, reducing energy consumption and GHG emissions. The climate system is largely regulated by the global balance of water and energy and its spatial and temporal variations, which involve the flow of energy and water within this system, besides exchanges with outer space and surface (Zhou et al., 2015). These flows are intrinsically interconnected, largely due to the characteristics and properties of water and energy. Water is essential for most energy-generation processes, while energy is indispensable in the distribution of water for different uses. On average, approximately 80% of the energy consumed by water supply systems (WSS) is spent to transport water from springs to consumers (Jeong et al., 2018; Oikonomou and Parvania, 2018). In Brazil, the sanitation sector uses roughly 2% of the country's total electricity consumption, equivalent to more than 11 billion kWh/year.

Over the last decades, due to the decrease in water availability, the need for environmental sustainability, and the increase in energy costs, Brazilian water utilities are being subjected to pressure to increase the efficiency of their processes. In contrast, most WSS have high levels of water loss. In developing countries, utilities are used to operating with high volumes of losses. The aging of systems, combined with failures in loss management in utilities, results in loss rates well above acceptable. To minimize the problem, the management of supply systems must involve multiple actions that include the control of real and apparent losses, including active leakage control, pressure management, elimination of illegal use of water services, educational campaigns, implementation or replacement of water meters, and rehabilitation of distribution networks.

Although water losses are inherent in all WSS, the high rates of infrastructure deterioration and operational deficiency considerably aggravate the problem. The aging of systems, combined with failures in loss management in utilities, results in loss rates well above acceptable. Lost water includes not only the value of water as a limited resource but also the added value of the treatments to make water potable (e.g., expenses with chemicals for treatment), the cost of operating distribution services (e.g., cost of energy), and the social impact of leaks that may prevent the provision of sufficient supply services to customers (D'ercole et al., 2016). The high rates of loss result in greater water extraction and increase the consumption of electricity for the collection, transportation, treatment, and disposal of water to consumers. Each cubic meter lost directly results in wasted energy, which in turn increases GHG emissions.

Activities that aim to reduce the volume of water abstraction can effectively generate their own environmental impacts, namely, the result of the works, equipment, and infrastructure used (Pillot et al., 2016). Leak reduction is clearly an important part of sustainable management in the water industry, and its impacts should be assessed with a broader environmental protection objective. In this regard, the life-cycle assessment (LCA) can provide more comprehensive analyses of the environmental issues associated with loss from WSS. Recently, this type of assessment is taking on a more prominent role in the formulation of environmental and sustainable development policies. Renowned institutions, such as the World Resource Institute, adopt the concept of life cycle in the evaluation of processes, and there is an increasing number of actors defending the reduction of the environmental impact associated with global consumption.

LCA methodology is a well-established and standardized analytical method to quantify environmental impacts, which has been applied to products or services (Jacquemin et al., 2012; Kjaer et al., 2018; Peña et al., 2021). The ISO 14040-14044 (ISO, 2006a, 2006b) standards demonstrate the methodological procedures for implementing the tool and analysis. This approach allows a comparison of different management systems in the sector and, through the identification of the most impactful phases, provides suggestions for improving environmental performance of goods and services (Bartolozzi et al., 2018). LCA is a versatile environmental tool that can be adapted for different uses in the water industry.

LCA can include the different phases of the urban water cycle, including the abstraction, treatment, transmission, distribution, consumption, and, in some cases, the collection, treatment, and disposal of wastewater (Meron et al., 2016). It has been used to analyze several urban water systems, including water treatment and distribution systems, and wastewater processing. Studies have focused on distribution, proposing predictive maintenance strategies or analyzing the selection of materials. The state of the art concentrates numerous works based on LCA for the analysis of WSS, with an emphasis on the comparison of the impacts caused by different sources or types of systems (Garfí et al., 2016; Li et al., 2016; Ghimire et al., 2017; Jeong et al., 2018; Hsien et al., 2019).

LCA studies on Brazilian WSS are still incipient, and the databases available for assessing environmental impacts are rare. Carrying out local work with a regionalized approach due to the peculiar characteristics of the different regions of the country, such as climatic conditions, production factors, productive systems, management systems, and waste recycling, is important. Therefore, given the fact that the application of LCA in the country is relatively a new field, a significant scarcity of studies available in the literature is noticeable.

In urban water management, LCA is considered the most dominant and appropriate method for assessing environmental impacts. In this context, the objective of this study was to evaluate the environmental and energy impacts of the life cycle of WSS in Caruaru City, Pernambuco State, for different levels of water loss, using system-specific data. Energy intensity and GHG emissions were selected as the major measurements for the water–energy–GHG emissions nexus.

Materials and Methods

Characterization of the study area

Caruaru City (Figure 1) is in the northeast of Brazil, about 130 km from Recife, capital of Pernambuco State (PE), Brazil. The region is

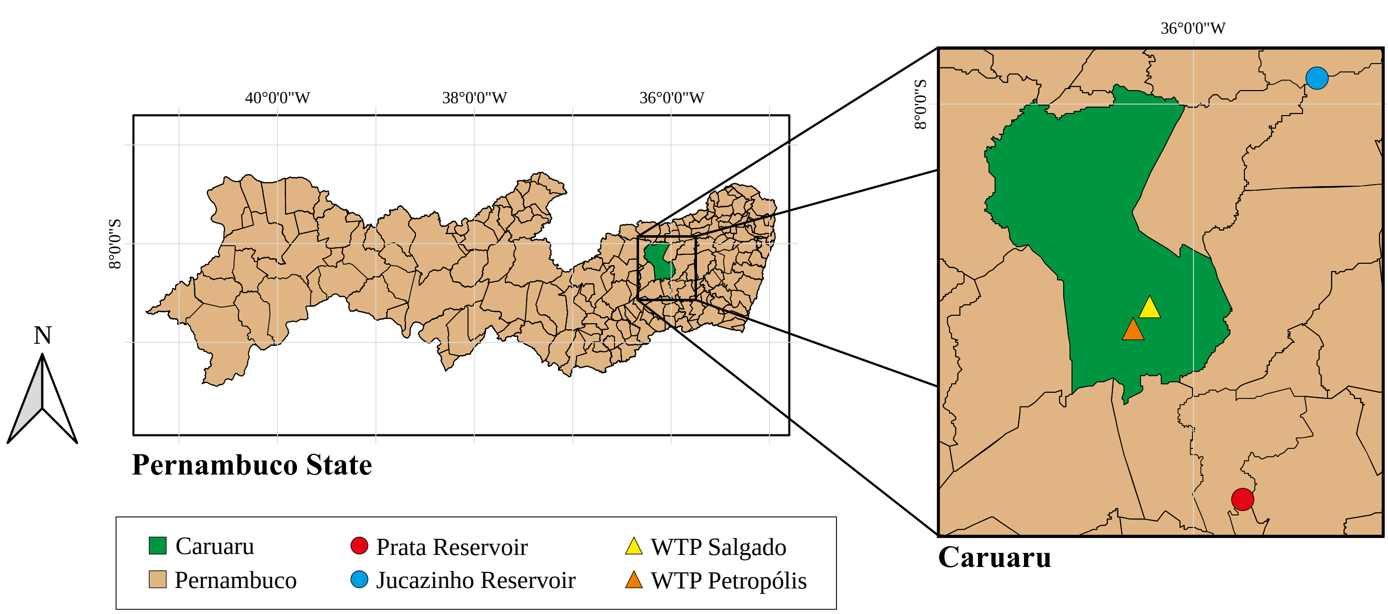

Figure 1 – Study area.

characterized as having a semi-arid climate, with hot, dry summers and mild winters. Its municipal headquarters has an average annual temperature of 22.7°C. The city's population surpasses 350,000 inhabitants, spread over a territorial area of 921 km².

Water supply in Caruaru City is provided by Companhia Pernambucana de Saneamento (Compesa), which is a Brazilian company that holds the concession of basic sanitation services in Pernambuco State. At present, the municipality can be supplied by the Jucazinho and Prata reservoirs, which are located on the Capibaribe and Una rivers, respectively, both in Pernambuco State. In 2016, Caruaru was supplied only by Prata's water system, because the reservoir of Jucazinho, which has a capacity of 202 million m³ and was the city's main source of water, collapsed in November 2016 (Santana et al., 2019).

The Prata reservoir was built in 1998, has a cumulative capacity of 42.1 million m³, and is in Bonito City (PE). It is inserted in the hydrographic basin of the Una river, whose drainage area is 151 km². The Prata pipeline system has three raw water pumping stations (*Estações Elevatórias de Água Bruta* — EEAB) and is responsible for supplying Petrópolis and Salgado Water Treatment Plants (WTPs). Table 1 shows the characteristics of the pumping stations of the water pipeline system, whereas Table 2 shows the electrical energy consumed by them. The average flow of the system is about 700 L/s.

According to information from the local service provider, the pumping stations that supply Caruaru City are among the 10 largest consumers of electric energy in Pernambuco State, demonstrating the importance of conducting energy efficiency studies in these units. Petrópolis and Salgado WTPs adopt the conventional treatment system composed of the following steps: clarification (fast mixing/coagulation, slow mixing/flocculation, decantation and filtration), disinfection, pH correction, and storage. In 2016, WTPs treated a total volume of 19.4 million m³; chlorine and aluminum sulfate are the chemicals used (Table 3).

Table 1 – Characteristics of the EEAB of the Prata pipeline system (base year 2016).

Discrimination	EEAB-01	EEAB-02	EEAB-03
Water origin	Prata reservoir	EEAB-01	EEAB-02
Water destination	EEAB-02	EEAB-03	WTP Petrópolis
Number of pumping systems	3 + 1 (reserve)	3 + 1 (reserve)	3 + 1 (reserve)
Rated motor power (cv)	750	750	750
Flow rate (L/s)	325	450	357
Pumping head (m)	98	96	130

The methodological structure of the LCA included the definition of objectives and scope, inventory analysis, impact analysis, and interpretation. The process cycle, on the other hand, includes the subsystems: water abstraction, transmission, treatment, and distribution. Four scenarios were proposed for WSS of Caruaru with different water loss rates to assess the energy intensity and, consequently, the system's GHG emissions. Scenario S0 was represented with the real conditions of the system, whereas the others considered hypothetical indices. The percentages proposed for Scenarios S1, S2, and S3 were based on indices that indicate good loss rate in the distribution network for the Brazilian reality (25%), reduction by half of loss rates, and excellent loss rates for the water pipeline system (5%) and distribution network (10%). The evaluated scenarios were as follows:

- Scenario S0: corresponds to the real scenario; that is, this scenario adopts the current operating conditions of the pipeline system (loss rate of 12.19%) and the water distribution network (loss rate of 54.09%) in 2016;
- Scenario S1: corresponds to the situation in which the loss rate of the producing system remains unchanged and admits a reduction of water loss in the water distribution network to the value of 25%;
- Scenario S2: admits a 50% reduction in the water loss index of the producing system and the water distribution network;
- Scenario S3: establishes a reduction in the loss rate to 5% in the water pipeline system and admits a loss rate in the water distribution network of 10%.

Life-cycle assessment

LCA was based on the International Organization for Standardization (ISO) 14040 series, which included definition of objectives and scope, inventory analysis, impact analysis, and interpretation.

Table 2 – Energy consumption of the EEAB of the Prata pipeline system (base year 2016).

EEAB ID	EEAB I	EEAB II	EEAB III
Annual consumption (kWh)	11,075,296	11,755,225	14,525,677
Specific energy consumption (kWh/m³)	0.50	0.53	0.66
Cost (BRL)	3,442,404.52	3,618,753.72	4,451,792.25

Table 3 – Annual consumption of chemical products used in Salgado and Petrópolis WTPs.

WTP	Chlorine (kg/year)	Aluminum sulfate (kg/year)
WTP Salgado	59,400	333,150
WTP Petrópolis	144,000	879,140
Total	203,400	1,212,290

GHG emissions were calculated as per the IPCC GWP 100a method (IPCC, 2013), with emissions expressed as CO2-Eq. per cubic meter of water distributed. The life-cycle inventory (LCI) was compiled with the Ecoinvent 3.1 database, available in the SimaPro® 8.0 software. This database is commonly adopted in the literature (e.g., Jeong et al., 2015; Pillot et al., 2016; Buyle et al., 2019; Esnouf et al., 2019; Duarte and Silva, 2020; Valencia-Barba et al., 2020). Cumulative energy demand (CED) (also called "primary energy consumption") was used to track the electricity consumption of the system's life cycle. The Brazilian electrical matrix was adopted in this study.

The SimaPro® software, faculty version, which has a large database and impact assessment methods, was used to build the LCI. This software has been widely applied by several researchers (e.g., Uche et al., 2015; Garfí et al., 2016; Rodriguez et al., 2016; Pokhrel et al., 2020; Rasul and Arutla, 2020; Trinh et al., 2020), as it allows creating a model of the studied system, inserting the inventory (manually or using databases), and calculating impacts using different life-cycle impact assessment methods.

The LCA aims to understand the process-based life-cycle model based on actual data from a WSS, so that utility managers can make targeted decisions; the importance of analyzing the environmental impacts associated with the cradle-to-gate life cycle of a system with different rates of water loss; and the environmental and energy impacts of WSS. Figure 2 shows the system limit of the LCA model. The processes begin with water collection in the Prata reservoir and end with distribution to consumers, excluding all subsequent phases (e.g., water use; and sewage collection, treatment, and discharge). The study considers the electricity consumption of the subsystems and the use of chemicals from the treatment plant, which included the processes of flocculation, sedimentation, filtration, adsorption, treatment, and primary disinfection.

The functional unit was defined as a 1 m^3 of drinking water distributed. In the literature, this functional unit is widely adopted for LCA in WSS (Jeong et al., 2015; Uche et al., 2015; Garfí et al., 2016; Rodriguez et al., 2016; Hsien et al., 2019; Meron et al., 2020). Primary inventory data were provided by Compesa. In parallel, technical visits to the site and periodic discussions were carried out with the company's technicians, in order to ensure the correct use of data. Electricity consumption and chemical products were inventoried, according to the system boundary. For chemical processes, data were taken from the Ecoinvent 3.1 database. The infrastructure was excluded from the LCI, as it is not directly impacted by the reduction of water loss (i.e., the existing pipes will not be replaced by smaller pipes due to the reduction of water loss). For applying the LCI, the collected data were processed to quantify GHG emissions and the CED for all evaluated processes.

The consumption of electricity from the pumping stations, the Sector Units of Petrópolis and Salgado WTPs, and the distribution of water to Caruaru City (Pernambuco State) were inventoried. Table 4 shows the data on the electricity consumption of the evaluated subsystems. The characterization factors allow to quantitatively compare the contribution of each elementary flow to the impact category indicator. The Impact Category for electric energy was Global Warming Potential (GWP), the class that represents the relevant environmental issues to which the results of the life-cycle impact assessment can be associated, that is, the IPCC method, 100-year horizon, was chosen for the study, considering the IPCC GWP 100 category. Cumulative Energy Demand V1.09 was used for energy charges.

The chemicals used in water treatment mainly consist of products for disinfection, coagulation, and flocculation. The manufacture of chemical products requires energy and, therefore, produces GHG emissions. The use of these products was determined using the raw data provided by Compesa. The energy required to manufacture the chemicals was determined using values published in the literature and was combined with chemical usage data to establish the energy intensity incorporated in the values for each chemical. With the type and quantity of chemical products used in kg/m^3 of treated water, the amount of carbon dioxide equivalent (CO2-Eq.) was obtained from the system, directly from the Ecoinvent 3.1 database. This international database

Table 4 – Electricity consumption of WSS in 2016.

Subsystem	Electricity consumption (kWh/year)
Abstraction and transmission	37,356
Treatment	3,828.
Distribution	14
Total	41,199

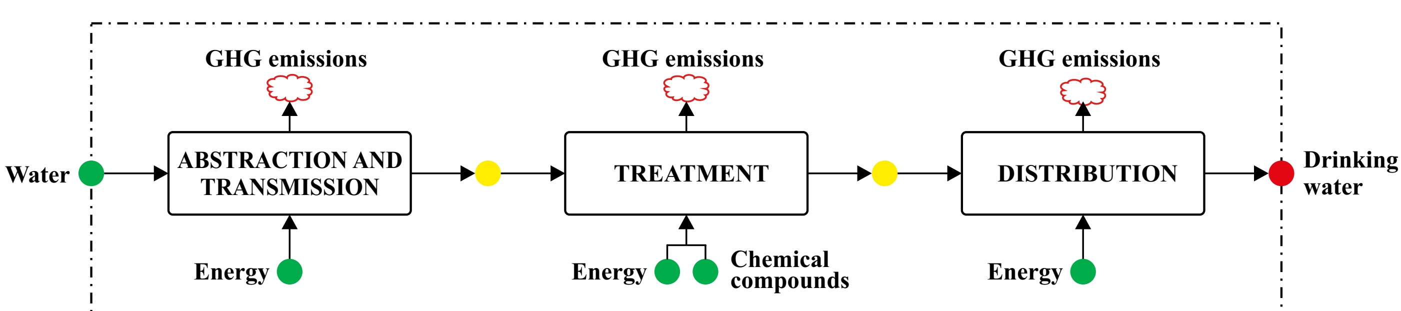

Figure 2 – Flowchart of the border of the evaluated system.

gathers elementary components, such as existing material, energy, processes, transports, and equipment. Input of resources and materials came from internal data of the water utility and was processed with the databases category IPCC GWP 100-year method.

The requirements considered in the life-cycle impact assessment were as follows:

- Temporal coverage: The collected data correspond to 2016; the spreadsheet contains monthly data of this year;
- Geographic coverage: The Prata reservoir is located in Bonito City, whereas the WTPs and the water distribution network are in Caruaru City;
- Technological coverage: This included raw water pumping stations, Petrópolis and Salgado WTPs, and water distribution network;
- Representativeness: The data for the study were acquired and collected at the operating site of the units under study, from internal company reports, satisfactorily reflecting the studied system.

Results and Discussions

Impacts of water loss on the WSS in Caruaru City (Pernambuco State), considering the water–energy–carbon nexus, were evaluated for each proposed scenario. Table 5 shows the water volume in each phase of the system. The great expansion of the city's water demand in recent years combined with the region's water scarcity has spurred the search for distant sources of supply, which makes the supply extremely energy intensive.

The energy consumption of Caruaru's WSS varied from 1.98 to 2.13 kWh/m^3, being higher than the specific energy consumption of Pernambuco's (0.29 kWh/m^3), the Northeast's (0.33 kWh/m^3), and Brazil's WSS (0.42 kWh/m^3) (SNIS, 2018). The process contribution analysis indicates that the electricity used for water supply was the main contributor to the categories of environmental impact. This study found that the system has a higher energy consumption than other systems in the United States. Arpke and Hutzler (2006) focused on the GWP energy consumption of water systems in the United States and reported that direct electrical consumption ranges from 0.32 to 1.43 kWh/m^3; whereas studies conducted in Cincinnati (Xue et al., 2019) and Atlanta (Jeong et al., 2018) resulted in 1.25 and 0.62 kWh/m^3, respectively. Given these results, the importance of adopting water demand management actions as an alternative to reduce the system's energy consumption is highlighted.

Table 5 – Water volume at each stage of WSS.

Scenario	Volume (m^3)		
	Abstraction and transmission	Treatment	Distribution
S0	22,075,200	19,383,485	19,383,485
S1	13,512,912	11,865,688	11,865,688
S2	12,990,038	12,198,295	12,198,295
S3	10,408,498	9,888,073	9,888,073

WTPs had an energy demand of 0.223 KWh/m^3, which is less than the values presented by Arpke and Hutzler (2006), 0.11–0.66 kWh/m^3, and Xue et al. (2019), 0.38 kWh/m^3. WTPs had the lowest GHG emissions (0.124 kg of CO2-Eq./m^3) because energy consumption is small and the content of chemical agents' requirements for water potability had a low impact. The chemical element with the greatest impact was aluminum sulfate, which represented 37.1% of emissions. This fact was also presented in the study by Mohamed-Zine et al. (2013), who estimated that the greatest environmental burden results from the preparation of coagulants (> 30% for all impacts). In this study, data related to the chemicals were analyzed using the Ecoinvent 3.1 database. Information may not accurately represent the Brazilian reality. Preparing an inventory with Brazilian data is thus highlighted.

The assessment and interpretation of impacts represents the fourth phase of the LCA. According to the proposed methodology, the energy consumption of the life cycle was tracked with the CED method, with the quantification of impacts of WTPs' chemical products quantified based on the data from Ecoinvent 3.1. The energy intensity of subsystems in water abstraction and transmission, treatment, and distribution resulted in 1.750, 0.223, and 0.0007 kWh/m^3, respectively. In all the analyzed stages of WSS, the greatest impacts are related to electricity consumption. The results are similar to those found in studies by Lemos et al. (2013), Mohamed-Zine et al. (2013), Igos et al. (2014), Rodriguez et al. (2016), and Xue et al. (2019), who assessed the environmental profile of the water sector based on the LCA in different regions and stated that the greatest impacts of these systems are attributable to energy consumption.

It is noteworthy that energy consumption and GHG emissions are strongly influenced by intrinsic characteristics of the systems (e.g., distance from water sources to consumers, topography of the region) and by the management models adopted by water utilities (e.g., efficiency in loss management). In addition, utilities located in more developed countries have more financial resources to improve the infrastructure of their systems, which generally allows for better conditions to increase energy efficiency.

Figures 3 and 4 show the estimate of environmental and energy impacts of the system for each scenario, respectively. Water loss was found to have significantly influenced the results. Scenario S0 represents the real operating conditions of Caruaru's WSS for 2016. In 2016, the system was estimated to have emitted more than 11.5 million kg of CO2-Eq. The high values are corroborated with the study by Pillot et al. (2016), whose results indicated that the main source of impact of WSS is the energy consumed in water abstraction and transmission (pumping). Therefore, local geography and distance from water source to WTPs are important aspects and must be considered when designing

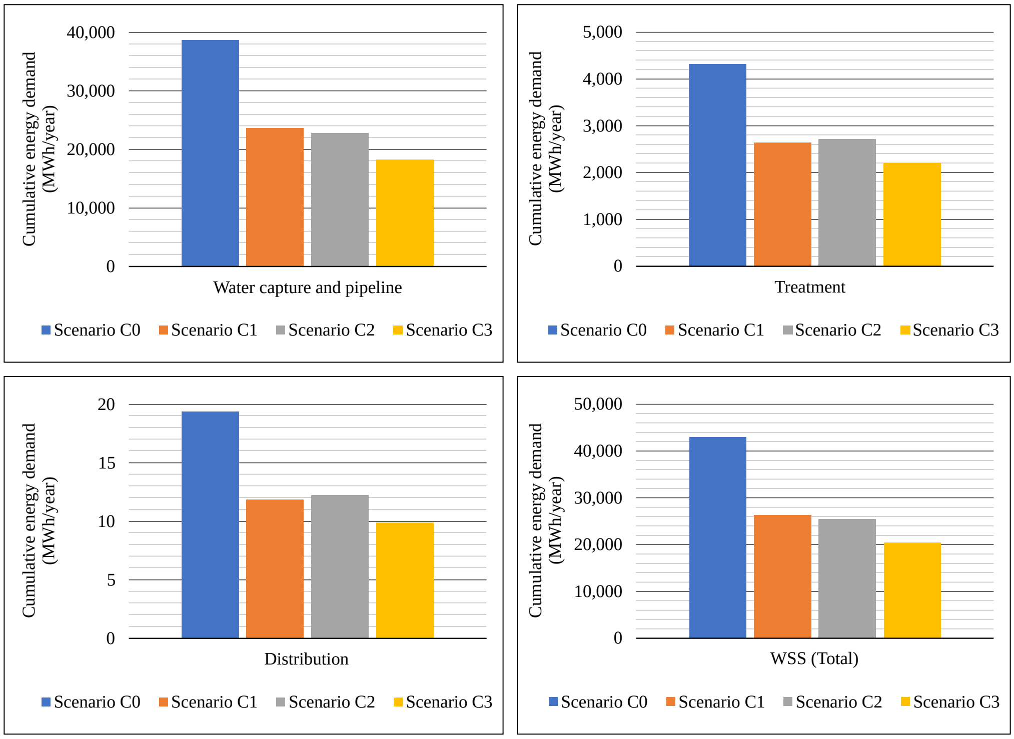

Figure 3 – Cumulative energy demand for the evaluated scenarios.

the urban water cycle. The water distribution network had an insignificant contribution to the impacts, as pipeline interventions were not considered, and the local topology allows for distribution by gravity (practically all the supply of treated water is carried out by gravity).

GHG emissions, considering the impact category chosen in the IPCC 100-year method, were 0.54 kg of CO2-Eq. for each cubic meter of water distributed in Scenario S0. The results were compatible with those by Meron et al. (2016), who stated that the GWP varies between 0.16 and 3.4 kg of CO2-Eq./m^3 of water supplied. Water abstraction and transmission stage was responsible for the GHG emissions of 0.42 kg of CO2-Eq./m^3, the treatment of 0.12 kg of CO2-Eq./m^3, and the distribution of 0.0002 kg of CO2-Eq./m^3. The low emission in distribution can be justified due to the low use of energy for pumping compared to the water pipeline system, which requires a high energy due to the topographic conditions of the water pipeline system of the Prata river. This is also justified by Rodriguez et al. (2016), who demonstrated that the topographic conditions of WTP location significantly influenced results. In that study, WTP presented a less favorable topology, emitting 0.38 kg of CO2-Eq./m^3, of which 86% corresponded to the prolonged consumption of energy during the pumping process.

In Scenario S1, the current operating conditions of the water pipeline system (loss rate equal to 12.19%) remain unchanged, whereas there is a reduction in the loss rate in the water distribution network to 25%. Results for this scenario estimated total emissions of 7.10 million kg of CO2-Eq. per year, a 38.8% reduction when compared to S0. According to D'ercole et al. (2016), even a small increase in operational efficiency can result in significant savings for water utilities.

In Scenario S2, by reducing the system's water loss index by 50% in relation to the value for 2016, there would be a reduction in the CED and GHG emissions of 40.7 and 40.3%, respectively. Scenario S3 is the one that considers the greatest reduction in water loss and, consequently, the best hydraulic and energy efficiency. It establishes a loss rate of 5% for the water pipeline system and admits a water loss rate in the water distribution network of 10%. The results showed a reduction of more than 50% in demand and emissions in Scenario S3 compared to S0, which corroborates the statement by Basheer and Elagib (2018), who highlighted that efficiency interventions in the sanitation sector can contribute considerably to reduce water use, decrease emissions, and meet climate-related mitigation goals.

To develop more environmentally responsible and sustainable WSS, the environmental implications of water loss must be incorporated into planning decisions. Pillot et al. (2016) demonstrated that the reduction of real water loss is clearly beneficial for ecosystems, human health, and the preservation of resources.

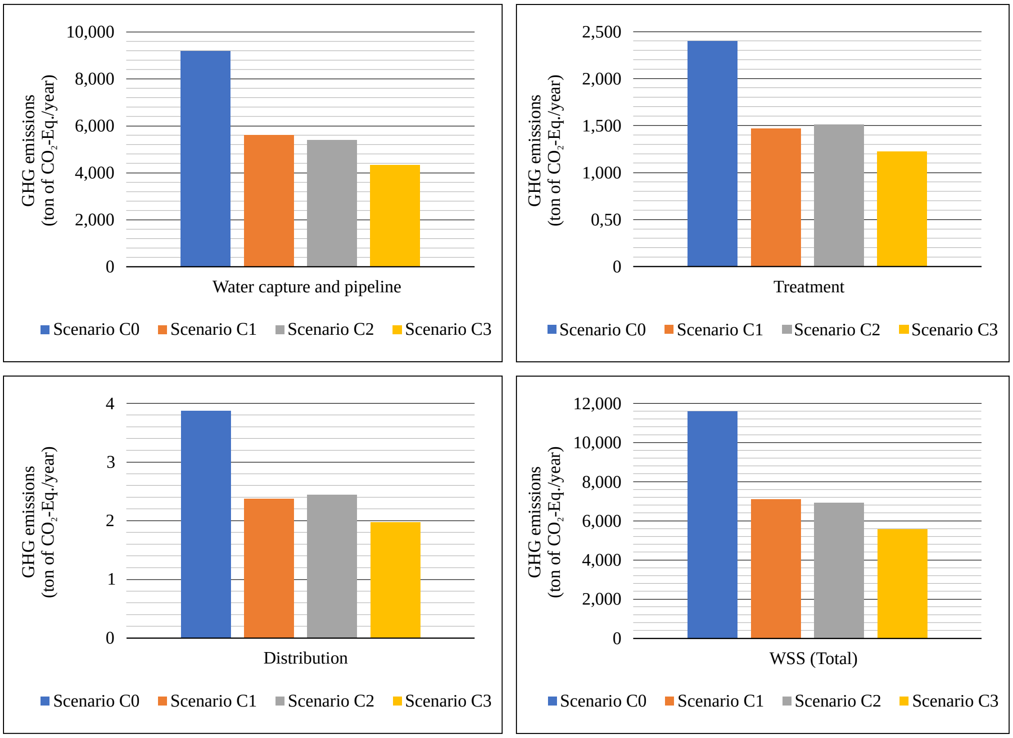

Figure 4 – GHG emissions (kg of CO2-Eq.) of the evaluated scenarios.

Conclusions

In a context of increasing water scarcity worldwide, the reduction of water loss is a key object to guarantee sustainable water management. In view of the hydrological conditions in which the northeast of Brazil is inserted, this region needs an even more effective position to combat the reduction of loss in WSS. The water–energy–carbon nexus arises from a perspective of water and energy security and environmental sustainability.

LCA was used to estimate the environmental and energy impacts of a WSS in the northeast of Brazil for different levels of losses, presenting utility managers with a tool that can include eco-efficiency values from project design, through implementation and finally to operation. This work is another study that highlights the importance of incorporating effective measures to control water losses in the management of systems, since these actions are expressively positive for water utilities and for the environment. The most efficient scenario evaluated showed a reduction in the CED and in the GHG emission higher than 50% in relation to the 2016 operating conditions.

Water pipeline is responsible for most of the GHG emissions and electricity demand, as it has the largest pumping stations in the system. In the water treatment phase, the chemical element with the greatest impact was aluminum sulfate, which accounted for 37% of environmental charges. Data related to the chemicals were analyzed with the Ecoinvent 3.1 database in this present study. Information in this database may not accurately represent the Brazilian reality. Therefore, the importance of collecting specific data for water treatment in Brazil is evident. The water distribution network has a low environmental and energy impact, as the water supply is carried out almost completely by gravity.

This study highlights the importance of incorporating LCA into other impact assessment tools to assist decision-making by managers, since most studies in the sanitation sector involve only wastewater treatment systems. LCA confirms that the environmental benefits of reducing both water and energy loss will increase as the efficiency of the system increases. Results show that improvement actions in the hydraulic efficiency of the distribution network and in the energy efficiency of pumping systems are clearly positive for the environment. Increasing the efficiency of these systems represents a significant opportunity to reduce electricity consumption, increase water availability, and reduce GHG emissions.

Finally, it is recommended for future research works to include actions to control water losses in the LCA of WSS. The reduction of losses generates its own environmental impacts, notably the results of the works to implement the actions, equipment, and infrastructure used for this purpose. This broader assessment can be used to establish at what point loss reduction is no longer effective in mitigating the environmental impacts of the systems.

Contribution of authors:

Alves, I.M.: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing — original draft; Bezerra, S.T.M.: Conceptualization, Methodology, Supervision, Project administration, Writing — revision and editing; Silva, G.L.: Investigation, Methodology, Supervision. Duarte, A.D.: Data curation, Investigation, Methodology; Maranduba, H.L.: Investigation, Methodology.

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Association between water for human consumption and health of the population of the state of Rio de Janeiro: the case of hepatitis A between 2007 and 2018

Associação entre água para consumo humano e saúde da população do estado do Rio de Janeiro: o caso da hepatite viral do tipo A entre 2007 e 2018

Daniele Gonçalves Nunes[1,2], *Nuria Pistón*[3], *Carlos José Saldanha Machado*[4]

ABSTRACT

This article analyzes the relationship between incidences of hepatitis A — a water-borne disease that can also be transmitted by lack of hygiene — and quality indicators in the provision of water supply services, through secondary data extracted from the National Information Systems for Notifiable Diseases and on Sanitation, in the period between 2007 and 2018, for the municipalities of the State of Rio de Janeiro, Brazil. The indicators were initially submitted to Principal Component Analysis (PCA) to reduce numerous variables that showed autocorrelation with each other. Subsequently, the principal components were submitted to Pearson's correlation analysis with the incidence of hepatitis A. A correlation coefficient of -0.32 was observed, at the level of significance ($p < 0.05$) between the cumulative incidences of hepatitis A and the principal component (PC3) formed by a set of quality indicators for the provision of water supply services. The indicators that best described PC3, with factor loadings ranging from -0.88 to 0.70, were those related to: hydrometer, water and revenue losses, water revenue, the participation of residential water savings, micro-measurement related to water consumption, water consumption and average water consumption per economy, average duration of outages, and the incidence of non-standard total coliform analyses. Thus, the observed results point to an association between the quality of water supply services and the incidence of hepatitis A, which may indicate both failures in treatment efficiency and lack of hygiene.

Keywords: hepatitis A; water supply; principal components; Rio de Janeiro; quality of public services.

RESUMO

Este artigo analisa a relação entre incidências de hepatite A — doença transmitida pela água ou falta de higiene — e indicadores de qualidade da prestação dos serviços de abastecimento de água por meio de dados secundários extraídos dos Sistemas Nacionais de Informação de Agravos de Notificação e sobre Saneamento, no período entre 2007 e 2018, para os municípios do estado do Rio de Janeiro. Os indicadores foram submetidos, inicialmente, à análise de componentes principais (PCA) para redução de variáveis numerosas que apresentaram autocorrelação entre si. Posteriormente, as componentes principais foram submetidas à análise de correlação de Pearson com a incidência de hepatite A. Foi observado coeficiente de correlação de -0,32, ao nível de significância $p < 0,05$, entre as incidências acumuladas de hepatite A e a componente principal (PC3) formada por um conjunto de indicadores de qualidade da prestação dos serviços de abastecimento de água. Os indicadores que melhor descreveram a PC3, com cargas fatoriais variando de -0,88 a 0,70, foram aqueles relacionados: à hidrometração, a perdas de água e de faturamento, ao faturamento de água, à participação das economias residenciais de água, à micromedição relativa ao consumo, ao consumo de água e ao consumo médio de água por economia, à duração média das paralisações e à incidência das análises de coliformes totais fora do padrão. Desse modo, os resultados alcançados apontam para uma associação entre a qualidade da prestação dos serviços de abastecimento de água e a incidência de hepatite A, podendo indicar tanto falhas na eficiência do tratamento como na higienização.

Palavras-chave: hepatite A; abastecimento de água; componentes principais; Rio de Janeiro; qualidade dos serviços públicos.

[1]Graduate Program in Environmental Studies, Universidade do Estado do Rio de Janeiro – Rio de Janeiro (RJ), Brazil.

[2]Instituto Federal do Rio de Janeiro — Rio de Janeiro (RJ), Brazil.

[3]Graduate Program in Ecology, Universidade Federal do Rio de Janeiro – Rio de Janeiro (RJ), Brazil.

[4]Graduate Program in Biodiversity and Health, Fundação Oswaldo Cruz — Rio de Janeiro (RJ), Brazil.

Corresponding address: Daniele Gonçalves Nunes – Rua Santo Amaro, 51 – Glória – CEP: 22211-230 – Rio de Janeiro (RJ), Brazil. E-mail: daniele.nunes@ifrj.edu.br

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Introduction

Water is essential for human and non-human life on this planet. For humans, adequate water quality and sufficient quantity are required to meet their needs, protect their health, and enable their economic activities (Plessis, 2017; Gurung et al., 2019; Singh et al., 2019), and access to water was established as a human right by the General Assembly of the United Nations on July 28, 2010 (United Nations, 2010; Palmer et al., 2018). However, it is possible to observe intense water degradation, both in quality and quantity, over the years. The worsening of climate change, disorderly urban growth, inadequate disposal of solid waste, deforestation of forests and riparian forests of rivers, the release of domestic and industrial effluents *in natura*, the diffuse pollution that causes pollutants, disorderly exploitation of water reserves, and the commodification of a common good are among the factors responsible for the pressures on water bodies, as demonstrated over two decades, by Machado and Klein (2003), Shiva (2016), Escher et al. (2019), Fonseca et al. (2020) and the Intergovernmental Panel on Climate Change (IPCC, 2021).

This reality directly impacts the access to safe water of quality and quantity for the population, especially in developing countries in Latin America and Africa facing severe health and environmental crises, intensified by the new coronavirus pandemic since 2020 (Britto et al., 2019; Ekumah et al., 2020; Gaber et al., 2021; Gwenzi, 2021; Purnama and Susanna, 2020). In this sense, the *Progress on drinking water, sanitation and hygiene report: 2000-2017: Special focus on inequalities* (UNICEF and WHO, 2019) points out that, since 2000, 1.8 billion people have been guaranteed access to basic drinking water services. Nevertheless, one in ten people (785 million) remains without access to basic water services, including 144 million who access untreated water sources. The report also shows that there is an inequality between the richest and the poorest countries, as the former have at least twice as much coverage of basic services than the later (UNICEF and WHO, 2019). According to Santos et al. (2015, p. 11), half of the urban population in Africa, Asia, Latin America and the Caribbean suffers from one or more diseases associated with inadequate water supply and lack of sanitation.

Within the Brazilian scenario, the results of the 2019 Continuous National Household Sample Survey (Continuous PNAD) demonstrate that 86% of the 72.4 million households had access to water supply through the general water network as the main source of supply, and 68.3% had a general network of sanitary sewer. However, there is regional inequality between North (58.8%), Northeast (80%), Midwest (87.2%), South (87.9%), and Southeast (92.3%) (IBGE, 2020). According to these data, regarding the availability and frequency of the water supply service provided by the general water network, 88.5% of households had daily availability, whereas the remaining 11.5% had frequency variations that could range between once and three times a week. Concerning the regions, the Northeast presented lower coverage of daily water supply (69.0%), followed by the North (89%), Midwest (94.9%) and Southeast (94.8%), and the best condition was observed in the South (97.0%) (IBGE, 2020). With regard to sanitary sewer, according to PNAD, there is regional inequality in access to the general network, as follows: North (27.4%) and Northeast (47.2%) had lower coverage; the South and Midwest reached 68.7%; and the Southeast had the best performance, with 88.9% (IBGE, 2020).

Among the water-borne diseases, hepatitis A stands out, a transmission disease associated with the quality of water for human consumption, hygiene habits, or water scarcity (Ensink and Cairncross, 2012; Singh and Mondal, 2019), which is the focus of the present study. In addition, Brazil recorded 1,189 deaths associated with hepatitis A between 2000 and 2018, of which 70.9% (843) had the disease as de underlying cause and 29.1% (346) as the associated cause, according to the "Epidemiological Bulletin on Viral Hepatitis" (*Boletim Epidemiológico Especial sobre Hepatites Virais*) published by the Brazilian Ministry of Health (Brasil, 2020). Also according to the Bulletin, the highest percentage of deaths from hepatitis A as the underlying cause occurred in the Northeast region (35.1%), followed by the Southeast (27.6%). It is noteworthy that the mortality rate due to hepatitis A as the underlying cause has shown a downward trend in all Brazilian regions in the last ten years (Brasil, 2020). Nevertheless, two recent outbreaks in the two largest Brazilian cities reversed the downward trend in the incidence of this disease.

In 2017, in the city of São Paulo alone, there were 694 cases of this infection (one third of that recorded in the entire country in 2015). Conversely, in the municipality of Rio de Janeiro (MRJ) there was a sudden increase in the disease at the end of that year, with most cases occurring in the neighborhood of Vidigal. This neighborhood ranked as the 121st in the social development index and, in 2010, as the 123th in percentage of households with water supply among the 163 neighborhoods of the MRJ, according to the Census of the Brazilian Institute of Geography and Statistics (IBGE), totaling 119 cases (Data Rio, 2010; Brasil, 2020); conversely, in 2016, there were only ten records. Although in São Paulo the main suspicion of the Municipal Health Department (*Secretaria Municipal de Saúde* – SMS) for the advancement of the disease was unprotected sexual intercourse, in Rio de Janeiro managers of the healthcare sector related its cause to the use of water contaminated with the virus. The high vulnerability of areas with lack of basic sanitation was highlighted, as observed in Vidigal, a slum with more than 2 million residents that gave rise to the neighborhood in the South region of the MRJ (Guimarães, 2018).

Considering the public health issue in question, it is worth questioning whether water supply services of the general network have been provided in sufficient quantity and quality to guarantee the human right to water for the served population. Hence, the State of Rio de Janeiro (SRJ) was prioritized as an object of identification and analysis of the relationships between the incidence of hepatitis A and the quali-

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ty indicators of water supply services in its 92 municipalities, based on a quantitative database methodology, with systematization, treatment, interpretation, and representation of data extracted from Government agencies. The SRJ proved to be an important territorial selection due to the history of water supply systems, dating back to the 19th century, and the strong dependence on few centralized water supply systems — such as the Paraíba do Sul basin, which supplies water to 17.6 million people, and the Guandu River basin, which receives water from the Paraíba do Sul River through transposition, supplying about 80% of the Metropolitan Region of Rio de Janeiro (MRRJ).

This article is organized into five sections, starting with this Introduction, followed by the presentation of the study area and the methods of data collection and analysis. Subsequently, the obtained results are presented, followed by the discussions and, finally, the conclusions of this article.

Study Area and Methods

Territorial selection of the study: the state of Rio de Janeiro

The study area covers the territorial extension of 43,750,427 km^2, with an estimated population, according to IBGE, of 17,366,189 million inhabitants (IBGE, 2021). Historically, the SRJ has water supply systems centralized in large pipelines and water treatment plants; in addition, these systems are dependent on water sources transported over long distances through transposition systems, especially for the MRRJ (Britto and Quintslr, 2017). According to Britto and Quintslr (2017), there are three periods of the development of urban water systems, between the years 1870 and 1980. The first consists of water transfers over long distances to overcome the absence of water treatment techniques. The second, in turn, is marked by the advent of new water treatment techniques based on the scientific technical development of sanitary engineering. Finally, the third period includes sustainable management, which seeks sustainable water use, demand management and supply control as well as water reuse (Britto and Quintslr, 2017).

Taking this into consideration, the choice for the SRJ is justified by three factors. The first is the centralized and infrastructural characteristic of the water supply systems of the state, especially the Water and Sewage Company of the State of Rio de Janeiro (*Companhia Estadual de Águas e Esgotos do Rio de Janeiro* – Cedae). Under public administration, this mixed-economy company fully or partially provides 64 municipalities with water supply, with an estimated population of 6,747,815 inhabitants in 2020, of which 97.41% were supplied with water services (Brasil, 2021c), and was recently taken to auction with a view to privatization (Silva et al., 2021). In addition, there are seven municipalities served by autarkies of the Autonomous Water and Sewage Services (*Serviços Autônomos de Água e Esgoto*); five by municipal governments operating as direct public administration and, finally, 16 private companies, according to the National Sanitation Information System (*Sistema Nacional de Informações sobre Saneamento* – SNIS) (Brasil, 2021c).

The second factor is related to the possibility of using secondary data on the quality of water supply services, based on the SNIS, with higher percentages of information due to the link between the filling of these data by the operators of water supply systems and the release of resources from investment programs of the Brazilian Ministry of Regional Development, including the Growth Acceleration Program (*Programa de Aceleração do Crescimento* – PAC). Finally, the third factor is the strong dependence on water supply sources, especially the Paraíba do Sul River and the Guandu River, the former being fundamental to maintain the quality of the water of the later through transposition – dated in the 1950s – between the Santa Cecília reservoir, in Piraí (RJ), which, integrated with other reservoirs, such as Ribeirão das Lajes, will supply the Guandu System.

Study design

In this article, the authors chose to use the data available in the Information Systems of institutional databases, namely: The Notifiable Diseases Information System (SINAN-Net), which is part of the system catalog of the Unified Health System Informatics Department (DATASUS) of the Brazilian Ministry of Health; the National Sanitation Information System (SNIS), of the Brazilian Ministry of Regional Development; and the 2010 Demographic Census, of IBGE (2011). Data collection was carried out through access to the database available in the aforementioned information systems, and several visits were made to the information systems until the year 2021. Then, the data were stored, organized, and processed using the *R Project*, version 4.0.2, and *Excel* software. Initially, descriptive statistics analysis techniques were used to perform exploratory analysis, as well as data pre-processing for later use in inferential statistics analysis.

A percentage of zeros and failures of 45% was observed in the samples of the historical series of the municipalities of the SRJ, both for the SINAN-Net and for the SNIS, making it necessary to exclude 35 municipalities. This enabled to identify that the period between 2007 and 2018 had greater data filling. In the case of SNIS, this fact can be justified by the requirement to regularly send data to the System as a criterion for selecting, ranking, and releasing financial resources. Therefore, the analysis was limited to municipalities with more complete data records (lower percentage of failures and zeros), reaching 57 of them (Angra dos Reis, Araruama, Arraial do Cabo, Barra do Pirai, Belford Roxo, Bom Jardim, Bom Jesus do Itabapoana, Cabo Frio, Cachoeiras de Macacu, Campos dos Goytacazes, Cantagalo, Duque de Caxias, Guapimirim, Itaboraí, Itaguaí, Italva, Itaperuna, Itatiaia, Japeri, Macaé, Macuco, Magé, Mangaratiba, Maricá, Mesquita, Miguel Pereira, Natividade, Nilópolis, Niterói, Nova Friburgo, Nova Iguaçu, Paracambi, Paraty, Paty do Alferes, Petrópolis, Pinheiral, Porciúncula, Queimados, Quissamã, Resende, Rio Bonito, Rio Claro, Rio das Flores, Rio das Ostras, Rio de Janeiro, São Fidelis, São Francisco de Itabapoana, São Gonçalo, São Joao da Barra, São Joao de Meriti, São Jose do Vale do Rio Preto, Sapucaia, Saquarema, Seropédica, Tanguá, Teresópolis, Trajano de Morais, Três Rios, and Volta Redonda). The same criterion was followed for data on hepatitis A.

Thus, the annual database referring to 57 of the 92 municipalities in Rio de Janeiro was used for this time frame regarding:

- indicators of the quality of water supply services, via SNIS, consolidated by municipalities (Brasil, 2019, 2021c) in the operational, economic-financial, and water quality categories, based on which the arithmetic means of these indicators were calculated per municipalities, in the period from 2007 to 2018. Components with excess zeros or lack of data were excluded, and 32 indicators were selected from the operational, economic-financial, and water quality categories (Brasil, 2019);
- cumulative incidence of hepatitis A (cases of hepatitis A per 100,000 inhabitants distributed per municipality), reported in the Brazilian Unified Health System (SUS), via SINAN-Net/DATASUS (Brasil, 2021b), with calculation of the cumulative frequency of the total reported cases of hepatitis A in the period from 2007 to 2018, divided by the respective population of each municipality x 100,000, as demonstrated by Rafael et al. (2020);
- census data, via the 2010 IBGE Demographic Census (2011), of the 57 studied municipalities of the SRJ and that were used for the calculations of the incidence of hepatitis A as previously mentioned.

Data analysis

To analyze the relationship between hepatitis A and the quality indicators of water supply services, the cumulative incidence of hepatitis A and the means of the indicators selected in the time frame of this study were calculated. Subsequently, both sets of variables were submitted to normality tests and validation of the principal component analysis. The Shapiro-Wilk normality test was chosen, with a significance level of $p < 0.05$. Regarding the data of the indicators of the quality of the provision of water supply services, the correlation matrix between the variables was first analyzed, and then the Bartlett's test of sphericity and the Kaiser-Meyer-Olkin (KMO) test, which consists in a measure of the adequacy of the Principal Component Analysis (PCA).

With regard to the normality test, the two data sets – cumulative incidence of hepatitis A and mean of the indicators of quality of the provision of water supply services – indicated a non-normal distribution according to the Shapiro-Wilk test, with a significance level of $p < 0.0001$. Thus, the authors opted for logarithmization of the variable "cumulative incidence of hepatitis A," which met the normality, as demonstrated by the Shapiro-Wilk test ($p > 0.05$). For data on the quality indicators of the provision of water supply services, normalization took place in the development of the statistical analyses in the *R Project* program, using the *vegan* package, *rda* function (Legendre and Legendre, 2012; Oksanen et al., 2020). Normality was also tested after PCA using the Shapiro-Wilk test, and the authors identified that the principal components presented normal distribution (PC1, PC2, PC3, PC4 — $p > 0.05$).

In the present study, it was observed that the quality indicators of water supply services are strongly associated with each other, a characteristic that may limit the type of statistical analysis to be used or produce spurious results – for example, the independence of the variables is a requirement for Pearson's correlation analysis (Taylor and Bates, 2013). Thus, PCA – a technique frequently applied by several authors to the most different areas, especially those related to the topic of the present article – proved to be interesting for the development of studies with these indicators as it allowed to reduce a set of correlated variables to a smaller number of principal components, independent of each other (Hernández-Flores et al., 2017; Zeinalzadeh and Rezaei, 2017; Corrêa et al., 2019; Tripathi and Singal, 2019). The results obtained from this statistical technique consist of eigenvalues of a sample covariance matrix (Legendre and Legendre, 2012; Santo, 2012). In this matrix, the principal components and the resulting eigenvalues are independent of each other and can therefore be used in subsequent statistical analyses (Logan, 2015).

Subsequently, the Pearson's correlation analysis was performed between the principal components and the incidence of hepatitis A. According to Callegari-Jaques (2003 *apud* Feil et al., 2015), the Pearson's correlation can be qualitatively evaluated regarding its intensity as follows: null, when the correlation is 0; weak, when it is between 0 and 0.3; regular, when it is between 0.31 and 0.6; strong, when it is between 0.61 and 0.9; very strong, when it is between 0.91 and 99; and full, when it is equal to 1. The sign of the coefficient indicates the direction of the association (Moore, 2007). To perform the analyses with the PCA and correlation techniques, the free *R Project* software, version 4.0.2, was used, as well as its *vegan, FactorMiner,* and *xlsx* packages.

Results

Table 1 presents the descriptive statistics for the variables used in the analyses developed in this article: cumulative incidence of hepatitis A and indicators of the quality of water supply services, between 2007 and 2018. Mean, median, standard deviation, and confidence intervals are presented, with their respective lower and upper limits for all variables.

Hepatitis A scenario in the state of Rio de Janeiro

The distribution of cumulative incidences of hepatitis A for the 2007-2018 period was determined, according to the territorial location of the highest rates, as well as the mean (20.2 cases per 100,000 inhabitants) for the SRJ (dashed line), as shown in Graph 1.

Among the analyzed municipalities, 13 had values of cumulative incidence of hepatitis A above the estimated state average for Rio de Janeiro. Among them, Mangaratiba, Paraty, and Sapucaia presented 86.56, 72.72, and 84.27% of average water supply coverage, respectively, in the period between 2007 and 2018. Still among these 13 municipalities, Três Rios (99.13%), Rio de Janeiro (97.41%), Petrópolis (96.93%), Angra dos Reis (90.44%), Macuco (86.94%), Duque de Caxias (84.50%), Macaé (75.05%), Porciúncula (74.95%), Magé (72.86%), and Tanguá (51.68%) stand out for their percentage of water supply. Graph 2 shows the percentages of coverage for water supply, based on SNIS data, for the 57 municipalities observed in the present study.

Table 1 — Descriptive statistics of hepatitis A incidences and quality indicators of water supply services.

Variables	Description of variables	Mean	Median	Standard Deviation	Confidence Interval (95%)	
					Lower Limit	Upper Limit
IHepA	Cumulative incidence of hepatitis A	20.70	10.97	43.55	9.40	32.01
IN001	Density of water economy per connection	16.28	15.66	3.74	15.30	17.25
IN005	Average water rate	37.86	37.06	12.26	34.68	41.05
IN009	Hydrometer index	807.46	892.23	343.77	718.21	896.71
IN010	Micro-measurement index related to the available volume	474.45	472.12	227.13	415.49	533.42
IN013	Revenue loss index	498.82	552.97	217.41	442.38	555.26
IN014	Micro-measurement of water consumption per economy	180.61	190.90	39.21	170.43	190.79
IN017	Water consumption billed per economy	169.64	173.80	41.57	158.85	180.43
IN020	Extension of the water network per connection	143.96	137.80	81.92	122.70	165.23
IN022	Average *per capita* water consumption	2,173.62	2,208.20	569.69	2,025.73	2,321.52
IN023	Urban water service index	983.62	1,025.60	185.87	935.37	1,031.88
IN025	Volume of water provided per economy	357.84	330.60	147.81	319.47	396.22
IN028	Water revenue index	653.81	622.36	211.05	599.02	708.60
IN043	Participation of residential water economies in the total water economies	1,060.38	1,094.74	109.03	1,032.08	1,088.69
IN044	Micro-measurement index related to consumption	782.20	803.90	333.97	695.50	868.90
IN049	Distribution loss index	430.09	407.69	149.32	391.33	468.86
IN050	Gross linear loss index	637.06	531.56	489.78	509.91	764.21
IN051	Loss index per connection	6,830.62	5,570.45	4,596.5	5,637.33	8,023.91
IN052	Water consumption index	722.54	742.93	143.90	685.18	759.90
IN053	Average water consumption per economy	195.04	202.10	50.31	181.98	208.10
IN055	Total water service index	935.65	980.37	198.62	884.08	987.21
IN057	Water fluoridation index	420.17	104.10	472.51	297.50	542.83
IN058	Electric energy consumption index in water supply systems	7.14	4.90	7.61	5.17	9.12
IN071	Economies affected by outages	29,210.16	7,759.00	51,791.53	15,764.65	42,655.67
IN072	Average duration of outages	62.61	52.70	43.41	51.34	73.89
IN073	Economies affected by intermittences	7,685.46	0.00	3,4031.93	-1,149.52	16,520.43
IN074	Average duration of intermittences	10.88	0.00	28.24	3.55	18.21
IN075	Incidence of non-standard residual chlorine analyses	13.84	4.60	21.69	8.21	19.47
IN076	Incidence of non-standard turbidity analyses	54.65	14.78	76.65	34.75	74.54
IN079	Sample quantity compliance index (free residual chlorine)	1,350.15	1,264.04	710.13	1,165.79	1,534.51
IN080	Sample quantity compliance index (turbidity)	1,378.55	1,291.36	705.73	1,195.33	1,561.76
IN083	Average duration of provided services	947.05	825.58	875.85	719.67	1,174.43
IN084	Incidence of non-standard total coliform analyses	25.98	6.81	37.45	16.25	35.70
IN085	Sample quantity compliance index (total coliform)	1,497.51	1,268.90	955.93	1,249.34	1,745.68

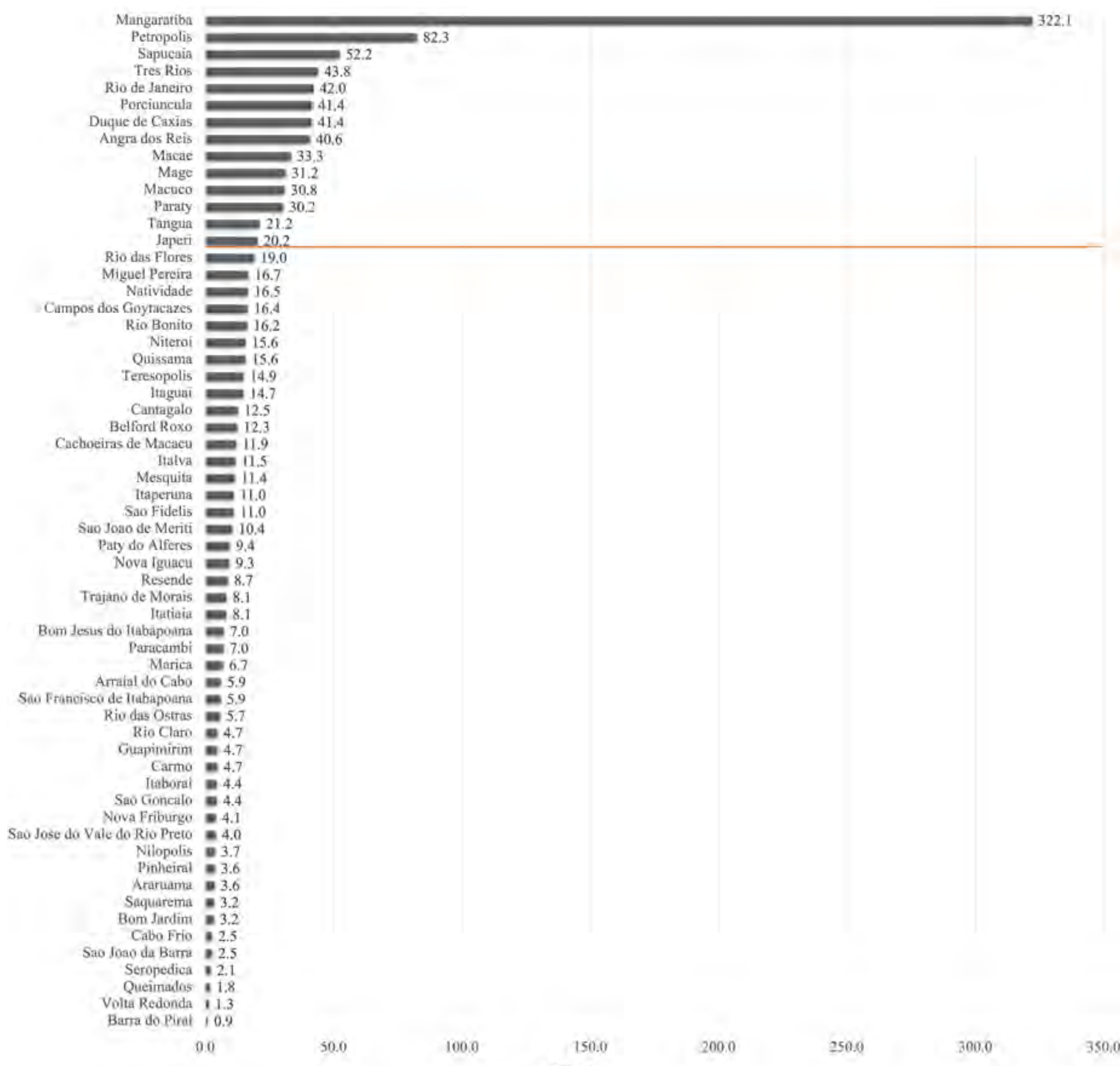
Source: Prepared by the authors based on data from SINAN-Net and SNIS, based on the cumulative incidence of hepatitis A and the average quality of water supply indicators, using the *R Project* software, version 4.0.2.

Analysis of principal components of the indicators of the National Sanitation Information System

As for the set of quality indicators of water supply services, the KMO suitability test obtained a value of 0.52, higher than the acceptable critical limit of 0.5 (Hair et al., 2009). Furthermore, Bartlett's test of sphericity was statistically significant ($p > 0.0001$). In both cases, the tests suggest that the data are suitable for statistical treatment.

Thus, the PCA of the quality indicators of the provision of water supply services evidenced those that significantly contributed to the variance of the main axes of the set of analyzed variables. Hence, the authors could identify four principal components (PC1 to PC4), which explain 54.5% of the variance of the set of analyzed variables. PC1 explains 21.4% of the total variance of the data and presents high positive factor loadings for the indicators concerning: micro-measurement related to the available volume (IN010), micro-measurement related to water consumption (IN044), hydrometer (IN009), and water revenue (IN028); and moderate-to-strong negative factor loading for the indicators concerning revenue losses (IN013) and the volume of water provided per economy (IN025), with correlation coefficients ranging from 0.92 to -0.72, at a significance level of $p < 0.001$.

PC2, in turn, explains 15.8% of the total variance of the data and presents high positive factor loadings for the indicators concerning average *per capita* water consumption (IN022), micro-measurement related to water consumption per economy (IN014), water consump-



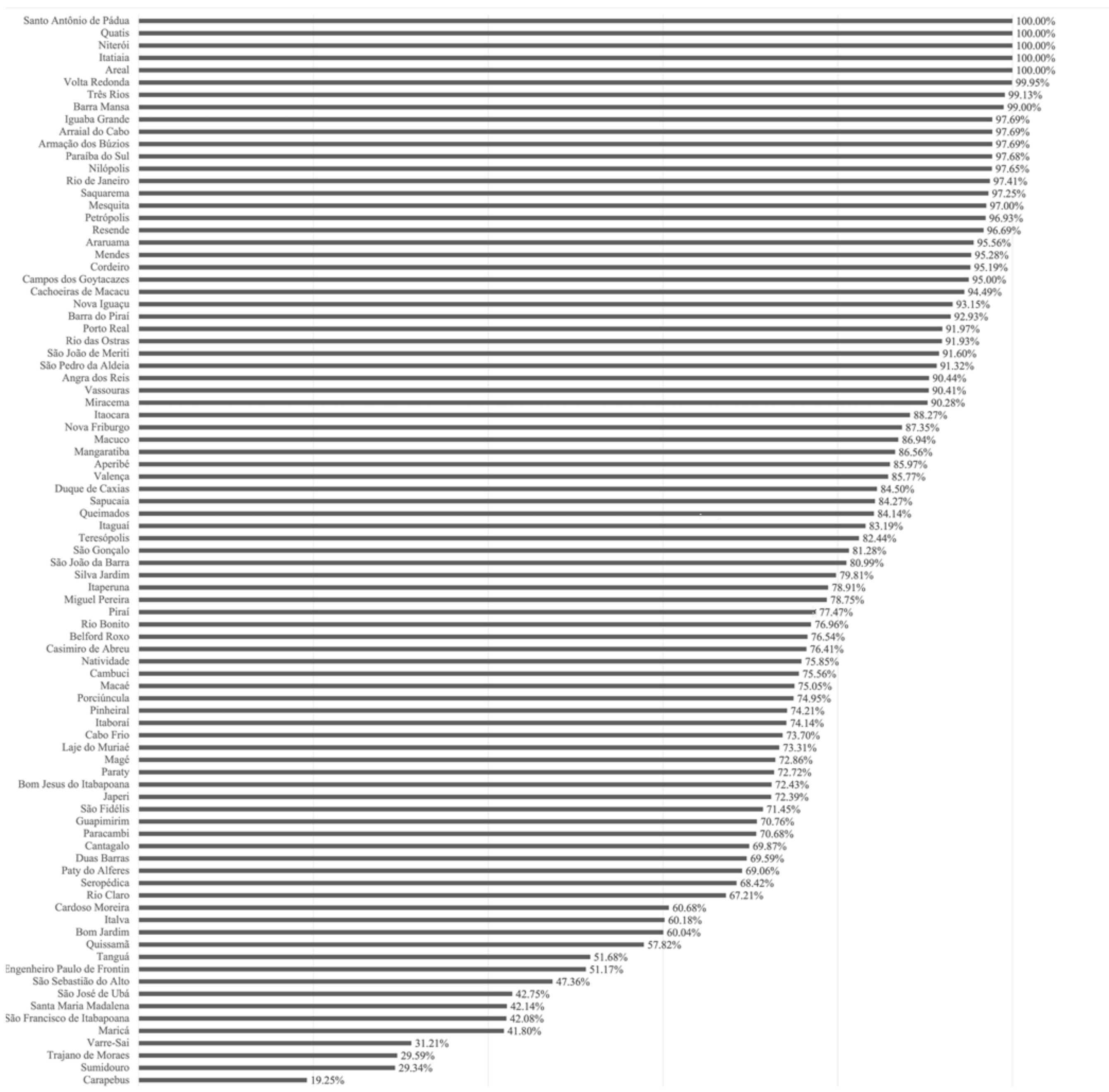
Graph 1 — Hepatitis A incidence per 100,000 inhabitants and per municipalities in the state of Rio de Janeiro and state average (orange line) for the period between 2007 and 2018.

Source: Prepared by the authors based on SINAN-Net data (Brasil, 2021b).

tion billed per economy (IN017), and average water consumption per economy (IN053), with correlation coefficients ranging from 0.80 to -0.43, at a significance level of $p < 0.001$.

Conversely, PC3 corresponds to 9.3% of the total variance of the data and presents a weak-to-moderate positive factor loading for indicators concerning water consumption (IN052) and the incidence of non-standard total coliform analyses (IN084) and strong negative factor loading for the indicator related to distribution losses (IN049), with correlation coefficients ranging from 0.71 to -0.88, at a significance level of $p < 0.001$.

Lastly, PC4 explains 7.9% of the total variance of the data and presents a weak-to-moderate positive factor loading for the indicators concerning economy achieved by outages (IN071), duration of outages (IN072) and water fluoridation (IN057) and presented a weak negative



Graph 2 — Water supply coverage of the municipalities of the state of Rio de Janeiro for the 2007-2018 period.
Source: prepared by the authors based on SNIS data (Brasil, 2021c).

factor loading for the indicator regarding extension of water network (IN020), with correlation coefficients ranging from 0.61 to -0.45, at a significance level of $p < 0.001$.

Association between hepatitis A and the principal components of the water supply

Based on the results achieved with the PCA technique in the study of water supply indicators, it was possible to solve multicollinearity and reduce the set of variables in the main axes for the analysis of the association with the incidence of hepatitis A. It is worth emphasizing that the choice for the PCA technique was made to meet the fundamental assumptions of many data analyses, including the Pearson's correlation — according to which the data are independent and the errors are independent and identically distributed (Taylor and Bates, 2013) — as well as to reduce the number of variables.

Therefore, Pearson's correlation analyses showed an association between the incidence of hepatitis A and the PC3 axis, with a correlation coefficient of -0.32, at a significance level of $p < 0.05$, as shown in Table 2.

As aforementioned, the most explanatory variables of PC3 are indicators related to water consumption (IN052), incidence of non-standard total coliform analyses (IN084), and distribution losses (IN049), as previously mentioned. Thus, observing the positive factor loadings of the IN052 and IN084 indicators, it is possible to infer that there is an inversely proportional relationship between them and the cumulative incidence of hepatitis A. In the case of IN052, this may indicate that greater water consumption means greater access to treated and distributed water, which contributes to the maintenance of hygiene habits, subsequently reducing the incidence of hepatitis A cases due to water scarcity.

Conversely, the IN084 initially indicates a strange relationship, as it was expected that the higher incidence of total coliform analyses with non-standard samples could increase the risk of contamination by the hepatitis A virus, whether due to failures in water treatment, or due to poor water quality in water supply sources or recontamination in the distribution networks. It was observed that 23 of the 57 municipalities present less than 85% of the required samples. However, it can be assumed that municipalities with the highest IN084 values are those that periodically monitor water supply systems, following the protocols defined by Ordinance No. 888 of May 4, 2021 (Brasil, 2021a), among other regulations and guidelines for the control and surveillance of water quality for human consumption. Therefore, the prior diagnosis of risk situations in monitoring the quality of water supply systems may contribute to reducing the incidence of hepatitis A.

Finally, the negative factor loading of IN049, related to distribution losses, demonstrates that the high rate of these losses can cause several problems in the access to water, compromising the health of the population due to increased risk of hepatitis A contamination, among other diseases that were not addressed in this study.

Table 2 — Pearson's correlation coefficients between cumulative incidence of hepatitis A and the principal components of the means of the indicators of the quality of the provision of water supply services. Significant results ($p < 0.05$) in bold.

Dimensions	Pearson's correlation coefficient	p-value	Confidence intervals	
			Lower limit	Upper limit
PC1	-0.06	0.69	-0.21	0.31
PC2	0.21	0.13	-0.06	0.44
PC3	**-0.32**	**0.02**	-0.53	-0.06
PC4	-0.14	0.30	-0.39	0.13

Source: Prepared by the authors based on data from SINAN-Net (Brasil, 2021b) and SNIS (Brasil, 2021c).

Discussion

The obtained results point to an association between the incidence of hepatitis A and indicators of the quality of water supply services — of the principal component (PC3), which explains 9.3% of the total variance of the data — in addition to what has already been found in other studies concerning the relationship between health and sanitation (Siqueira et al., 2017; Paiva and Souza, 2018; Dall'agnol et al., 2019). Some authors highlighted the presence of hepatitis A virus in urban sanitation networks (Holanda and Vasconcellos, 2015), especially in the MRJ (Prado et al., 2012), demonstrating high viral activity in summer and spring, under the presence of coliforms (Prado et al., 2012).

This association indicates a relationship between the cumulative incidence of hepatitis A and PC3, in which the quality indicators of the provision of water supply services IN052, IN084, and IN049 stand out, with higher factor loadings. In this sense, it is suggested that this relationship may be due to several factors, such as: poor quality of water from water supply sources, inefficiency in water treatment in ensuring its potability for human consumption, absence or precariousness in the monitoring and control of the surveillance of water quality in the supply systems, interruptions and outages in supply, which compromise water and food security, and the hygiene habits of the population.

With regard to the loss of water quality in water sources, the presence of viruses in sewage becomes more severe when there is low coverage of sanitary sewer, as was evidenced in the SRJ, especially in the state capital and in the metropolitan region, according to data on average sanitation coverage of sanitary sewer presented in this article, which corroborate the discussions of Britto et al. (2019). Moreover, the release of untreated effluents contributes to the degradation of water quality of water sources in the SRJ, as highlighted by Nunes (2021), in line with the historical framework of the abandonment of water sources to degradation, rectification, and channeling presented by Britto and Quintslr (2018).

Furthermore, this scenario of degradation of water quality of the water supply sources compromises, *a posteriori*, the water that will be used in water catchment, treatment, and distribution to supply the population (SOS Mata Atlântica, 2019). This is because the water from water sources may not meet the quality standards required by Resolution No.

357/2005 of the National Environment Council of Brazil (Conselho Nacional do Meio Ambiente – CONAMA) for human supply, influencing the efficiency of water treatment. In turn, compromising this efficiency may lead to non-compliance with potability standards, as established by Ordinance No. 888 of the Brazilian Ministry of Health of May 4, 2021, which amends Annex XX of the GM/MS Consolidation Ordinance No. 5, of September 28, 2017, to provide information on the control and surveillance procedures for the quality of drinking water and its potability standard. For illustrating this type of situation, what the MRRJ has been facing can be mentioned, in which the presence of geosmin has been associated with poor water quality in water bodies and the inefficiency of water treatment in achieving the potability standard required by Ordinance No. 888 of the Brazilian Ministry of Health (Brasil, 2021a).

This corroborates what some authors have demonstrated regarding the association of hepatitis A and other fecal-oral diseases, transmitted by water or due to lack of hygiene habits or water scarcity, with the quality of consumed water and access to water services (Holanda and Vasconcellos, 2015; Santos, 2019; Jesus, 2020). With regard to access, the water consumption indicator (IN052) – which showed a strong correlation (0.71) with PC3 – may indicate that, when access to water is guaranteed, higher consumption rates imply lower incidence of hepatitis A. Furthermore, higher consumption rates may be related to socioeconomic factors, as demonstrated by Fan et al. (2017). In other words, according to the authors of the aforementioned study conducted in China, the socioeconomic situation was one of the main factors that contributed to high water consumption and, in cities with low water consumption, this consumption was lower than the minimum amount required to sustain life, being "restricted by water supply capacity and household economic status" (Fan et al., 2017, p. 131).

As for the indicator related to the incidence of analyses of total coliforms with non-standard samples (IN084), it is suggested that efficient monitoring of water supply systems may lead to the recording of incidents, which in turn contributes to the monitoring of water quality for human consumption. In this sense, studies have shown that the monitoring performed by the quality control of the water supply was relevant in reducing diarrhea and hepatitis A, including during periods with records of intermittent supply (Castro et al., 2019).

With regard to the indicator related to distribution losses (IN049), Orellana et al. (2018) stress that the ageing of water supply systems is inevitable because they are among the first infrastructures installed and also because they accompany the development of cities. The authors emphasize that, as systems age, the trend is the increase in the number of leaks, ruptures, and interruptions in supply, as well as incrustation in the pipes. Such impacts can compromise water quality, increase internal roughness, reduce the hydraulic diameter and consequently the pressures that, in turn, cause intermittences and outages (Orellana et al., 2018).

Concerning distribution losses – which can aggravate intermittences and outages –, the impermanence of water supply through the general network interferes with access to water in quantity and quality due to problems of under pressure and recontamination in the network, as well as induces the search for alternative sources of supply, enabling the spread of water-borne diseases or those transmitted due to lack of hygiene habits resulting from water scarcity, such as hepatitis A — as discussed in the manuals prepared by the Secretariat of Health Surveillance of the Brazilian Ministry of Health (Brasil, 2006a, 2006b). Another factor related to intermittences is the operation of the general network, which guides the performance of systematic discharges to clean the pipes, preventing contamination of the water inside them (Brasil, 2006a, 2006b). This procedure is essential for monitoring and controlling the quality of water for human consumption. However, more detailed studies are needed in order to expand the knowledge of this relationship, using, for this purpose, other water-borne diseases or those transmitted due to lack of hygiene resulting from water scarcity, under multiple methods of analysis, and even considering the increase in historical series on specific regions and intra-urban studies.

Although the correlation between the incidence of hepatitis A and the principal component is not strong, it is still significant, with a significance level of $p < 0.05$, which encourages further investigation of this relationship. Hepatitis A is an oligosymptomatic disease, that is, it is presented by several factors that interact with each other and influence its manifestation. As previously discussed, among these factors are: lack of hygiene and access to water; consumption of water contaminated by animal feces, for example, through inadequate disposal of sewage into water bodies; and the risk associated with water contamination in the general network, which may occur due to losses, intermittences and supply outages, which produce a negative pressure in the pipes and, consequently, end up absorbing whatever is on the ground.

Furthermore, diseases such as hepatitis A, persistent in developing countries, are characterized as "diseases of poverty" because they are more prevalent among vulnerable social groups, or neglected diseases triggered by the absence or precariousness of sanitation and water supply services and housing conditions (Machado et al., 2017). Accordingly, Sotero-Martins et al. (2020) developed a study that evaluated the spatial distribution of municipalities and subnormal clusters of the SRJ according to the regional concession blocks for the privatization of Cedae, relating it to data on the incidence of diseases associated with inadequate environmental sanitation (*Doenças Relacionadas ao Saneamento Ambiental Inadequado* – DRSAI). The results achieved by the authors show that there is a spatial association between the municipalities of the SRJ and the incidence rate of DRSAI in 31 municipalities covered by Cedae. Also according to this study, 45.6% of the municipalities in the SRJ have subnormal clusters, especially the capital, Rio de Janeiro, which has the highest percentage of subnormal clusters in the entire state, 57.3% (Sotero-Martins et al., 2020).

In addition, it is worth deepening the investigation into the knowledge and formulation of these indicators of the quality of the provision of water supply services, enabling a better understanding of the information contained by them. Given the importance for the quality of life and health of the population served by the general water supply network, such research may contribute to the improvement of the information system and the quality of the provided service.

Nonetheless, the association of these indicators of the quality of the provision of water services with the analyzed disease points to the existence of deficiencies or inadequacies in the water supply systems for human consumption. In addition to the technical aspects of water supply systems, it is worth highlighting the structural nature of the decision-making processes regarding the choices of political-institutional actors. Hence, Britto and Quintslr (2018, p. 9, free translation) state that the review of the historical and structural process in the development of water supply macrosystems – such as in the case of the MRRJ – enabled to observe that the decisions were centralized "by political actors and engineers from the civil engineering sector, acting as builders of these urban service networks," which led to the concentration of supply in a single system for this region to the present day. According to the authors, Cedae has been operating since 1975 as a "developer of this macrotechnical system," although the development and expansion of the macrosystem over the years has not guaranteed the universalization of water services for the entire population, in terms of quality and quantity.

Conversely, the privatization process of Cedae demonstrates that social groups lacking the access to quality and quantity water services, residing in more vulnerable regions, may end up remaining outside the urgent universalization of access to safe water for human consumption (Nunes, 2021). Furthermore, centralization in a single system can also increase the risk of collapse in the face of the worsening of successive water crises and the worsening of the water quality conditions of the water sources. This was evidenced in the consecutive geosmin crises in the city of Rio de Janeiro (Formiga-Johnsson and Britto 2020; Nunes, 2021), but it had already been observed in a study for almost two decades (Machado, 2004). During the water crisis, the transposition flows of the Paraíba do Sul River, the main water supply source of the SRJ, were reduced; together with the degraded waters of the Guandu River, they supplied the MRRJ (Castro et al., 2019), which could justify the poor quality of the water and the worsening of interruptions in their supply networks.

Finally, no studies were found in the literature that explored the relationship between hepatitis A and SNIS variables based on the PCA technique, specifically in the SRJ, although some authors have analyzed this relationship to a lesser extent, using other methodologies.

Conclusions

The results achieved in this study contribute to a deeper understanding of the indicators contained in official databases and data systems regarding water supply and their relationship with the health of the population served, regarding the cumulative incidence of hepatitis A. They also contribute to a proposal for a differentiated analysis, such as the one performed with the application of the PCA technique, which allowed the identification of the principal components and their respective sets of variables with higher factor loadings, aiming to later analyze the correlation between the components and the *cumulative* incidence of hepatitis A. The use of this technique may allow further analyses with other types of dependent variables other than hepatitis A.

In addition, the association between hepatitis A and indicators of the quality of the provision of water supply services also proves to be important, as it indicates a certain vulnerability in the supply system, especially due to failures in water distribution, evidenced by the increase in the disease when related to indicators concerning distribution losses (IN049). The results also demonstrate the importance of monitoring and controlling water quality from treatment, undergoing distribution, and up to consumption, as a way of guaranteeing safe water for the population, in the face of environmental degradation and the negligence of the Government in solving a public health issue.

Finally, we emphasize the need – already pointed out by Machado and Klein (2004) for almost two decades – to rethink and promote actions in an integrated manner with policies on public health, environment, water resources, and sanitation, seeking to meet the fundamental needs of the population in a safe, equitable, and fair manner. The universalization of good quality water supply services for human consumption is an existential imperative of present and future generations and which integrates the right to health, as determined by Article 225 of the 1988 Federal Constitution of Brazil. In democratic state ruled by law, the Constitution is above everyone else.

Contribution of authors:

Nunes, D.G.: Conceptualization, Methodology, Analysis, Research, Writing – Original Draft. Machado, C.J.S.: Conceptualization, Methodology, Writing – Review & Editing. Pistón, N.: Analysis, Writing – Review & Editing.

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Institutional frameworks for human dimensions: reflections for marine protected areas in Brazil

Marcos institucionais para as dimensões humanas: reflexões para áreas marinhas protegidas brasileiras

Giovanna Carla Barreto[1], Manuela Dreyer da Silva[1], Décio Estevão do Nascimento[2], Thiago Zagonel Serafini[1], Rodrigo Pereira Medeiros[1]

ABSTRACT

Human Dimensions (HDs) have appeared in the scientific literature linked to the application of alternative approaches to natural resource management. National and international institutions (policies, guidelines, and global goals) guided these discussions on Marine Protected Areas (MPAs). The study aimed at relating these frameworks to the components of HDs. In this sense, a literature review was carried out based on criteria established by Barreto et al. (2020), guiding the selection of 92 peer-reviewed articles complemented by documents related to institutional frameworks. The analysis linked the institutional aspects selected to the components of HDs outlined in the literature. The research revealed the theory of the commons as an influencer in creating the concept of HDs, showing that its understanding goes beyond the univocal idea of human dimensions as the control and regulation of human behavior. Furthermore, five challenges for the integration of HDs in management approaches are highlighted from the connection between the institutional frameworks and the components of HDs. There are signs of a management model in transition that considers and emphasizes human dimensions; however, technocratic and centralizing approaches still prevail.

Keywords: components of human dimensions; institutional framework; natural resource management.

RESUMO

Com o aumento da complexidade nas discussões sobre a conservação da natureza, o conceito de dimensões humanas (DH) começou a aparecer na literatura científica com indicativos de aplicação nas abordagens alternativas de gestão dos recursos naturais. Os marcos institucionais nacionais e internacionais (políticas, diretrizes e metas globais) pautaram essas discussões, e aqui interessa especialmente aqueles associados às Áreas Marinhas Protegidas (AMP). O estudo objetivou relacionar esses marcos com os componentes dessas DH. Para isso, foi feita revisão da literatura pautada pelos critérios de busca estabelecidos por Barreto et al. (2020), que orientou a seleção de 92 artigos revisados por pares, complementados por documentos relativos aos marcos institucionais. A análise consistiu na articulação dos marcos institucionais selecionados aos componentes das DH mapeados pela literatura. A pesquisa apontou a teoria dos comuns como influenciadora da criação do conceito, mostrando que seu entendimento vai além da ideia unívoca de dimensões humanas como controle e regulação do comportamento humano. Cinco desafios à incorporação das DH nas práticas de gestão são apresentados, com base na articulação entre os marcos institucionais e os componentes das DH. Há indicativos de um modelo de gestão em transição que considera e enfatiza as dimensões humanas; entretanto, ainda prevalecem elementos de uma gestão que também é tecnocrática e centralizadora.

Palavras-chave: componentes das dimensões humanas; marcos institucionais; gestão dos recursos naturais.

[1]Universidade Federal do Paraná – Curitiba (PR), Brazil.

[2]Universidade Tecnológica Federal do Paraná – Curitiba (PR), Brazil.

Correspondence address: Giovanna Carla Barreto – Programa de Pós-Graduação em Meio Ambiente e Desenvolvimento – Universidade Federal do Paraná – Rua dos Funcionários, 1540 – Cabral – CEP: 82590-300 – Curitiba (PR), Brazil. E-mail: contato@giovannabarreto.com.br

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Introduction

In the growing debate of the global environmental crisis, the role of societies as key players in the deterioration and/or protection of the conditions of ecosystems and biodiversity has countless meanings (MEA, 2005; COP 21, 2015). This discussion also encompasses the context of coastal zones which, under significant socio-environmental and socioeconomic pressures (Rebouças et al., 2006; Neumann et al., 2015), reflect different conservation and planning strategies adopted by the governments (Mascia et al., 2017; Fairbanks et al., 2019) and exert an influence on the traditional peoples and communities livelihoods (Bavinck et al., 2017; Foppa et al., 2018, 2020).

The strategies include Marine Protected Areas (MPAs), recognized for their role in biodiversity conservation (Humphreys and Clark, 2019). Gradually, they also gained importance as a fisheries management tool (Jones, 2007; Voyer et al., 2012; Macedo et al., 2019), also creating conditions for the maintenance of livelihoods associated with small-scale fisheries (Kalikoski, 2007; Charles et al., 2016; Garcia et al., 2017; Campbell and Gray, 2019; Goti-Aralucea, 2019). On the other hand, such expansion of goals has been inconsistent, especially in terms of meeting human dimensions and promoting human rights (Barreto et al., 2020; Rasheed, 2020). The challenge arises from the need to understand that the management of biodiversity and marine protected areas transcends the limits of "managing nature". Likewise, it exposes the limits of science to the management of natural resources (Holling and Meffe, 1996; Price, 2003; Vieira, 2005), showing the need for interdisciplinary approaches and greater participation of the social sciences and social scientists (Bennett, 2019; Bennett and Roth, 2019; Moon et al., 2019).

Therefore, new challenges to the designation, implementation and management of the MPAs emerge from human dimensions (HDs). Aspects related to the diversity of stakeholders' interests in creating the MPAs (for example, NGOs, philanthropic organizations, the private sector, foreign states, national governments, political elites, local population) are included; the equitable distribution of costs and benefits of the conservation strategies (Bennett et al., 2016, 2017); among others. In an attempt to integrate conservation and fisheries management objectives, several factors affect MPA management performance, starting with their design and planning (Kalikoski, 2007; Giraldi-Costa et al., 2020). For example, when the MPAs are superimposed on fishing territories, they experience several conflicts related to access to and management of resources (Calegare et al., 2014; Bavinck et al., 2017).

In addition to the definitions and management principles of MPAs advocated in the scientific arenas, there is an important role for the institutional frameworks to promote compliance with the conservation goals. Agenda 21, the Convention on Biological Diversity and the Aichi Goals, among others, have sought to provide conservation targets, commitments and guidelines for governments and rulers to increase their ability to manage biodiversity (Thomas et al., 2014; Rees et al., 2018; Donald et al., 2019). On the other hand, setting up MPAs, motivated by international conservation models and goals (Campbell and Gray, 2019), leads to management strategies that reflect a dominant know-how (Corson et al., 2014), with little support in HDs, impairing the conservation processes themselves (Christie, 2004; Pomeroy et al., 2007; Charles and Wilson, 2009; Kittinger et al., 2012; Christie and Lewis, 2016). On the other hand, other frameworks, such as the The Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (Jentoft and Bavinck, 2014), henceforth the Voluntary Guidelines for Sustainable Small-Scale Fisheries, advocate promotion of human dimensions as components of ecosystem sustainability and resilience (Jentoft and Bavinck, 2014).

Understanding the influence related to the scientific contributions and institutional frameworks on the MPA management aspects helps to understand the factors affecting management performance at regional and local levels. Due to the recent emergence of the term HDs in the discourses of science and marine conservation management, with emphasis on marine ecosystems and small-scale fisheries systems, its framing as a concept is still incipient and points to the need for a more detailed approach to replace the old concept of restricted nature conservation. Starting from a global scenario, it is also important to locate this debate in Brazil, especially due to the diversity of components related to HDs in the Brazilian MPAs.

In Brazil, the term "protected areas" encompasses broader definitions and legal aspects than the same generic term used in international literature. The generic term is close to the legal definition of Brazilian "conservation units", as protected areas can also include indigenous lands, *quilombola* territories and "permanent preservation areas", defined in specific laws (Medeiros, 2006). In turn, marine protected areas include conservation units defined by the National System of Nature Conservation Units (*Sistema Nacional de Unidades de Conservação da Natureza* – Brasil, 2000), and areas excluded from fishing, defined in various instruments of fishing legislation. However, for the purposes of standardizing the nomenclatures, MPAs (Dudley, 2008) this article refers to conservation units as established for the Brazilian marine-coastal biome.

The National System of Nature Conservation Units establishes two groups of protected areas: No-Take and Sustainable Use protected areas. While the former is restricted to indirect uses, such as tourism, education and research, in Sustainable Use, extractive use, such as fishing, is allowed through specific regulations. A total of 12 categories of protected areas are promoted, for example, from the maintenance of ecosystems excluding human presence in Biological Reserves to conservation of the biodiversity associated with protection of the livelihoods and culture of traditional populations in Extractive Reserves (Medeiros, 2006). Although Brazil is a signatory to many of such conventions and institutional frameworks, in both groups, the Brazilian protected areas present numerous failures in the integration of human dimensions into the decision-making processes (Vivacqua et al., 2009;

Dias and Seixas, 2017; Macedo and Medeiros, 2018; Vivacqua, 2018; Macedo et al., 2019).

Therefore, there is a need to understand how it is possible to advance in promoting MPAs human dimensions. Thus, this study aimed at relating the institutional frameworks (policies, guidelines and goals that contain these discourses) adopted to outline the concept of HDs in the context of the MPAs with the components of these HDs. This objective was thought to broaden the understanding of HDs by scholars and managers, as the presence of these components in MPA management is directly related to the creation of alternative management processes already narrated in the literature. This objective unfolded into: Systematization of these institutional frameworks and description of the elements that define HDs; and Analysis of these institutional frameworks from the components of the HDs mapped by the scientific literature. To such end, the article begins by exploring in greater detail the definitions and construction process of the term "Human Dimensions" and its importance for the management of marine protected areas.

Brief synthesis about the human dimensions

The idea of HDs gained evidence from new perspectives on natural resource management, such as the ecosystem approach (Berkes et al., 2001; Young et al., 2008), and the expansion processes for the creation of marine protected areas (Christie et al., 2017). Criticism starts from the perspective of command and control of the natural resources (controlling ecosystem components and State-centered perspective) (Holling and Meffe, 1996) and highlights the importance of human dimensions for the management processes (Charles and Wilson, 2009; Kittinger et al., 2012; Bennett et al., 2017; 2019).

The use of the term HDs in the literature is recent and comprehensive; it sometimes appears as the social aspect of the social-ecological systems, and others as a more participatory management strategy, seeking to balance the human and ecological factors of the social-ecological systems (SES) (Barreto et al., 2020). The SES perspective is aligned with the systemic theory, and emphasizes connections, contexts and feedback mechanisms between *nature-society*, that is, the interdependence of social and ecological systems (Allen et al., 2014). This perspective and its variations — especially the ecosystem approach applied to fishing (CDB, 2004; Young et al., 2008) and adaptive co-management (Armitage et al., 2009) — have emphasized HDs as a fundamental component of these approaches (Pomeroy et al., 2007; Folke et al., 2016; Armitage et al., 2020).

Concrete cases and the literature itself have demonstrated the possibility that the MPAs may come to produce ecological benefits in combination with socioeconomic benefits (Macedo et al., 2019) and, certainly, the recognition of HDs is included in these cases. In order to broaden application of HDs in fisheries management and in the MPAs, it is necessary to elucidate what this concept involves and its relationship with the discourse about national and international nature conservation strategies. For this purpose, the study starts from a critical conception in the reflection of the fundamentals of the so-called institutions in the management of resources in the SES (Vieira, 2005; Seixas and Kalikoski, 2009; Tebet et al., 2018), and thus assumes that human beings are inserted as a constitutive part of the ecosystems and landscapes (human being in nature or human-in-ecosystem) (Davidson-Hunt and Berkes, 2003; Vieira, 2009; Folke et al., 2016).

Material and methods

In this study, a literature review was performed based on the search criteria established by Barreto et al. (2020), which guided the selection of 92 articles aimed at descriptions and use of the term "Human Dimensions" in the context of marine protected areas. To this end, the following descriptors were used: human dimensions, marine protected areas, small-scale fisheries and ecosystem approach applied to fishing (ecosystem-based fisheries), as well as their related terms and synonyms. The descriptors associated with fishing were included, as a complement to expand the search scope, given the association in the literature between MPAs and fisheries management, especially small-scale fisheries (Hart and Reynold, 2002; Young et al., 2008; Kittinger, 2013; Koehn et al., 2013; Christie et al., 2017; Hornborg et al., 2019). The Scopus and Web of Science (WoS) databases were used due to their representation of journals on environmental management, governance and natural and social sciences, with only peer-reviewed articles, with no time limit being selected.

Complementary documents on the institutional frameworks mentioned in the articles were added to the initial portfolio (reports from conferences and conservation goals). From this set of information, the particularities about the institutional frameworks that structure the HDs were extracted, with each framework selected being briefly described to show its connection with the concept of HDs and with MPA management. These frameworks were then organized in chronological order, indicating the reference source (Table 1).

Considering that these institutional frameworks also guided debates in the scientific literature, Figure 1 was prepared, which explores the occurrence relationships between the components of the HDs found in the literature and the institutional frameworks selected. To assess these components, the systematization made by Barreto et al. (2020) was considered, which described 35 components of the HDs, ordered into five analytical categories: governance (G), economics (E), social (S), cultural (C) and political (P). According to the authors, the components of the HDs organized in this way can be considered as indicators or results for the robust management and governance of small-scale fisheries and marine protected areas, and that is why they were brought to the current discussion.

For presenting the syntheses described herein, the sets of information (institutional frameworks, scientific articles and components of the HDs) were organized in the Atlas TI Software and guided data triangulation (Weyers et al., 2008). This proposal accompanied the analysis effort that had already been initiated on the components of

Table 1 – Description of the Human Dimensions' aspects present in the frameworks of the international environmental debate in the context of the management of marine protected areas, small-scale fisheries and ecosystem approach (alternative management).

Institutional Frameworks	Date	Description	References
Stockholm Conference	1972	Creation of the United Nations Environment Programme (UNEP). It includes the ecological, ethical and moral dimensions in the debate on economic growth.	(PNUMA, 1972)
UN Convention on the Law of the Sea	1982	It provides the legal framework for the conservation and sustainable use of ocean resources.	(MMA, 1982)
Convention 169 - The International Labor Organization on Indigenous and Tribal Peoples	1989	It protects the rights of these peoples, defends their territorial autonomy and establishes self-definition or self-determination as a criterion for identifying these groups.	(ILO, 1989)
International Human Dimensions Program (IHDP) of the International Social Science Council	1990	It establishes a scientific agenda for research on the HDs of global environmental change. In 1996, it becomes the International Human Dimensions Programme on Global Environmental Change.	(Hogan, 2007)
Eco-92 Conference	1992	Elaboration of Agenda 21 (chapter 26) and Rio Declaration (principle 22), which recognize the vital role of indigenous peoples and local communities in environmental management and recognize traditional knowledge and practices.	(UN, 1992, 1995)
19th IUCN General Assembly	1994	It mentions the importance of community-based approaches (recommendation 19.23), emphasizing the construction of partnerships with local organizations to establish Community-Based Conservation (CBC).	(IUCN, 1994)
Code of Conduct for Responsible Fisheries (FAO)	1995	It recommends that responsible fishing takes into account not only the biological aspects, but also technological, social and socio-environmental aspects and traditional knowledge.	(FAO, 1995)
Ecosystem Approach (CBD)	2000	Official adoption of the principles and guidelines that advocate a holistic and participative management approach, seeking to reconcile human uses and environmental conservation.	(MMA, 2000)
Millennium Development Goals (MDGs)	2000	They address, among others, goals to ensure poverty reduction and environmental sustainability.	(UN, 2000)
World Summit on Sustainable Development (WSSD, Johannesburg)	2002	It encourages the application by 2010 of the ecosystem approach and the promotion of integrated and multi-sector coastal and marine development through the creation of a global MPA network by 2012.	(Prates, 2014)
5th World Congress on Parks (IUCN)	2003	A debate on collaborative management and governance, recognizing the conservation practices of local communities (Community Conserved Areas).	(Borrini-Feyerabend et al., 2004)
Millennium Ecosystem Assessment	2005	The largest assessment ever carried out on the health of ecosystems and their connections to human well-being.	(MEA, 2005)
Strategic Biodiversity Plan (CDB)	2010	Elaboration of the Aichi goals (2011-2020) aiming to reduce planetary biodiversity loss. Goal 18 mentions the full and effective participation of the indigenous and local communities in conservation management. Goal 11 establishes that, by 2020, at least 10% of the marine and coastal areas must be preserved.	(CDB, 2010)
Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries (FAO)	2015	It emphasizes aspects such as food security, poverty eradication, employment, gender equality and participation as fundamental to ensuring the sustainable management of small-scale fisheries.	(FAO, 2015)
Sustainable Development Goals (SDGs)	2015	It maintains and extends the MDGs and includes conservation and sustainable use of the oceans (Goal 14).	(UN, 2015)
Think Tank on Human Dimensions (TTHD)	2016	First broad initiative to formally debate the MPA HDs on a large scale. The meeting brought together 17 countries.	(Christie and Lewis, 2016)

Source: own elaboration.

COMPONENTS OF THE HDs

G - Governance

1G Policies and laws
2G Institutional arrangements
3G Participation of the actors
4G Conflicts
5G Application and compliance with the rules
6G Information and communication flow
7G Community organization

C - Culture

1C History and context
2C Cultural values and heritage
3C Traditional and local knowledge
4C Fishing customary practices and rights
5C Sense of belonging and displacement

E - Economy

1E Costs and benefits
2E Ecosystem's goods and services
3E Sustainable livelihoods
4E Income and assets
5E Markets, commerce and market values

P - Politics

1P Power relations
2P Equity and justice
3P Representation and legitimacy
4P Rights to access and manage resources
5P Funding and investment
6P Ethics and customs
7P Ownership title

S - Social

1S Attitudes, perceptions, beliefs, preferences
2S Human uses, activities and pressures
3S Well-being
4S Goals, needs and aspirations
5S Demographic aspects
6S Social capital
7S Social vulnerability and resilience
8S Food security
9S Employment
10S Poverty
11S Gender issues

INSTITUTIONAL FRAMEWORKS	RELATIONSHIPS PERCEIVED
Stockholm Conference	2E; 2C; 3E; 5E; 6P
United Nations Convention on the Law of the Sea	1G; 2G
Convention 169 - The International Labor Organization on Indigenous and Tribal Peoples	1G; 3G; 3C; 2C; 4C; 4P; 6P; 7P
International Human Dimensions Program (IHDP) of the International Social Science Council	2E; 6S
Eco-92 Conference	4S; 4C; 3C
19th IUCN General Assembly	2G; 3G; 3C; 5C;
Code of Conduct for Responsible Fisheries (FAO)	6S; 2C; 3C; 4C ; 8S
Ecosystem Approach (CBD)	2G; 3G; 6G
Millennium Development Goals (MDGs)	2E; 4S; 8S; 10S
World Summit on Sustainable Development (WSSD, Johannesburg)	2G; 5G
5th World Congress on Parks (ICUN)	2G; 3G; 3C
Millennium Ecosystem Evaluation	2E; 3S
Biodiversity Strategic Plan (CBD)	1G; 3G; 3C; 4S; 4P
Voluntary Guidelines for Securing Sustainability of Small-Scale Fisheries (FAO)	4C; 8S; 9S; 10S; 11S
Sustainable Development Goals (SDGs)	2E; 5E; 4S; 8S; 10S; 11S
Think Tank on Human Dimensions (TTHD)	6S; 1C

Figure 1 – Perceived relationships between components of Human Dimensions as described by Barreto et al. (2020) and the institutional frameworks mapped.
Source: own elaboration.

HDs in nature conservation and natural resource management (Kittinger et al., 2012; Gruby et al., 2016; Heck et al., 2016; Christie and Lewis, 2016; Barreto et al., 2020).

Results and Discussion

International institutional frameworks and the path for the construction of human dimensions

Setting up protected areas has been the political practice adopted worldwide to minimize biodiversity loss. However, this practice alone is not sufficient and, in many cases, has failed to meet the conservation goals (Brito, 2000; Berkes et al., 2001; Kalikoski, 2006; Rebouças et al., 2006). As already shown, incorporation of HDs in discussions about the management of these areas and the adjustments between the institutions created (formal and informal rules) can minimize the impact of policies that prioritize certain dimensions (ecological or economic) over others (human and social) (Pomeroy et al., 2007; Voyer et al., 2012; Loring and Harrison, 2013; Bennett et al., 2016, 2017).

Thus, the influence of the institutional frameworks in this context and in the construction of the concept of HDs is assumed. Results of the institutional frameworks identified in this study and some information about them are presented (Table 1). It is noteworthy that the institutional frameworks described are not unique, and those considered for this study support the definition of a concept of HDs.

The Stockholm Conference (1972) is generally considered a framework on the construction of another development because it incorporated nature conservation aspects into the productive process. This framework highlighted the conflict of interests between short-term development and the limits of material growth (Meadows et al., 1972), pointing out the need to devise a global ethic of development that "mutually recognizes and promotes social and ecological values" (Engel, 1990, p. 19).

The systemic concept of ecodevelopment emerged in the same decade (1970s), emphasizing the need to include the ecological, ethical and moral dimensions in the debate on economic growth (Sachs, 1986; Vieira, 2009). In this context, the integrated view of the social and natural systems, as social-ecological systems, mobilized the resumption of the human-in-nature perspective linked to the theoretical-methodological elaborations of the scientific community (Davidson-Hunt and Berkes, 2003). This resumption checkmated the theoretical, scientific and also political paradigm of protected areas interpreted as biodiversity islands supported by management models that exclude human populations from these areas (Ferreira, 2004).

Highlighting the visibility of this human-nature interaction, other global socio-environmental events gave visibility to human and social aspects in the context of MPA management and the use of natural resources, covering a period of six decades (1970-2020). Between the 1980s and 1990s, the Brundtland Report or Our Common Future (1991) stands out, which introduced the human dimension of "solidarity" with the future generations through the concept of "sustainable development", stating that nature needs to be preserved for development to be sustained. The notion of intergenerational solidarity added social, political, cultural and technological dimensions to the idea of sustainability. Reinforcing this understanding, Katona et al. (2017) recognize the Brundtland Report as the turning point of ecological thinking symbolizing yet another theoretical break in the artificial separation between human beings and nature. At the same time, the concept of sustainable development was also criticized for neglecting the predecessor concept of "ecodevelopment" and also for fostering a discourse of ecological sustainability at the expense of the commodification of nature (Vieira, 2005, 2009; Leff, 2006).

During this same period (1980-1999), the 19th General Assembly of the IUCN and Convention 169 of the International Labor Organization (ILO) on Indigenous and Tribal Peoples established, respectively, the implementation of shared management processes and legal frameworks with a view to guaranteeing the human and social rights of the traditional and local communities. Convention 169 guaranteed the peoples' right to self-determination, thus safeguarding their territorial autonomy, primarily in the legal context (ILO, 1989). However, many of the decisions regarding nature conservation end up devaluing the identity of the populations that live in these territories (Calegare et al., 2014; Evans and Reid, 2016; Vivacqua, 2018).

The scientific community devoted to the study of Global Environmental Change (GEC) started talking about HDs in the late 1980s (NRC, 1999). In 1996, the International Human Dimensions Program (IHDP) was created, which included "human activities" in the conceptual model that explains the functioning of the Earth system (Bretherton Diagram), scientifically recognizing that analyzing human actions is extremely important for nature conservation and understanding its biophysical effects (Mooney et al., 2013).

The following decades (2000-2015) reinforced aspects that have been raised since the Stockholm Conference, such as the fight against poverty, and included and highlighted other relevant aspects such as gender, human rights and social well-being. Two frameworks can be highlighted in this period: the ecosystem approach that seeks to reconcile human uses and nature conservation, and the Sustainable Development Goals (SDGs) proposed by the United Nations (UN). With roots in the traditional models of community management (Garcia and Cochrane, 2005), the principles and guidelines of the ecosystem approach started to be systematically adopted by the Convention on Biological Diversity (CBD) in 2000, during the 5th Conference of the Parties decision number 6 - COP V/6 (CBD, 2000). Despite being included as a precept in the regulation of the fisheries management instruments (Brasil, 2009), incorporation of the ecosystem approach is hampered by the scarcity of fishing monitoring data and continuity of the participatory processes (fishermen's engagement in decision-making) (Dias and Seixas, 2019).

In relation to the Millennium Development Goals (UN, 2000) and the Sustainable Development Goals (UN, 2015), the goals proposed by the UN emphasized aspects related to the eradication of poverty, gender issues and the integral development of human beings associated with a healthy environment. Goal 14 of the SDGs seeks to consolidate specific strategies for the conservation and sustainable use of the oceans, seas and marine resources. However, the very title of this SDG ("Life Below Water") still emphasizes the biological aspects of conservation at the expense of living beings under water (Jentoft, 2020).

With regard to the marine ecosystems and small-scale fisheries systems, the United Nations' Food and Agriculture Organization (FAO) provides a wide range of guidelines for the conceptual management models in the operational contexts. These include the International Code of Conduct for Responsible Fisheries (FAO, 1995) and the Voluntary Guidelines for Sustainable Small-Scale Fisheries (FAO, 2015). They advocate for participation rights, also covering issues such as customary tenure rights, gender equality, employment and health. These Guidelines were developed through a process that has been presented by the literature as effectively participatory (Pedrosa and Lessa, 2017). According to Pedrosa and Lessa (2017), by placing human rights at the center of fisheries management, the Guidelines brought to the management discussions aspects of collective law, gender issues, culture, contribution to global food safety, nutrition and poverty eradication (Goti-Aralucea, 2019). On the other hand, the Code of Conduct established the ecosystem approach applied to fisheries (EAF) as an analytical and operational perspective, offering concepts and tools for its implementation (Garcia and Cochrane, 2005; Young et al., 2008; FAO, 2013).

The idea of HDs perceived in these institutional frameworks analyzed can be summarized in the following key terms: integrated and decentralized management, participation in decision-making processes, different uses of resources, human and social rights, equity (including gender) and justice. In a way, these terms appear among the guiding principles of the alternative approaches to management. Their presence indicates that the conservation goals, guidelines and agendas have progressively taken on broader, interdisciplinary and participatory management perspectives, emphasizing the notion of HDs as an essential element to improve the conservation outcomes (Charles and Wilson, 2009; Voyer et al., 2012; Bennett et al., 2017; Moon et al., 2019; Barreto et al., 2020).

Perceived relationships of the institutional frameworks in Brazil

Much of the Brazilian environmental policy has developed in response to the demands of the international environmental movement (Vieira, 2009; Peccatiello, 2011). The legal contours related to environmental protection gained greater consistency after the enactment of the 1988 Brazilian Constitution (Brasil, 1988), which integrated the actions of the public power that were isolated and fragmented into new legal regulation instruments (Vieira, 2009; Lima, 2011).

CF 88 represented a milestone and advance in the legal protection not only of biodiversity (ecological system) but also of sociodiversity (Santilli, 2005). Preceding Eco-92, the creation of the Brazilian Forum of Non-Governmental Organizations (NGOs) and Social Movements for the Environment and Development, promoted the articulation of networks of NGOs and social movements that organized the participation of civil society in this conference (Santilli, 2005). However, in practice, the governmental actions remained "fragmented and contradictory, occupying a peripheral space in the dynamics of the political system's functioning and in the daily life of the majority of the Brazilian people" (Vieira, 2009, p. 29).

Since the creation of the Special Secretariat for the Environment (*Secretaria Especial de Meio Ambiente* — SEMA, 1973), in the post-Stockholm-72 period, through the creation of environmental agencies such as the Brazilian Institute for the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* — IBAMA, 1989), of the Ministry of the Environment (*Ministério do Meio Ambiente* — MMA, 1993), and the Chico Mendes Institute for Biodiversity Conservation (*Instituto Chico Mendes de Conservação da Biodiversidade* — ICMBio, 2007), there has been a growing effort to develop an environmental apparatus in the country (Lima, 2011), which also had repercussions on the establishment of organizational charts responsible for the implementation of protected areas (Brito, 2000). This agenda has been accompanied by discussions on social participation, and the National Environmental Policy (*Política Nacional de Meio Ambiente* — PNMA, 1981) is cited as the starting point for this debate.

Therefore, it was in the 1980s that the country began to consolidate a more integrated environmental policy system, culminating in the creation of the National System of Nature Conservation Units (Brasil, 2000). Although considered as an advance for the creation of protected areas in the country (Peccatiello, 2011), the first bill of law to create the SNUC pointed to the human presence as a threat to biodiversity conservation (Calegare et al., 2014).

A complex subject matter by itself, although not the focus of this paper, the different typologies of protected areas reflect the set of political, social, economic and environmental interests that were found in the process of creating the SNUC. The most controversial points included popular participation in the process of creation and management of protected areas, as well as the role given to the traditional communities (Medeiros, 2006; Peccatiello, 2011). In any case, the creation of protected areas of the Sustainable Use group, such as Extractive Reserves (*Reservas Extrativistas* — RESEX) and Sustainable Development Reserves (*Reservas de Desenvolvimento Sustentável* — RDS), represented an important step forward by also incorporating into the conservation objectives the cultural values associated with the traditional practices (Medeiros, 2006). These two categories of protected areas emerged in the context of the institutional struggles of social movements and NGOs, representing a change in the perspective of nature conservation management, now more aligned with the SES. This notion of integrated systems has acquired important status in the discussions about protected areas in the coastal and marine zones, creating other institutional arrangements for MPA management (Prado and Seixas, 2018), and fostered debates about the legal rights of the Brazilian traditional populations, mainly since the 1990s (Diegues, 2008).

In 2006, the National Plan for Protected Areas (*Plano Nacional de Áreas Protegidas* — PNAP) was established (Brazil, 2006), in line with decisions taken within the scope of the Convention on Biological Diversity (CBD). This Plan sought to integrate the policies of the protected areas managed under the SNUC framework with those for the conservation of indigenous lands and *quilombola* territories (MMA, 2006). Even at a theoretical level, incorporation of these territories into the PNAP recognizes the role of these communities in biodiversity conservation.

The National Coastal Management Plan (*Plano Nacional de Gerenciamento Costeiro* — PNGC) and the Bill of Law for the National Policy for Conservation and Sustainable Use of the Brazilian Marine Biome (*Política Nacional para a Conservação e o Uso Sustentável do Bioma Marinho* — PNCMar) are specific national frameworks for coastal and marine areas, the latter still in progress as a bill of law (Brazil, 2004, 2013). Presupposing integrated, participatory, proactive and ecologically prudent management processes, the PNGC aimed, for example, at implementing zoning for uses and activities along the Brazilian coast. However, it is criticized for establishing participatory mechanisms that are not very expressive, technocratic and notably budgetary (Vivacqua et al., 2009). According to Moura (2017), the PNGC is a technical and disciplinary environmental planning instrument for the use and occupation of the coastal and marine areas, with little openness to the incorporation of ways of life and uses of natural resources by traditional communities in the management instruments. In addition, it lacks the implementation of a good part of its management instruments foreseen for over 30 years. PNCMar (LB No. 6,969), also known as the Law of the Sea, intends to adopt marine spatial planning as one of its main management instruments and a governance system that is adaptive and ecosystemic, in line with the international treaties which Brazil is a party to. Elaboration and implementation of a formal marine spatial planning policy in the country must be carefully made so as not to be also guided by a technocratic, centralizing perspective and aligned with major economic interests, disregarding other interests and needs, such as small-scale fisheries (Gerhardinger et al., 2007). Thus, what seems to be the discussion focus is the context for managing areas in this complex social-ecological system, the participation modalities and quality and its limits when considering the structuring institutional frameworks of the MPAs.

In relation to Brazilian fisheries management, its path has been marked by constant political instabilities through displacements and extinction of secretariats and ministries, which exert an impact on its normative legal framework. Among the latest changes is the temporary suspension of closed-end insurance with the justification of re-registration to correct the illegalities in granting the benefit (MAPA/MMA Interministerial Ordinance No. 192, of October 5, 2015). Closed-end insurance is known in Brazil as seguro-defeso, a resource equivalent to a minimum wage paid by the government to professional artisanal fisherwomen and fishermen during periods of prohibition of capture for the reproduction of the species. Suspension was followed by the extinction of the Fisheries and Aquaculture Ministry (*Ministério da Pesca e Aquicultura*, Law No. 13,266/2016). Once the Ministry was terminated, the Aquaculture and Fisheries Secretariat (*Secretaria de Aquicultura e Pesca* — SAP) housed in 2015 in the Ministry of Agriculture was transferred to the Ministry of Industry, Trade and Services (*Ministério da Indústria, Comércio e Serviços* — MDIC) in early 2017 (decrees No. 9,004 and No. 9,067, dated 2017). Then, Law No. 13,502, dated November 2017, determined the re-creation of the Aquaculture and Fisheries Special Secretariat, linking it again to the Presidency of the Republic (*Secretaria Especial da Aquicultura e da Pesca/Presidência da República* — SEAP/PR). As a result, Law No. 13,844 of 2019 returned the administrative competence of the fisheries exclusively to the Ministry of Agriculture, Livestock and Supply (*Ministério da Agricultura, Pecuária e Abastecimento* — MAPA).

There is a reading that all these changes in the competence of fisheries management are being made to the detriment of small-scale fisheries, as there is not enough institutional structure and human resources to meet the demands and interests of this category (Azevedo and Pierre, 2017). The same authors argue that, in addition to these changes, in Brazil there is a very diverse and broad legal framework with regard to small-scale fisheries, based on development and conservation policies that aggravate inequalities resulting from the unequal distribution of benefits, costs and risks in fishing territories. The interface of this context in the management of MPAs is often controversial, permeated by conflicts of competences and uncertainties in the authority to implement the management demands (Tebet et al., 2018; Macedo et al., 2019). Even the National Policy for the Sustainable Development of Traditional Peoples and Populations in Brazil (Law No. 6,040 of 2007) (Brazil, 2007), which supports alternative activities in the fishing territories (Moura, 2017) by guaranteeing recognition and respect for livelihoods and traditional territories, collides with the fragility of participation formats and access to resources in the MPAs (Voyer et al., 2012; Goti-Aralucea, 2019). Locating the HDs in this context can, therefore, aid visibility of these rights and improve the management of these areas, aspects which are dealt with below.

Locating the human dimensions and the challenges for their application in Brazil

Different national and international institutional frameworks contributed to delineate the concept of HDs in the context of the management of marine protected areas. In the international political arena, it is clearer that the frameworks, management guidelines and global conservation goals are increasingly taking on approaches that seek to associate the ecological and human dimensions, including the ecosystem approach applied to fishing (Young et al., 2008; FAO, 2013) and the think tank on MPA HDs in 2016 (Christie and Lewis, 2016).

In the environmental sciences, although human activities were officially included in the conceptual model that explains the functioning of the Earth system only in 1996, studies such as the one by Olson (1971) already dealt with the collective action related to decision-making in the use of natural resources. The theory of the commons (or common pool-resources), whose studies intensified in the 1990s, also contributed to this area with important aspects about the ways in which individuals define the patterns of access, use and reproduction of natural resources (Ostrom, 1990). These studies highlighted the local mechanisms for controlling the use of resources, such as communication and bonds of trust, with an emphasis on natural resource community management. In other words, they emphasized some HD related to nature conservation. It is noteworthy that this study pointed to the theory of the commons as a great mobilizer of the concept of HDs in this MPA context, superimposed on fishing territories, and that its understanding can (and should) go beyond the univocal idea of human dimensions as control and management of human behavior (Shove, 2010; Castree et al., 2014; Barreto et al., 2020).

In this context, studies on sociocultural characteristics, power dynamics and their institutions, and shared, participatory and adaptive management (co-management) somehow became part of this analysis. However, it is necessary to locate HDs in this discussion, as there are many meanings attributed to this concept (undoubtedly a polysemic term). And, despite the interpretations coming from different knowledge areas and relating the concept to components such as "attitude, perception, beliefs and preferences", there are approaches that still relate them exclusively to "human uses, activities and pressure" (Barreto et al., 2020), supporting command and control management processes (Shove, 2010; Castree et al., 2014).

Also, on the definition and use of the term, Barreto et al. (2020) identified that few articles using the concept of HDs were published in social and human science journals (most were published in environmental and natural science journals). When mobilized especially by natural and environmental scientists, the concept of HDs related to MPA management also carries with it natural science paradigms in resource management. Due to this bias, the debate on HDs has still been dominated by behavioral perspectives arising from interpretations of currents linked to methodological individualism and functionalism, with little opening for the so-called "more critical" readings (Castree et al., 2014; Moon et al., 2019). In a simplified manner, it can be asserted that the functionalism theory found in the social sciences explains the institutions from their specific functions in society and their effects. The greater emphasis on the management components, with emphasis on the institutional aspects and parameters associated with the regulation of the use of natural resources, points to the already mentioned influence of the theory of commons school on the genesis of the concept of HDs (Ostrom, 1990). This emphasis also indicates a widespread (and often imposed) acceptance of the requirement to adapt specific human behaviors and controls especially applied to local populations in areas that are rich in biodiversity and resources (Evans and Reid, 2016).

By integrating other sciences, such as the social sciences, there is a growing expansion in the discussions about HDs, with questioning of these exclusive paradigms and incorporation of themes related to the social impacts of the MPAs, to the divergent interests in the creation of the 'institutions' and to the management processes of these areas. However, components, such as gender, employment, poverty, ethics and property rights, which have been gradually incorporated into global institutional frameworks such as the MDGs and SDGs, are less noticeable in the current literature when compared to the governance HDs, for example.

In general, in the literature reviewed, the HDs appeared defined by the *actor-institutions-nature* interaction, interpreted as a mutual influence relationship. Its essence lies in the process of interaction (and conflict) between diverse interests and needs, which in this study are considered through the 35 components mapped by Barreto et al. (2020). They consider that the minimum human living conditions must be guaranteed (see, for example, FAO's Voluntary Guidelines for Securing Sustainability Small-Scale Fisheries, Table 1) and point out to the construction of multi-interest processes, with the influence of science in the elaboration of policies, and with relationships with other agents, such as NGOs and social movements. According to this reading, the articulation between HDs and the institutional frameworks becomes evident. Figure 1 was structured to show this relationship.

These already established relationships reveal the complexity in the application and elaboration of new socio-political agendas related to the theme, by showing the challenges of working on the 35 components of HDs in an integrated way. Figure 1 shows that the "institutional arrangements", "participation of the actors", "traditional and local knowledge", "food security", "poverty" and "gender" components were more frequently mentioned in institutional frameworks. This shows the need to incorporate the other components of HDs, both in the political field as well as in the daily management of the MPAs, in order to achieve more equitable and fair processes. In this context, it is also necessary to visualize the political strategies and funding mechanisms to deal with all this multiplicity of dimensions in the management of natural resources (Jentoft et al., 2007; Thomas et al., 2014).

Complexity also refers to the fact that the political, scientific and management elements are interactive and interdependent. Integrating the components of the HDs related to small-scale fisheries to these elements requires monitoring of these processes and mutual learning. As an example, there was a mention to the difficulty connecting the different scientific and political languages (Caveen et al., 2013). Literature points out that information exchange between researchers and managers is one of the bottlenecks cited for improvement in the decision-making systems, and contemplating HDs in these processes seems to be a possibility to build a more robust management (Voyer et al., 2012; Cvitanovic et al., 2015; Dias and Seixas, 2017; Ranzani and Serafini, 2020).

Therefore, literature reports that integrating HDs into biophysical and ecological dimensions creates space for the adoption of broader (and effective) approaches to natural resource management. This integration structures more participative management policies and processes, aiming to improve the conservation outcomes. However, it is noted that the focus on aspects that establish reference points on the regulation and forms of use of the natural resources (i.e., on human behavior), ends up resulting in a low prioritization of essential parameters for evaluating the social impacts arising from these regulations.

In this context, the analyses carried out in the current study allow pointing out important challenges faced in Brazil with regard to the effective implementation of more integrated approaches that consider HDs, namely:

- Recognition in the scientific and legal-normative field of the role of local communities in the maintenance of the ecosystems finds little support in the executive and decision-making fields *(de jure and de facto)*;
- Conditioning to a world view and rationality unique to the scientific community and to a reductionist conception of management and development, based on the use of strictly economic parameters *(positivism in environmental sciences and command and control type management)*;
- The distance between the studies, proposals and global goals and the different national and local realities *(scale problem)*;
- Integrated research on the social-ecological systems is still primary and much of the contemporary literature does not fully achieve the necessary interdisciplinarity (inter- and trans-disciplinary projects, involving social and natural scientists, are incipient). See Sowman et al. (2013) and Hidalgo et al. (2015);
- Guidelines and legal frameworks play a dual role: they both influence public policies and can hinder certain types of adjustments and

adaptations necessary to respond to new sets of problems in the current context of accelerated transformations (e.g., adversities at different scales, such as climate change and the COVID-19 pandemic).

These challenges corroborate the argument that, despite the advances made by the institutional frameworks (especially regarding the recognition of human populations as subjects of law that have their livelihoods overlapped with protected areas), these spaces continue to be the scene for conflicts, social exclusions and disputes between uses and conservation. In a way, the management of natural resources shows indications of a model in transition; however, especially in the fishing activity, elements of technocratic and centralizing management still prevail, objectives regulated by market laws and command and control mechanisms (Vivacqua et al., 2009; Corson et al., 2014; Medeiros et al., 2014; Seixas et al., 2011, 2020).

On the other hand, the incorporation of the concept of HDs into policies and in the daily management routine, even in an incipient way, built space for innovative management experiences, which can provide opportunities for practices involving different actors in open and deliberative arenas that value sociobiodiversity and the debate on social beliefs, norms and values (e.g., deliberative councils). In relation to Brazil, despite institutional weaknesses, successful local experiences of fisheries management and marine protected areas can constitute possibilities for integrating HDs, as already noticed in some realities (Macedo and Medeiros, 2018; Seixas et al., 2020).

Conclusions

Even though there is still a need to improve the incorporation of human dimensions into the management of natural resources in MPAs, the current study made it possible to perceive, in a promising way, that the understanding of HDs goes beyond the univocal idea of control and management of human behavior. To collaborate in the understanding of these issues, the national and international institutional frameworks associated with the discussions on MPAs were revisited and articulated to the components of the HDs presented by Barreto et al. (2020). The components and relationships established with the frameworks selected show indications of a management model in transition in Brazil. At the same time, this transition imposes several challenges related to the integration of HDs into the current practices of MPA management, with emphasis on overcoming institutional arrangements that are still centralizing and technocratic.

The study also allowed to understand that several authors use the term "HDs" with different connotations or conceptualizations, although it is perceived that this conceptual abundance is more of an understanding effort than a point to focus on the scientific field. This multiplicity of interpretations highlights the characteristic of the systemic, transdisciplinary and multi-scale aspects in the discussion about MPAs. If the reductionist approaches to management usually fail, the five challenges summarized in this article showed that the simple adoption of goals and agreements does not guarantee adequate resource management in Brazil. If they are fundamental to achieving conservation objectives, it is necessary to look more deeply at human dimensions.

As this is not a comprehensive review (research limitation), it is assumed that some relevant documents may have been left out from the synthesis presented. However, the articulation between institutional frameworks and the components described by the literature indicates how the term "HDs" has been translated from an academic concept to a set of policies and normative management practices, and how this process models social, political and environmental changes both inside and outside the protected areas (policy influence & science nurturing).

Contribution of authors:

Barreto, G.C.B.: Funding Acquisition, Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing — original draft, Writing — review & editing. Silva, M.D.: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing — original draft, Writing — review & editing. Nascimento, D.E.: Writing — Review & editing. Serafini, T.Z.: Writing — Review & editing. Medeiros, R.P.: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing — original draft, Writing — review & editing, Supervision.

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Qualitative assessment in river and phreatic aquifer water in a rural watershed in the Atlantic Forest biome

Comportamento qualitativo da água de rio e aquífero freático de bacia hidrográfica rural do bioma Mata Atlântica

Mateus Nascimento Vieira de Melo[1], *Gustavo Antonio Piazza*[2], *Adilson Pinheiro*[1], *Edson Torres*[1], *Vander Kaufmann*[1]

ABSTRACT

Watersheds have different water compartments (surface, subsurface, and underground) connected by the soil-water interface. In order to be able to relate these compartments, monitoring data are necessary, such as the case of the Ribeirão Concórdia watershed, in Lontras, Santa Catarina (SC). This study aimed to evaluate the behavior and the correlation between rainfall-runoff and phreatic surface levels with chemical species concentrations in surface and groundwaters in a rural watershed. Data of 3 piezometers installed in the hydrographic basin were used: PZ2127, PZ3, and PZMC. The piezometers are equipped with hydrostatic level sensors. A fluviometric station is located adjacent to PZ2127 (near the catchment outlet). Concentrations of anions and carbon forms were analyzed in water samples (river and piezometers) taken every 2-3 weeks, from January 14, 2012, to December 23, 2016, totaling 103 samples. Correlations between daily data were verified using Pearson's correlation coefficient (ρ). The river presented a dilution effect, while the adjacent piezometer had the highest average concentrations of chemical species. Precipitation and chemical species concentration showed no seasonal pattern, with events/peaks throughout the year. Higher concentrations of carbon forms were found in the summer, while lower concentrations were observed in the winter. Positive correlations between concentrations of anions and carbon forms in surface and groundwaters were obtained.

Keywords: hydrographic basin; water quality; surface water; groundwater.

RESUMO

Bacias hidrográficas apresentam diferentes compartimentos de água (superficial, subsuperficial e subterrâneo) que estão ligados pela interface solo-água. Para conseguir relacionar esses compartimentos são necessários dados de monitoramento, como é o caso da bacia hidrográfica do Ribeirão Concórdia, em Lontras (SC). Este estudo avaliou o comportamento e a correlação entre o escoamento fluvial e a elevação da superfície freática, com concentrações de espécies químicas, em águas superficiais e subterrâneas em uma bacia hidrográfica rural. Utilizaram-se dados referentes a três piezômetros instalados na bacia hidrográfica: PZ2127, PZ3 e PZMC. Estes são equipados com sensores de nível hidrostático. Adjacente ao PZ2127 (próximo ao exutório), existe uma estação de monitoramento fluviométrico (R). Amostras de concentrações de ânions e formas de carbono foram coletadas no rio e nos piezômetros em uma frequência de 2–3 semanas, entre 14 de janeiro de 2012 e 23 de dezembro de 2016, totalizando 103 amostras. Correlações de dados diários foram verificadas por meio do coeficiente de correlação de Pearson (ρ). O rio apresentou menores concentrações das espécies químicas analisadas, enquanto o piezômetro adjacente apresentou as maiores concentrações médias dessas espécies. Precipitação e concentração das espécies químicas não exibiram padrão sazonal, com ocorrência de eventos/picos ao longo do ano. Formas de carbono apresentaram maiores concentrações nas coletas no verão e menores no inverno. Obteve-se correlação positiva entre as concentrações de ânions e das formas de carbono da água do rio e dos piezômetros.

Palavras-chave: bacia hidrográfica; qualidade da água; água superficial; água subterrânea.

[1]Fundação Universidade Regional de Blumenau – Blumenau (SC), Brazil.

[2]Secretaria de Desenvolvimento Econômico Sustentável, Governo de Santa Catarina – Florianópolis (SC), Brazil.

Correspondence address: Mateus Nascimento Vieira de Melo – Rua Francisco Ax, 137, ap. 201 – Centro – CEP: 89150-000 – Presidente Getúlio (SC), Brazil. E-mail: mateusnvm@gmail.com

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Introduction

Groundwater management requires an in-depth understanding of hydrological processes. Aquifers, for example, are influenced by meteorological conditions, runoff processes, human interventions, and geological characteristics at different spatial and temporal scales (Winter et al., 1998). The interactions of these water reservoirs play a decisive role in the quality of water bodies, and understanding them can provide information on sources and transport of pollutants in rivers and aquifers in watersheds (Guggenmos et al., 2011; Martinez et al., 2015).

Rural experimental hydrographic basins are environmental research observatories that enable enlightening hydroclimatic processes and the impact of human activities on water resources. Given the ever-expanding Brazilian agribusiness, it is vital to develop agricultural activities strategically, ensuring adequate quality and quantity of water for its various uses. Inadequate land use management and anthropogenic activities degrade aquatic systems, reducing the availability and quality of water resources (Santos et al., 2019). Pollution of these environments in rural areas occurs by contaminants resulting from agricultural activities, specifically pesticide and fertilizer application, and the risk of water contamination is usually associated with rainfall and the consequent transport of these substances (Soares et al., 2020). In this scenario, water quality can become limiting for sustainable development. Therefore, monitoring the qualitative parameters of this resource represents a crucial indicator to formulate public policies and apply control actions (Azevedo et al., 2016). Brazil has an excellent water potential; however, according to Santos and Hernandez (2013), it lacks sufficient quali-quantitative monitoring to support the expansion of knowledge about the dynamics of aquatic systems.

Water quality, where human actions exert great influence, is an increasingly recurrent issue due to the growth in demand, increased pollution, and the reduction of natural areas (Freitas, 2020). Monitoring water quality is a complex activity and requires a large number of resources. In Brazil, a growing number of actions to monitor surface and underground water has been currently observed, which expands the knowledge of the spatiotemporal dynamics of water quality in these reservoirs. Nevertheless, studies dealing with the qualitative behavior of these aquatic systems with a long period of monitoring and high frequency are scarce. For instance, regarding rural watersheds with family farming management, the scientific discussion lacks adequate information for establishing spatiotemporal standards in surface and groundwater quality. Analyses of the qualitative behavior of water from rivers and aquifers were developed by Guggenmos et al. (2011), Martinez et al. (2015), Kumar et al. (2017), Li et al. (2018), and Park et al. (2018). However, these studies generally have short monitoring periods and few samples, which hampers the temporal and exploratory interpretation of chemical species concentrations in water. Monitoring data enable the establishment of water quality indices (WQI) that aim to synthesize monitored parameters providing weights to the most important ones in a given region, helping the general public to interpret the data.

In this study, we investigated the behavior of chemical species concentrations in the interaction between piezometers and rivers, in a rural watershed in the Atlantic Forest biome, southern Brazil, in order to identify patterns and characteristics related to the use and occupation of the local land (small properties).

Material and Methods

Study area

The study was carried out in the Ribeirão Concórdia hydrographic basin, located in Lontras, Santa Catarina, Brazil. The hydrographic basin has its catchment outlet at 27°10’54.19” S latitude and 49°31’37.28” W longitude (Figure 1). It has an area of 30.93 km^2, with approximately half of it occupied by agricultural activities (Piazza et al., 2014). The distribution of land use and occupation is shown in Figure 1. Rural properties have a good distribution along the watershed and are characterized as small and medium-sized properties (Lubitz et al., 2013). In the region, practices of direct planting, minimum cultivation, and conventional planting with soil management are adopted. The main crops produced are maize, beans, irrigated rice, tobacco, tomato, and cabbage. The planted forests are composed of eucalyptus and pine, and the areas destined for pasture are characterized by perennial crops with the constant presence of cattle.

According to Strahler, the climate is subtropical with hot, humid summers and cold, dry winters. The average annual temperature and precipitation are 20°C and 2,000 mm, respectively. The climate is classified as Cfa, with an average temperature in the coldest month below 18°C and an average temperature in the warmest month above 22°C (Alvares et al., 2013). The hydrographic basin presents altitudes that vary between 300 and 900 m in relation to the sea level, and it is found, for the most part, above the Taciba unit (Paleozoic). The head area is located at the Rio Bonito (Paleozoic) unit (Piazza, 2019). The hydrographic basin belongs to the Itararé geological formation group, with intrusive granitic suites. One of its subgroups, located in the lower portion of this formation, is from the Rio do Sul formation, with dark gray shales and argillites. Above them, there are grayish diamictites, with a sandy matrix interspersed with very fine sandstones. These are covered by shales, usually varvites, argillites, rhythmites, and siltstones (EMBRAPA, 2004). The soils are derived from this geological formation and have the following distribution in percentage area:

- Cambisols: 62.2%;
- Argisols: 32.9%;
- Gleisols: 0.9% (Piazza et al., 2014).

Data

Phreatic level

Groundwater level data referring to 3 monitoring piezometers installed in the hydrographic basin were used. The piezometers were installed according to the different uses and occupations of the land, positions relative to the watershed, depths of impermeable soil layers, and distances from the river in order to assess the possible influence of these factors on the phreatic surface elevation and chemical species concentrations in groundwater. PZ2127 and PZ3 are located in pasture areas, while PZMC is located in an area covered by a riparian forest. PZ2127 is located close to the watershed catchment outlet (Figure 1). PZ2127, PZ3, and PZMC have depths of 5.1, 3.8, and 2.6 m and are located 35, 60, and 3 m away from the river, respectively. Their altimetric dimensions are 367, 372, and 433 m, respectively. The piezometers are equipped with hydrostatic level sensors connected to dataloggers, and groundwater levels were recorded every 15 min. The characterization of land use around the piezometers can be seen in Figure 2.

Fluviometric quota

Quota data were obtained from the fluviometric station (R) installed in the cross-section of the river, adjacent to PZ2127. This section features an automatic level sensor with a float-operated axis encoder, which recorded this data at 1-h intervals in a datalogger.

Precipitation

Rainfall series recorded in eight pluviographs (seven tipping-bucket rain gauges and one weighing rain gauge) installed in the hydrographic basin were used. The tipping-bucket and weighing rain gauges are installed at 1.5 m and 0.5 m from the ground surface, respectively. These devices performed readings every 5 min. Data were stored in dataloggers.

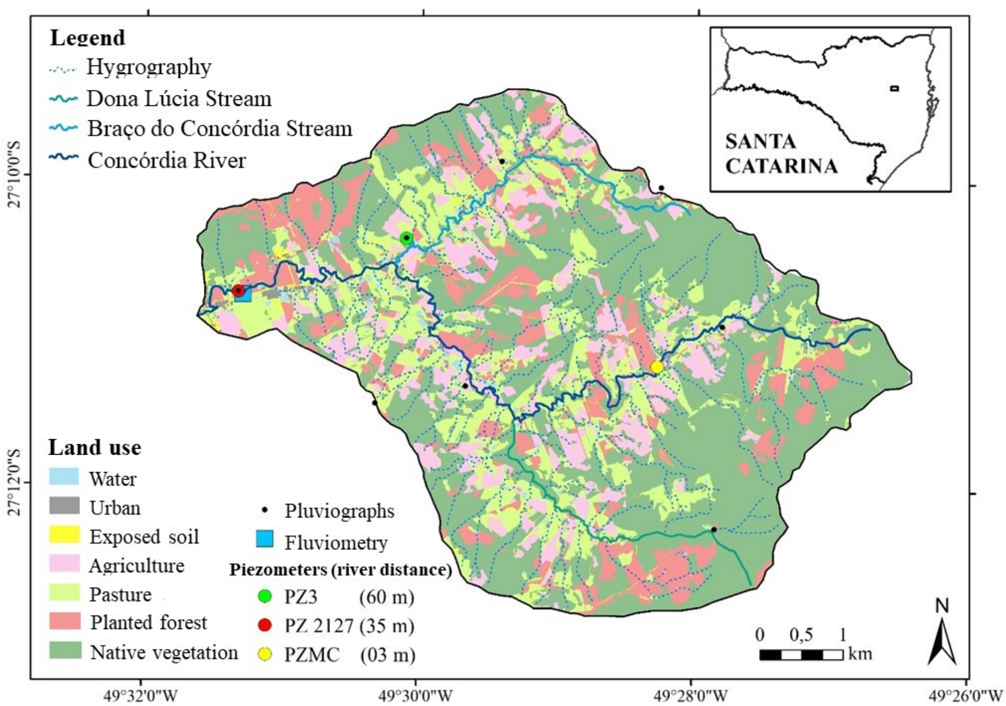

Figure 1 – Location of piezometers and land use and occupation distribution in the Ribeirão Concórdia watershed, Lontras, Santa Catarina, Brazil.

Figure 2 – Characterization of land use around the piezometers.

Chemical species concentrations in water

Chemical species concentrations in surface and groundwater were taken from sampling in the river (in the fluviometry measurement section - R) and piezometers (Figure 1). The collections respected the national standard established by NBR 9898 (ABNT, 1987) and took place every 2-3 weeks, totaling 103 samples. Collections in R were performed manually, and the samples were placed in polyethylene bottles. A syringe connected to a silicone tube was used to collect 100 mL water samples from the piezometers. After suction, the samples were also stored in polyethylene bottles (Figure 3). The first sample of each collection was discarded to clean the vials.

The concentrations of chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}) anions, and total organic carbon (TOC) and inorganic carbon (IC) were determined. The anions were analyzed using the Dionex AG4A ion-exchange chromatograph (DIONEX, 2010), and the carbon forms were quantified using the SHIMADZU TOC - V CPH Carbon Analyzer.

Data analysis

Groundwater levels, fluviometric quotas, precipitation, and chemical species concentrations in the water from January 1, 2012 to December 31, 2016 were used.

Temporal and exploratory analysis

A temporal analysis of monthly precipitation data and chemical species concentrations per compartment was performed, that is, for R, PZ2127, PZ3, and PZMC. An exploratory analysis of concentrations was carried out to understand the data set and significant variations thereof. Arithmetic mean and standard deviation were used. The means were subjected to analysis of variance (ANOVA) and compared using the Tukey test, with a significance level of 5%. Statistical tests were performed using PAST software (version 3.25). Calculations were performed on a monthly basis.

Figure 3 – Collection of water samples in the river using a piezometer.

Correlations

The correlations between phreatic levels and fluviometric quotas, both in daily frequency, with chemical species concentrations, and the correlations between concentrations per compartment were verified using the Pearson correlation coefficient (ρ). Statistical tests were performed using PAST software (version 3.25).

Results and Discussion

Temporal and exploratory analysis

The temporal variations in precipitation and chemical species concentrations in water from the river and piezometers (Figure 4) presented no seasonal pattern, with the occurrence of events/peaks throughout the year. None of the chemical species were correlated with precipitation. Carbon forms showed higher concentrations in summer collections and lower values in those conducted in the winter. Average TOC concentrations were 4.14, 2.85, 1.99, and 3.11 mg L^{-1} for summer, autumn, winter, and spring, respectively. As for CI concentrations, average values were 10.09 mg L^{-1} for the summer, 8.95 mg L^{-1} for the autumn, 7.34 mg L^{-1} for the winter, and 7.97 mg L^{-1} for the spring. According to Nascimento and Barbosa (2005), higher IC concentrations in the summer are related to intense precipitation, which carries a greater flow of particles from the surface to aquifers and rivers. Likewise, Kaufmann et al. (2009) assessed the Ribeirão Concordia watershed and found higher concentrations of IC and TOC in the summer, related to intense rainfall as well. However, higher soil temperature and moisture may also have benefited microbial activity and, consequently, contributed to higher concentrations of CI (Bayer et al., 2012).

The highest chemical species concentration peaks were observed in PZ2127, while the lowest values were found in R. The greater concentrations in PZ2127 can be explained by the larger drainage area, accumulating nutrient input. Feitosa and Manoel Filho (2000) also detected higher concentrations of chemical species near the watershed catchment outlet, justified by the slow characteristic of water movement and accumulation of chemical species in the flow direction. Another trait observed in the monitored watershed was the occurrence of lower chemical species concentrations in the river section compared to the piezometers. This result was expected since in free aquifers or with local recharge, the up and down movements in the unsaturated zone favor rock leaching and the transport of products present on the surface to the interior of the soil, contributing to higher concentrations of nutrients in groundwater (Silva and Migliorini, 2014). Another factor to be considered when explaining the differences in chemical species concentrations is the influence of the riparian zone in regulating the supply of nutrients from the saturated zone of the soil into surface water bodies, acting on nutrient absorption (Martí et al., 2000) and inducing the occurrence of biogeochemical transformations.

Table 1 shows the mean concentrations and standard deviations of chemical species in the river and piezometers. The values followed by the same letter for different compartments do not differ significantly from each other, according to ANOVA and Tukey post-hoc test with a significance level of 5%. For most parameters, river concentrations are statistically similar to those of the PZMC piezometer. On the other hand, the concentrations in piezometers PZ3 and PZ2127 present, for most parameters, statistically different concentrations from those measured in the river, with higher values. The PZMC piezometer located near the surface watercourse is directly influenced by it. The other two piezometers are far from the river. Thereby, their waters may not be affected by the river flow during a flood wave passage. The water quality of these two piezometers is influenced by land use in their contributing area.

Average Cl^- concentrations in the hydrographic basin were below 14.6 mg L^{-1}. Park et al. (2018), in an area with intensive agricultural activity, obtained average concentrations of 98.9 and 297.0 mg L^{-1} in surface water and 623.0 and 464.0 mg L^{-1} in groundwater. In a region with similar characteristics, Li et al. (2018) obtained an average Cl^- concentration of 219.7 mg L^{-1} in groundwater.

Regarding NO_3^- concentration in the Ribeirão Concórdia watershed, values varied from 2.94 to 15.86 mg L^{-1}. In an area of ag-

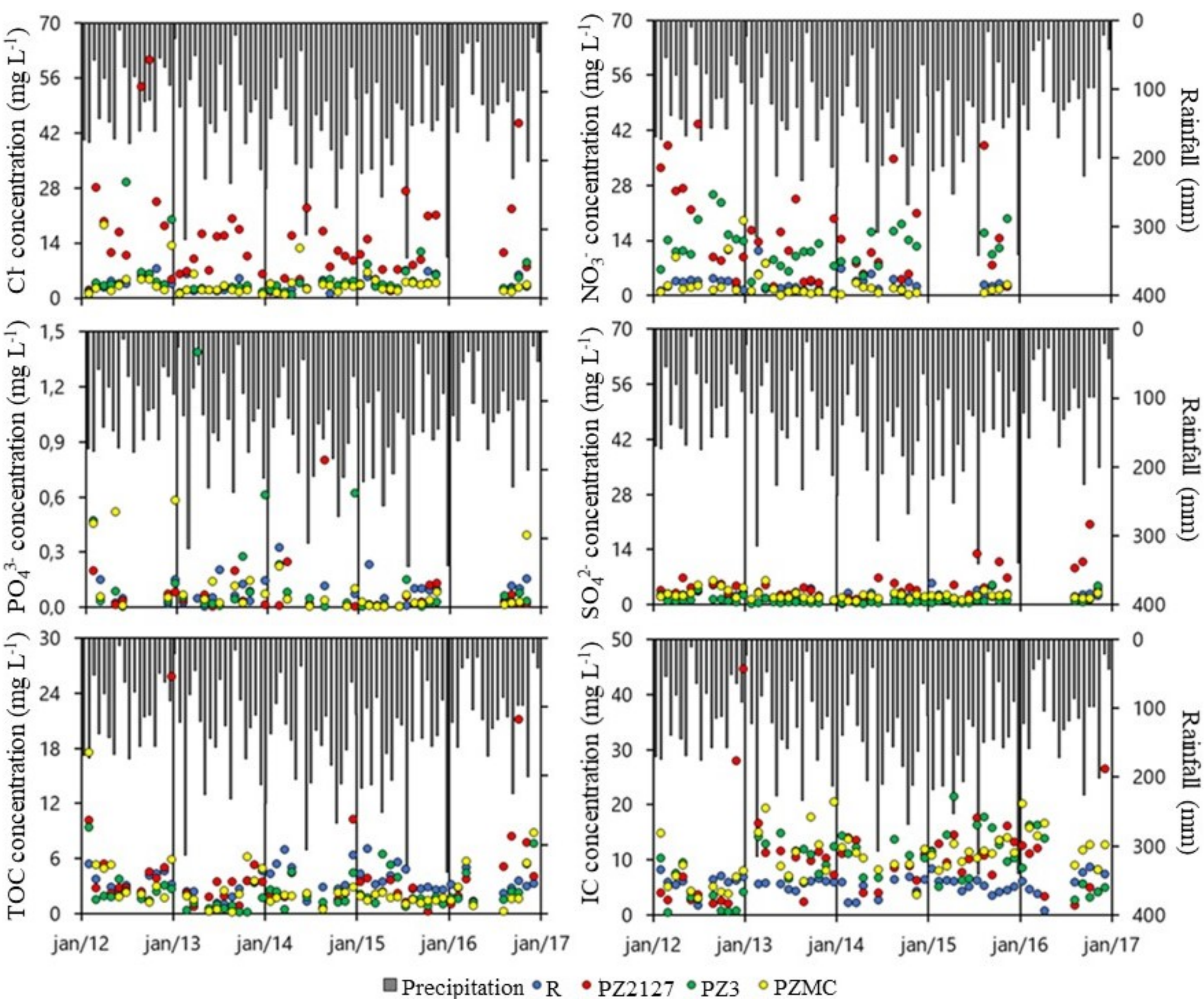

Figure 4 – Temporal variations of precipitation and chemical species concentrations in river water and piezometers.

ricultural intensification, Guggenmos et al. (2011) found average concentrations of NO_3^- around 46.00 mg L^{-1} in groundwater. Park et al. (2018), also in an area intended for agricultural activities, obtained average NO_3^- concentrations of 25.9 and 118.0 mg L^{-1} in surface water, and 575.0 and 265.0 mg L^{-1} in groundwater.

Average concentrations of PO_4^{3-} in the Ribeirão Concordia watershed were below 0.13 mg L^{-1}. Kumar et al. (2017) obtained average PO_4^{3-} concentrations of 4.90 and 4.80 mg L^{-1} in surface and groundwater, respectively.

The average concentrations of SO_4^{2-} did not exceed 4.11 mg L^{-1}. Park et al. (2018) found SO_4^{2-} concentrations of 53.00 and 164.00 mg L^{-1} for surface water, and 127.00 and 110.00 mg L^{-1} for groundwater. Guggenmos et al. (2011) and Li et al. (2018) obtained concentrations of 7.00 and 152.97 mg L^{-1} on average for groundwater, respectively.

The discrepancies between the average concentrations of Cl^-, NO_3^-, PO_4^{3-}, and SO_4^{2-} obtained in this study and those presented by other studies can be explained by the fact that the Ribeirão Concordia watershed has a predominance of extensive agricultural and livestock systems, unlike the other evaluated areas, characterized by the predominance of intensive agricultural activity.

In an overview (surface x underground), it is observed that the surface compartment (river) had lower average concentrations of Cl^- and IC, compared to piezometers, an effect resulting from the regulation of the riparian zone and the transport of products from the surface and interior of the soil to the groundwater, as described above. The same results were found by Piazza (2019) at the same sites. The location factor of the piezometers suggests that it influences the concentrations of anions and carbon forms. The installation of piezometers in places with different total depth and unsaturated soil zones, distances from the river and watershed catchment outlet, and land uses proved essential for verifying different water quality behaviors among these sites and in relation to the river water. PZ2127 had the highest average concentrations of chemical species, except for PO_4^{3-}, also obtained by Piazza (2019). This result may be due to the larger drainage area of PZ2127 compared to other piezometers and because groundwater increases the concentrations of dissolved substances along its path. The greater depth of PZ2127 may also have contributed to greater nutrient dissolution along the water path (Silva and Migliorini, 2014). Piazza (2019) did not find statistically significant differences between the concentrations of carbon forms in river water and piezometers, unlike this study.

Table 1 – Mean concentrations and standard deviations of chemical species in river water and piezometers (mg L^{-1}).

Chemical species	Measurement	Compartments			
		R	PZ2127	PZ3	PZMC
Cl^-	Mean	3.3a	14.6b	4.5a	3.5a
	Standard deviation	1,7	12.2	4.8	3.2
NO_3^-	Mean	2.9a	15.9b	11.7b	2.6a
	Standard deviation	1,9	12.2	5.4	3.8
PO_4^{3-}	Mean	0.091a	0.131a	0.098a	0.072a
	Standard deviation	0.097	0.267	0.151	0.140
SO_4^{2-}	Mean	2.189a	4.111b	1.006c	2.359a
	Standard deviation	1.046	3.589	1.035	1.206
TOC	Mean	3.415ab	3.943a	2.294b	2.711ab
	Standard deviation	1.481	4.562	1.911	2.776
IC	Mean	5.451a	10.473b	9.803b	8.973b
	Standard deviation	1.662	4.262	7.511	5.190

What was observed with the analysis by compartment is in line with what was found in areas with agricultural activities by Vega et al. (1998) in north-central Spain, by Palácio et al. (2008) in the state of Ceará, and by Piazza (2019) at the same site of this study. The dynamics of Cl^-, NO_3^-, and SO_4^{2-} concentrations were related to the location and human intervention around the piezometer. For example, the proximity of residences in PZ2127 (Figure 2) justifies higher average Cl^-, NO_3^-, and SO_4^{2-} concentrations due to the possibility of contamination via septic tanks and infiltration into surface areas of animal husbandry. The location of the piezometer can strongly influence the geochemical behavior of water. Observing the standard deviations, it can be seen that Cl^-, NO_3^-, and IC presented greater data variability around the averages, which suggests the possible association of the concentrations of these chemical species with surrounding anthropogenic factors through precipitation.

Despite the different lad uses, the studied hydrographic basin presents low concentrations of the analyzed chemical species. The little significant impact on the quality of surface and underground water can be explained by the characteristics of the properties (small and medium) and the agricultural activities carried out in them (low to medium intensity). Nevertheless, it is worth highlighting the accumulation of chemical species in the direction of the hydrographic basin drainage, that is, close to its catchment outlet. According to Fernandes et al. (2014), solute concentrations tend to increase with increasing distance from the preserved forest sampling point, similar to what is observed in the studied hydrographic basin.

Moreover, it is worth highlighting the role of vegetation in physical, chemical, and biological processes in the surface drainage system. The occurrence of lower concentrations in surface water than in groundwater demonstrates that the effects of nutrient absorption by channel vegetation, sedimentation of chemical species adhered to sediments, biochemical transformations of nitrogen, carbon, and phosphorus compounds, reduce the mass in the surface drainage system. The river channel works as a reactor to reduce the load of chemical species transported by the river flow, which is especially important for minimal flows. For flood wave runoff conditions, the surface runoff can generate dilution of chemical species introduced by the underground runoff.

Correlations

Figure 5 shows the Pearson correlation coefficients (ρ) between the fluviometric quota and phreatic levels with chemical species concentrations and the correlation coefficients per compartment. The blue or red circles represent positive or negative correlations, and the size of the circles indicates how close they are to the maximum variation (1), according to a significance of $p < 0.05$ (gray background).

Specific behaviors related to water quality were verified, considering the physiography of the watershed, soil type and texture, hydroclimatological variables, land use, and agricultural practices.

In the river, significant correlations were obtained between total carbon concentration (TC) and TOC (0.73), IC and TC (0.67), SO_4^{2-} and Cl^- (0.49), PO_4^{3-} and NO_3^- (0 .24), TC and fluviometric quota (-0.23), and IC and NO_3^- (-0.29). The significant negative correlation between CT and the fluviometric level is considered weak, but it can be explained by the increase in the river flow and the consequent dilution effect, described by Torres et al. (2011). The negative correlation between IC and NO_3^-, although weak, indicates the different behaviors of carbon forms and NO_3^-. According to Bruland et al. (2008), NO_3^- is related to fertilization and soil prepa-

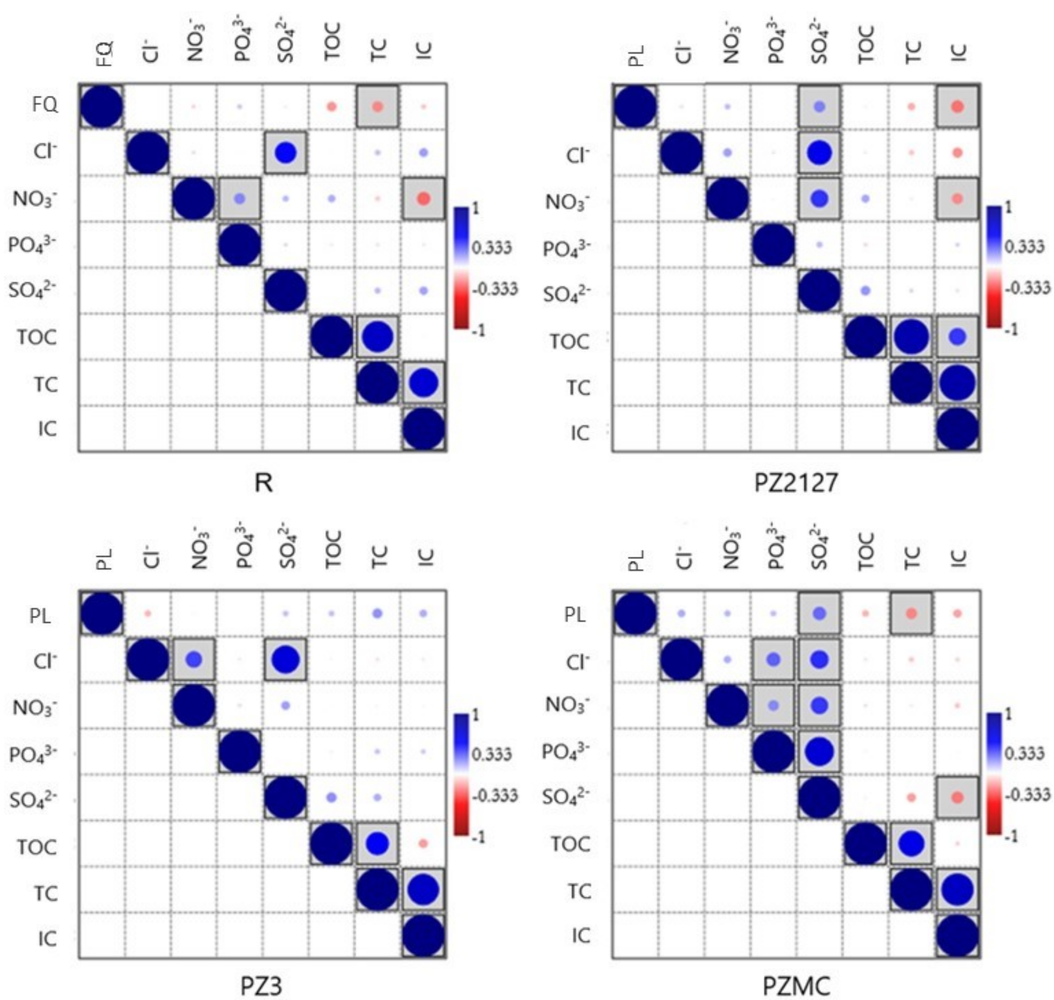

Figure 5 – Pearson correlation coefficients (ρ) between fluviometric quota (FQ), phreatic level (PL), and chemical species concentrations in the river and piezometer water.

ration, that is, the effect of land use. On the other hand, the concentrations of carbon forms can be influenced by biological activity, temperature, edaphic factors, vegetation cover, and terrain slope. The significant positive correlations between TOC and CI with CT, strong and moderate, respectively, are explained by the fact that these two carbon forms compose CT, which was previously found by Kaufmann et al. (2009) in the Ribeirão Concórdia hydrographic basin. The correlation between TOC and CI with CT occurred for all compartments, except for PZ2127, which also showed a TOC/CI correlation.

In PZ2127, significant correlations were obtained between the concentrations of SO_4^{2-} and phreatic level (0.25), SO_4^{2-} and Cl^- (0.57), SO_4^{2-} and NO_3^- (0.40), TC and TOC (0.82), IC and phreatic level (-0.27), IC and NO_3^- (-0.23), IC and TOC (0.39), and IC and TC (0.85). The significant positive correlation between SO_4^{2-} and the phreatic level, although weak, may be associated with the infiltration of this compound into the soil during periods of higher precipitation. SO_4^{2-} results from the leaching of sulfated compounds; it is also present in precipitation, decomposition of organic matter, and sulfated fertilizers (Feitosa and Manoel Filho, 2000; Midões et al., 2001). Considering the physiographic characteristic of the site, the lower slope and the soil texture, PZ2127 may be favoring the infiltration of SO_4^{2-}. The moderately significant positive correlation between SO_4^{2-} and NO_3^- may indicate the impact of domestic sewage discharges or the misuse of fertilizers, factors that cause the input of these chemical species (Moura et al., 2010; Esteves, 2011). A significant negative correlation between IC and the phreatic level was also found by Torres et al. (2011).

In PZ3, significant correlations were obtained between the concentrations of NO_3^- and Cl^- (0.37), SO_4^{2-} and Cl^- (0.65), TC and TOC (0.53), and IC and TC (0.73). The moderately significant positive correlation between NO_3^- and Cl^- can be explained by the high solubility and stability of these chemical species in groundwater and by the distance between this piezometer and the river, which gives a longer permanence for these chemical water constituents (Silva and Borges, 2009). Another factor that may explain this correlation is pasture fertilization in this location (manure and chemical fertilization).

In PZMC, significant correlations were obtained between the concentrations of PO_4^{3-} and Cl^- (0.21), PO_4^{3-} and NO_3^- (0.22), SO_4^{2-} and the phreatic level (0.28), SO_4^{2-} and Cl^- (0.30, SO_4^{2-} and NO_3^- (0.38), SO_4^{2-} and PO_4^{3-} (0.67), TC and the phreatic level (-0.24), TC and TOC (0.59), IC and SO_4^{2-} (-0.26), and IC and TC (0.75). The greatest significant positive correlations between anions occurred in this compartment, the place with the shortest distance from the watercourse (soil x water interface). As was observed between TC and the fluviometric quota, a weak significant negative correlation was identified between TC and the phreatic level in PZMC, also resulting from the dilution effect, since the elevation of levels indicates a greater volume of water in this reservoir (Torres et al., 2011).

The significant positive correlations between SO_4^{2-}, Cl^-, and NO_3^- in the PZ2127 and PZMC piezometers can be explained by the common origin of these anions, possibly agricultural inputs (Fernandes et al., 2014). Especially in PZMC, the correlation between SO_4^{2-} and NO_3^- can originate from the occurrence of nitrification and denitrification processes, once that a strip of riparian forest protects the surroundings of the site.

The temporal and exploratory analysis and the correlations between chemical species concentrations carried out in this study allow a better understanding of the variations in groundwater quality in points with different characteristics of the hydrographic basin and with different factors that influence them. In addition, comparison with surface water concentrations proved to be of great value for understanding the different qualitative behaviors of these compartments and expanding knowledge about them.

Conclusions

The results presented contribute to understanding processes related to water quality at the surface, subsurface, and underground interfaces (soil x water interface). However, the sources of contamination still lack a concrete identification since land uses and their impacts on these reservoirs did not have a spatial pattern. In addition, seasonality was not identified in the variations of quality peaks, which occurred throughout the year.

The river had lower chemical species concentrations than groundwater. Effects of nutrient absorption by vegetation in the surface drainage system, adsorption to particles and plants, and biochemical transformations contribute to reducing the drained mass. Higher average chemical species concentrations were found in PZ2127 (near the catchment outlet and R).

The present study, combining a surface water sampling point and 3 groundwater sampling points, allowed a comprehensive assessment of the system's characteristics, integrating qualitative and quantitative water information (fluviometric quota and phreatic level).

It is recommended to continue the intensive monitoring carried out in the hydrographic basin, in addition to expanding the number of monitoring points for surface and underground water in order to broaden knowledge of the spatial and seasonal dynamics of chemical species and the relationships between them and hydroclimatological variables. Furthermore, monitoring the phreatic levels in each of these piezometers and the fluviometric levels could provide information on the underground discharge to the river with regard to the amount of water and nutrient input.

Contribution of authors:

Melo, M.N.V.: Conceptualization, Methodology, Data Curation, Formal Analysis, Writing — Review and Editing. Piazza, G.A.: Data Curation, Formal Analysis, Writing — Review and Editing. Pinheiro, A.: Conceptualization, Methodology, Writing — Review and Editing, Supervision, Project Administration. Torres, E.: Data Curation, Formal Analysis. Kaufmann, V.: Data Curation, Formal Analysis; Supervision.

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Analysis of average annual temperatures and rainfall in southern region of the state of Rio Grande do Sul, Brazil

Análise anual de temperatura média e precipitação para a região sul do Rio Grande do Sul

Iulli Pitone Cardoso[1], *Tirzah Moreira Siqueira*[1], *Luis Carlos Timm*[1], *Aryane Araujo Rodrigues*[1], *André Becker Nunes*[1]

ABSTRACT

This work aimed to analyze the average temperature and rainfall in the Southern and Steppe regions of the State of Rio Grande do Sul, Brazil, obtained by three global climate models regionalized by the Eta model (CANESM2, HADGEM2-ES and MIROC5) for the historical period, and two future climate scenarios (RCP 4.5 and RCP 8.5), subdivided into three periods: F1 (2006-2040), F2 (2041-2070), and F3 (2071-2099). The analysis was conducted by applying the trend tests Mann Kendall's, Sen's Slope and Pettitt's to the dataset. The study noted an increase in temperature, and that the highest temperatures will occur at the end of the century. For the three climate models, temperatures will be milder in the RCP 4.5 scenario, mostly, when compared to the RCP 8.5. For those scenarios, a significant increase up to 0.95°C/year was observed in the temperature of all series, with the years of change in the mean values occurring between 2048 and 2060. The projections also suggest that there may be an increase in the average accumulated rainfall in the future periods analyzed, with exception of the result found with CANESM2 model at the RCP 8.5 scenario, which showed a significant decrease of annual rainfall in all series, ranging approximately from -3,1 to -6,6 mm/year. Those significant changes in mean of the rainfall series are expected for the late 2070's. With exception of this result, most cities and models indicate an increase in rainfall regimes, with clear variations between models and scenarios.

Keywords: climate models; RCP 4.5 and RCP 8.5; climate changes; ETA regional model; nonparametric trend tests.

RESUMO

Este trabalho teve como objetivo analisar a temperatura média e a precipitação da região sul e Campanha do estado do Rio Grande do Sul, obtidas por três modelos climáticos globais regionalizados pelo modelo ETA (CANESM2, HADGEM2-ES e MIROC5) para o período histórico e dois cenários climáticos futuros, RCP 4.5 e RCP 8.5, subdivididos em três períodos: F1 (2006–2040), F2 (2041–2070) e F3 (2071–2099). A análise foi conduzida aplicando-se os testes de tendência Mann-Kendall, *Sen's Slope* e Pettitt. Foi observado o aumento na temperatura média; as maiores temperaturas ocorrerão no final do século. Sob os três modelos, as temperaturas serão mais amenas no cenário RCP 4.5 quando comparadas às do cenário RCP 8.5, no geral. Nesses cenários foram identificadas tendências de aumento na temperatura de até 0,95°C/ano em todas as séries, com mudança abrupta entre 2048 e 2060. As projeções também indicam aumento na precipitação média acumulada nos períodos futuros, com exceção dos resultados obtidos com o CANESM2 sob o cenário 8.5, cuja precipitação demonstrou diminuição significativa em todas as séries, variando entre -3 e -6 mm/ano. Ademais desse resultado, grande parte dos municípios e modelos indica o aumento nos regimes pluviométricos, com claras variações entre modelos e cenários.

Palavras-chave: modelos climáticos; RCP 4.5 e 8.5; mudanças climáticas; modelo regional ETA; testes de tendência não paramétricos.

[1]Universidade Federal de Pelotas – Pelotas (RS), Brazil.

Correspondence address: Iulli Pitone Cardoso – Programa de Pós-Graduação em Ciências Ambientais, Centro de Engenharias, Universidade Federal de Pelotas – Rua Benjamin Constant, 989, Sala 203 – Centro – CEP: 96010-450 – Pelotas (RS), Brazil. E-mail: iulli.pitone@gmail.com

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Introduction

Climate variability can change the economic and social dynamics of a population (Gomes Junior and Ely, 2021), since it is closely linked to power generation, agricultural activities, tourism and, even if indirectly, to the entire productive sector. Climate changes can be perceived through variations that occur over time, such as the increase in the air temperature, strong storms, floods, among others (Queiroga et al., 2022).

Due to the climate changes, it is reported that this may result in more extreme events occurring around the world (Yuan et al., 2017), so the importance of researches like this on this topic can be highlighted, especially at tropical regions, where rainfall events have greater intensity and, consequently, potential to flooding (Oliveira, 2019). Regarding extreme weather events, there is a high occurrence of rainfall extremes that affect the southern and steppe region of the state of Rio Grande do Sul (RS), in the Southern of Brazil. For example, Kulman et al. (2014) assessed the occurrence of drought in the RS in the period of 1981 to 2011, and concluded that there were 22 occurrences of drought in the municipality of Bagé, in Steppe region of RS, being considered the region with the highest recurrence of drought events. Brondani et al. (2013), in a study about the occurrence of droughts and water supply problems in the municipality of Bagé, concluded that the city residents of Bagé have noticed the existence of drought in the municipality at least in the last 25 years, which has caused lack of water for public supply. According to Fernandes et al. (2021), the 2019/2020 drought event occurred in the first quarter of 2020 with great intensity and expansion, as we can see through the impacts caused on the population in the municipality of Pelotas, during the summer of 2019/2020. The Santa Bárbara Dam, mainly responsible for supplying the municipality, reached the historical level of retreat, being 4,40 meters below the normal level since its construction (Diário Popular, 2021; Silveira, 2020). In addition, drought events have frequently occurred in different regions of the RS along the recent decades, which have directly affected agricultural activities and, consequently, the gross domestic product in the RS (Braz et al., 2017).

As mentioned by Quesada-Montano et al. (2018), the occurrence and magnitude of droughts and floods have increased in many locations in the world, causing, as a consequence thereof, impacts related to the environment, society and economy (Winsemius et al., 2018). Thereby, not only drought events have occurred in the RS, but also flood events have been more frequently observed. Based on the flooding records, Pereira and Nunes (2018) separated the events of intense precipitation into “cases of attention” and “cases of alert” and both showed a positive trend in Pelotas in the period (1964-2013).

According to Nedel et al. (2012), the climate in the RS state suffers interference from extreme weather events because it is influenced by atmospheric systems that favor the occurrence of some natural disasters, such as droughts and floods. There are scientific evidences that the El Niño-Southern Oscillation (ENSO) phenomenon has high interference on the climatic anomalous rainfall in the RS state (Rao and Hada, 1990; Grimm et al., 1998; Britto et al., 2008), and despite some monthly variation, in general, the periods of El Niño (La Niña) are associated with precipitation above (below) the normal in RS (Grimm, 2009).

According to Miguel (2017), climate models are computational tools applied to meteorology and climate sciences, to carry out studies about the changes in atmospheric phenomena, and allowing researchers to simulate the past, the present climate, and the future climatic variability and its changes and projections for the globe. For example, Ongoma et al. (2018) investigated future changes in temperature and rainfall over equatorial east Africa by applying trend tests on a dataset obtained by CMIP5 multimodel ensemble, considering the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios, and the results showed a significant increase in both variables until the end of the century, especially in 1-day and 5-day events of rainfall.

To explicitly simulate the smaller scales controlled by local aspects it is necessary to refine the grid of general circulation climate models, which can be done with the use of regional climate modeling (Marengo et al., 2010; Chou et al., 2012). Many studies of regional climate modeling simulating future scenarios for South America can be found. Chou et al. (2014a; 2014b) assessed climate change in South America according to two global climate models downscaled by the Eta model, and they found, in general, that the climate change response of the Eta simulations nested in HADGEM2-ES is larger than the Eta nested in MIROC5. Using the same regional model, Dereczynski et al. (2020) found that simulated trends are compared to observed trends using extreme temperatures and precipitation indices for South America. Some of these specifically address RS. Cera and Ferraz (2015) used the RegCM3 model and found that future climate data (2070-2086) maintained the same precipitation trend as the present climate for southern RS. Tejadas et al. (2016) employed an optimistic and pessimistic scenario according to IPCC AR4 (the Fourth Assessment Report of the Intergovernmental Panel on Climate Change) and found anncreasee in the streamflow at the Mangueira lake watershed, in the south of RS, between 2030-2070.

Silva et al. (2020) analyzed the future scenarios of the Brazilian hydrographic regions (HR) according to different regional climate models. RS is inserted in two hydrographic regions, Uruguay to the west and South Atlantic to the east. The results show that Uruguay HR will present smaller increase in temperature in relation to the present climate than the South Atlantic HR. As for the precipitation, the authors found no significant differences in both RH with respect to the present climate.

The southern half of Rio Grande do Sul has agriculture and livestock as the main base of its economy, the first being linked to the climatic conditions of the region, as this is a fundamental factor for the proper development of crops, thus ensuring good results (Radin and Matzenauer, 2016).

Therefore, the purpose of this study was to analyze the average annual temperature and the annual rainfall data generated by three general circulation models regionalized by using the Eta model for the Southern and the Steppe regions of the state of Rio Grande do Sul. Further, anomaly trends were also assessed for the rainfall annual data sets.

Material And Methods

Study area

The state of Rio Grande do Sul is located in the southern region of Brazil (Figure 1). The state is divided into nine functional planning regions and the two regions under study account for a total population of 1,103,276 inhabitants (FEE, 2015). The climate of Rio Grande do Sul is classified as Humid Mesothermal, being influenced by the polar air masses and the Tropical Continental and Atlantic zones, where the summers are hot and the winters rigorous (SEPLAG, 2020).

Projeta data

Numerical daily data on rainfall and monthly averaged air temperature are generated by the Center for Weather Forecast and Climate Studies of the National Institute for Space Research (CPTEC/INPE) and posted on the PROJETA (Climate Change Projections for South America Regionalized by the Eta Model) Platform (Chou et al., 2014a, 2014b; Lyra et al., 2018) (available at: https://projeta.cptec.inpe.br), with a 20-km resolution grid.

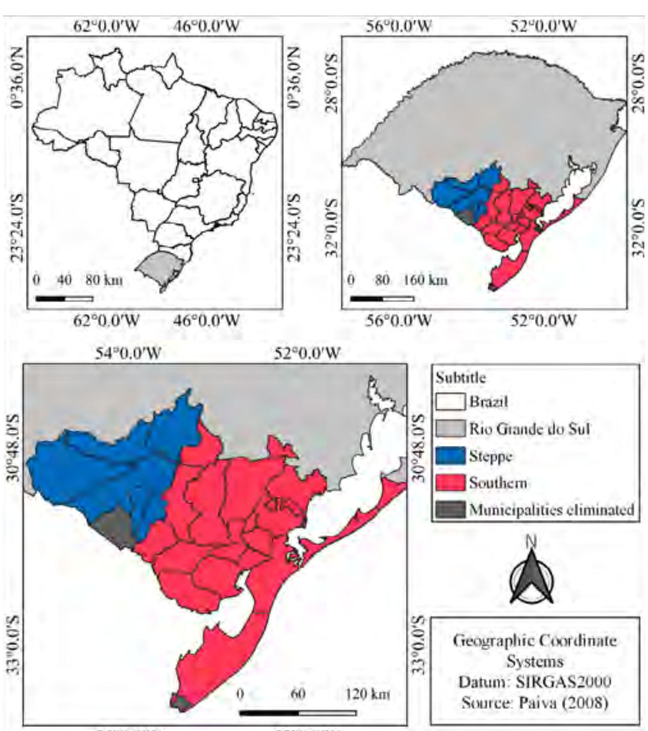

Figure 1 – Map of Rio Grande do Sul, and of the Southern and Steppe regions.
Source: elaborated by the authors.

According to Moura et al. (2010), ETA is a mesoscale model of primitive equations, and its version that runs on CPTEC/INPE is hydrostatic, with 28 vertical layers covering practically all South America. The ETA model was developed by the University of Belgrade together with the Institute of Hydrometeorology of Yugoslavia (Vieira et al., 2015). The PROJETA platform, on the other hand, aims to automate the data of climate projections from the ETA model, offering a simple platform with quick results to requests made by users, thus reducing waiting time (Hölbig et al., 2018).

Series of three general circulation models: CANESM2 (Arora et al., 2011; Chylek et al., 2011), HADGEM2-ES (Martin et al., 2011), and MIROC5 (Watanabe et al., 2010) were regionalized according to the Eta model (Mesinger et al., 2012), for the base period, which comprises the years from 1961 to 2005, and for the projections of two future climate scenarios, RCP (Representative Concentration Pathways) (Van Vuuren et al., 2011) 4.5 and 8.5 (optimistic and pessimistic scenarios, respectively), which cover the years from 2006 to 2099. For better understanding, future scenarios have been subdivided into F1 (2006 to 2040), F2 (2041 to 2070), and F3 (2071 to 2099). Projections were obtained by city, totaling 27 cities, part of the Steppe and Southern regions. The analysis by cities is useful because it meets the needs of decision makers in each municipality, as pointed out in Nunes and Silva (2013) and Pereira and Nunes (2018). The coordinates of the three models used to download each one can be seen in Figure 2.

Annual analysis of average temperature and total rainfall

For the analysis of the annual numerical data of rainfall and average temperature, the annual averages for each model were calculated, considering the base period, as well as the future periods for climate scenarios RCP 4.5 and RCP 8.5. Thus, the annual averages of the base period were compared with the annual averages of future projections for each city.

To detect trends in these variables, considering all series, Mann-Kendall and Sen's Slope nonparametric trend tests were applied. The Mann-Kendall (MK) test (Mann and Whitney, 1947; Kendall, 1975) is widely used to detect time trends in hydrometeorological series (Zamani et al., 2017), while Sen's Slope (SS) test (Sen, 1968) provides the magnitude of the trend, when it is statistically significant.

The Pettitt test (Pettitt, 1979) is a nonparametric homogeneity test used to identify a significant turning point in the series of a variable. It verifies if two observations belong to the same population, locating the point of sudden change in its mean. This test is widely used, for example, in studies carried out by Lima et al. (2021) and Ribeiro et al. (2021).

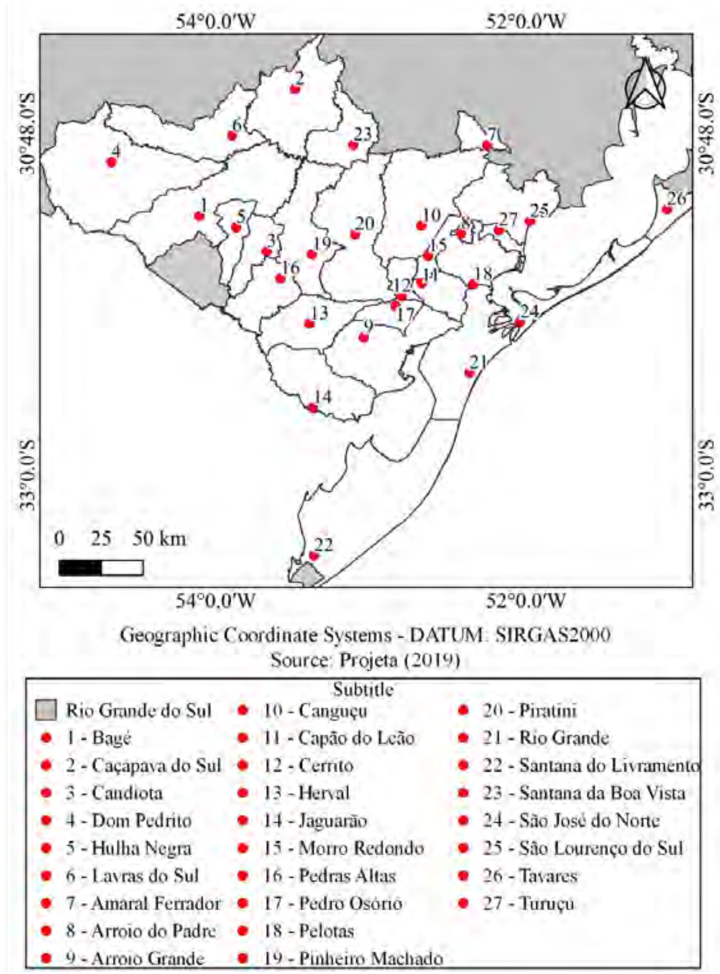

Figure 2 – Points of the climate models in each city in the study area.
Source: elaborated by the authors.

Anomalies

The anomalies of a variable are usually positive or negative departures from the normal climatology mean for a season and study area (Fazel-Rastgar, 2020). Thus, the average annual value of each future (F1, F2 and F3) was considered for each model regionalized by the Eta model for scenarios RCP 4.5 and RCP 8.5, and also for the base period (Lopes et al., 2021).

Results and Discussion

Analysis of the average temperatures of the southern and steppe regions of RS

The results of the trend tests are shown in Table 1. In general, the application of the MK test to the base period series indicated that, for the CANESM2-ETA and HADGEM2-ES-ETA models, the series of all cities show a significant trend of increasing average annual temperatures, with the exception of Tavares for the HADGEM2-ES-ETA model. This partially agrees with Sansigolo and Kayano (2010), who, considering the average of data observed over the entire RS, found a non-significant trend (1960-2006) for the maximum temperature, but a significant positive trend for the minimum temperature. The IPPC AR5 (IPCC, 2013) also indicates a positive trend for the 1901-2012 period. Conversely, the MIROC5-ETA model did not predict a significant trend for any city for the base period. For future scenarios RCP 4.5 and 8.5, all models indicate an average annual temperature increase trend.

In the temperature analysis for the Steppe region, in the RCP 4.5 and 8.5 scenarios, the CANESM2-ETA (Figure 3A), HADGEM2-ES-3TA (Figure 3B) and MIROC5-ETA (Figure 3C) models indicate a trend of temperature increase average for future periods for both scenarios, with scenario RCP 8.5 presenting higher values when compared to RCP 4.5. For the RCP 4.5 scenario, the MK test indicated a significant trend of average temperature increase for the MIROC5-ETA model, which was also observed for

Table 1 – Results of Mann-Kendall, Sen's Slope and Pettitt nonparametric tests applied to the series of average annual temperatures for the cities in the Steppe and Southern regions of RS.

Scenario	Mann-Kendall's test	Sen's Slope test	Pettitt's test	
	Significant temporal trend[1]	Magnitude of the trend[2] (min. – max.)	No. of series	Year(s) (Changing point)[1]
	CANESM2-ETA Model			
Current (Base)	In all series	0.0163 – 0.02141	18	1976; 1983.
RCP 4.5	In all series	0.0206 – 0.02231	27	2055; 2056; 2057.
RCP 8.5	In all series	0.0351 – 0.95312	27	2048; 2049; 2050
	HADGEM2-ES-ETA Model			
Current (Base)	In all series, except for Tavares	0.01422 – 0.0256	16	1968; 1972; 1973; 1984
RCP 4.5	In all series	0.01305 – 0.02140	27	2056; 2058
RCP 8.5	In all series	0.01473 – 0.04415	27	2048; 2052; 2054; 2058.
	MIROC5-ETA Model			
Current (Base)	None of the series	-	-	-
RCP 4.5	In all series	0.0096 – 0.0113	27	2036; 2054; 2057.
RCP 8.5	In all series	0.01875 – 0.0526	27	2044; 2048; 2049; 2057.

[1]at 5% significance level; [2]°C.year^{-1}.
Source: elaborated by the authors.

the RCP 8.5 scenario, but it is smaller when compared to the other models for the same scenario, as observed by Chou (2014b), where the MIROC5 model presented lower values when compared to HADGEM2-ES.

The analysis of annual average temperatures for the RCPs 4.5 and 8.5 scenarios of the CANESM2-ETA (Figure 3D), HADGEM2-ES-ETA (Figure 3E) and MIROC5-ETA (Figure 3F) models for the southern region indicate an increased temperature trend by the end of the century. For the RCP4.5 scenario, the CANESM2-ETA model presents values above 20°C, this analysis being very similar to that observed for the same scenario and model in the Steppe region, where the same trend was observed by Anjos et al. (2018), who used the same models in an analysis for the municipality of Pelotas, located in the southern region. The MK test results were the same for the municipalities in this region. The HADGEM2-ES-ETA model for the two scenarios, when compared to the others, has a lower average tendency of increase when compared to the others. As for the MIROC5-ETA model, the MK test revealed that the rising trends are significant for the Southern region in both future climate scenarios.

The average temperature results observed for the Southern and Steppe regions for the two future scenarios corroborate Bravo et al. (2011), who, when analyzing the projections of 20 Global Climate Models (GCM) for AR4 considering two futures (2030 and 2070) and two scenarios — A2 (more pessimistic) and B2 (more optimistic) — for the Taim region (Santa Vitória do Palmar and Rio Grande), found projections that suggest an increase in temperature for all the months of the years analyzed, but with discrepancy between the results of the models used.

Therefore, studies covering the Southern and Steppe regions, and involving Rio Grande do Sul as a whole, agree with these results, indicating a growing increase in temperature, from 1 to 3°C, on average, until the end of this century. The results of the IPCC AR5 indicate positive trends of this order of magnitude over the studied region (Collins et al., 2013).

Analysis of annual rainfall in the steppe and southern regions

The results of the trend tests are shown in Table 2. In general, the MK test applied to the base period series indicated that the CANESM2-ETA and HADGEM2-ES-ETA models found that no city had a significant trend to increase or decrease total annual rainfall.

This, in general, is consistent with the results of the IPCC's AR5 for 1951-2010 (Hartmann et al., 2013). For 1960-2006 over the entire RS, Sansigolo and Kayano (2010) also did not find any significant trend in annual total numbers of observed precipitation. Cera and Ferraz (2015) analyzed the precipitation trend (1982-2006) of observed data and the data simulated by the RegCM3 model, both at grid points, and over the study region a spatially heterogeneous behavior was observed, with most of the points having a positive trend (with or without statis-

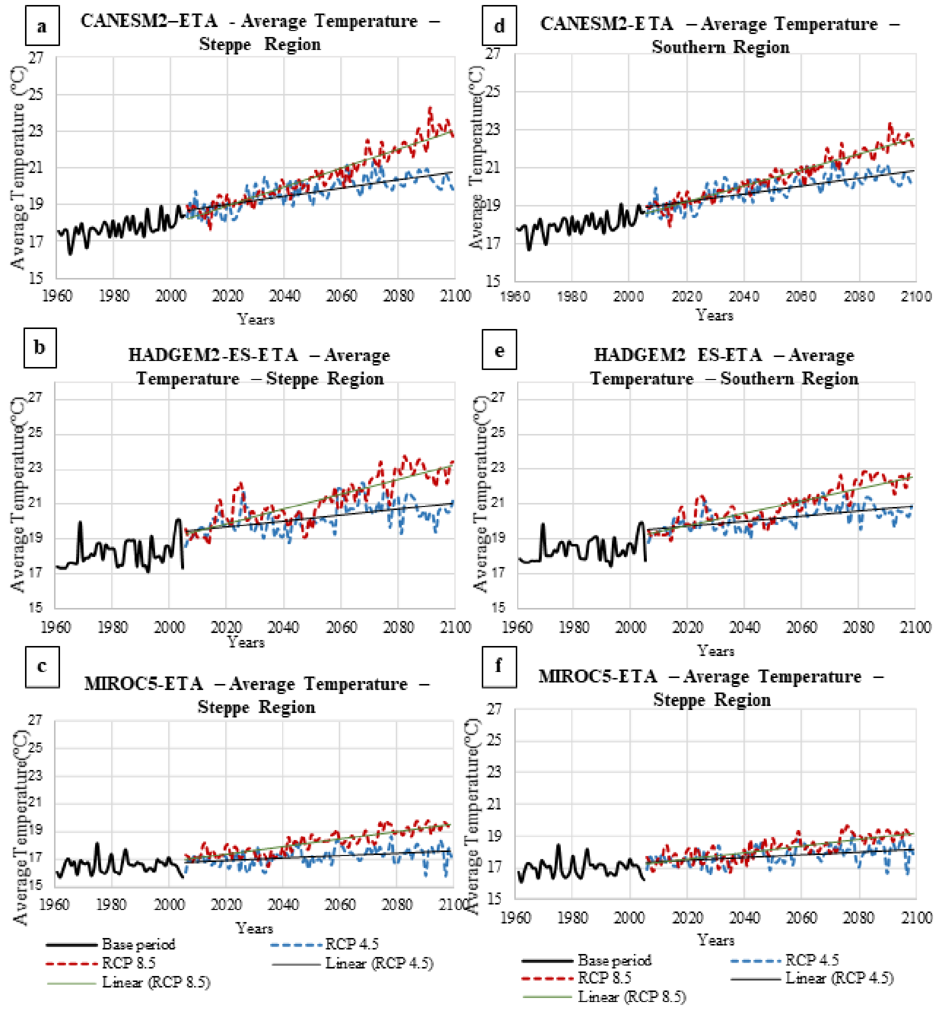

Figure 3 – Annual average temperature for base and future periods (F1, F2 and F3) for scenarios RCP 4.5 and RCP 8.5 for: (A) CANESM2-ETA model for Steppe region. (B) HADGEM2-ES-ETA model for Steppe region. (C) MIROC5-ETA model for Steppe region. (d) CANESM2-ETA model for the Southern region. (E) HADGEM2-ES-ETA model for the Southern region. (F) MIROC5-ETA model for the Southern region.
Source: elaborated by the authors.

tical significance) and some points in the Southern region of RS having a negative trend.

The simulated data, on the other hand, showed positive trends with significance between 90 and 99.9%. Salviano et al. (2016) used grid points data from CRU (Climatic Research Unit) and identified a significant positive trend (1961-2011) in the studied region only in three months (February, April and May).

Caballero et al. (2018) analyzed data in the city of Pelotas, on 1982-2015, and also found no significant trend in annual total figures. The MIROC5-ETA model, on the other hand, found a significant trend for both regions for the base period. For future scenario of RCP 4.5, few cities (CANESM2-ETA and HADGEM2-ES-ETA) or none (MIROC5-ETA) showed a trend in the series. For the RCP 8.5 scenario, the series of all cities indicate a trend towards increase in total annual rainfall, except for the city of Tavares (HADGEM2-ES-ETA), which may have occurred due to its geographical position, and may thus suffer interference from local circulations, more difficult to be detected by climate models.

The results of the SS test (Table 2) indicate the magnitudes of the significant trends of total annual rainfall for the base period, ranging from 4.82 to 9.32 mm/year for the MIROC5-ETA model. For cities that showed trends for the RCP 4.5 scenario, the magnitudes ranged from 2.079 to 3.01 mm/year. For the RCP 8.5 scenario, they ranged from -6.632 to 3.68 mm/year. The RCP 8.5 scenario of the IPCC AR5 over the study region shows a positive trend but without 90% agreement between the models for the periods 2046-2065 and 2081-2100 (Collins et al., 2013). The results of the Pettitt's test show that, for the base period, the MIROC5-ETA model could detect the trend changing point

Table 2 – Results of Mann-Kendall, Sen's Slope and Pettitt nonparametric tests applied to the series of average annual rainfall for the cities in the Steppe and Southern regions of RS.

	Mann-Kendall's test	Sen's Slope test	Pettitt's test	
	Significant temporal trend[1]	Magnitude of the trend[1,2] (min. – max.)	No. of series[3]	Year(s) (Changing point)[1]
	CANESM2-ETA Model			
Current (Base)	No cities	-	-	-
RCP 4.5	3 cities	2.092 – 2.949	3	2039; 2050.
RCP 8.5	All cities	-6.632 – -3.189	27	2068
	HADGEM2-ES-ETA Model			
Current (Base)	No cities	-	-	-
RCP 4.5	5 cities	2.079 – 3.01	4	2062; 2065
RCP 8.5	26 cities	1.294 – 6.13	26	2029; 2032; 2033; 2034; 2074; 2076
	MIRO C5 Model			
Current (Base)	All cities	4.819 – 9.32	27	1985; 1986; 1987; 1989; 1990
RCP 4.5	No cities	-	-	-
RCP 8.5	All cities	-5.84; 2.33 – 3.68	27	2058; 2059; 2061; 2068.

[1]at a 5% significance level; [2]mm/year; [3]no. of series for which the changing point was significant.
Source: elaborated by the authors.

in the series of all 27 cities, and this generally occurred between 1980 and 1990. For scenario RCP 4.5, it was possible to detect the year of significant trend changing point over the series of total annual rainfall for the future period in only 3 (CANESM2-ETA) and 4 (HADGEM2-ES-ETA) of the 27 series, in years of the F1 and F2 periods. For the scenario RCP 8.5, the test detected the trend changing point in practically all series, in years within all future periods: F1, F2 and F3.

Many researchers have been using Pettit's test in association with other tests to analyze statistical changes in temperature and rainfall time series, and also in other variables as streamflow, evapotranspiration, wind speed, etc., although studies including climate models on their investigation are scarce in Brazil. Penereiro e Meschiatti (2018) investigated temporal trends in temperature and rainfall series in Brazil by applying MK's and Pettitt's test, and found increasing trends of both variables in the majority of series with significant trend all over the country. Using MK's and Pettitt's tests, Ouhamdouch et al. (2020) found significant increasing trends in evapotranspiration and streamflow at the Essaouira basin, Morocco, expected to the late 2050's (F2 period), when under the RCP 8.5 scenario of an ensemble of models including CANESM2.

Also, while investigating the human influence in hydrological and meteorological variables in the northwest of Iran from scenarios generated by the CANESM2 model, Dariane and Pouryafar (2021) found through MK's and Pettitt's test results that, under the RCP 8.5 scenario, the study area will face a notable increasing trend in the average temperature and a decreasing trend in the precipitation and streamflow, with an abrupt change especially in the years between 2050 and 2100. A last example of application of Pettitt's test is a dataset of climate variables obtained by climate models is the study conducted by Sane et al. (2019) in a river basin in the southwest of Senegal, which found significant trends and the moment of the abrupt change in the streamflow series simulated for this basin.

Of course, despite the clear and important differences between the studies' locations and their climatological particularities, it is clear that the use of nonparametric trend tests like MK, SS and Pettitt can be helpful to investigate the observed time series of the variables and their projections under different future scenarios.

Figure 4 showed the average annual rainfall values for the Southern and Steppe regions in the base period with the three general models. According to the MK test, no city showed a trend in the series for the base period with the CANESM2-ETA and HADGEM2-ETA models, the opposite of what was indicated by the MIROC5-ETA model, which still indicated lower average annual precipitation for the base period.

The three futures of the RCP 4.5 e 8.5 scenarios according to the CANESM2-ETA model are shown in Figure 5. Comparing the base period with future scenario F1, there are signs that, in some cities, the average rainfall range will remain the same (Dom Pedrito, Lavras do Sul, Bagé, and others) and will increase in others (Amaral Ferrador, Herval, Piratini, among others). For the F2 period, it was observed that in some cities the average rainfall will remain in the same range, while, in others, there will be an increase. In F3, there will be a decrease in rainfall in three cities. The MK test applied to the CANESM2-ETA model for the RCP 4.5 climate scenario found a significant trend of increasing rainfall only for the cities of Amaral Ferrador, São Lourenço do Sul, and Turuçu. Of these, São Lourenço do Sul is one of the cities that suffers the most from flooding issues.

The results of the CANESM2-ETA for the RCP 8.5 scenario, F1 period of this projection, shows an annual rainfall increase similar to that of the RCP 4.5 scenario, but includes a greater number of cities with values between 1,900 and 2,100 mm. In the second future period (F2), there is an increase in rainfall in several cities, when compared to F1. For F3, there is a decrease in rainfall, when compared to F1 and F2, in practically all cities in the region.

The MK test applied to the total annual rainfall series of the CANESM2-ETA model for the RCP 8.5 scenario, indicated a downward trend for all cities, due to the behavior of future F3 in the series. Although there are increases between future periods F1 and F2, when the series are analyzed for the entire future period (2006-2099), the test indicates a decrease due to the behavior of the variable in future F3.

The results of total average annual rainfall with the HADGEM2-ES-ETA model for the three future periods in the RCP 4.5 and 8.5 scenario (Figure 6) are varied. In the F2 period, there is an increase in the total accumulated rainfall range in most cities. In the periods F2 and F3, there is a change in the average accumulated rainfall range. Despite the differences between the future periods in the HADGEM2-ES-ETA model and the RCP 4.5 scenario, the MK test indicated a significant trend of increasing total annual rainfall over the century only for the cities of Arroio Grande, Capão do Leão, Jaguarão, Rio Grande and São José do Norte. According to Chou et al. (2014b), this positive trend of increased advantage was already expected for the study region, and Anjos et al. (2018) also observed the trend of increased precipitation in their study for the municipality of Pelotas using the same climate models applied in this study.

For the RCP 8.5 scenario, the HADGEM2-ES-ETA model found, for the F1 period, an increase in average total annual rainfall in Dom Pedrito

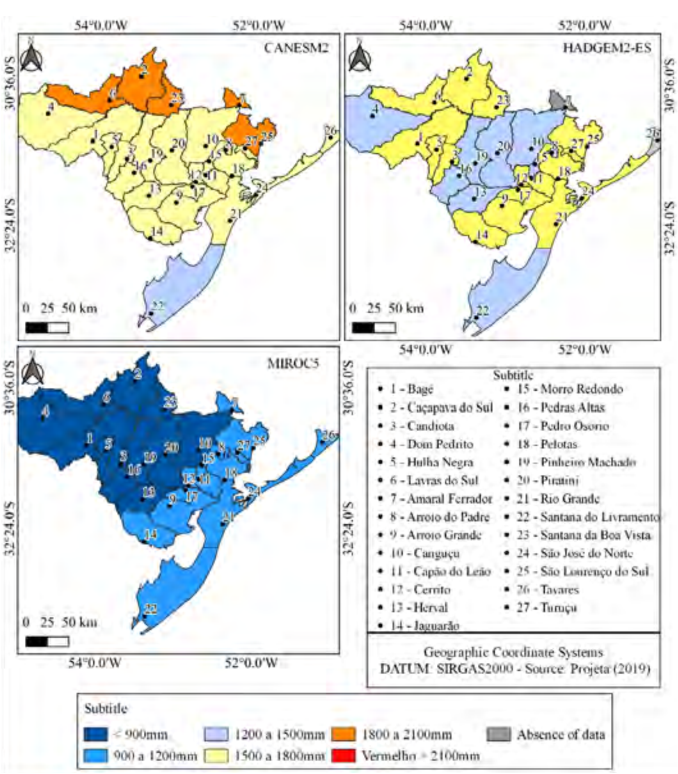

Figure 4 – Average rainfall for cities in the Southern and Steppe regions, in the base period (1961-2005), for the three regional climate models.
Source: elaborated by the authors.

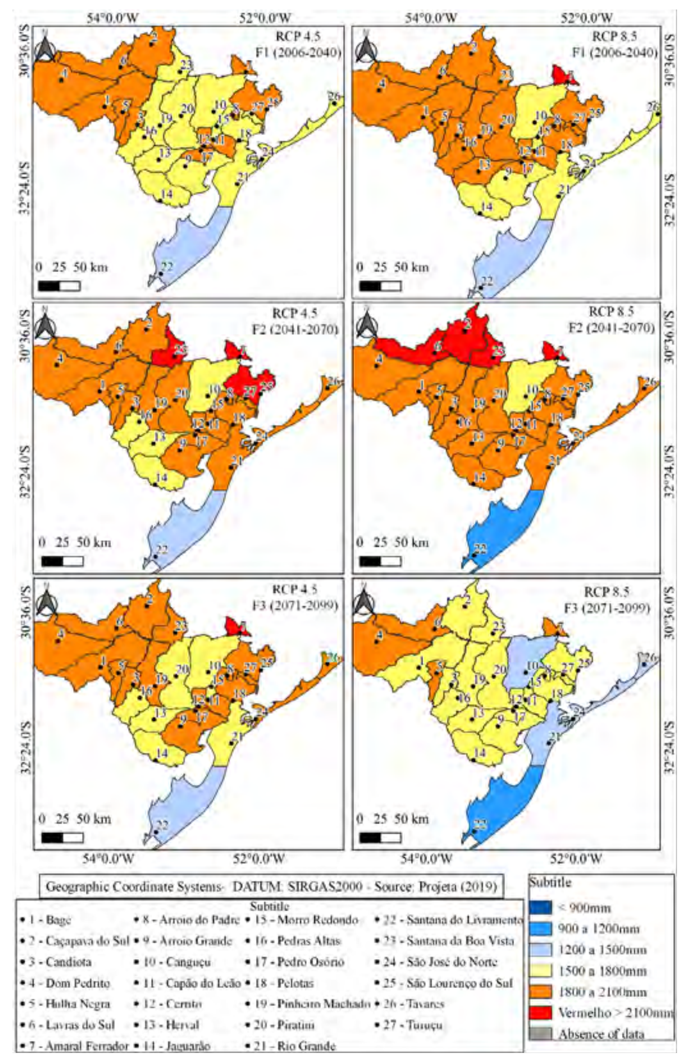

Figure 5 – Average total annual rainfall for cities of the Southern and Steppe regions, according to the CANESM2-ETA model, scenario RCP 4.5 and RCP 8.5, for the three future periods (F1, F2 and F3).
Source: elaborated by the authors.

and Pedras Altas, and a decrease for Rio Grande and São José do Norte, when compared to the base period. Comparing the F1 and F2 periods, there are projections of increased rainfall in most cities. Comparing the F3 period with the F2 period, most cities tend to maintain the same range of average total annual rainfall values, when compared to the base period. The trend analysis at the level of significance considered by the MK test for the HADGEM-ES-ETA model and the RCP 8.5 scenario, suggested a significant trend of increasing total annual rainfall over the century for all cities, except for the city of Tavares, which showed no trend.

The projections of the MIROC5-ETA model for scenario RCP 4.5 (Figure 7) were different from the other models, in addition to finding no decrease in average rainfall for future periods F2 or F3, as happened in some cities in the other models. The analysis of the base period to the F1 period shows that the great trend is for the same average rainfall ranges of the base period to be kept, except in four cities, which increased the annual average of rainfall, and Piratini, which is the only city in which the average is lower in the F1 period than in the base period. Despite these increases in total annual rainfall between the base period and future periods, they are not significant, according to the MK test, when analyzing the entire series of future climate scenario RCP 4.5 with the MIROC5-ETA model.

Analyzing the RCP 8.5 scenario, the MIROC5-ETA model (Figure 7) found increasing rainfall when comparing the F1 period with the base period. For the F2 period, there was an increase in the city

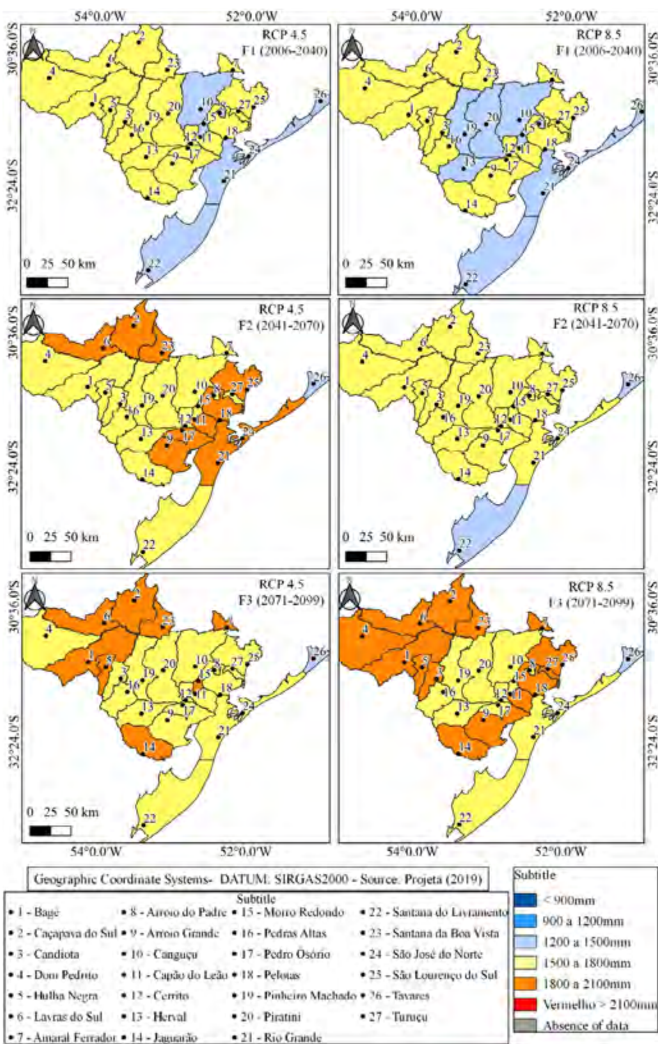

Figure 6 – Average total annual rainfall for cities of the Southern and Steppe regions, according to the HADGEM2-ES-ETA model, scenario RCP 4.5 and RCP 8.5, for the three future periods (F1, F2 and F3).
Source: elaborated by the authors.

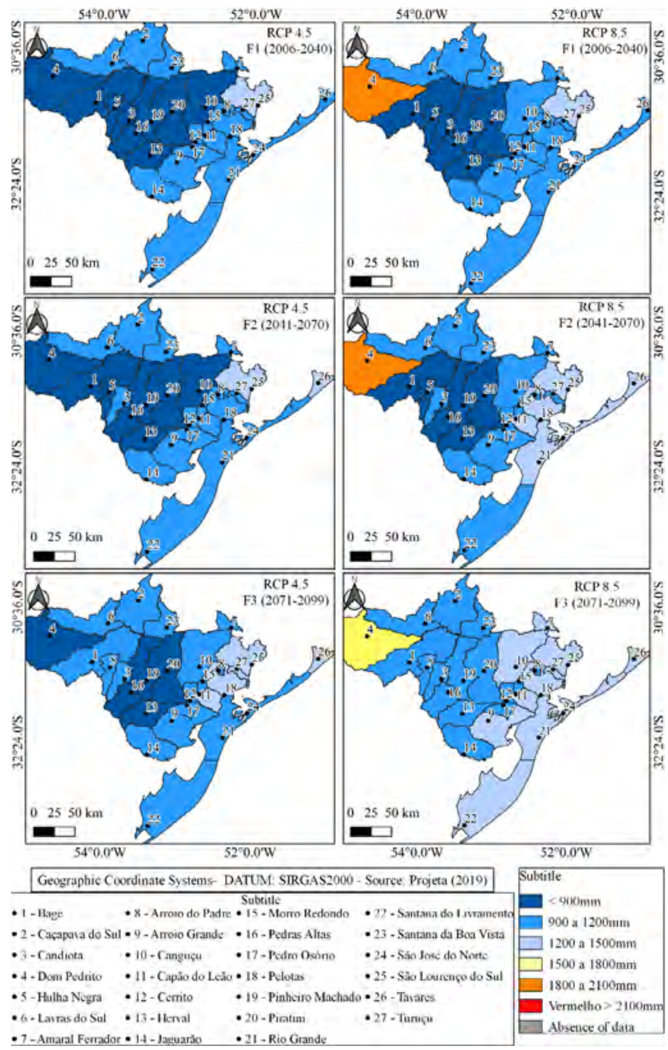

Figure 7 – Average total annual rainfall for cities of the Southern and Steppe regions, according to the MIROC5-ETA model, scenario RCP 4.5 and RCP 8.5, for the three future periods (F1, F2 and F3).
Source: elaborated by the authors.

of Candiota. When comparing the F2 and F3 periods, there are only increases in total annual rainfall, observed in ten cities. It is important to note that the city of Dom Pedrito, which had the highest total annual rainfall value, increased even more in the last future period, going up to the range of 1,500 to 1,800 mm.

These increases between different future periods justify the significant trend detected by the MK test. Contrary to what was found for scenario RCP 4.5, the MIROC5-ETA model found, for scenario RCP 8.5, a significant trend of increasing rainfall in virtually all cities, except Dom Pedrito, which showed a significant trend of decreasing rainfall throughout the century.

There are no great similarities between the three models and the scenarios of the projections, and the MIROC5-ETA model differs from the others in that it does not show decreases in total average annual rainfall in future periods when compared to the base period. In addition, for some cities, higher rainfall values were observed in the most pessimistic scenario (RCP 8.5).

The values of total annual rainfall of the climate models bring some uncertainty when it comes to inferring the trend of rainfall regimes for the cities, as some tend to increase, others show peaks of increase and then decrease, and others remain constant for much of the time. The same was observed by Bravo et al. (2011), who, in addition to assess-

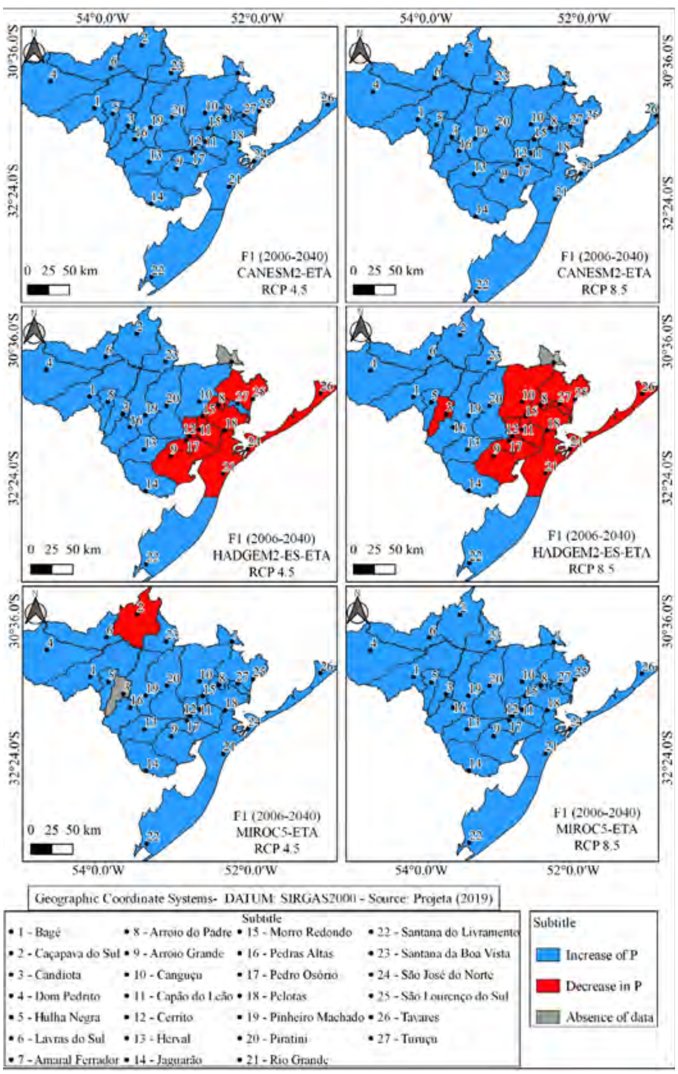

Figure 8 – Anomalies in total annual rainfall (R) for scenario RCP 4.5 and 8.5 with the three regional climate models (CANESM2-ETA, HADGEM2-ES-ETA and MIROC5-ETA) for future F1.
Source: elaborated by the authors.

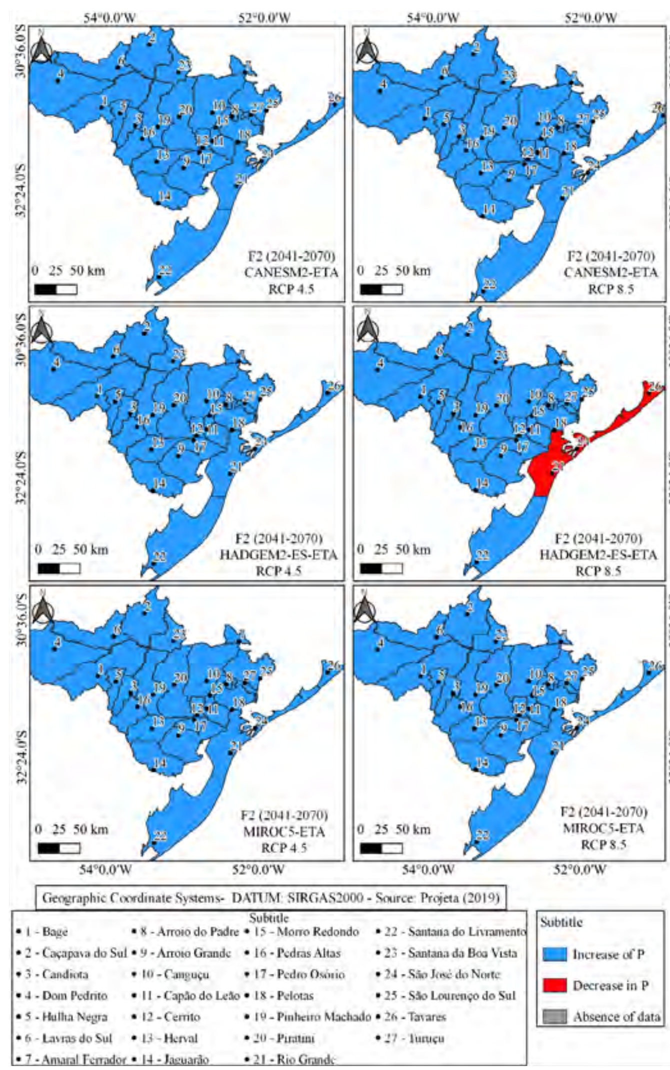

Figure 9 – Anomalies in total annual rainfall (R) for scenario RCP 4.5 and 8.5 with the three regional climate models (CANESM2-ETA, HADGEM2-ES-ETA and MIROC5-ETA) for future F2.
Source: elaborated by the authors.

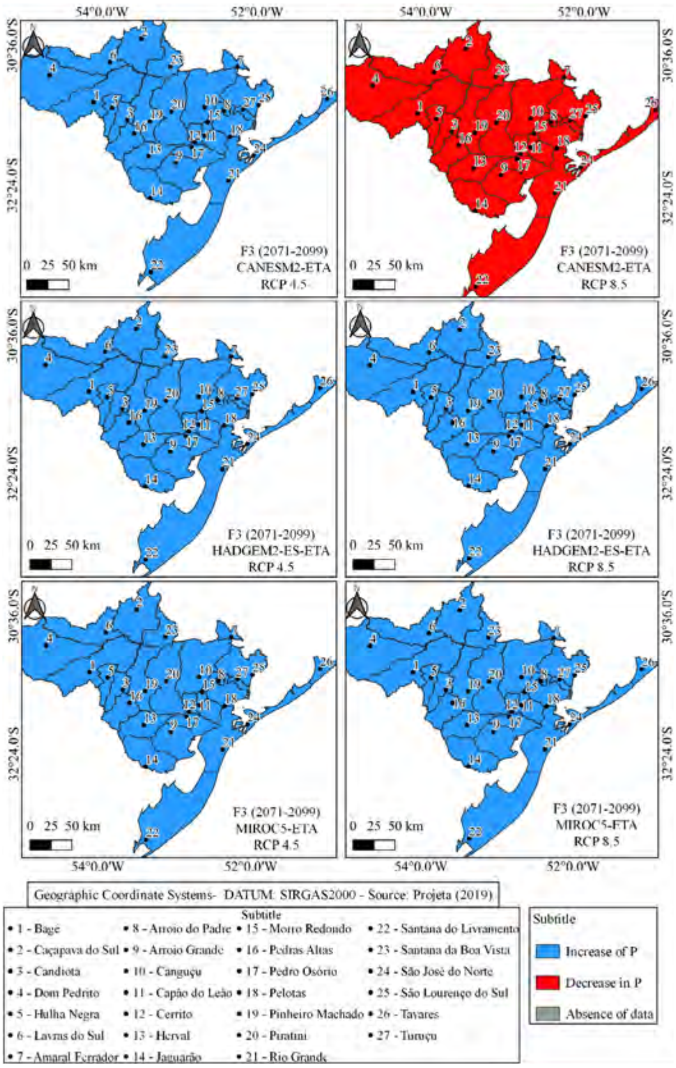

Figure 10 – Anomalies in total annual rainfall (R) for scenario RCP 4.5 and 8.5 with the three regional climate models (CANESM2-ETA, HADGEM2-ES-ETA and MIROC5-ETA) for future F3.
Source: elaborated by the authors.

ing temperature projections, found both an increase and a decrease in rainfall regimes, and observed uncertainties, especially in long-term future periods (2070). Gonçalves and Back (2018), when researching rainfall trends in the southern region of Brazil in the period from 1976 to 2015, considered the series stationary, since 83% did not have any significant trends of increase or decrease in rainfall volume.

The three models suggest an increase in rainfall for a large part of the Steppe region, including the city of Bagé, which, as already mentioned, has recurring periods of drought. Thus, it can be expected that, in the coming years, when compared to the base period, there will be greater water availability in the city and in the adjacent regions.

The cities of Pelotas and São Lourenço do Sul may also experience an increase in rainfall. The two cities have already suffered serious flooding problems, including the municipality of São Lourenço do Sul, which in 2011 presented an event of large volumes of precipitation that ended up affecting approximately 15 thousand people (Rocha, 2011). Therefore, it is extremely important to carry out periodic climate models and forecasts, as a way to issue alerts to the population, in order to avoid or minimize the occurrence of impacts arising from these extreme events.

Anomalies

In the RCP 4.5 scenario, for the first period (F1) (Figure 8), there are signs of positive rainfall anomalies for all cities in the projections of the CANESM2-ETA and MIROC5-ETA models. As for the HADGEM2-ES-ETA model, there are negative anomalies for some cities in the Southern region.

The calculation of anomalies in the RCP 8.5 scenario for the F1 period, represented in Figure 8, with the three climatic models, according to the projections of the CANESM2-ETA and MIROC5-ETA models, indicate positive anomalies for all cities. The HADGEM2-ES-ETA model, on the other hand, presents negative anomalies for 14 cities. This result, when compared to scenario RCP 4.5, is different, since for the same model only positive anomalies were observed in the same period.

For the second period (F2) in the RCP 4.5 scenario (Figure 9), anomaly calculations are positive for all cities, in the three models. In the last future period (F3) (Figure 10), for the same scenario, the projection is the same as the F2 future period, with the three models suggesting positive anomalies for rainfall averages.

For the F2 period (Figure 9), the CANESM2-ETA and MIROC5-ETA models indicate positive anomalies for all cities. The HADGEM2-ES-ETA model projects positive anomalies, except for the cities of São José do Norte, Rio Grande and Tavares. Figure 10 presents the anomalies found for the F3 period. The HADGEM2-ES and MIROC5 models project that annual rainfall anomalies will be positive for all cities.

The CANESM2 model, however, does not have the same projection, finding that the anomaly will be negative for cities in the Southern region, differing from that projected in scenario RCP 4.5, which indicated positive anomalies for the 27 cities. This result of negative precipitation anomaly of the CANESM2 model for the RCP 8.5 scenario and of positive anomaly of the same model for the RCP 4.5 scenario is in accordance with what was observed by Anjos et al. (2018) for the municipality of Pelotas, which makes up the southern region.

Conclusions

The present study carried out in the South region and Rio Grande do Sul Campaign using the CANESM2, HADGEM2-ES and MIROC5 models regionalized by the ETA model and made available on the PROJETA Platform, indicate a possible increase in the average temperature until the end of the 21st century, regardless of which path of greenhouse gas emissions and preservation of the environment humankind chooses to follow, since the two scenarios of future climate projections (RCP 4.5 and RCP 8.5) indicate this increase. However, the average annual temperatures will be milder according to the projection of scenario RCP 4.5, and harsher when considering a more pessimistic scenario (RCP 8.5).

Analyzing the total annual rainfall averages in the different periods (base and future), it is concluded that there are indications that rainfall may increase in volume over time in the two future scenarios, whereas in RCP 8.5 this increase can be repeatedly observed. There are also models that project a decrease in rainfall after a peak period. Therefore, a probable increase in total annual rainfall is foreseen in the future, when compared with the values of the base period. The analysis concludes that the anomalies can be positive or negative in the total future annual rainfall in both projections, however, there is a predominance of positive anomalies for the periods, scenarios and models analyzed.

Contribution of authors:

CARDOSO, I.P.: Conceptualization, Methodology, Writing — Review and Editing, Writing — Original Draft, Software, Investigation.; SIQUEIRA, T.M.: Formal Analysis, Conceptualization, Supervision, Methodology, Software, Writing — Review and Editing, Data Curation, Investigation.; TIMM, L.C.: Formal Analysis, Conceptualization, Supervision, Methodology, Writing — Review and Editing, Investigation.; RODRIGUES, A.A.: Methodology, Writing — Review and Editing, Conceptualization, Investigation.; Nunes, A.B.: Writing — Review and Editing, Formal Analysis, Investigation.

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Wavelet transform for medium-range streamflows projections in national interconnected system

Transformada em ondeletas para projeções de vazões em médio prazo no sistema nacional interconectado

Carlos Eduardo Sousa Lima[1], *Marx Vinicius Maciel da Silva*[1], *Cleiton da Silva Silveira*[1], *Francisco das Chagas Vasconcelos Junior*[2]

ABSTRACT

This study aimed to analyze the variability of average annual streamflow time series of the National Interconnected System (NIS) (Brazil) and create a projection model of future streamflow scenarios from 3 to 10 years using wavelet transform (WT). The streamflow time series were used and divided into two periods, namely, 1931–2005 and 2006–2017, for calibration and verification, respectively. The annual series was standardized, and by the WT, it was decomposed into two bands plus the residue for each base posts (BP) for later reconstruction. Then, an autoregressive (AR) model per band and residue was made. The projection was obtained by adding the AR models. For performance evaluation, a qualitative analysis of the cumulative probability distribution of the projected years and an analysis of the likelihood were performed. The model identified the probability distribution function of the projected years and obtained a likelihood ratio of > 1 in most SIN regions, indicating that this methodology can capture the medium-range variability.

Keywords: autoregressive wavelets; National Interconnected System; climate variability; streamflow projection.

RESUMO

O presente trabalho objetiva analisar a variabilidade das séries temporais de vazão média anual do Sistema Nacional Interconectado (SIN) (Brasil) e criar um modelo de projeção de cenários de vazão de três até dez anos utilizando transformada em ondeleta. As séries temporais de vazão foram divididas em dois períodos — 1931 até 2005 e 2006 até 2017 — para calibração e validação, respectivamente. As séries anuais foram padronizadas e, por meio da transformada em ondeleta, foram decompostas em duas bandas e no resíduo para cada Posto Base (BP) para uma futura reconstrução. Em seguida foi feito um modelo autorregressivo por banda e para o resíduo. A projeção foi obtida pelo somatório das projeções desses modelos autorregressivos. Para avaliar a *performance*, uma análise qualitativa da distribuição de probabilidade acumulada dos anos projetados foi realizada e a verossimilhança foi calculada. O modelo identificou a distribuição de probabilidade dos anos projetados e obteve verossimilhança maior que 1 na maioria das regiões do SIN, o que indica que essa metodologia é capaz de capturar a variabilidade de médio prazo.

Palavras-chave: ondeletas autoregressivas; Sistema Nacional Interconectado; variabilidade climática; projeção de vazão.

[1]Universidade Federal do Ceará – Fortaleza (CE), Brazil.

[2]Fundação Cearense de Meteorologia e Recursos Hídricos – Fortaleza (CE), Brazil.

Correspondence address: Carlos Eduardo Sousa Lima – Departamento de Engenharia Hidráulica e Ambiental – Campus Pici, Bloco 713 – Pici – CEP: 60455-900 – Fortaleza (CE), Brazil. E-mail: eduardolima@alu.ufc.br

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Introduction

The expansion planning of the Brazilian electric system is composed, among other activities, of computational simulations of future electric energy system configurations (Costa et al., 2007). In these simulations, it is sought to locate and measure future electricity and energy needs, as well as adjusting entry schedules of generation projects, among others. Such adjustments are made following criteria that mainly aim at the security of supply and minimization of investment and operating costs.

To supply the growing power demand, the country has strongly invested in their power energy generation, mainly in hydroelectric plants over whole country. In Brazil, power generation went from 223 billion kilowatts hours in 1990 to 626 billion in 2019, with an average rate growth of approximately 3.5% per year. The hydropower participation was always prominent in its power plant grid, varying from 93 to 64% in the same period (IEA, 2020). The hydroelectric generation and planning of the hydropower sector in Brazil presents correlation with the water stocks in the hydroelectric power plants reservoirs and their inflows.

Emergency thermoelectric plants are used to supply the country's power demand, mostly in critical dry periods, with low volume in reservoirs. These thermoelectric plants are considered virtual reservoirs because they provide security of supply when the water reservoirs are low and relief the needs of stocking water to deals with inflow uncertainty. The hydropower plants are operated in combination with thermoelectric plants by the National System Operator (ONS in Portuguese) and the junction of all sources that comprises the Brazilian power grid called National Interconnected System (NIS).

The variation of the river flow is influenced by several factors, among which the precipitation in the contribution basin and land use changes are highlighted. Therefore, the hegemony of hydroelectricity in the Brazilian electric energy matrix imposes cautious analysis on river regimes and their temporal variation patterns, considering the significant impact that these variations can produce in the energy supply and consequently throughout the national economy (Alves et al., 2013).

Power systems, such as the Brazilian one, are subject to impacts arising from climate variability and change and shifts in power production and consumption. Thus, climate variability can condition the risk associated with the generation of electric energy. The possibility of quantification of risks allows decisions to be taken so that the impacts of adverse events are minimized, thus reducing the degree of vulnerability of a given region.

A large part of the interannual climate variability over South America is modulated by the atmospheric patterns in response to the El Niño-Southern Oscillation (ENSO) phenomenon in the equatorial Pacific (Grimm et al., 2020) and by the meridional gradient of sea surface temperature (SST) anomalies over the tropical Atlantic (Kayano et al., 2018). The combination of the anomalous atmospheric circulations induced by the spatial patterns of SSTs on the equatorial Pacific and tropical Atlantic Oceans affects the latitudinal position of the Intertropical Convergence Zone (ITCZ) over the Atlantic in addition to the moisture transport into the continent, influencing the seasonal precipitation anomalies over the northern and central portions of South America.

Kayano et al. (2018) reported the fluctuations of SST anomalies in the Northern Tropical Atlantic and the Southern Tropical Atlantic as part of two decadal modes of distinct periodicities separated by the ITCZ. Zhang et al. (1997) described another characteristic Pacific Ocean SST oscillation, in addition to ENSO, occurring on an interdecadal scale. This phenomenon has been called the Pacific Decadal Oscillation (PDO).

The PDO has two phases: in the negative phase, the characteristics are negative anomalies of SST in the tropical Pacific and, simultaneously, positive SST anomalies in the extratropical Pacific, with tendency for the occurrence of a larger number of La Niña episodes, which are also likely to be more intense. Conversely, in the positive phase of PDO, the tendency is for a larger number of El Niño episodes that tend to be more intense. In contrast, there is a lower number of La Niña, which tends to be less expressive. PDO fluctuations have two main periodicities, one presenting a cycle of 15–25 years and the other presenting a cycle of 50–70 years (Kayano et al., 2019; Wang et al., 2019).

The influences of this interdecadal scale oscillation on South American climate variability were also investigated by Grimm and Saboia (2015) and references therein. These studies have demonstrated that the PDO phenomenon influences the volume of precipitation. Furthermore, extreme rainfall events are more likely to occur when both ENSO and PDO are in the same phase.

Grimm et al. (2020) and references quoted therein pointed to the influence of ENSO and Atlantic Multidecadal Oscillation (AMO) on precipitation over South America, in the respective interannual and interdecadal oscillation scale. Rocha and Souza Filho (2020) have identified a strong coherence between the changes of ONS streamflow time series and SST interdecadal oscillation patterns (AMO and PDO) in the key stations of ONS, including Sobradinho, Itaipú, and Furnas.

Considering the importance of hydroelectric generation for the Brazilian NIS and the various mechanisms responsible for the climate variability in this region, which associate a risk to this system, this study aimed to propose a model for the medium-term projection for the NIS, based on the climatic variability of the series of naturalized streamflow of the ONS using the wavelet transform (WT) method. This study is organized as follows: an overview of the NIS structure and describes the methods and data, the results, and, finally, discussion and conclusion.

Methodology

The methodology utilized covers climate variability and trend analysis to identify patterns through the streamflow data. WT and band decomposition are performed to bring up the prominent modes of variation. Then, statistical modeling takes place, building, validating, and applying the autoregressive wavelets (WAR) model to produce streamflow medium-range forecasts. A workflow scheme is depicted in Figure 1.

National Interconnected System

NIS is responsible for the production and transmission of electric energy in Brazil. NIS is a large hydrothermal system with predominance of hydroelectric plants. Only 1.7% of the country's electricity production capacity is outside the NIS, in small isolated systems located mainly in the Amazon region (ONS, 2016).

For forecasting outflows, ONS generally adopts a subset of basins, called base post (BP). In the rest of the places of use, the flows are predicted through monthly linear regressions based on the data provided in the BP to complement the forecasts of flow for the whole NIS. ONS currently works with 88 BPs that are representative of the various regional hydrologic regimes found in Brazil (ONS, 2010b). These BPs are listed in Figure 2 and are used in the flow projections of this study. Moreover, four reference BPs were adopted for a more extensive analysis due their relevance, including Tucuruí, Sobradinho, Itaipú, and Água Vermelha. These reference BPs are highlighted in Figure 2.

Data, trend, and variability analysis

To calibrate and evaluate the dexterity of the model, the ONS naturalized flow database was used for the period from 1931 to 2016 for the SIN. The series of annual average naturalized flows were divided into two periods, namely, 1931–2005 and 2006–2017, for calibration and verification, respectively. Projections are also made for the period from 2017 to 2026.

Knowing that the observed flow is composed of both natural processes and anthropogenic activities, the naturalized streamflow, generally speaking, is an estimate of the natural flow obtained by removal of anthropogenic impacts on the observed streamflow. These impacts are generated by human activities, such as reservoir operations upstream of the streamflow gauge, water withdrawal, and river flow alteration by control infrastructures, among others. More information can be accessed in ONS (2010) and Terrier et al. (2021).

Regarding the approach, the methodologies of trend/variability evaluation can be distributed in two groups: classical methods and modern methods. The classical methods used in this study were 10-year moving average and Mann–Kendall–Sen (MKS) for annual mean flow.

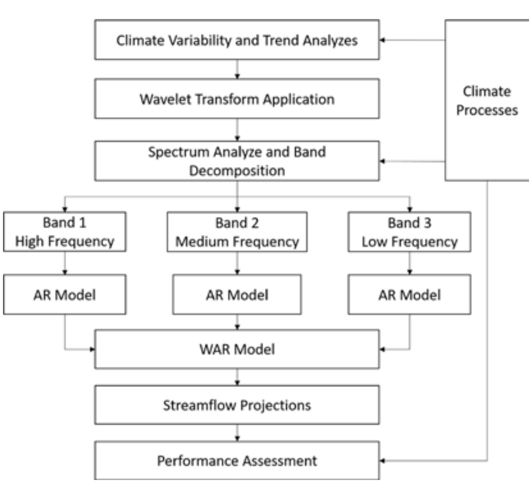

Figure 1 – Workflow diagram of the methodology used in this study.
AR: autoregressive; WAR: autoregressive wavelets.

The MKS method is composed of nonparametric Mann–Kendall test and nonparametric Sen's slope estimate procedure. These methods are used, respectively, for trend detection and, if there is, trend magnitude determination. The MKS is widely used in trend analysis because it does not require initial assumption about the probability distribution and has a low sensitivity to outliers. More information can be obtained from a study by Moreira and Naghettini (2016).

Among the modern methods, the WT analysis (Torrence and Compo, 1998) of the standardized annual series was considered. This analysis consists of the decomposition of the series into bands, as described, for all the stations of SIN and the discussion of the band relationship with temporal series variability.

The WAR model

The WAR model contains at least six steps:

- Standardization of the annual series based on its mean and standard deviation (Equation 1).

$$z_i = x - \frac{x}{\sigma_x} \tag{1}$$

Where:
x: the data to be standardized;
$\bar{x}$: the mean of the series;
σ_x: the standard deviation of the series.

- Analysis of the WT power spectrum for the identification of the most energetic bands, filtration of the series for the bands of greater energy, and reconstruction of filtered series in time domain for each considered band;

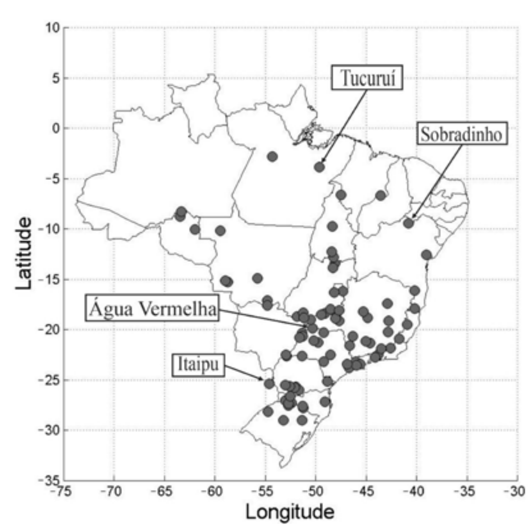

Figure 2 – Eighty-eight base gauge stations highlighting the four reference base posts adopted in this study.

- Obtaining the parameters of the autoregressive (AR) models that are generated for each one of reconstructed series in time domain of each adopted band. This procedure is repeated for all BPs;
- Noise generation for each AR model obtained from the mean and standard deviation of the difference between the bands and the value obtained by the AR model in the calibration period;
- Integration of the bands, considering that they are orthogonal, then the sum of projected bands is equal to projected streamflow.

Wavelet transform

One of the methods used in this study to characterize the variability both in space and in time is the WT (Torrence and Compo, 1998; Morettin, 1999). This method is widely utilized for the determination of the dominant variability modes and the variation of these modes throughout a nonstationary time series, enabling the decomposition of this kind of time series in a time–frequency domain.

The wavelet transform is defined in terms of a convolution integral between the analyzed signal and a known wavelet function. The Morlet wavelet continuous function was considered for this analysis and is given by Equation 2:

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \quad (2)$$

with $w_0=6$ and $\eta=t/s$

where:
t: time;
s: the scale of the wavelet;
w_0: the nondimensional frequency representing a wave modulated by a Gaussian envelope.

This function is complex and has characteristics similar to those of the analyzed time series, such as symmetry or asymmetry, and sudden or soft temporal variation. The algorithm used was developed by Torrence and Compo (1998). More details about WT can be found at Morettin (1999).

In this study, the WT was performed to decompose the streamflow time series in specific frequency bands. Beside this, the signal of each adopted frequency band in the decomposition was reconstructed in time domain, being used as input to the AR model.

Decomposition and reconstruction of the bands

The signal power of the global spectrum of the wavelet can be used to identify the most significant variation frequencies of a time series. The power is associated with the signal strength of the historical series for a given frequency or band (range) of frequencies (Torrence and Compo, 1998).

To create the WAR model, an important step is the decomposition of the bands, which consists of analyzing the global energy spectrum over the time series and then identifying the frequencies, or frequency bands, of greater power and filter the series for these bands. The signal decomposition is done to obtain the wavelet coefficients in the transformed domain (frequency domain).

As suggested by Alves et al. (2013), three bands were used in this study: a high frequency, 1–8 years; a medium frequency, 9–39 years; and a low frequency, > 40 years (residue).

After the signal decomposition in both high- and medium-frequency bands, the signals of these bands were reconstructed in time domain. For low-frequency band, considering that the wavelets and their bands are orthogonal functions, so the correlation between them is not significant, then the reconstructed low-frequency band in time domain can be obtained using the Equation 3:

$$R(i) = Q(i) - Q_1(i) - Q_2(i) \quad (3)$$

Where:
$Q(i)$: the annual mean streamflow value;
$Q_1(i)$: the value of the reconstructed high-frequency band (1–8 years) at i year;
$Q_2(i)$: the value of the reconstructed medium-frequency band (9–39 years) at i year;
$R(i)$: the value of the reconstructed low-frequency band (> 40 years).

Autoregressive model

After the signal reconstruction, an AR model is applied to each band, considering that they are orthogonal, given by Equation 4:

$$z_i{}^p = \sum_{i=1}^{b} \left(ARs_b(i) + ARs_{R(i)}(i) \right) \quad (4)$$

Where:
ARs_b: the autoregressive model of each band;
ARs_R: the autoregressive model of the residue.

A linear regression of the data is then performed, considering the previous years as predictors. The linear regression is given by Equation 5:

$$z_i{}^p = \varepsilon_1 + \sum_{j=i-n}^{i-1} z_j . \beta_n \quad (5)$$

Where:
z_j: the years considered as predictors;
βn: the coefficient calculated for each predictor;
ε_1: the bias/noise/residue;
n: the number of terms used in the AR model;
z_i^p: the set of values projected by the model for the period of p years.

The period used for the calibration of the parameters was from 1931 to 2006 in SIN, all with lag1 (1 year). The determination of ε_1

is done by generating m values randomly distributed in a normal multivariate function of mean, standard deviation, and covariance of the difference between the estimated and observed variables with lag1 over the course of 1931–2006. Thus, z_i^{1} has m possible scenarios. The generation of the forecast with lag2 admits that all the scenarios generated for z_i^{1} are plausible futures, with the previous years being predictors of the projected year. It stands out that m is an arbitrary value; in this study, it was adopted that m is equal to 1,000.

By definition, the original time series can be considered equal to the sum of the adopted frequencies bands reconstructed in time domain. Thus, the projected streamflow is equal the sum of the projected adopted bands, which were already been reconstructed in time domain before the application of AR model.

Model performance evaluation

After calculating streamflow projections for the region of interest, it is necessary to evaluate the performance of the proposed models. For the statistical models based on wavelet series, the qualitative analysis of the cumulative probability distribution of the projected years' period and an analysis of the likelihood between observation and projection are performed. It is worth noting that the purpose of the WAR model is to identify the probability distribution of the set of projected years and not specifically a 1-year forecast.

Maximum likelihood estimator

To calculate this estimator, it is necessary to define the likelihood function. The principle of likelihood states that "a statistical inference must be consistent with the hypothesis that the best explanation of a data set is provided by $\hat{\theta}$, a value of θ which maximizes the likelihood function." Intuitively, maximizing likelihood means getting the population most likely to have generated the sample.

In case of the regression model, the parameter vector of interest is given as Equation 6:

$$\theta' = (\beta', \sigma^2) \quad (6)$$

and defining L as a function of β' and σ^2 (Equation 7):

$$L(\beta, \sigma^2) = \prod_{i=1}^{n} f_{Y_i}(y_i|\beta, \sigma^2) \quad (7)$$

Finding the vector of estimated parameters that maximize the likelihood function is equivalent to maximizing likelihood. Therefore, to obtain this vector, the likelihood is derived in relation to each parameter and equals zero. This is the usual calculation method. For this, the median of the set of scenarios generated per year is approximated to a gamma distribution function and compared to the gamma distribution of the climatology.

The calculation of the projection performance, using the projection of the WAR and the climatology, in comparison to the total observed data, is attained using Equation 8:

$$\text{Performance} = \left(\frac{L(\beta,\sigma^2)_{\text{projection}}}{L(\beta,\sigma^2)_{\text{climatology}}}\right)^{\frac{1}{n}} \quad (8)$$

Where:
n: the number of years of the historical series utilized here.

When Performance > 1, it means that there was an improve on the forecast in relation to the climatology. Instead, when Performance > 1, it means that there was a worsening in projection.

Results and Discussion

Variability analysis

Streamflow time series can present several variability modes in different timescales, which can be conditioned by simultaneous action of many atmospheric systems of various temporal scales and the dynamic of their interactions. Due to these multi-scale meteorological phenomena, their combination determines the weather state in a given temporal scale and, consequently, the variability of the hydrologic cycle components. Furthermore, climate changes and alterations in the land use of a basin can modify the runoff patterns and create trends in the temporal series.

The annual series of average flow of SIN stations present different traces of trends (Mann–Kendall method and Sen's declivity) in Brazil. Figure 3 indicates that, as for the trend signal, there are three areas in different situations in the country: positive tendency (south regions: Mato Grosso do Sul and São Paulo), negative (northeast regions: Espírito Santo and Minas Gerais), and the absence of trend (further regions and states).

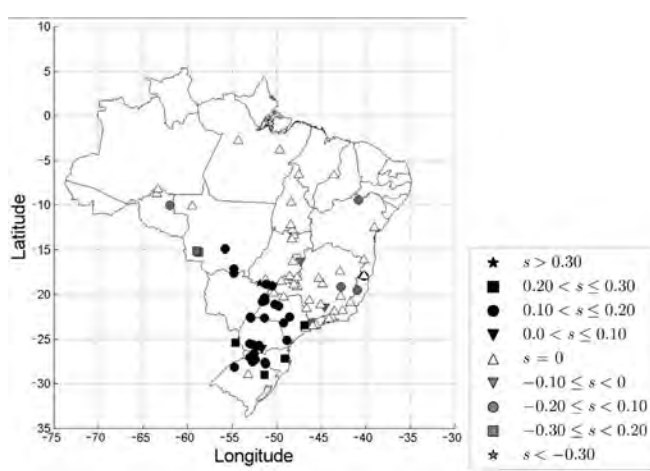

Figure 3 – Slope of the trend line of the Mann–Kendall–Sen test (s) for the variable z (standardized annual flow, according to Equation 1) for the period from 1931 to 2016.

The naturalized flows of Sobradinho, Água Vermelha, Tucuruí, and Itaipú in the period from 1931 to 2016 illustrate the variation modes in different temporal scales. There is an interannual variation of the average annual flow in these stations; for example, Sobradinho in the Northeast subsystem of the SIN has years with average values between 2,000 and 4,000 m³/s, that is, there is a multiplicative factor greater than 2 between the minimum and the maximum, as can be seen in Figure 4. A similar behavior can be seen in other SIN subsystems; for example, in Tucuruí at the north of the country, the flow rate ranges from 6,000 and 14,000 m³/s, and in Água Vermelha at the Southeast/Midwest subsystem, the flow rate ranges from 1,200 to 2,500 m³/s. In Itaipú, despite presenting a trace of positive trend in the average annual flow, there is a sign of interannual variability, with flow rates in the period from 1931 to 1950 ranging between 6,000 and 10,000 m³/s, as shown in Figure 4 where the interannual variability is explained between 30 and 45% of the variance of the historical series.

Besides the significant interannual variability, a series of annual average flow indicates significant hydrologic decadal variability, especially in the series of North, Northeast, and Southeast of SIN, for example, in a period of 10 years the average value is 3,000 m³/s in the operation of Sobradinho, while in the other period of 10 years the average value decreases to approximately 2,500 m³/s (Figure 4A). This behavior is also evidenced in the exploitation of Tucuruí, with a period of 10 years where the average value is 12,000 m³/s and the other with the average value of approximately 9,000 m³/s (Figure 4B).

This evidences a possible low-frequency variation mode, because this behavior is recurring along the whole time series. This variability can introduce in the water systems the alternation of consecutive wet and dry years. In the case of consecutive dry years, it should intensify the water rationing policies and the reduction in the granting of water use permission.

The lower frequency variability modes shape the climate on a global scale (Wang et al., 2012). These variability modes occur in the Pacific and Atlantic Oceans, overlapped and influenced by interannual modes, such as ENSO, and, as already mentioned, can influence the effects of these variabilities on South America. Rocha and Souza Filho (2020) detected low-frequency anomalies in the SST of Pacific (PDO) and Atlantic (AMO) in the period 1931–2016 with change-point analysis. The cold (C) and warm (W) phases of PDO and AMO detected were in the following periods: W-AMO (1931–1963 and 1995–2016), W-PDO (1931–1943, 1976–1998, and 2014–2016), C-AMO (1964–1994), and C-PDO (1944-1975 and 1999–2013). These periods are very close to the phases of PDO and AMO reported by Kayano et al. (2019) and, respectively, by Mantua et al. (1997) and Zhang and Delworth (2006).

The temporal series of Sobradinho in the period from 1932 to 1942 shows some years with average annual value lower than the historic mean, coincident with periods of the warm phase of PDO and AMO. In the next period, between 1943 and 1950, the annual flow in this exploitation reached higher values which are twice the historical mean, period that comprises the end of the warm phase and beginning of the cold phase of PDO, and according to Zhang and Delworth (2006), also within the minimum point of the warm phase of AMO.

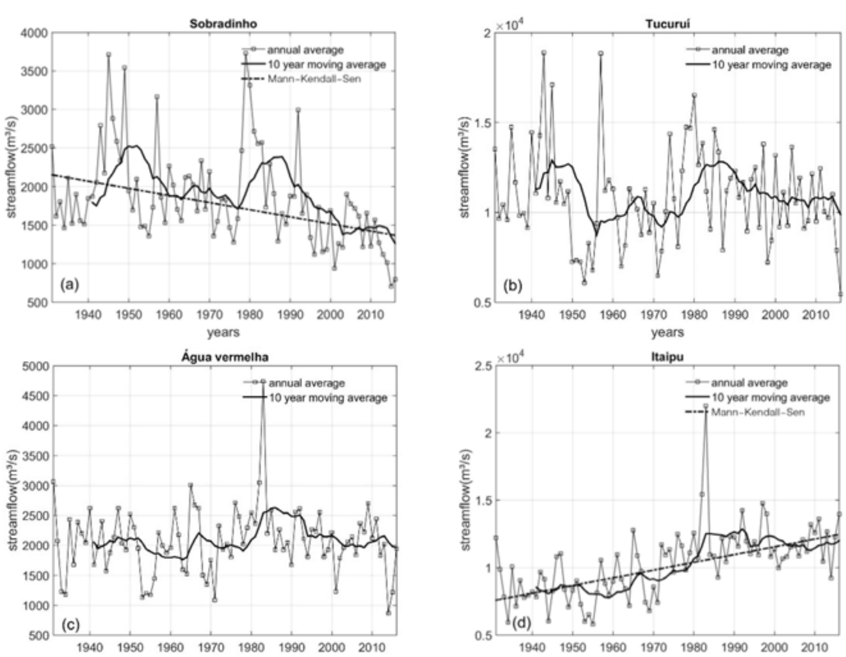

Figure 4 – Time series of annual average flow of some hydroelectric exploitations in the SIN: (A) Sobradinho; (B) Tucuruí; (C) Água Vermelha; (D) Itaipú.

In the period from 1973 to 1980, the AMO reached minimum points in the cold phase, coincident with maximum flow, according to the historical series. The period from 1963 to 1970 is a transition period between phases of AMO and a weak cold phase of the PDO, which is consistent with annual flow close to the historical mean. According to Rocha and Souza Filho (2020), the period between 2014 and 2016 was a warm phase of both PDO and AMO. In this period, the annual average streamflow of Sobradinho reached to the minimum of the entire series.

Especially on the Northeast region of Brazil (NEB), the principal phenomenon responsible for the rainfalls is the ITCZ, which migrates from the north to the south along the year. Naturally when closer to the coastal area of NEB, it causes higher precipitations, and consequently, flows there. Therefore, when AMO is in the cold phase, there is a tendency that the water of the North Atlantic is cooler than that in the South Atlantic, which indicates a higher possibility of precipitation in the region, and the reciprocal is also accepted.

The flow response of Tucuruí (Figure 4B) resembles to that of Sobradinho (Figure 4A); however, the impact of the warm and cold phases of the phenomena seems more intense in this region. In the Southern and Southeastern regions of the country, the Pacific affects the flow in an opposite way; therefore, the Água Vermelha (Figure 4C) flow series in the period from 1977 to 1995, in the warm phase of PDO, presented the annual value of around 20% higher than the annual mean of the period between 1931 and 2016.

Itaipú shows a clearly defined positive trend (Figure 4D); however, the flow fluctuations are lower in the warm phase of AMO and higher in the cold phase. Different mechanisms can act as modulators in the large-scale pattern in the ocean–atmosphere interaction, changing the basic state of southern circulation over South America and the South Atlantic Ocean and leading to variation in the precipitation pattern in the Southeastern and Southern Brazil in this timescale. Further analysis is required to understand the cause and effect of these variations.

Figure 5 shows the spatial distribution of the variation's proportions explained by high-, mean, and low-frequency bands, respectively. The high-frequency band (Figure 5A) is responsible for more than 45% of the variance in most of the series of annual average flow of SIN, indicating strong dependency of the interannual variability.

In the Midwest and Northeast regions, the high-frequency bands is responsible for at least 45% of the variance in most of the stations, similar to the stations localized in the extreme north of the country and in the coastal part of Southeast region. This behavior indicates that the signal associated with the interannual and decadal variability prevails over the tendency and the medium- and low-frequency variation modes.

Figure 5B shows that the mean frequency band is responsible for more values between 15% and 30% of the variance in the flow series of the stations at Southern region and east of the Southeast region, in the state of São Paulo. In the Midwest region and part of Northeast, in the northern part of the North and in the coast of the Southeast, the mean band frequency is responsible for more than 30% of the series variance.

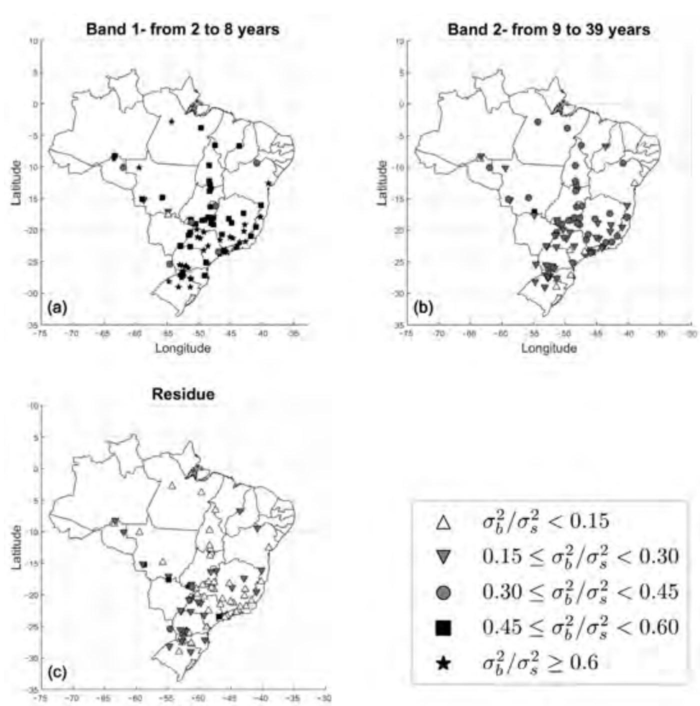

Figure 5 – Percentage of the explained variance for each band variation. (A) 2–8 years band, (B) 9–39 years band, and (C) residual band. σ_b^2 is the variance of the reconstructed series by the specific band and σ_s^2 is the variance of the original time series.

Figure 5C shows that in most part of the country, the low-frequency band is responsible for at least 15% of the variance in the flow series, except in some stations in the South, Midwest, and Southeast of the country, where it has a pronounced positive trend, according to Figure 3.

WAR model analysis

Figure 6 shows the WAR model calibration for different bands for Água Vermelha, Sobradinho, and Itaipú. The model represents well the low- and mean frequency bands, with bias close to zero in these bands. However, for the high-frequency band, the model softens the majority of the minimums and maximums, indicating high uncertainty and randomness in this band. There is a periodic oscillation in the low-frequency band, associated with a periodic oscillation in the mean frequency band with period between 10 and 20 years. The model captures well the low-frequency band, mainly in Itaipú and Água Vermelha, where there is a coincident phase inversion with the AMO phase.

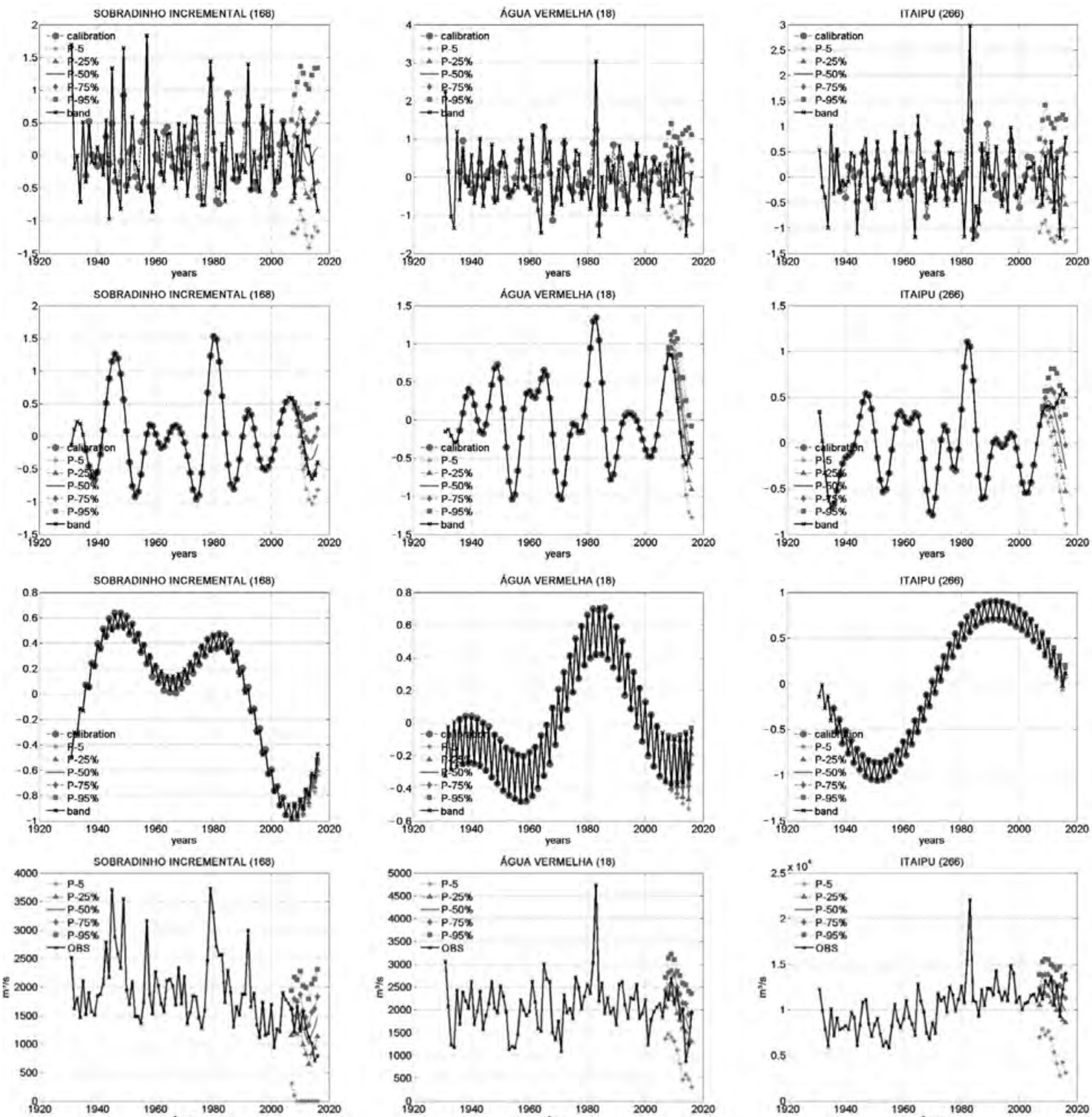

Figure 6 – Frequency bands of the wavelet transform, calibration, and projection of the WAR model. From top to bottom and left to right: 2–8 years band, 9–39 years band, and residue for Sobradinho, Água Vermelha e Itaipú.

The main flow peaks in Sobradinho are followed by maximum in the mean frequency band; as shown in the previous section, they are associated with the onset of the cold phase in the PDO.

The negative trend in Sobradinho (Figure 4A) is represented in the low-frequency band, especially since the 1990s when this band reaches values well below those obtained in others periods of the century. In the 1940s and beginning of the 1980s, the mean frequency band reaches maximum peaks (2,500 m^3/s), a value 25% above the time series average.

In the Água Vermelha station, the low-frequency band presented phase change in the second half of the 20th century, with strong peak in the 1980s. The influence of this band on the historical series and its inversion may have led to a period of lower flow for the next 30 years, especially between 2003 and 2016 when the mean and low-frequency band reached minimum point. In the 1950s, when the mean and low-frequency bands presented minimum values, the annual mean flow for consecutive years was lower than 1,500 m^3/s, at least 30% below the historical average value between 1931 and 2016. In the period of 1968–1971, the temporal series also reached values lower than 1,500 m^3/s coinciding with a minimum point of the mean frequency band, indicating that this phase may influence the flow distributions. Moreover, in the 1980s, there was a coincidence between the maximum of the three bands, which led to anomalous years above average.

In Itaipú, the positive trend (Figure 4D) is well characterized by the low-frequency band, especially since the 1980s when this band reached positive values, with maximum point in the 1990s. The possible phase inversion of this band may indicate reduction in the flow of this sector.

As for the projections to the period of 2007–2016, the noise amplitude grows with the horizon of the projection, which seems consistent with the uncertainty representation associated with climatic processes. The high-frequency band shows noise with high amplitude, higher than one standard deviation for Água Vermelha, Sobradinho, and Itaipú, which characterizes much uncertainty in this variation pattern. The model identifies patterns in the mean and low-frequency bands, indicating phase changes in the mean frequency band of Sobradinho and Água Vermelha in the evaluation period associated with minimum points in the low-frequency band, coincident with very dry years in the region.

In Itaipú, the bands differ in the response of NEB and part of Southeast region; therefore, the model suggests a possible reduction trend in the low-frequency band, identified by the model. However, the model suggests a reduction in the mean frequency band since the fourth projected year, which does not happen.

Figure 7 shows the likelihood ratio between WAR model (represented by the median of the scenarios) and the climatology. Comparing the model with the climatology of the time series of streamflow in the NIS, it demonstrates gain in most of projections over the country between 5 and 10 years. In southern Brazil, the model presents a best performance than climatology in most of BPs in until 4 years of projection; after this projection time, the model loses efficiency, that is, the climatology has a better performance in most of BPs.

It is noteworthy that, in regions strongly influenced by ENSO-driven interannual variability, like the northern and southern Brazil, several BPs exhibit likelihood ratio < 1 in projection periods above 4 years, highlighting the south region. Further of this ENSO-driven interannual variability, Jesus et al. (2016) pointed that the weather and climate in some regions of Brazil, more specifically in the southeastern South America, have a strong relation with Cold Fronts (CFs), which act on a smaller timescale (synoptic scale) from that considered in the WAR model (interannual). These abovementioned two points may have affected the performance of the model in these regions.

Figure 8 shows the projections for the years from 2017 to 2026 of the WAR models for the Água Vermelha, Sobradinho, and Itaipú stations. For Sobradinho, the model indicates above the historical average flow, probably associated with the end of the warm phase of both PDO and AMO. Água Vermelha responds in a similar way, however, with a maximum lag in the mean frequency band from 3 to 4 years regarding to Sobradinho. In contrast, in Itaipú, the model suggests reduction in the low-frequency band, which suggests reduction in the south sector of the country.

Discussion and Conclusions

In this study, time series analyses showed different behaviors in the annual average flow regarding the trend in the period from 1931 to 2016, depending on the region of hydroelectric sector. There is a positive trend in the South region and a negative trend in the Northeast region of the country. Meanwhile, in the North and Midwest regions, most of the exploitations do not present a meaningful trend.

The series of average annual flow also showed traces of interannual and decadal variability. This pattern can be associated with temperature oscillations in the surface of Pacific and Atlantic Oceans. Most of the low- and mean frequency modes are related to the PDO and significantly affect the flow regime in the stations of the NIS. The analysis presented in this study indicates that there are changes in flow values coinciding with changes in the PDO index. Therefore, there is a correlation between the PDO index and the changes in the level of the average annual flow for most of the analyzed stations and more strongly for the stations in the North and Northeast sectors of the NIS. For this reason, the stationarity hypothesis of the streamflow series can be discarded in several NIS locations.

The WAR model can recognize the various patterns of the streamflow time series in the Brazilian electric sector and project

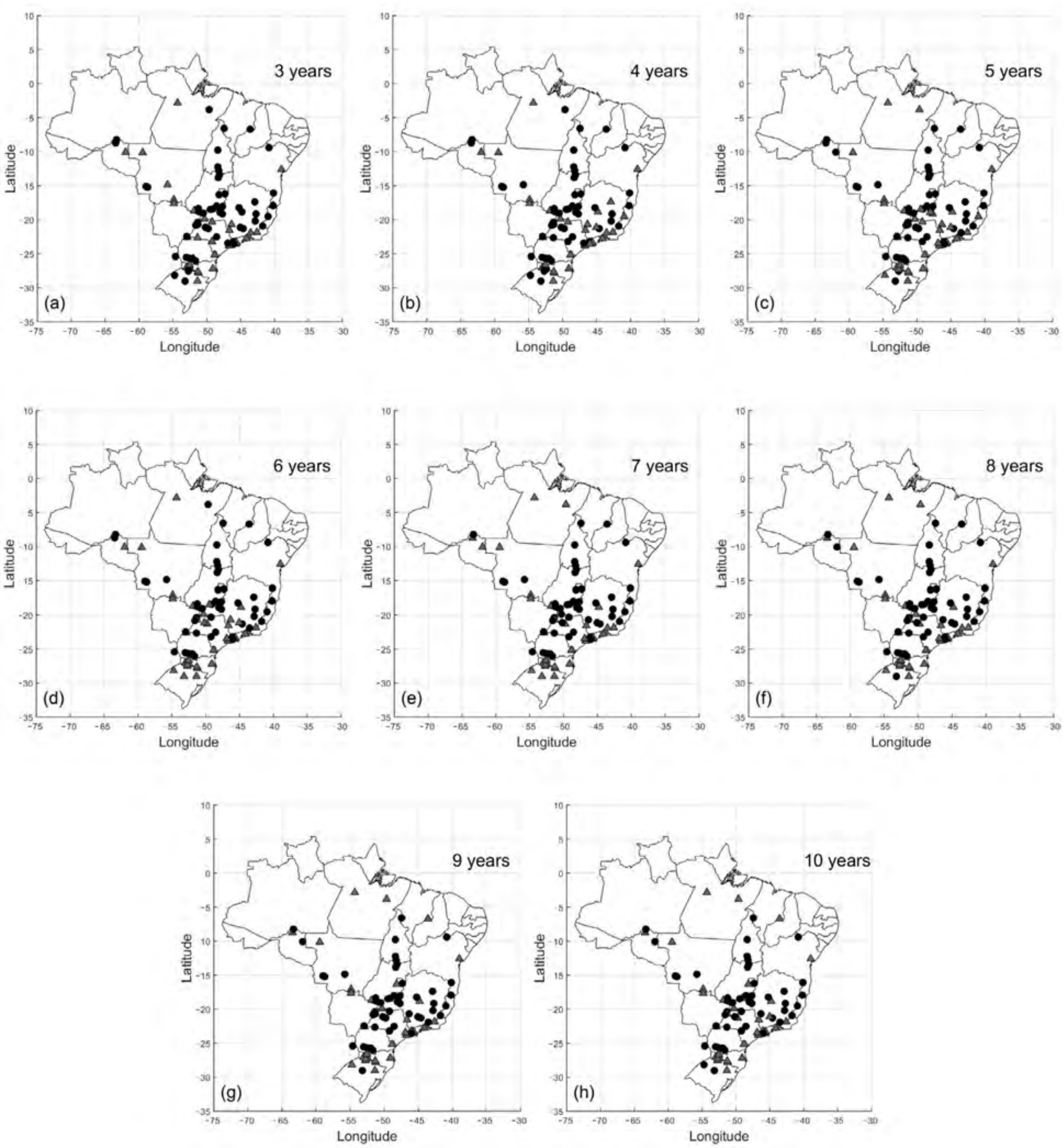

Figure 7 – Likelihood ratios between the WAR model and the climatology for the base posts of NIS. Likelihood ratios > 1 are represented by black circles and < 1 by gray triangles.

the subsequent years. This model presented a better performance than the climatology in most of NIS stations analyzed, indicating that it can be used by managers in the planning of energetic policies and in the search of measures that minimizes the impacts of climate variability on society. In contrast, several BPs in the North and South regions of Brazil presented worse performance than the climatology. It is worth mentioning that these regions are strongly influenced by ENSO-driven interannual climate variability. Furthermore, phenomena that act in a smaller timescale from that considered in the WAR model, such as CFs in synoptic scale, influence the climate in some regions of Brazil. Thus, it is supposed that these points could be responsible for the lower performance of the model in some Brazilian regions, especially the South region of Brazil.

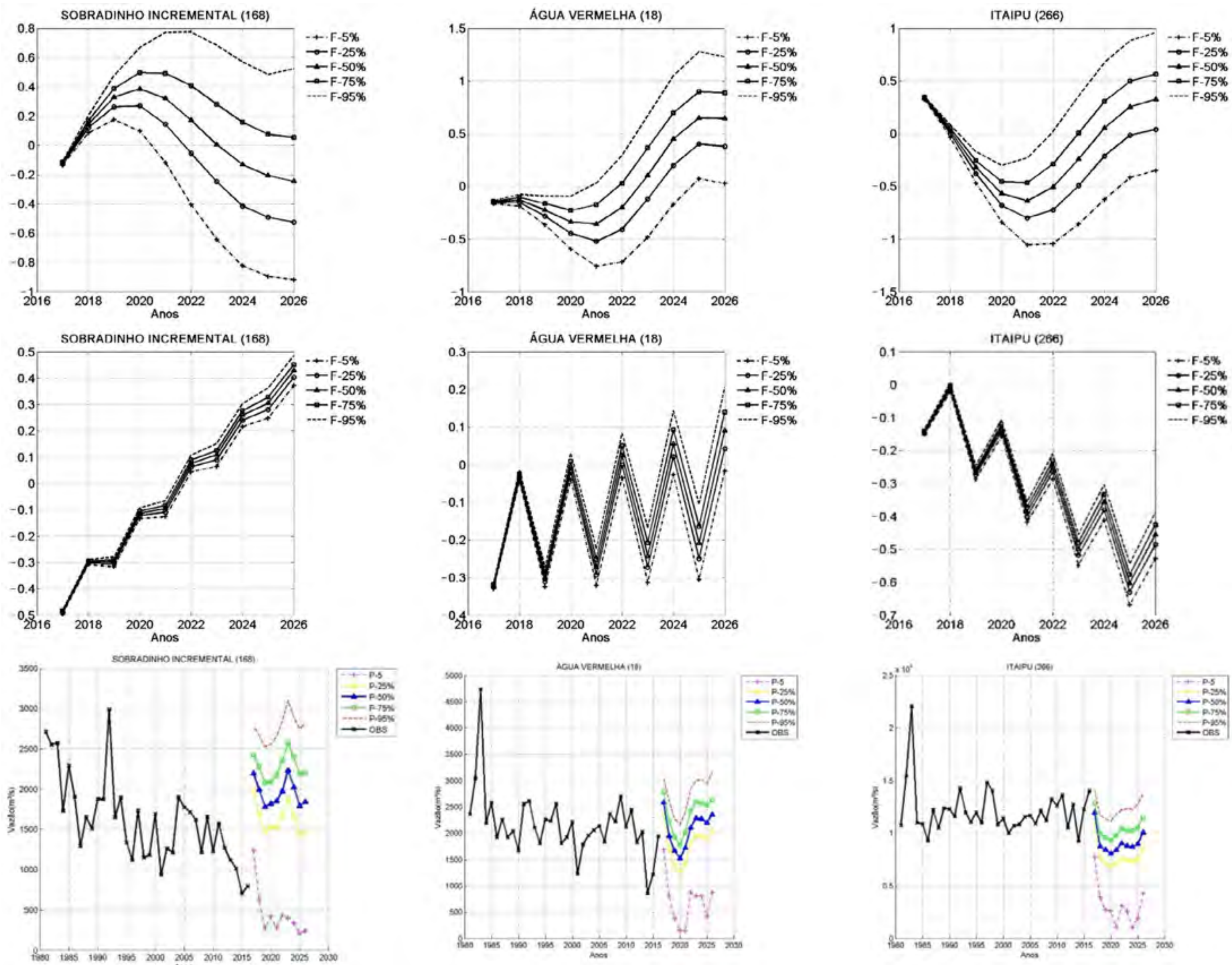

Figure 8 – WAR model streamflow projections for the period from 2017 to 2026.

This methodology permits the evaluation of the flow guarantees and regularization considering the non-stationarity of the time series due to the low-frequency variability, thereby enabling assessment of the guarantees in granting water use and dynamically dealing with the risk.

The energy growth projections indicate that its expansion occurs mainly in Northern Brazil. Therefore, it is necessary to account for the climate variability as one possible element of reduction or increase in the energy supply of the region. Furthermore, it is fundamental that the Brazilian energy growth policy regard, for a long-term energy security, mitigation strategies of both climate change and climate variability impact, an improvement of energetic efficiency, and an increased participation of renewable sources of electricity in the Brazilian energy matrix, which do not have a high sensibility to climate variability.

Contribution of authors:

Lima, C.E.S.: Conceptualization, Methodology, Validation, Software, Formal analysis, Investigation, Resources, Data curation, Writing — original draft, Writing — review and editing. Silva, M.V.M.: Software, Formal analysis, Investigation, Resources, Data curation, Writing — review and editing. Silveira, C.S.: Conceptualization, Methodology, Validation, Software, Formal analysis, Investigation, Resources, Data curation, Writing — original draft, Writing — review and editing, Visualization, Supervision. Vasconcelos Júnior, F.C.: Writing — review and editing, Visualization, Supervision.

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Animal welfare assessment in nine dog shelters of southern Brazil

Avaliação de bem-estar animal em nove abrigos de cães do Sul do Brasil

Luciana do Amaral Gurgel Galeb[1], *Tâmara Duarte Borges*[1], *Camila Jardim dos Santos*[1], *Cecília Pedernera*[2], *Antonio Velarde*[2], *Amanda Anater*[1], *Alexander Welker Biondo*[3], *Cláudia Turra Pimpão*[1]

ABSTRACT

The present study has tested the Shelter-Quality Protocol (SQ) and its applicability in nine long-term dog shelters in the Curitiba metropolitan area, State of Paraná, southern Brazil. Welfare indicators were scored on three different levels including shelter, pen and dogs. Data were qualitatively analyzed, presenting an average of 66.67 (±27.63) allocated dogs per shelter, receiving only dry food, with meal frequencies varying from once (44.4%), twice a day (33.3%), and *ad libitum* (22.2%). Water was available *ad libitum* in 98.5% of pens and was clean in (89.5%) of shelters. Most of the shelters grouped the dogs by size. Animals were kept indoors (41.0%) or entirely outdoors with only close movable shelters (41.3%), from which 78.5% had materials that could hurt the animals. None of the dogs were panting, crowding, or had any stereotypy behavior. No cough, swelling, and ectoparasites were observed. Animals were in satisfactory body-score condition and clean; no lameness was observed. In the human-animal relationship test, 15.3% of animals showed fearful and aggressive reactions. Hence, the level of shelter-quality was feasible and provided relevant information about the Brazilian dog shelter welfare. However, it is important in future studies to include and adopt additional indicators to gather other relevant aspects of dogs' welfare, such as health management, environmental enrichment, dogs' socialization, people involved in the chain, rate of adoption, and turnover of dogs.

Keywords: shelter medicine; population control; ethology; abandonment; relinquishment.

RESUMO

O presente estudo testou o Protocolo Shelter-Quality (SQ) e sua aplicabilidade em nove abrigos de cães de longa permanência na região metropolitana de Curitiba, estado do Paraná, Sul do Brasil. Os indicadores de bem-estar foram pontuados em três níveis diferentes, incluindo abrigo, recinto e cães. Os dados foram analisados qualitativamente, apresentando média de 66,67 (±27,63) cães alocados por abrigo, que recebem apenas ração seca, com frequência de alimentação variando entre uma (44,4%), duas vezes ao dia (33,3%) e *ad libitum* (22,2%). A água estava disponível *ad libitum* em 98,5% dos currais e era limpa em 89,5% dos abrigos. A maioria destes agrupou os cães por tamanho. Os animais eram mantidos em ambientes fechados (41,0%) ou inteiramente ao ar livre, apenas com abrigos móveis próximos (41,3%), dos quais 78,5% possuíam materiais que pudessem machucar os animais. Nenhum dos cães estava ofegante, aglomerado ou com comportamento estereotipado. Não foram observados tosse, inchaço e ectoparasitas. Os animais estavam em condição corporal satisfatória e limpos; nenhuma claudicação foi observada. No teste de relação humano-animal, 15,3% dos animais apresentaram reações de medo e agressão. Assim, o nível de qualidade do abrigo foi viável e forneceu informações relevantes sobre o bem-estar do abrigo de cães brasileiros. No entanto, é importante em estudos futuros incluir e adotar indicadores adicionais para reunir outros aspectos relevantes do bem-estar dos cães, como gestão da saúde, enriquecimento ambiental, socialização dos animais, pessoas envolvidas na cadeia, taxa de adoção e rotatividade de cães.

Palavras-chave: medicina veterinária do coletivo; controle populacional; etologia; abandono; desistência.

[1]Pontifícia Universidade Católica do Paraná – Curitiba (PR), Brazil.

[2]Institute of Agrifood Research and Technology – Monells, Girona, Spain.

[3]Universidade Federal do Paraná – Curitiba (PR), Brazil.

Correspondence address: Luciana do Amaral Gurgel Galeb – Rua Imaculada da Conceição, 1,155 – Prado Velho – Zip Code: 80215-901 – Curitiba (PR), Brazil. E-mail: lucianagaleb@hotmail.com

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Introduction

The worldwide population of domestic dogs has been estimated at around 700 million, with around 75% identified as "free-roaming" (Smith et al., 2019). Out of this total, an estimated 52.2 million dogs (7,5%) live in Brazil, representing 1.8 dogs per household. In the southern region of Brazil, 58.6% of households have at least one dog, the highest proportion in Brazil (Arruda et al., 2020).

Thus, the "unowned" or stray dog population's growth is a significant problem in urban centers, especially in developing countries (Smith et al., 2019). The World Organization for Animal Health (OIE, 2018) estimates that there are approximately 200 million stray dogs globally and 30 million only in Brazil. As a result of systematic and multi-causal abandonment, stray dogs present a social and economic problem related to the costs of population control strategies and zoonotic risks, especially in Latin America (Mota-Rojas et al., 2021).

Stray dog reallocation to shelters has been a Brazilian governmental strategy for free-roaming dog populations, besides responsible guard education, castration, and community dog programs (Kwok et al., 2016; Mota-Rojas et al., 2021). Within this context, dog shelters are getting increasingly overpopulated, which can directly compromise animal welfare, particularly in long-term shelters where dogs present lower adoption rates (Raudies et al., 2021).

A dog shelter is a place that receives and takes care of a considerable number of these animals, most of which were collected from the streets. Its main activities are being a safe haven for animals, acting as a place of passage, seeking permanent homes, and being a reference center in terms of animal care, control, and welfare programs, facilitating the safe release back into society. Meeting the needs of animals in the shelter environment is not an easy task and requires a lot of planning and commitment, including physical and behavioral assessments (Clay et al., 2020).

Building and maintaining a shelter requires many other considerations, such as obtaining a license, meeting regulatory requirements, planning activities, and staff training. The shelter is not always the best strategy to solve animal welfare problems. These places do little to solve the problem of stray animals, and provide no solution to animals on the street. Inadequate planning, lack of experience, and insufficient resources can seriously compromise the welfare of shelter animals, and, if the dog stays too long, adoption becomes more difficult due to social isolation, one of the major stressors for dogs living in animal shelters (Gunter et al., 2019).

Shelters should be one of the strategies that make up a humane management program, which aims to collect, rehabilitate, and reintroduce animals into society through adoptions (Arruda et al., 2019; Arruda et al., 2020). In addition, shelters can be governmental, private, non-governmental organizations, or government-controlled private entities. In Paraná, in southern Brazil, government-run shelters include Municipal Kennels, Zoonosis Control Centers, Zoonosis Surveillance Units (Brasil, 2016), Animal Screening Centers and Reference Centers for Animals at Risk (Prefeitura de Curitiba, 2016). In Paraná, all municipal shelters work as animal adoption sites (Arruda et al., 2020).

Regardless of the shelter type, size, or ownership, dogs are often subjected to specific stressors just by being in a shelter environment (Arruda et al., 2019), and unfortunately they might spend a long period of their life without any important behavior stimuli (Gunter et al., 2019). This proliferation of long-term dog sheltering, combined with low adoption rates and absence of facilities or basic management standards, has become a vital concern for kenneled dogs and their welfare assessment (Miller and Zawistowski, 2014; Polgár et al., 2019). Furthermore, although there is a growing interest in improving dog welfare in Brazilian shelters, acceptable management practices are often limited due to staffing, time, and budgetary constraints (Mota-Rojas et al., 2021).

So far, there have been no studies that assess shelter dogs' welfare at housing and animal level in Brazil, even though it is a well-known problem. Measuring dog welfare in shelters is not an easy task because many indicators must be applied involving shelter management, housing, environmental conditions, dog health, sociability status, food quality restriction, lack of veterinary care, and even genetic changes (Clay et al., 2020; Raudies et al., 2021). Therefore, it is essential to have a tool that directly evaluates the real welfare state of dogs housed in shelters by simultaneously observing all these indicators.

The Shelter Quality protocol was developed to provide a valid, reliable, and practical tool for assessing shelter dog welfare (Berteselli et al., 2019). This protocol was built and based on Welfare Quality® protocols for livestock (Welfare Quality, 2009), and respected the four welfare principles — good feeding, adequate housing, good health, appropriate behavior, having the twelve specific shelter dog outcome criteria.

There is a historic scientific recognition about animal captivity (Cambridge Declaration, 2012). Consequently, its degree of well-being is defined as the mental and physical state of the animal based on its attempts to adapt to its environment. Therefore, knowing the holding environment of shelter animals and their management is critical for diagnosing and implementing improvements (Berteselli et al., 2019).

Accordingly, to estimate the actual welfare state of the Brazilian dog shelters, this protocol was applied, and further indicators were proposed to bring the protocol closer to the Brazilian reality.

Materials and Methods

This study was approved by Pontifícia Universidade Católica do Paraná (PUCPR), by the Animal Research Ethics Committee (CEUA), under protocol number 01129, and by the Ethics Committee for Research on Human Beings (CEP), under number 2.401.931.

Nine dog shelters were visited in Curitiba's metropolitan region (Figure 1). Only those shelters that voluntarily accepted to participate in the study were considered. The Shelter Quality (SQ) protocol was applied to assess the dogs' welfare using well-defined parameters, divided into four principles and twelve evaluation criteria (Table 1).

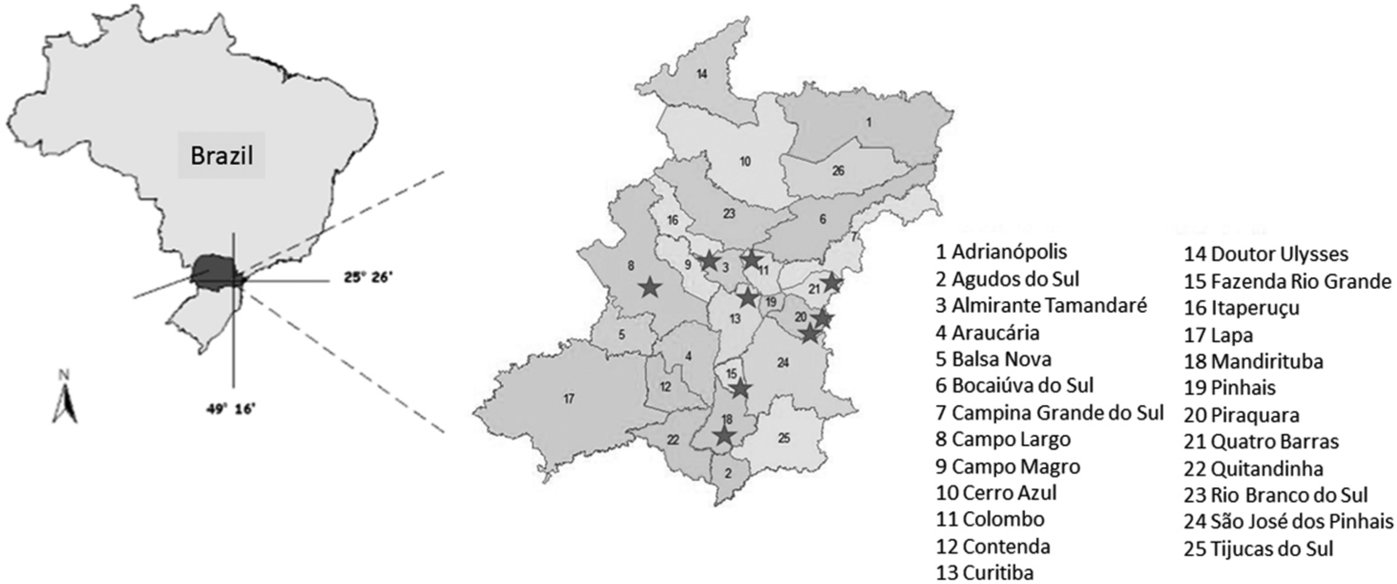

Figure 1 – Nine shelter locations evaluated in Curitiba-PR in the metropolitan areas, Brazil.

Table 1 – Animal welfare indicators based on Shelter Quality® protocol.

Principles	Criteria	Measures
Good feeding	Absence of prolonged hunger	- Body condition - Feeding
	Absence of prolonged thirst	- Water supply
Good housing	Comfort regarding resting	- Bedding - Sharp edges - Cleanliness
	Thermal comfort	- Shivering - Huddling - Panting
	Ease of movement	- Space allowance
Good health	Absence of injuries	- Skin condition - Limping
	Absence of disease	- Evidence of pain - Diarrhea - Coughing - Mortality - Morbidity
	Absence of pain induced by management procedures	- Surgeries - Pain relief
Appropriate behavior	Expression of social behaviors	- Social housing
	Expression of other behaviors	- Abnormal behavior barking - Stereotypy - Exercise
	Good human-animal relationship	- Reaction to humans
	Positive emotional state	- Emotional state – QBA

For each criterion, there were specific indicators based on the shelter's records (management data), based on environmental resources (facilities), and the animals (behavior and health). The protocol was applied by a single evaluator who was trained by one of the SQ authors.

The study was divided into two steps: the first one was the Shelter dog welfare evaluation by SQ protocol, and, finally, the adaptation of the protocol indicators and suggestion of new measurements based on the Brazilian reality.

Management-based indicators involved a questionnaire that was answered by the shelter manager or another competent person, and referred to the total shelter dog population and its condition on the day of the visit, including the following variables:

- number of dogs in the shelter;
- number of hospitalized dogs;
- operating procedures for post-surgical monitoring;
- analgesia protocol;
- whether dogs were walked on leash by shelter personnel or by volunteers;
- number of hospital pens;
- number of single pens (pens containing only one isolated animal), pens in pairs, pens in groups of less than 5 dogs, and pens with more than 5 dogs;
- total number of shelter pens;
- outdoor area and size;
- number of euthanized animal for health and behavioral reasons;
- number of deaths other than euthanasia;
- animal behavioral assessment by a visual analog scale, called QBA (Qualitative Behavior Assessment);
- the type of diet (dry pellet, cooked, wet/canned);
- whether there was any specific diet for puppies, geriatrics or hospitalized animals;
- feeding regime (once a day, twice a day, or *ad libitum*);
- annual shelter clinical treatment expenses.

Resource-based indicators assessed animal pens, their living environment, and all animals confined to them (regardless of the number of dogs), thus, assessing:

- the number of animals over and under 20 kg;
- pen area dimensions;
- whether there was any indoor space (for sun protection) and outside area;
- beds and their type;
- sharp edges in the animals' living environment;
- type and function of water supply;
- water cleanness;
- the number of animals panting, shivering, huddling;
- the number of animals barking insistently in the evaluator's presence;
- the number of stereotyped animals (active repetitive/other compulsive behavior);
- the number of animals in pain;
- diarrhea on the pen floor.

Animal-based indicators included:

- animal age class;
- body condition;
- animal cleanness;
- number of animals hurt;
- hair loss;
- swelling;
- ectoparasites;
- limping;
- cough;
- human-animal relationship tests.

For these evaluations, a dog subsample was individually evaluated according to the sample proposed by the protocol (Table 2), using the minimum sample required for reliable data.

Since it is a descriptive study with a methodological approach, all welfare indicators of the nine evaluated shelters were compiled into a database and were synthesized, analyzed, and presented in a predominantly qualitative manner to summarize and describe the most important aspects of the Brazilian shelter dog welfare.

Results

Indicators based on shelter management

On average, the shelters housed 66.67 (±27.63) dogs, ranging from 112 to 21, according to the largest and smallest shelters assessed. Dogs were mostly housed in pens with less than 5 animals, representing 32.30% (n=42), formed by groups of mainly four dogs. However, a high rate of single housing was also observed in 26.15% (n=34), excluding 9% (n=11) of dogs that were in isolation for health reasons. Most of the animals (91%, n=23) were isolated due to behavioral problems, with aggressiveness being the main cause.

Five (55.5%) out of nine shelters visited left the dogs in an outdoor fenced area every day, while three (33.3 %) had no outdoor access. Just in one shelter (11.1%) dogs were walked on a leash by volunteers once a week. All shelters provided dry pellets to the ani-

Table 2 – Sample suggested by the *Shelter Quality*® protocol for individual assessment based on shelter population size.

Total number of dogs in the shelter	Total number of dogs to be evaluated
Up to 59	30
60-89	40
90-139	50
More than 140	60

mals with a noncooked or wet/canned diet. Furthermore, all shelter managers continuously offer a mix of dry pellet ingredients and raw materials based on donation availability. However, most of the shelters (n=9) had a standard procedure to provide a special diet for puppies (88.8%, n=8), as well as mature (77.7%, n=7), and hospitalized (88.8%, n=8) animals. Meals varied in shelters, where 44.4% (n=4) provided animals with food once a day, 33.3% (n=3) twice and 22.2% (n=2) *ad libitum*.

Regarding surgical procedures, 77.7% (n=7) of the managers said that the shelters had postoperative monitoring, and 66.6% (n=6) affirmed to have some analgesia protocol, especially for castration surgeries. Nevertheless, just a few shelters had specific pens for keeping the hospitalized animals; on the day of the visit, only one shelter (11.1%) demonstrated this resource. Shelters recorded 4.5% (n=27) of natural deaths without human intervention, adding to the rate of 2.5% (n=15) of dogs euthanized for health reasons, and 0.16% (n=1) euthanized for behavioral problems.

Pen evaluation

In total, 130 pens were evaluated; 37 % (n=48) of them housed animals weighing more than 20 kg (large dogs), 42% (n=55) housed animals weighing less than 20 kg (medium dogs), and 16 % (n=21) had mixed large and medium-sized animals in the same pen. Exclusive small dog (less than 10 kg) pens were also present in Brazilian shelters with a 5% (n=6) prevalence.

The pens with only an indoor area and no outdoor access represented 41% (n=53) of the cases; in contrast, 41% (n=53) of the shelters only had an outdoor area with a small, roofed area within a movable shelter made of plastic or wood material, which allows the animal to hide from mild adverse weather conditions. Finally, 18% (n=24) of the pens had both indoor and outdoor areas. The pens had on average 65.65 m² (±10.12), ranging from 100 m² for the largest one, and 4 m² for the smallest.

Regarding bedding (considered by the protocol as any structure that allows dogs not to have direct contact with the floor, that is easy to clean and disinfect, and made of good material, ensuring the safety of the dog — i.e., without harmful edges or ingestible parts) 78% (n=101) of the pens had appropriate bedding requirements. However, 9% (n=12) of the pens had less than one bed per dog, dangerous conditions (9%, n=12), or the material provided was wet or with feces (4%, n=5).

The most common type of bed found was the movable shelter (79%, n=102), followed by the basket bed (11%, n=14), and a bed with a pallet material (6%, n=8). Most of the pens (79%, n=103) had visible edges in the environment that could hurt the animals, the most common being wires and wood pieces.

Drinking water was supplied in bowls or buckets, which were manually filled by shelter staff in 99% (n=128) of the pens, and the remainder pens (1%, n=2) provided water in cement troughs. No automatic drinker was found in any shelter. Of all pens evaluated, 9% (n=12) of them had little or no water available for the dogs. Regarding drinker safety, only 4% (n=5) were not considered safe because they contained sharp edges or rust. The water was clean in 90% (n=117) of the evaluated pens, with the other 10% (n=13) with feces and sludge inside.

During the behavioral evaluation at the visit, no animals were found under thermal stress conditions since no animal was shivering or panting. In the behavioral assessment, it was observed that 28% (n=37) of the pens had insistently barking dogs (defined by the protocol as a short and repetitive continued vocalization), 0.18% (n=2) had animals with behavioral characteristics of pain, and 0.56% (n=7) with diarrhea on the ground. No dogs were observed performing stereotyped movements or any other compulsion.

Individual animal evaluations

A total of 131 dogs were evaluated individually, 97% (n=127) of them were adults (between 1 and 6 years old) and 3% (n=4) were elderly (over 6 years). Young animals (under one year old) are not evaluated by the protocol. Thus, most of the dogs (99.3%, n=130) had an adequate body score condition, and only one animal (0.7%) had an overweight score (obese). All animals were clean, no coughing, no big injuries, and no ectoparasites. There were a few skin wounds (6.16%, n=8) and alopecia conditions (9.24%, n=12) in the animals. However, it is noteworthy that, only in one shelter, out of the 19 dogs evaluated, 7 had hair loss (representing 36.8% of the total for this shelter). It can be inferred that such alopecia is associated when the type of material used to cover the ground around the animal pen is wood straw, which, when in constant contact with the animals' coats, may cause irritation and extensive hair loss at this specific shelter.

Regarding limping, only 2 dogs from different shelters presented moderate limping score (1.5%). During the fear test, 84.6% (n=110) of the animals showed no signs of fear or aggressiveness in the presence of the evaluator. However, in two shelters (22.2%), out of 39 animals evaluated, 19 showed signs of fear, dodging, or hiding in human presence (48.7%).

Welfare indicators added in SQ protocol

Shelter management

The protocol adaptation consisted of identifying, during SQ application, critical points of Brazilian shelter dog welfare that were not included in the protocol or did not have any indicator to assess. During the management questionnaire, eight questions were added to better characterize the shelters:

- vaccination protocols, endo and ectoparasites control;
- environmental enrichment;
- dog socialization program;
- castration program;
- shelter adoption rate and turnover dog rate;

- the number of stakeholders involved in shelter activities;
- main shelter income;
- detailed veterinarian care.

It was found that all the shelters had a vaccination protocol with an annual calendar, including multipurpose and rabies vaccines. However, deworming was received twice a year just in one shelter (11.1%), and that was because of pharmaceutical donations. For ectoparasite control, two shelters (22.2%) said they performed environmental control, and no shelters administered animal drugs for this purpose.

Environment enrichment was present in just one shelter (11.1%) in a single dog's pen, consisting of a raw bone functioning as a portion of food and bite item. Two shelters (22.2%) affirmed to have a dog socialization program. In one of them, the socialization was developed by a veterinary student group (n=8) consisting of a one-hour session, three times a week, as part of a Vet course subject. The students performed basic dog training and inter and intraspecies socialization techniques. The other shelter had volunteers during the weekends who interacted with the dogs in 30-min sessions in each shelter pen, one person at a time.

All the shelters evaluated were registered in the Brazilian government castration program, performing an average of 6.2 (±2.0) castrations per month. In general, the adoption rate in Brazilian shelters is low, with an average of four animals being adopted in each marketplace (usually four per month), aside puppies, whose adoption is higher. In all the shelters, the dog turnover had dog behavior as the main problem, non-adaptation to the environment, increasing destructive and aggressive behavior.

Few people were involved in daily shelter activities. It was more common to find just three (66.6%) or four (33.3%) fixed workers for each shelter. All the shelter costs (food supply, cleaning and maintenance, medical care, employees salary, water, and energy were mainly paid by donations raised through shelter campaigns (88.9%, n=8), with a few having some governmental supply (11.1%, n=1).

All shelters except one (which represented 11.1%) did not have their own veterinarian, and different professionals attended dogs at private clinics or veterinary hospitals (88.9%, n=8).

Pen evaluation

Hygiene assessment was included in the Brazilian protocol, once 88.8% (n=8) of the shelters had the floor clean (scored 0), without urine and feces accumulation during the visit. However, 22.2% (n=2) of the shelters scored 1 — with the floor dirty and wet.

We also added a new pen classification according to dogs' size and weight, once an exclusive pen for small-sized dogs (less than 10 kg) appeared in 5% (n=6) of Brazilian shelters. It was also necessary to include another type of bed (despite those required by the original protocol) with pallet material. This characteristic bed was present in 6% (n=8) of the evaluated shelters.

The positive emotional state (QBA assessment) was not applied in this study since the evaluator did not feel confident in applying the methodology, nor performing the measurements. For individual animal evaluations, no other parameters were added.

Discussion

The uncontrolled stray dog population on the streets is perceived by society as a problem, both because of the zoonoses risk and, more recently, the recognition of animal suffering (Arruda et al., 2020).

The Federal Constitution of 1988, in its Art. 225, was the first in the world to consider cruelty to animals. There is also the Environmental Crimes Law 9.605/98, Art. 32 (Brasil, 1998), which provides that mistreatment of animals is a crime. This law has been recently amended by Law 14,064, of September 29, 2020, which increased to 5 years the penalties provided for the crime of mistreatment of animals when it comes to dogs or cats. Furthermore, in Paraná, State Law 14,037/2003 establishes protective measures for animals, while State Law 17,422/12 prohibits the extermination of dogs and cats for population control purposes.

Public shelters in Paraná have a proposal to care for the animals at risk, through Ordinance No. 1138/2014. The Ministry of Health establishes that the Zoonosis Surveillance Units (ZSU) perform public health services focused on the surveillance, prevention, and control of zoonoses (Brasil, 2014). Thus, ZSUs can house street animals suspected of zoonotic diseases, aggressive dogs, and cats with a history of biting people, and victims of mistreatment or abandonment on public areas. Thus, regardless of their mission, all these establishments must follow the precepts of shelter medicine (Arruda et al., 2019).

Shelters are facilities that keep a considerable number of animals, usually coming from situations of risk or abandonment. These facilities should rehabilitate, re-socialize, and reintroduce the animals into society through adoption, that is, they are places of passage; they should be a reference in veterinary care, animal welfare, and educational programs on responsible ownership and for preventing abandonment (Mota-Rojas et al., 2021).

The SQ protocol was widely applicable to Brazilian shelters with the inclusion of some additional indicators that complete the welfare diagnosis. So far, no study has been published involving a complete animal welfare assessment in Brazilian shelters.

Barnard et al. (2016), using the same protocol tool, evaluated 29 shelters in different countries — Italy (11), Spain (10), Croatia (3), Romania (3), Serbia (1) and Montenegro (1) —, concluding that systematic data collection across different countries provides relevant information that could be included in policy-making processes, or integrated in international organization recommendations as the World Organization for Animal Health (OIE) code. The authors also highlight that those refined measures could also provide important research advance.

Brazilian shelters had the characteristic of being mainly maintained by donators, with a few government suppliers (Catapan et al., 2015). This particularity often risks dog welfare due to the constant absence of basic resources. However, no animal welfare diagnosis has been used to point out the Brazilian challenges and qualities. Thus, the present study brings an overview of shelter dog welfare and places Brazil in the welfare framework and their world ranking.

After the nine-shelter assessment, the mainly Brazilian management welfare problems are: low rate of single dog housing; a percentage of indoor facilities lacking outdoor access for dogs; varying diet because of mixing different ingredients based on type of food donated; few shelters with specific pens for hospitalized animals; percentage of natural deaths; deworming and ectoparasite control failure; lack of environment enrichment; low adoption rate and few shelter employees.

It is common knowledge that providing dogs with social contact moderates their temperament over time, making it more attractive for adoption and probably increasing their welfare (Arruda et al., 2020). Isolating an animal causes intense frustration since the dog, an intrinsically social animal, is unable to make physical contact, compromising animal welfare particularly in long-term shelters (Raudies et al., 2021). Other drastic changes include increased excitement and aggression, which may require a behavior modification program (Clay et al., 2020). In Brazilian shelters, dogs with the worst behaviors are the ones that are put into isolation. This suggests that the cases will become even worse, significantly reducing the adoption chances for these animals, perpetuating their shelter enclosure.

Dogs also commonly sunbathe to stimulate important vitamins production for their maintenance and because sun exposure releases serotonin, responsible for pleasant sensations (Serpell, 2016). Shelters that did not provide the dogs with outdoor areas are directly impairing animal welfare. The shelter environment itself is characterized by a large proliferation of pathogens (Smith et al., 2019) easily transmitted from dog to dog, causing unhealthiness in dogs. In this study, only one shelter had hospital pens, which may represent a health risk. Together with feed quality, deworming and ectoparasite control failure, this could worsen animal health, reflecting on natural deaths in Brazilian shelters.

At the pen level, the main factors that affected the dog welfare were poor environmental conditions, and visibly sharp edges that could hurt the animals. Many of these points were related to facility maintenance, which intrinsically needs financial investment. The problem worsened with the shortage of people involved in daily shelter activities.

Regarding the bed, almost all types were considered adequate for dogs; however, none proved to be effective in offering thermal comfort to the animals in low temperature situations. We suggest, as a complementary indicator, that shelters have temperature measurement (a thermometer) in the dogs' sleeping accommodations in order to identify the risk of thermal stress during the year.

Another issue at the pen level evaluation is barking, destructive and repetitive behavior in Brazilian shelters, indicating a high stress level, as previously described in Austrian no-kill shelters (Raudies et al., 2021). Depending on the noise level, barking could damage a dog's hearing. Although dogs living in the shelter for a prolonged period may decrease barking over time, panting increases it, which reflects fatigue and acute anxiety (Clay et al., 2020).

During the individual evaluation, skin wounds and alopecia at a specific shelter deserved attention, mainly because of the inappropriate material used to cover the ground. The wood straw used, when in constant contact with the animals, can cause alopecia and wounds; as a result, an allergic reaction and other skin disorders may occur (Dowgray and Shaw, 2018). The allergic procedure causes intense itching associated with a painful sensation, significantly decreasing the animal's welfare.

All in all, the Brazilian shelter dog welfare depends on several factors related to the animal itself, management procedures, and the environment, which can be addressed to improve the animals' coping abilities and adaptation (Rowan and Kartal, 2018). SQ protocol addresses various criteria and critical points of dog welfare, proving to be a useful tool in a scientific manner, or as normative standards, and offering a practical tool for shelter managers to identify potential welfare risks to animals under their care. By improving Brazilian shelter management, we expect to provide a better quality of life for dogs by avoiding suffering situations. Finally, dogs may play an important part in the Brazilian cultural shifting, in which most families now consider their pet dogs as non-human family members, as previously reported in the USA (Rowan and Kartal, 2018).

Conclusions and animal welfare implications

The quality of the shelters interferes with the welfare, behavior, and adoption of these animals. Therefore, it is essential and relevant to evaluate the animals' and the shelters' quality, seeking to identify critical points that may harm the animals and should be corrected.

For dogs kept in shelters to have a high degree of well-being, their nutritional, health, environmental, psychological, and behavioral freedoms must be met; this requires adequate facilities, resources within the enclosures, and good facility management.

Based on the new reality, shelters have been trying to adapt their facilities, train their employees, invest in education on responsible ownership, and encourage animal adoption. The sterilization of these animals is also fundamental for an effective program of humane management. Therefore, it is essential to establish the animal capacity of each shelter. Shelters should also implement, monitor, and evaluate program efficiency, develop, disseminate, and enforce laws related to animal protection, register, and identify the animals, and offer preventive veterinary treatment to protect the animals' health and welfare, reducing zoonotic risk.

The SQ protocol is an internationally valid tool for assessing the welfare of shelter dogs, built on the four principles of well-being, good food, suitable accommodation, good health, appropriate behavior, and respecting and involving the five freedoms. In addition, it independently assesses facilities, existing resources, and shelter management.

SQ protocol was feasible and practical for Brazilian shelter dog evaluations with significant indicators, highlining the main critical points, and exalting those that had better results. Although it contemplates extra measures, it was necessary to make adjustments to the original protocol to gather more relevant dog welfare aspects. The included elements, such as health management (vaccination, endo and ectoparasite control, castration, veterinary care), availability of environmental enrichment, aspects of dog socialization, adoption, dog turnover dog rate, and several employees involved in the chain and shelter income, enriched welfare indicators. For further validation, this adapted protocol must be applied to many Brazilian shelters in different regions to characterize the dog shelters' current situation.

Considering that abandoned animals are protected by the State, it is of great importance to talk about public policies regarding shelters.

It is necessary to have specific laws for animal protection to ensure the safety and welfare of animals, but it is just as important to ensure sound management and proper functioning of shelters since living in this environment influences the animals' physical and mental health.

Issues such as population control, animal abandonment, animal abuse, and encouragement of adoptions must be handled together with the shelters. Only a systemic vision can find solutions to solve these issues that are of great importance to society's growth and evolution.

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Contribution of authors:

Galeb, L.A.G.: Conceptualization, Investigation, Methodology, Data acquisition, Data analysis, Writing – first draft; Writing – review and editing. Borges, T.D.: Conceptualization, Methodology, Data acquisition, Data analysis; Writing – first draft. Santos, C.J.: Data acquisition. Pedernera, C.: Methodology; Writing – review and editing. Velarde, A.: Methodology; Writing – review and editing. Anater, A.: Data analysis; Writing – first draft; Writing – review and editing. Biondo, A.W.: Data analysis; Writing – first draft; Writing – review and editing. Pimpão, C.T.: Methodology, Data analysis; Writing –– review and editing; Supervision.

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Identification of the urban heat islands phenomenon in a small city: the study case of Três Rios/RJ, Brazil

Identificação do fenômeno de ilha de calor em cidade de pequeno porte: estudo de caso de Três Rios/RJ, Brasil

Yuri Matheus Neves Silva[1], *Helder Martins Silva*[2], *Raiany Dias de Andrade Silva*[3], *Eduardo Duarte Marques*[4], *Olga Venimar de Oliveira Gomes*[1]

ABSTRACT

The phenomenon of urban heat islands (UHIs) is caused by an increase in temperatures in a given urban area as a result of human activities and is usually studied in medium and large cities. This study aimed to verify if the phenomenon of UHIs occurs in the city of Três Rios, RJ, a small-sized town. In this study, a mobile measurement transect was performed considering preestablished data collection points/stations. Five points were selected, including a rural area, an urban park within the city (Parque Natural Municipal), and three points within the urbanized area. The equipment used was the Brunton®/ADC PRO handheld weather station. The data collection period ranged from September 2018 to July 2019, which included the four seasons of the year. Measurements were taken at 6:00, 12:00, 15:00, 18:00, and 21:00 in alternate days during the study period. Considering the temperature measurements, two different indicators of thermal variability were used. Strong magnitude heat islands were detected taking into consideration the relevant variation of maximum temperatures observed in the urban area when compared to the rural area. The results point out that the most affected population are the ones located within urban areas, mostly individuals under socioeconomic vulnerability. The results obtained can be used as support for the development of strategies to minimize the thermal discomfort to populations exposed to the influence of higher magnitude UHIs.

Keywords: anthropogenic heat; small town; thermal magnitude; thermal anomaly.

RESUMO

O fenômeno ilha de calor urbana (ICU) consiste no aumento de temperaturas de uma área urbana e é influenciado pelo desenvolvimento de atividades antrópicas e comumente estudado em cidades de médio e grande porte. Esta pesquisa buscou verificar a ocorrência do fenômeno ICU na cidade de Três Rios/RJ, um município de pequeno porte. Para este trabalho foi estabelecido um transecto móvel de medição das temperaturas em locais com diferentes tipos de ocupação. Os pontos medidos foram: um na área periurbana, no parque municipal, e dois locais de urbanização consolidada, além de uma área rural, pontos estes para os quais foram considerados dados da estação meteorológica automática existente no município. O equipamento portátil utilizado foi uma central meteorológica Brunton®/ADC PRO. O período analisado compreendeu de setembro de 2018 a julho de 2019, englobando as quatro estações climáticas. As medidas foram realizadas às 6, 12, 15, 18 e 21 h em dias alternados dos meses em questão. Com base nas medições de temperatura, dois indicadores distintos de diferenciação térmica foram considerados, e foi possível constatar ilhas de calor de forte magnitude, considerando-se a relevante variação das máximas das temperaturas identificadas para a zona urbana em relação à zona rural. De acordo com a análise dos resultados, a população mais afetada seria a que reside na área urbanizada, sobretudo aquela em vulnerabilidade socioeconômica. Os resultados obtidos poderão servir como subsídios para a elaboração de estratégias que visem minimizar o desconforto térmico na população em áreas onde ocorreram maiores amplitudes sob influência das ilhas de calor.

Palavras-chave: calor antropogênico; região centro-sul fluminense; magnitude térmica; anomalia térmica.

[1]Universidade Federal Rural do Rio de Janeiro – Rio de Janeiro (RJ), Brazil.

[2]Universidade Federal do Rio de Janeiro – Rio de Janeiro (RJ), Brazil.

[3]University of Alberta – Edmont, Alberta, Canada.

[4]Serviço Geológico do Brasil – Belo Horizonte (MG), Brazil.

Correspondence address: Yuri Matheus Neves Silva – Instituto Três Rios, Universidade Federal Rural do Rio de Janeiro – Avenida Prefeito Alberto da Silva Lavinas, 1847 – Centro – CEP: 25802-100 – Três Rios (RJ), Brazil. E-mail: yurimatheus21@outlook.com

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Introduction

Air temperature can be affected by the human interventions in a region, once urbanization creates a new space and shifts general environmental conditions, such as creating changes in energy flow (Fialho, 2009). Gunawardena et al. (2017) explained that the energy absorbed by urban surface is related to solar radiation and to the anthropogenic heat generated, and that its balance is established by convection and humidity evaporation processes and by the configuration of the urban environment. The impacts of urban development on energy balance can define the climate within the cities, by not just causing thermal discomfort but also affecting habitat conditions and human health (Oke, 1988). Considering this scenario, the increasing level of temperatures within urban areas can lead to the phenomenon of urban heat islands (UHIs).

The phenomenon of UHIs is characterized by an increase in temperatures in an urban area when compared to the surrounding rural areas, and this is considered a consequence of anthropogenic influence (Ward et al., 2016). Analyzing the phenomenon of heat islands, in terms of an "urban energy balance," the way energy enters and leaves a system considers that the solar radiation that enters the system is retained for a longer period on artificial surfaces when compared to natural surfaces (Oke, 1988; Gartland, 2010; Gunawardena et al., 2017). The formation of UHI is influenced by several factors, such as the reduction in wind circulation, as a consequence of tall buildings; atmospheric pollution; reduction in tree cover; reduction of humidity rates; and the emission of particles (Yow and Carbone, 2006).

While the spatial configuration of cities can alter the energetic balance in a way that heat is retained, in rural areas, heat absorption is lower and the dissipation of solar radiation is more efficient. This is stimulated by the constant wind flow and vegetation cover, which naturally absorbs less heat and contributes to the increase in air humidity through evapotranspiration (Gallo et al., 2019). Moreover, the highest cover of permeable surfaces on natural spaces allows water infiltration, which contributes to the process of evaporative cooling (Gartland, 2010; Santos et al., 2012; Oliveira et al., 2018).

Studies on the relationship between the urban climate and human health found an association of thermal stress to pollution, thereby affecting children, elderly, and people in socioeconomic vulnerability with chronic disease (Gabriel and Endlicher, 2011; Scherer et al., 2013; Larsen, 2015). Also, studies pointed to the spread of infectious diseases as a consequence of climatic conditions of the cities (Munyuli et al., 2013; Ribeiro et al., 2016). According to the previous report published by the Intergovernmental Panel on Climate Change (IPCC, 2014), which examined the negative effects of UHI on the population, this phenomenon might aggravate and become more frequent in a near future. Considering this, Viegas et al. (2013), Dhar and Khirfan (2017) and Jiang et al. (2017) discussed the importance of evaluating and identifying UHI when making decisions about plans and adaptation projects regarding the impacts of urbanization and climate change and their mitigation.

Yamashita (1996) reported the occurrence of UHIs in Tokyo and concluded that these UHIs remained constant in the summer but presented thermal variation in the winter in different areas, reaching differences of 5°C. Montávez et al. (2000) showed that in the city of Granada (Spain), densely developed areas presented intense UHIs, showing an increase in temperature of up to 3°C when compared to the rural areas. In contrast, this same study registered a decrease in temperature of up to 1°C in a specific region, associated with the buffer effect of an urban park.

A study involving 397 global cities, between 2001 and 2007, considered the differences between urban and rural temperatures. This study pointed a significant variation in the intensity of temperatures of the cities with 42.1% for day time and 30.5% for night time (Yao et al., 2019). Vegetation was also pointed by the authors as an important factor driving differentiation between day and night times in rural areas, as it causes a lower variation in temperature. Amorim (2012) analyzed the variation in temperature during the day, taking into consideration the urban–rural configuration in the city of Presidente Prudente, SP, and observed that in the first hours of the day, the solar energy reaches the land surface in an inclined degree, which creates a "shade effect," making it difficult for solar rays to penetrate on the urban structure. Whereas in environments with sparse rural buildings, the transformation of solar energy from short to long waves happens more quickly, generating warmer environments.

Because of their magnitude, studies on UHIs are usually made on medium or big cities, such as Brasília (Vianna, 2018), Presidente Prudente — SP (Amorim, 2012), Belo Horizonte — MG (Almeida and Abreu, 2010), and Goiânia — GO (Nascimento and Oliveira 2011), in Brazil. Nowadays, some studies on the theme have also been published for small cities (i.e., cities with < 100,000 population), such as Ilha Solteira — SP (Romero, 2016) and Iporá — GO (Alves, 2016), and those have applied different methods.

Some of the methods used to analyze the effect of urbanization include geotechnical analyses, fixed-base weather stations, and mobile transects. Romero (2016) used images from the satellite Landsat 8/TIRS and found UHIs of weak and medium magnitudes, following the UHIs indicators proposed by Garcia (1996). Even though this is an effective method to visualize temperatures of large areas, the satellites that provide the images do not record continuous information along the day, as they are constantly moving around the Earth (Gartland, 2010). Other than the limitation in providing images, it is also necessary to choose proper images, with clear days and few levels, for better analyses, as the visualization of satellite images can be affected by atmospheric conditions.

Alves (2016) collected data on air temperature and humidity using two fixed-base weather stations in urban and rural areas and found that UHI intensity varied between 0.5 and 3.5°C. The fixed-base weather stations method is the simplest method for analyses of UHI effects. However, there are not always enough weather stations in the target areas and the position of weather stations might bias the results. The possibility of installing temporary weather stations might be unfeasible due to financial and logistical limitations (Gartland, 2010).

Considering the limitations of satellite images and fixed-base weather stations, mobile transects are an alternative method for the evaluation of UHIs. In this method, data collection points are preestablished along transects, and then data are collected with the use of portable equipment, such as a portable thermohygrometer. Studies developed with the use of mobile transects (Silva et al., 2018; Sun et al., 2019) found important information and had relevant results involving the identification of heat islands. However, these studies were completed in a period of days within one season and did not cover longer periods of time, which would be ideal to describe and identify heat islands and their patterns.

This study brings out a novel approach to identify heat islands using the mobile transects method in the city of Três Rios, a small city that had a considerable increase in urbanization rates in the past 10 years. The city of Três Rios is in a naturally hot and dry region, which has presented progressive discomfort caused by high temperatures, as reported by the population.

A second novel aspect of this study is the time frame of data collection; meteorological data were collected in a whole year, on specific times of the day. The analyses covered all four seasons, which allowed a complete and consistent analysis of the studied phenomenon.

The objective of this study was to verify the occurrence of UHI in the city of Três Rios, considering the analyses of differences in temperatures between rural and urban areas.

Materials and Methods

Study area

The city of Três Rios (Figure 1) is located in the central south region of the state of Rio de Janeiro. Its territory covers an area of 322.843 km^2 and it has a population of 81,804 habitants (IBGE, 2015). Its proximity to the three largest consumer centers of the country (São Paulo, Rio de Janeiro, and Minas Gerais), its water availability, and its government program of tax exemption attracted the industry sector to the city in the past 10 years, speeding the process of urbanization.

About 97% of the habitants in the city of Três Rios live in the urban zone, which has a territorial area of about 28 km^2; 88% of this area is classified as densely urbanized, and 12% with low urbanization (IBGE, 2015). Densely urbanized areas contain land with continuous occupation, constructions very close to each other, normally composed of buildings without outdoor areas or with small backyards (IBGE, 2017).

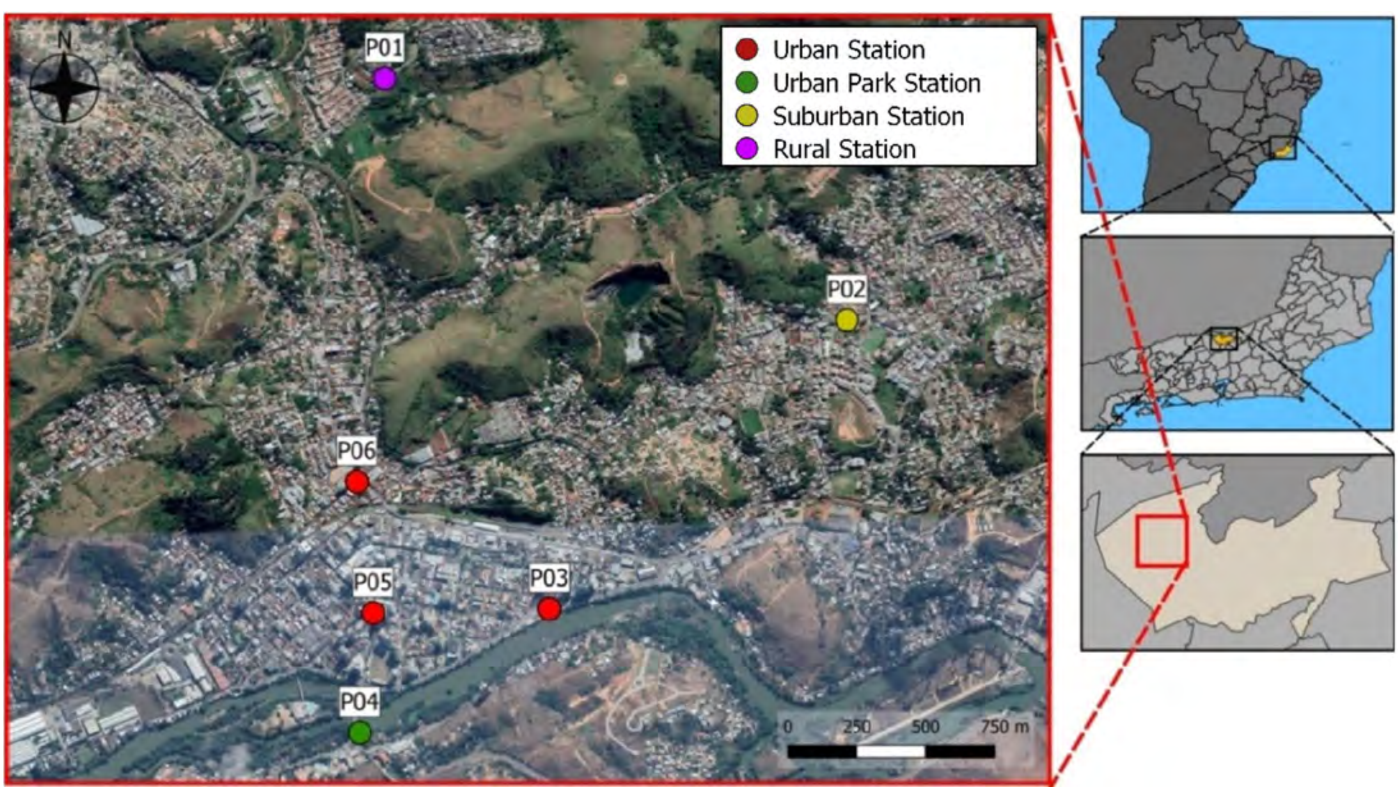

Figure 1 – Location of measurement points in the city of Três Rios/RJ.

The city is located in the unit of ridge alignments of the Paraíba do Sul river with morphological forms separated by mountain ranges and from 300 to 800 m. Some important mountain ranges in the region are the hilly areas such as Alto da Terra Seca, Retiro, and Cavaru; in these examples, the topography ranges from 200 to 400 m and the hills are shaped with ample round tops and moderate slopes with amplitude inferior to 100 m (Valladares et al., 2012; COHIDRO, 2016). Because of the presence of hills, the land urban occupation in the city is mostly focused in the valleys, which tend to be the flooding areas.

When it comes to climate, the city of Três Rios is in the subtropical humid zone, presenting cold dry winters and warm wet summers. The mean annual temperature is 22°C, the warmest month is February, with historic mean temperatures of 25.5ºC, and the coldest month is July, with mean temperature of 18.4ºC. Mean annual precipitation is 1592 mm, with most precipitation happening from November to January, and the driest period is from June to August (Alvares et al., 2013).

The city of Três Rios has low wind frequency, with mean speed of 1.90 m/s, during almost all year, with exception of August to October, when the predominant direction is Northeast. The highest wind intensities occur during the Spring and lowest during the Fall (INEA, 2015).

Fieldwork

To understand the dynamics of the urban climate in the city of Três Rios, air temperature was monitored between September 2018 and July 2019, using mostly the method of mobile transects. The measurements encompassed the four seasons of the year in the city of Três Rios. The periods of weather instability (rain and weather fronts) were disregarded during analysis, to avoid bias.

The mobile transects method consists of covering preestablished routes in order to obtain data points about locations along the routes with the use of meteorological portable equipments. Spronken-Smith and Oke (1998) noted that in small study areas, it is possible to cover the region with the use of a bicycle. Among the negative sides, Gartland (2010) points out the impossibility of collecting data from different locations simultaneously.

The temperature measurements were taken on five collection points in a preestablished circuit. Temperature data were also collected from a weather station in the city. The measurement points were as follows: P01, weather station located in a rural area; P02, located in a suburban area; P04, located in the Natural Municipal Park of Três Rios (i.e., urban park), and points P03, P05, and P06, which were located in the urban area. P03 and P04 are located in the Paraíba do Sul river's buffer zone, while P05 and P06 are located in the oldest urban area within the city, which has high vehicle traffic and dense land occupation. The locations of measurement points are presented in Figure 1 and Table 1.

The measurements were done considering the urban canopy, which is characterized as the ideal location to measure temperatures

Table 1 – Measurement points within the city of Três Rios/RJ, including type of area, coordinates, and elevation.

ID	Type of area	Coordinates UTM (WGS84) (m)		Elevation (m)
P01	Rural	684794.0	7555182.0	305
P02	Suburban	686437.7	7554200.7	278
P03	Urban	685347.3	7553091.3	269
P04	Urban park	684653.6	7552616.0	270
P05	Urban	684707.6	7553082.0	274
P06	Urban	684654.7	7553592.8	279

of heat islands. Measurements were taken 1.50 m from the soil surface, which comprises the volume below the tops of buildings and trees (Gartland, 2010).

An ADC PRO summit (handheld weather station Brunton®) was used to measure air temperature. For better accuracy, equipment calibration was done weekly and/or when weather conditions were altered. P01 (Três Rios weather station-A625), the fixed weather station operated by the National Institute of Meteorology (INMET), was used as a reference for alterations in weather conditions. P01 is located in the rural area of the Purys neighborhood.

A bicycle was used for moving along the mobile transect. The bicycle was a solution to avoid traffic jam, reducing delays on the measurement times. Data collection was performed at 06:00, 12:00, 15:00, 18:00, and 21:00 considering a 1-min cool down for equipment stabilization. Moving along transects and running the whole circuit took about 40 min, which is in accordance with Araujo et al. (2010), that recommends a maximum of 1 h for the duration of a measurement circuit in mobile transects. Collections were interspersed each three days during the measurement period.

Measurement times were selected based on the energy entry and dissipation flux (i.e., solar radiation) through the city as well as atmospheric and human activities. Also human activities were considered, including the density of constructions, geometry of streets, population size, and intensity of flux of vehicles and paving (Fialho, 2009). For morning measurements, 06:00 h was the time chosen since this is the time with lower urban movement within the city and low incidence of solar radiation. The 12:00 h measurement represents the period of higher incidence of solar radiation. The 15:00 h measurement was chosen based on strong solar radiation incidence and energy retention in the atmosphere, which is influenced by land use and urban movement. The 18:00 h measurement was influenced by rush hour and the consequential increase in vehicle traffic. The 21:00 h measurement, after sunset, was chosen based on the influence of thermal emissions from urban constructions and possible presence of relevant magnitudes of anthropogenic heat (Oke, 1988; Fialho, 2009).

In total, this study included 505 field campaigns for air temperature measurement, during 11 consecutive months, totaling 3030 measurements in a period that included the 4 climatic seasons of the year.

Indicators of thermal differentiation

Magnitude of heat islands

Two indicators of thermal differentiation based on temperature measurements were considered. The first method is the calculation of the magnitude of heat islands or freshness islands adapted from Garcia (1996). Considering magnitudes as the difference between mean temperatures in the urban and rural areas, Garcia (1996) proposed magnitude degrees to characterize intensity levels of heat islands; positive numbers indicate heat islands, negative numbers indicate freshness islands. This approach assumes that the rural area incurs lower influence of urbanization, and therefore, this area is considered a reference to indicate the impacts caused by urban occupation on the temperatures.

This study's indicators differed from the ones considered by Garcia (1996), as in this study, not only the differences between mean temperatures of rural and urban areas were considered. Here the temperatures on each collection point were computed from the mean values obtained from the reference point, that is, the rural area, P01. This approach was used taking into consideration that the number of collection points for each type of area (urban, suburban, urban park, and rural) was small, so comparing means and running statistical analysis would not be representative of the land use classes, as areas had a sample size of one experimental unit. Also, calculating the magnitudes for each point would allow a higher spatial differentiation of thermal differences. Equation 1 represents the expression for the thermal magnitude.

$$M_{i,n} = T_{i,n} - T_{0,n} \quad (1)$$

Where:

$M_{i,n}$: the UHI magnitude on collection point *i* in the *n* moment;

$T_{i,n}$: the temperature of point *i* in the *n* moment;

$T_{0,n}$: the temperature of point 0 (rural) in the *n* moment.

Thus, different magnitudes were calculated for each point that was not P01. After the magnitude was calculated, a categorization of results was made based on the intensity levels proposed by Garcia (1996), as presented in Table 2.

Table 2 – Intensity degrees of freshness and heat islands according to calculated magnitudes.

Magnitude (°C)	Category	Intensity
< -6	Freshness island	Very strong
-6 to -4		Strong
-4 to -2		Moderate
-2 to 0		Weak
0 to 2	Heat island	Weak
2 to 4		Moderate
4 to 6		Strong
6		Very strong

Source: Garcia (1996, p. 285).

Thermal anomalies

The second indicator to evaluate thermal differentiation is the calculation of thermal anomalies for each point, following the method used by Alves (2016) and Alcoforado and Andrade (2006). This method is calculated using the standardized scores that consider the mean temperature of a specific time and the standard deviation of the mean. Equation 2 represents the expression for the calculation of this indicator.

$$A_{i,n} = \frac{T_{i,n} - \underline{T_n}}{\sigma_{T_n}} \quad (2)$$

Where:

$A_{i,n}$: the thermal anomaly in the moment *n* and at the point *i*;

T_n: the mean temperature in the moment *n*;

$T_{i,n}$: the temperature of point *i* in the moment *n*;

σ_{Tn}: the standard deviation of temperatures in that moment.

The reference for the evaluation of thermal anomalies is not the temperature of a specific area, as it was for the measurement of magnitude, but it is the mean temperature of all points.

Data analyses

For a better visualization and description of the variations of the phenomenon for different time periods, data were subdivided in two ways: one considering the four seasons of the year, and the other considering the different times of the day. Following the subdivisions, the results for temperature, magnitude, and anomalies were analyzed using descriptive statistics (e.g., means, standard deviations, median, frequency analysis, and quartiles) and boxplot graphics, which represent the distribution of results. This type of graphic was chosen as it presents the values of most interest for the research, that is, extreme and central values. Iversen and Gregen (1997) and Montgomery and George (2003) supported the use of boxplot for these purposes. These authors explained that boxplots are strong tools for the comparison of data divided in groups, such as the data included in this study, which were grouped into three categories: occupation, time, and season.

Outliers were removed to avoid bias. The reference for outlier removal was based on the method suggested by Montgomery and George (2003), which is considered as criteria for the removal of the values that were higher than the sum of the third quartile with 1.5 times the interquartile interval or smaller than the subtraction of the first quartile from 1.5 times the interquartile interval.

Statistical analyses and figures were obtained using RStudio v. 1.2.5042, based on the R language R v. 3.6.1. Following these methods, discussion was made based on the frequency, intensity, and variability of thermal differentiation among the collection points and conclusions were elaborated.

Results and Discussion

The temperatures ranged between 7.2 and 37.8°C, with mean temperature of 24.3°C, at the rural point P01; at P02 (suburban point), the values ranged between 6.3 and 39.1°C, with average of 24.5°C; and at P04 (urban park), the range was between 6.3 and 40.6°C, with mean of 24.4°C. At the urban points, the values ranged between 6.6 and 40.4°C at P03, between 6.6 and 40.1°C at P05, and between 6.0 and 39.4°C at P06, with average temperature of 24.6°C.

Figure 2 includes the daily means by land use types. It is possible to observe situations in which the means are lower for the rural area (less impacted by urbanization) and higher for the other type of areas.

Analyses of results for temperature

The boxplots presented in Figure 3 include the distribution of temperatures during the different times of the day for the entire series of data (102 days). From these results, it is observed that the temperatures were generally lower around 06:00, with an increase during the day, reaching maximum values around 15:00, and after this time of the day, the temperatures decrease.

Table 3 presents minimum and maximum temperatures observed, as well as their amplitude (difference between maximum and minimum values, considering all points and the entire monitoring period) by time of measurement. The lower amplitude (considering all points and the period analyzed) happened at 06:00, with value of 18.6°C. Following that, the highest amplitudes were found at 15:00 (21.8°C), 18:00 (20.3°C), 12:00 (19.4°C), and 21:00 (17.3°C).

The values between the base and the top of the block represent 50% of the boxplot data, and the distance between the two limits can be considered to establish a measure of dispersion, related to variability. For this analysis, it is observed that the smaller box occurs for the time of 06:00, with a difference of 3.60°C, indicating that this was the time with smallest variability, followed by the times of 21:00, 18:00, 15:00, and 12:00, which presented differences of 4.38, 5.10, 5.40, and 5.92°C, respectively. That way, the highest intensities happened on the times of solar irradiation, representing the influence of this variable on the temperatures, as observed by Capelli de Steffens et al. (2001).

The boxplots in Figure 4 present the distribution of results for the entire data series, similar to what was previously presented, but instead of time of the day, data were looked by season (considering all times). From these data, it is noted that the lowest temperatures occurred in

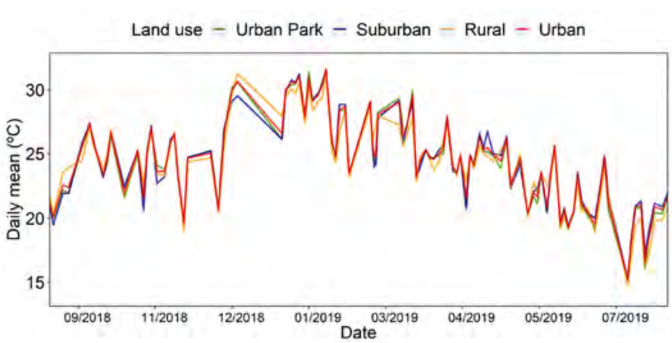

Figure 2 – Mean daily temperatures by land use types.

Table 3 – Minimum and maximum temperatures and the amplitudes observed by time of measurement (considering all points).

Time	Minimum temperature (°C)	Maximum temperature (°C)	Amplitude (°C)
06:00	6.0	24.4	18.6
12:00	18.2	37.6	19.4
15:00	18.8	40.6	21.8
18:00	14.8	35.1	20.3
21:00	11.4	28.7	17.3

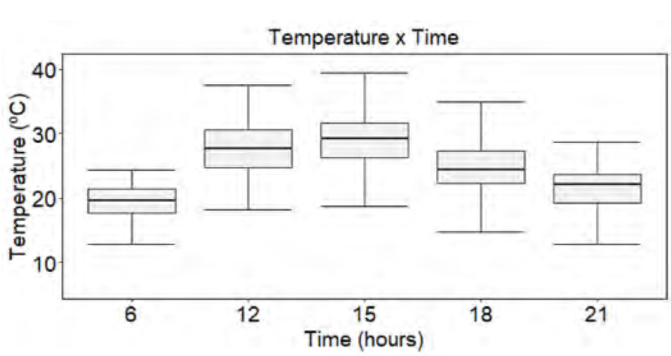

Figure 3 – Boxplots including temperature variation by time of the day.

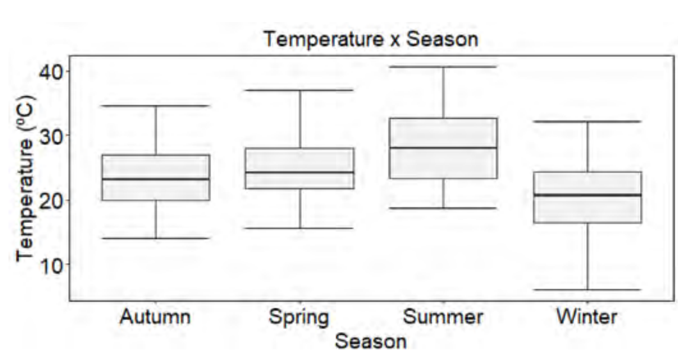

Figure 4 – Temperature boxplots by season of the year, including median values.

the winter, followed by autumn, spring, and summer. When analyzing amplitudes, the highest occurred in the winter (26.2°C), and the lowest occurred in the autumn (20.6°C), followed by summer (21.9°C) and spring (23.7°C). This agrees with what was stated by Fialho (2009) about highest variations in temperatures occur in the winter, as it is the driest season in the studied region.

The differences between the first and the third quartiles were of 7.85°C in the winter, 7.1°C in autumn, 6.1°C in the spring, and 9.3°C in the summer. Thus, even though winter amplitude was higher than the other seasons, the highest dispersion (size of the box) happened in the summer, season in which solar irradiation is more intense.

Thermal magnitude indicator

Thermal magnitude indicators varied from -8.2 to 7.6°C at P02, from -8.0 to 5.7°C at P03, from -8.0 to 5.5°C at P04, from -7.8 to 5.8°C at P05 and -8.2 to 6.0°C at P06. An analysis of frequency of the UHI intensity categories for each point of collection was done, without the removal of outliers, and is presented in Table 4.

For all points, more than 50% of measurements presented weak heat island, that is, temperatures up to 2°C higher than the temperature at the rural area P01. Considering all points in urban areas (P03, P05, and P06), more than 5% presented moderate heat island. Points P02 and P06 presented very strong heat islands, with three occurrences at P02 and one at P06. In all points, freshness islands occurred in less than 35% of the measurements.

Thus, the indicator of thermal magnitude points to a thermal differentiation between the rural area (P01) and the other types of land use for most of the measurement period with predominance of heat islands of weak intensity. These observations are in accordance to what was exposed by Sun et al. (2019) and Rodríguez et al. (2020), which pointed that weak heat islands are common in small cities. The points in urban area presented lower frequency of freshness islands than the suburban (P02) and urban park (P04) points. Among the urban points, P03 presented the highest frequency of weak and moderate heat islands; however, P06 was the only one that presented very strong intensity of heat island. Another relevant observation is that the suburban station (P02) presented the highest magnitude value and also the highest frequency of very strong heat islands. Figure 5 presents boxplots for the magnitude results by time of day and season.

The boxplots for urban points only presented positive values at the second quartile, which means that, for all conditions considered, at least at 50% of the time the temperature of the urban area was higher than the temperature of the rural area. The same pattern is observed for the suburban area, except for the 06:00 in the spring and autumn seasons. At the urban park, it is observed a high frequency of values around zero or negative for the second quartile: at 15:00 in the winter; 06:00 in the autumn, summer, and spring; and 18:00 in the spring.

When looking at 18:00 in the winter, for all points, the second quartile presented values > 2, which means that in at least 50% of times it was observed the occurrence of heat islands of moderate intensity during this time at this station.

Thus, the magnitudes with predominant positive values, and higher frequency of heat islands than freshness islands, indicate that there is thermal differentiation between the urban, suburban, urban park, and rural points. The frequency analysis showed the predominance of weak heat islands; however, moderate and very strong heat islands were also observed. Moderate heat islands were observed mostly during the winter at 18:00.

The four occurrences of very strong intensity happened on February 9, 2019 (summer) at 15:00 at P02 and P06, on April 27, 2019 (autumn) and June 29, 2019 (winter) at 18:00 at P02. These data are outliers, which means they are not representative of the average series of data. Still, extreme temperatures can become more frequent and have impacts on the well-being and health of the population, as described in several studies (Akhtar et al., 2016; Misslin et al., 2016; Brousse et al., 2019).

Table 4 – Number of occurrences (N) of the heat and freshness islands intensity categories and relative frequency (%) for the period of monitoring.

Intensity		P02 (Suburban)		P03 (Urban)		P04 (Park)		P05 (Urban)		P06 (Urban)	
		N	%	N	%	N	%	N	%	N	%
Freshness island	Very strong	1	0.20	3	0.59	1	0.20	1	0.20	1	0.20
	Strong	7	1.39	11	2.18	10	1.98	7	1.39	5	0.99
	Moderate	30	5.94	18	3.56	17	3.37	18	3.56	20	3.96
	Weak	129	25.54	89	17.62	155	30.69	117	23.17	122	24.15
Heat island	Weak	307	60.79	337	66.73	293	58.02	323	63.96	318	62.97
	Moderate	24	4.75	40	7.92	24	4.75	30	5.94	34	6.73
	Strong	4	0.79	7	1.39	5	0.99	9	1.78	4	0.79
	Very strong	3	0.59	0	0.00	0	0.00	0	0.00	1	0.20
Total		505	100	505	100	505	100	505	100	505	100

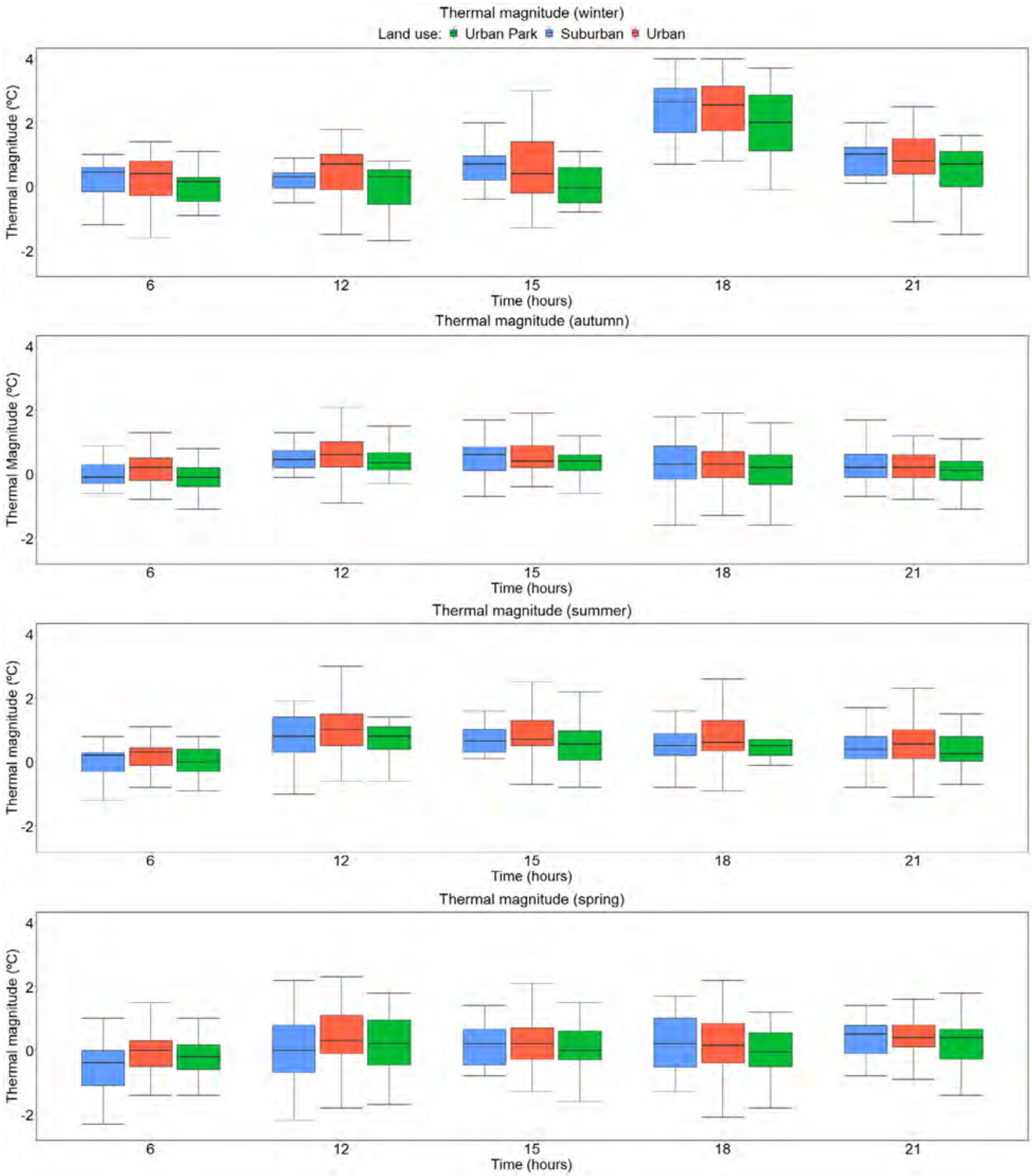

Figure 5 – Boxplots including magnitude by time of the day and season.

Thermal anomalies

Thermal anomalies are presented in Figure 6. The results show that for the rural point, the second quartile has negative values for all subgroups, with the exception of 06:00 and 18:00 h in the spring. The negative second quartile means that, in at least 50% of the observations, the temperatures in the rural point were lower than the mean of all collection points. Also, negative values were observed for the third quartile at the rural point, for 18:00 and 21:00 h in the winter; 12:00, 15:00, and 18:00 in the summer; and 12:00 h in the autumn, indicating that at these subgroups, in at least 75% of the observations, the temperatures

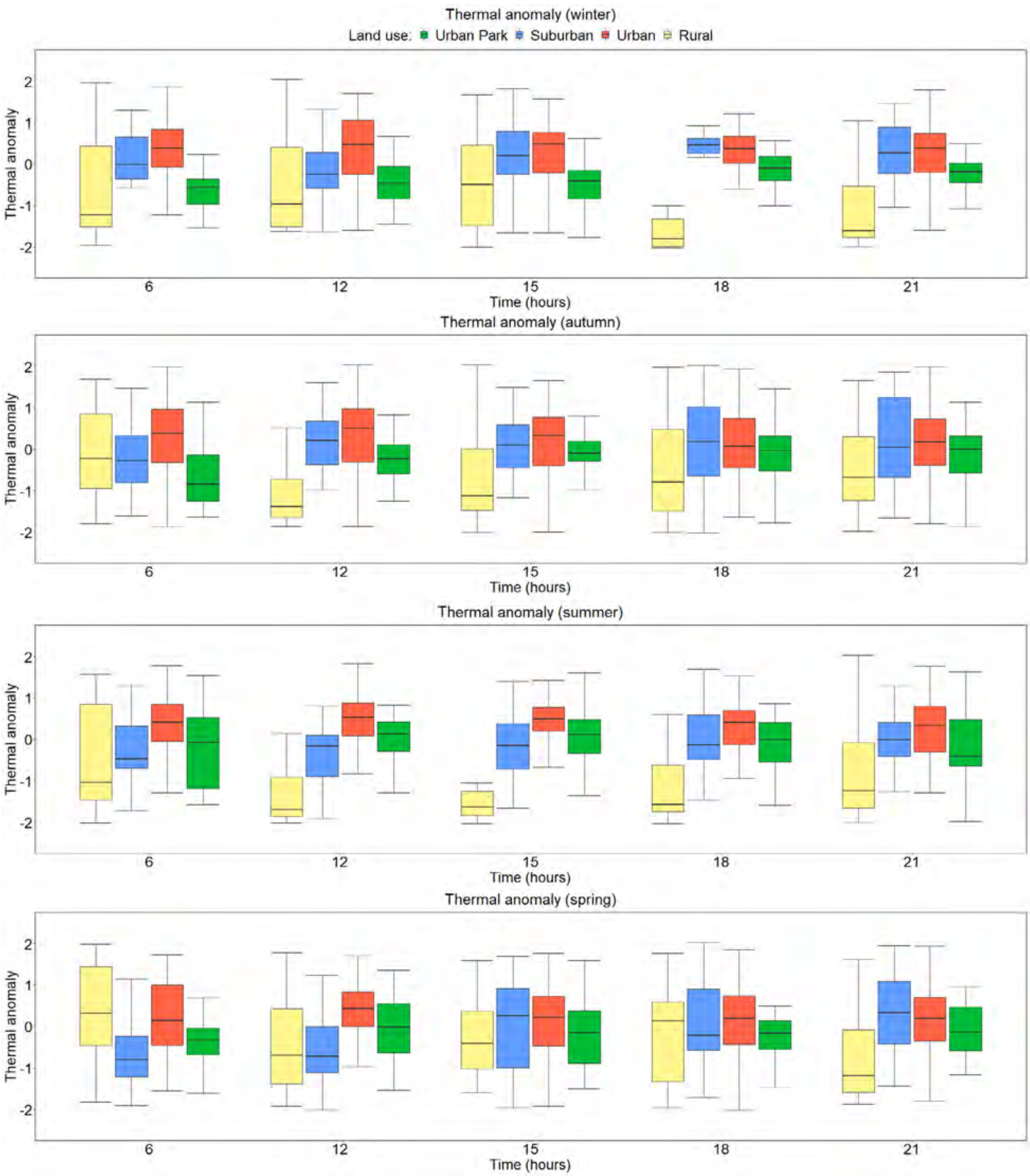

Figure 6 – Thermal anomalies by collection point, season, and time of the day.

at the rural area were lower than the average. When looking at the rural point, the 06:00 time point in the spring presented higher values than the other points at the second and third quartiles.

At the urban points, the second quartile values are higher than the ones for the other collection points in most times of the day, followed by suburban and urban park points. In addition, when looking at patterns of different times, there is a trend that the urban park and suburban areas behave similarly to the urban areas as the day goes by.

The suburban point presented the second quartile values lower than the rural point at 06:00 and 12:00 in the summer and spring, seasons with higher intensity of solar irradiation. This might be an indicator of the sun's influence and the reduction of humidity on these spaces.

A pattern of dispersion was not identified for the rural area, as the differences between the second and third quartiles can be big when compared to the other collection points and, in some cases, they can be very small.

Predominant negative values for thermal anomalies at the rural station and higher values for the urban stations indicate that there is thermal differentiation between the urban and non-urban areas in Três Rios. The urban park and suburban points presented, in most cases, values for the indicators of thermal differentiation that were lower than the ones obtained at the urban points. This observation indicates that the heat islands tend to be less intense at the points P04 and P02. The urban park (P04) is the only space around the downtown area of Três Rios with substantial tree cover and the heat islands might be lessened in this area due to the contribution of the vegetation cover to the maintenance of lower temperatures in this region. The suburban area (P02) is characterized by less intense urbanization when compared to the urban area, thus the impacts on microclimate are less intense.

However, the differences between suburban, urban park, and urban areas are not very big, following the categories proposed by Garcia (1996). Still, very strong heat islands were identified at P02. Thus, it is possible that the process of urbanization might be causing impacts on the microclimate of the suburban area and the urban park even if in low intensities. At the suburban area, the impacts are likely a consequence of the density of urban occupation, while at the urban park, this process might be related to what was described by Andrade et al. (2016), in which the fragmentation of a habitat can be drastically affected by the external environment and the humidity from the river was added to the evapotranspiration, all these were not the enough factors to provide freshness islands in this area.

As a caveat, it is important to mention that the rural point is close to surrounding urban areas, so it is also under the influence of the impacts caused by urbanization, but in less intensity if compared to the urban and suburban areas included in this study. It is possible that these impacts reflected on the results.

Thus, the results indicate the occurrence of heat islands in Três Rios potentially caused by urban densities in the city, which have been increased in the recent past years. The UHIs might also be related to the low vegetation cover in the urban area (Santiago and Gomes, 2016).

In contrast with cities from developed countries, where the growth rates are limited or inexistent, cities in developing countries, such as Brazil, can use the intensities of UHIs to guide urban planning (Zhou et al., 2017). Therefore, this study brings attention to the importance of UHIs on the public management of cities. We recommend that the issue is considered, studied, and monitored moving forward.

Três Rios is still considered a small city, although it is going through an intense process of growth. Thus, if prevention is not applied to the public management during the growth process of the city, the impacts indicated in this study can become aggravated in the future, resulting in negative effects on the health and well-being of the population.

Conclusions

In face of the results presented, this study is relevant as it introduces the existence of initial state UHIs in the city of Três Rios. This can be considered by the government and public management to guide urban development applying preventive measures. Such measures could include the increase in urban trees and afforestation of surrounding conservation areas affected by constant burns.

There is a need to sustainably plan the growth and development of the city, adopting preventive measures, inhibiting the increase in vertical buildings, and considering from an orderly and contiguous growth.

It is important to highlight the social aspect of this study, considering that the population most affected by the impacts of UHIs is concentrated in central and suburban areas and therefore establishing the importance of creating public policies that consider, above all, those who are in greater socioeconomic vulnerability.

The fact that the research was developed within a large time frame was interesting, as it allowed the observation of the variability of the phenomenon in the city, which is not common in other studies published on the theme.

This study had a limitation related to the number of collection points observed, which complicated the analysis of the spatial influence of the phenomenon. We suggest that future studies include more collection points representing each type of area, considering also more variables other than temperature.

Contribution of authors:

Silva, Y.M.N.: Conceptualization, Data curation, Investigation, Formal analysis, Methodology, Validation, Visualization, Writing — original draft, Writing — review and editing; Silva, H.M.: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing — review and editing; Silva, R.D.A.: Data curation, Formal analysis, Software, Writing — review and editing; Marques, E.D.: Supervision, Validation, Visualization, Writing — review and editing; Gomes, O.V.O.: Funding acquisition, Project administration, Resources, Methodology, Supervision, Visualization, Writing — original draft, Writing — review and editing .

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Ant assemblages (Hymenoptera: Formicidae) from areas under the direct influence of two small hydropower plants in Brazil

Assembleias de formigas (Hymenoptera: Formicidae) de áreas de influência direta de duas pequenas centrais hidrelétricas no Brasil

Junir Antônio Lutinski[1], Milton Carlos de Filtro[2], Leandro Baucke[3], Fernanda Emanuela Dorneles[1], Cladis Juliana Lutinski[1], Carin Guarda[1]

ABSTRACT

Current energy production has been the subject of studies on environmental impacts and the need to adequately understand that the relationship to biodiversity loss is growing. One of the ways of assessing environmental changes is the use of bioindicator species, and ants represent an alternative in this regard. This study aimed to evaluate ant assemblages occurring in different environments in areas under the direct influence of two small hydropower plants (SHPP). Sampling was carried out using pitfall traps in forest and agricultural fragments, as well as pasture areas, along the Andrada River, municipality of Cascavel, state of Paraná, in July 2016 and March 2017. The sampled ant assemblages were evaluated for richness, abundance, and composition. The rarefaction analysis was used to compare the richness sampled in the two areas under direct influence. Abundance was analyzed based on the number of occurrences. The nonmetric multidimensional scaling (NMDS) was applied to test whether the abundance and composition of ant assemblages differ at the same site when sampled in both seasons. In total, 63 species belonging to 23 genera and 6 subfamilies were identified. The subfamily Myrmicinae was the most species-rich (S = 25), followed by the subfamily Formicinae (S = 21). The most species-rich genus was *Camponotus* (S = 15) followed by *Pheidole* (S =11). A total of 41.3% richness was registered concurrently in the two assemblages. The study contributes to the expansion of knowledge of the ant fauna occurring in the state of Paraná and serves as a basis for monitoring impacts caused by the implementation of SHPP and other developments.

Keywords: biodiversity; bioindicators; conservation; production of energy.

RESUMO

A produção energética vigente tem sido alvo de estudos sobre seus impactos ambientais, e cresce a necessidade de se compreender adequadamente sua relação com a perda de biodiversidade. Uma das formas de avaliação das alterações ambientais é a utilização de espécies bioindicadoras, e as formigas representam uma alternativa nesse quesito. Esta pesquisa objetivou avaliar diferentes ambientes quanto às assembleias de formigas que ocorrem nas áreas de influência direta de duas pequenas centrais hidrelétricas. A amostragem foi conduzida em ambientes de fragmentos florestais, agrícolas e de pastagens, junto das margens do Rio Andrada, no município de Cascavel, estado do Paraná, nos meses de julho de 2016 e março de 2017. Foram utilizadas armadilhas do tipo *pitfall* nas amostras e foram avaliadas a riqueza, a abundância e a composição das assembleias de formigas amostradas. Efetuou-se a análise de rarefação para comparar a riqueza amostrada nas duas áreas de influência direta. A abundância foi analisada com base no número de ocorrências. Foi construída uma análise nonmetric multidimensional scaling (NMDS) para testar se a abundância e a composição das assembleias de formigas diferem em um mesmo ponto quando amostradas nas duas estações. Registraram-se 63 espécies pertencentes a 23 gêneros e a seis subfamílias. A subfamília Myrmicinae foi a mais rica (S = 25), seguida da Formicinae (S = 21). O gênero mais rico foi *Camponotus* (S = 15), seguido por *Pheidole* (S = 11). O total de 41.3% da riqueza foi registrado concomitantemente nas duas assembleias. O estudo contribui para a expansão do conhecimento sobre a mirmecofauna que ocorre no território paranaense e serve de base para o monitoramento de impactos causados pela instalação de pequenas centrais hidrelétricas e de outros empreendimentos.

Palavras-chave: biodiversidade; bioindicadores; conservação; produção de energia.

[1]Universidade Comunitária da Região de Chapecó – Chapecó (SC), Brazil.
[2]MF Consultoria Ambiental – Chapecó (SC), Brazil.
[3]Impacto Assessoria Ambiental – Chapecó (SC), Brazil.
Correspondence address: Junir Antonio Lutinski – Rua Beija-Flor, 254 E – Efapi – CEP: 89809-760 – Chapecó (SC), Brazil. E-mail: junir@unochapeco.edu.br
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Introduction

Human activities such as the conversion of forests into agricultural or pasture areas, the expansion of urban areas, and the implementation of projects that result in river damming are the examples that impact the environment, modify the area where they are developed, cause changes in physical and chemical properties of soils, interfere with watercourses, modify the habitat, and impact the flora and fauna (Tsoutsos et al., 2005; Costa et al., 2019). Environmental impacts, such as the emission of greenhouse gases and, consequently, global warming, from the current energy matrix based on fossil fuels, have been the subject of studies and public policies (Laurent and Espinosa, 2015). Thus, the need to explore renewable energy sources emerges, whose impacts on biodiversity are also observed; however, they are considered minor in relation to the burning of fossil fuels (Gasparatos et al., 2017; Bracco, 2020). The exploration of renewable energy sources modifies the environment, results in river damming, as in the case of hydropower plants (HPP) and in the suppression of vegetation, and alters the local microclimate (Gasparatos et al., 2017). These changes in the directly affected areas result in the loss of habitats for terrestrial organisms, such as invertebrates. The impacts resulting from these processes on biodiversity are still less known.

Hydropower is an alternative to fossil fuels; however, environmental impacts resulting from the implementation and operation of HPP on invertebrates, and more specifically on the entomofauna, are still incipient (Kjærstad et al., 2018). The impacts are related to vegetation suppression, land removal, soil compaction, and flooding that can destroy remnants of vegetation, change the dynamics of the affected ecosystem, and make it impossible the permanence of animal species (Moran et al., 2018). Insects are affected by this process, and the study of these organisms can reveal the level of environmental quality from which interventions can be determined in order to maintain, recover, or restore the balance of the environment, aiming at the ecological sustainability of ecosystems (Rocha et al., 2015; Moura and Franzener, 2017; Parikh et al., 2021).

Only in the last decade, the invertebrate community became the target of environmental impact studies and reports of these impacts (EIA/RIMA) when such projects are implemented in Brazil, and in only a few Brazilian states, such as Paraná. In southern Brazil, approximately 48 HPP and 146 small HPP (SHPP) are in operation (ANEEL, 2016, 2019). Electrical energy represents the main source of energy production in Brazil, which is justified by entrepreneurs due to the low cost of production, low emission of polluting gases, and also for being a source of energy considered clean (Oliveira, 2018). Despite the favorable arguments, studies begin to point out negative environmental and social impacts of the implementation of large HPP, such as the release of greenhouse gases (Carreira, 2016), social transformations in the territory, and impacts on fauna and flora (Marín and Torres, 2013). As SHPP have more accessible legislation and faster implementation, they have been installed in small- and medium-sized rivers (Kusma and Ferreira, 2010; Lutinski et al., 2017b). Despite the smaller impact, the construction of these developments also causes impacts that need to be better understood both to support the planning of such projects and to establish bases for monitoring after the implementation.

One of the ways to assess and monitor changes in biodiversity is the use of bioindicator species (Parmar et al., 2016; Araújo et al., 2018). The presence, absence, or change in the abundance of a population can serve as a parameter to be evaluated (Gerlach et al., 2013; Rocha et al., 2015). Among the bioindicators used, insects have achieved prominence, both for being the most diverse group in terms of richness and for easy sampling (Lutinski et al., 2018).

Predominant in most terrestrial environments, ants are recognized as bioindicators (Tibcherani et al., 2018). The study of their richness and abundance allows the effective assessments of environmental conditions and the level of restoration of impacted areas (Blinova and Dobrydina, 2018). These insects fulfill this function because they have a wide geographic distribution, are locally abundant, functionally important at different ecological and trophic levels, and are susceptible to ecological changes (Lawes et al., 2017; Tibcherani et al., 2018).

Habitats have been and continue to be transformed by human action, and the study of ant assemblages enables us to assess the impact of these activities in these locations (Tibcherani et al., 2018). Some are cited as pests; however, they play essential roles in nutrient cycling, due to feeding on living or dead organic matter. They also act in the construction of underground galleries, aiding in soil drainage, and, consequently, aiding in the penetration of plant roots. In addition, they are important in the trophic chain, as they act as predators and also serve as prey (Hölldobler and Wilson, 1990).

Studies on the ant fauna in Paraná are recent and still restricted (Lutinski et al., 2017a, 2017b; Franco and Feitosa, 2018), with regions and environments still unexplored regarding the biodiversity of these insects. The diversity and richness of ant assemblages are affected by human activities. A reduction in ant richness is observed in forested environments that are transformed into monocrops or pasture areas. In contrast, generalist species tend to be more abundant under such conditions (Baccaro et al., 2015). Considering the bioindicator potential of ants, understanding the changes in assemblages of these insects becomes relevant to support studies and monitoring of environmental impacts. In this context, this study aimed to evaluate the richness, abundance, and composition of ant assemblages occurring in the areas under the direct influence of two small hydroelectric power plants in the southwest region of the state of Paraná.

Material and Methods

Study area

Sampling was conducted in transects established in forest fragments, agricultural areas, and pastures, along the banks of the Andrada River, municipality of Cascavel, state of Paraná. In that river, the implementation of two SHPP, namely, AL and SM, among others, was planned. The two SHPP were designed one continuous with the other, with SHPP 2 upstream of SHPP 1. In the areas under the direct influence (DIA) of each of these two SHPP, five sampling sites were defined, on both banks of the river, equidistant from each other, in order to cover the greatest possible heterogeneity of environments in the DIA, as described below:

- SHPP 1 (AL): *Site 1* (S 25°10′25″; W 53°24′53″), in early and medium stages of natural restoration with native vegetation, surrounded by agricultural cultivation areas, located at the final portion of the reservoir and upstream of the flooded area; *Site 2* (S 25°10′44″; W 53°25′07″), with native and arboreal vegetation, consisting of a forest fragment, located in the final portion of the reservoir and upstream from the flooded area; *Site 3* (S 25°11′12″; W 53°24′59″) located in the middle portion of the area expected to be flooded. Low-density tree vegetation limited by pastures and crops and a forest fragment; *Site 4* (S 25°11′25″; W 53°25′44″) also located in the middle portion of the area expected to be flooded. Low-density tree vegetation limited by pastures and crops; *Site 5* (S 25°11′29″; W 53°25′59″), where the installation of a powerhouse was planned, sloped relief with native arboreal vegetation;
- SHPP 2 (SM): *Site 1* (S 25°08′25″; W 53°24′06″) located in the final portion of the reservoir and upstream of the flooded area, With native and secondary vegetation, surrounded by agricultural cultivation areas; *Site 2* (S 25°08′59″; W 53°25′06″) located in the final portion of the reservoir and upstream of the flooded area, with arboreal native vegetation, composing a forest fragment bordering the river bed; *Site 3* (S 25°08′18″; W 53°24′04″) located in the middle portion of the area expected to be flooded. Low-density arboreal vegetation limited by pastures and crops; *Site 4* (S 25°10′12″; W 53°24′08″) located in the middle portion of the area expected to be flooded. Low-density arboreal vegetation limited by pastures and crops; *Site 5* (S 25°08′46″; W 53°24′07″), downstream of the development with native vegetation and at an advanced stage of succession.

Sampling

Two seasonal samplings were carried out, covering the predefined sampling sites. The samplings were carried out in July 2016 (winter) and March 2017 (summer), during the study to obtain licenses for the two projects.

Pitfall traps were used for sampling, which consisted of plastic cups with a capacity of 500 mL (7.5 cm in diameter by 11.5 cm in height), fully buried, so that their openings are at the ground level. Each cup was added with 200 mL water with a drop of detergent to break the surface tension of the water, leading the ant to sink as it fell. At each of the sampling sites, five pitfall traps were installed, equidistant 20 m from each other, which remained open for 48 h (Bestelmeyer et al., 2000) in each of the samplings. A total of 25 pitfalls were installed in each DIA, in each sampling (summer and winter), 50 for each SHPP, i.e., 100 in total.

The use of pitfall traps is justified by the heterogeneity of the sampled environments, aiming at standardizing the sampling effort. Areas devoid of vegetation prevent the use of sampling techniques for canopy ants, nor do they have a uniform litter that allows the use of some extraction method.

Screening and identification

Specimens sampled were transferred to flasks containing 70% alcohol. In the laboratory, they were screened and mounted for later identification under a binocular microscope. Ants were identified according to the keys proposed by Gonçalves (1961), Kempf (1964, 1965), Watkins (1976), Della Lucia (1993), Lattke (1995), Taber (1998), Fernández (2003), Longino (2003), Longino and Fernández (2007), and Wild (2007).

Statistical analysis

Richness was defined as the number of ant species occurring in each of the samples. Abundance was defined based on the number of occurrences of each species in each pitfall (Tavares et al., 2008). The number of records minimizes the effect of foraging habits and colony size and is more appropriate for studies of ant assemblages (Romero and Jaffe, 1989). The percentage relative frequency was defined by the number of occurrences (i.e., the sum of records of the presence of a particular species in each pitfall) divided by the sum of occurrences of all species in the respective DIA and multiplied by 100 (percentage).

Diversity (richness and abundance) was evaluated using the Shannon–Weaver Diversity Index. This analysis was obtained using the EstimateS 8.0 software (Colwell, 2006). Evenness represents the participation of each taxon in the assemblage and was estimated by the Pielou index (Magurran, 1988). To assess the sample sufficiency, the nonparametric Chao 1 index was used and estimates were generated with the EstimateS 8.0 software (Colwell, 2006). The Chao 1 estimator essentially uses information about species occurring in only one sample (singletons) and those occurring in two samples (doubletons) (Chao, 1987).

Ant richness of the DIA of the two SHPP was compared using the rarefaction test based on the number of occurrences (Gotelli and Colwell, 2001). These analyses were obtained using the EcoSim 7 software (Gotelli and Entsminger, 2001), which allows the comparisons of richness between assemblages that differ in terms of species occurrence.

Nonmetric multidimensional scaling (NMDS) was applied to test whether the abundance and composition of ant assemblages differ at the same site when sampled in both seasons. The data matrix was previously transformed into log(x+1); the Bray–Curtis index was used as an association index, and the analysis was performed with the statistical software Primer 6.1.9 (Clarke and Gorley, 2005). Additionally, PERMANOVA was used to test the difference between groups.

The research was carried out under license ICMBio/SISBio number 50736-1. The sample specimens, as well as the accompanying fauna, were listed in the educational collection of the Universidade Comunitária da Região de Chapecó, Unochapecó.

Results

A total of 196 occurrences of ants were recorded with the sampling effort used. In all, 63 species belonging to 23 genera and 6 subfamilies were recorded. The ant assemblage of DIA of SHPP 1 showed greater richness (S = 47) and abundance (n = 115) compared with the assemblage of DIA of SHPP 2 (S = 42; n = 81). The subfamily Myrmicinae was the most species-rich (S = 25), followed by Formicinae (S = 21), Ponerinae (S = 8), Dolichoderinae (S = 6), Pseudomyrmecinae (S = 2), and Ectatomminae (S = 1) subfamilies. The most species-rich genus was *Camponotus* (S = 15) followed by *Pheidole* (S = 11). The most abundant species in the records were *Pheidole* sp. 2 (n = 18; 9.2%), *Pachycondyla striata* F. Smith, 1858 (n = 13; 6.6%), *Camponotus cameranoi* Emery, 1894 (n = 10; 5.1%), and *Gnamptogenys striatula* Mayr, 1884 (n = 10; 5.1%) (Table 1).

A total of 41.3% (S = 26) of the richness was registered concomitantly in the two assemblages. Altogether 33.3% (S = 21) of the richness was registered exclusively in the DIA of SHPP 1 and 25.4% (S = 16) exclusively in the DIA of SHPP 2. The Chao 1 estimate for the assemblage of SHPP 2 was 96.2 species and for the assemblage of SHPP 1, 74.6. Shannon and Evenness indices were similar for the two assemblages (Figure 1).

The greater richness of the assemblage of SHPP 1 (Table 1) was also demonstrated by the rarefaction analysis (Figure 2). The curves did not reach asymptote (Figure 2), indicating that the richness of both assemblages may be greater than that sampled according to Chao 1 estimates (Figure 1).

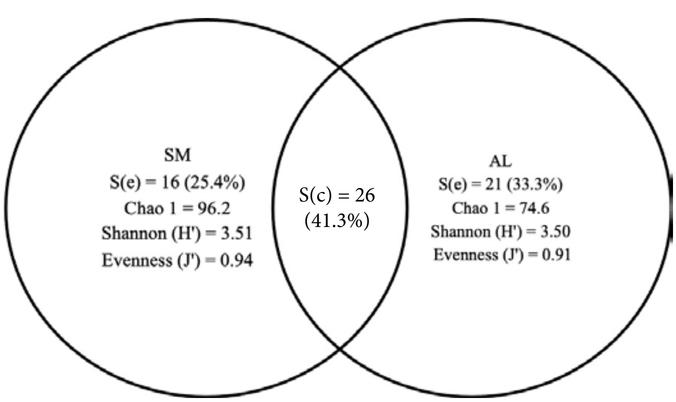

Figure 1 – Exclusive (S(e)), shared (S(c)), and estimated (Chao 1) richness, Shannon diversity index, and Evenness of ant assemblages sampled in DIA, in the pre-implementation period of two SHPP in the municipality of Cascavel, state of Paraná, July 2016 (winter) and March 2017 (summer).
AL: SHPP 1; SM: SHPP 2.

Table 1 – Richness, occurrences, and percentage relative frequency of ants sampled in DIA, in the pre-implementation period of two SHPP in the municipality of Cascavel, state of Paraná, July 2016 (winter) and March 2017 (summer).

Taxon	SHPP AL		SHPP SM	
	(n)	(%)	(n)	(%)
Subfamily Dolichoderinae				
Dorymyrmex brunneus (Forel, 1908)			1	1.23
Linepithema gallardoi (Brèthes, 1914)	1	0.87	1	1.23
Linepithema micans (Forel, 1908)	1	0.87	3	3.70
Linepithema humile (Mayr, 1868)	1	0.87	1	1.23
Linepithema sp. 1			6	7.41
Linepithema sp. 2	1	0.87		
Subfamily Ectatomminae				
Gnamptogenys striatula Mayr, 1884	8	6.96	2	2.47
Subfamily Formicinae				
Brachymyrmex aphidicola (Forel, 1909)	1	0.87		
Brachymyrmex coactus Mayr, 1887	2	1.74	1	1.23
Brachymyrmex sp.			1	1.23
Camponotus cameranoi Emery, 1894	5	4.35	5	6.17
Camponotus cingulatus Mayr, 1862	2	1.74	2	2.47
Camponotus fastigatus Roger, 1863	1	0.87		
Camponotus lespesii Forel, 1886	2	1.74	1	1.23
Camponotus melanoticus Emery, 1894	1	0.87	1	1.23
Camponotus mus Roger, 1863			1	1.23
Camponotus rufipes (Fabricius, 1775)			4	4.94
Camponotus sp. 1	3	2.61	1	1.23
Camponotus sp. 2			1	1.23
Camponotus sp. 3			2	2.47
Camponotus sp. 4			1	1.23
Camponotus sp. 5	4	3.48	1	1.23
Camponotus sp. 6	5	4.35		
Camponotus sp. 7	2	1.74		
Camponotus sp. 8	1	0.87		
Myrmelachista sp.	1	0.87		0.00
Nylanderia fulva (Mayr, 1862)	1	0.87		
Paratrechina longicornis (Latreille, 1802)	1	0.87		

Continue...

Table 1 – Continuration.

Taxon	SHPP AL		SHPP SM	
	(n)	(%)	(n)	(%)
Subfamily Myrmicinae				
Acromyrmex rugosus (F. Smith, 1858)	1	0.87	1	1.23
Acromyrmex subterraneus (Forel, 1893)			1	1.23
Apterostigma pilosum Mayr, 1865	2	1.74		
Apterostigma wasmannii Forel, 1892	1	0.87		
Atta sexdens (Linnaeus, 1758)	3	2.61	2	2.47
Atta sp.	6	5.22	1	1.23
Crematogaster sp.			1	1.23
Monomorium floricola (Jerdon, 1851)	1	0.87		
Mycocepurus goeldii (Forel, 1893)			1	1.23
Mycocepurus sp.			1	1.23
Pheidole pubiventris Mayr, 1887	3	2.61	4	4.94
Pheidole risii Forel, 1892	1	0.87		
Pheidole sp. 1			4	4.94
Pheidole sp. 2	13	11.30	5	6.17
Pheidole sp. 3			4	4.94
Pheidole sp. 4	3	2.61	1	1.23
Pheidole sp. 5	3	2.61		
Pheidole sp. 6	3	2.61	1	1.23
Pheidole sp. 7	2	1.74	1	1.23
Pheidole sp. 8	1	0.87		
Pheidole sp. 9	1	0.87		
Pogonomyrmex naegelii Forel, 1878	1	0.87	1	1.23
Solenopsis saevissima (F. Smith, 1855)	1	0.87	3	3.70
Solenopsis sp.	2	1.74	1	1.23
Wasmannia auropunctata (Roger, 1863)	1	0.87		
Subfamily Ponerinae				
Hypoponera trigona (Mayr, 1887)			1	1.23
Hypoponera sp. 1	1	0.87		
Hypoponera sp. 2	1	0.87		
Neoponera villosa (Fabricius, 1804)	5	4.35	2	2.47
Odontomachus chelifer (Latreille, 1802)	1	0.87	1	1.23

Continue...

Table 1 – Continuration.

Taxon	SHPP AL		SHPP SM	
	(n)	(%)	(n)	(%)
Pachycondyla striata F. Smith, 1858	9	7.83	4	4.94
Pachycondyla sp. 1	2	1.74		
Pachycondyla sp. 2	1	0.87		
Subfamily Pseudomyrmecinae				
Pseudomyrmex flavidulus (F. Smith, 1858)	2	1.74	1	1.23
Pseudomyrmex gracilis (Fabricius, 1804)			3	3.70
Richness	47		42	
Abundance (occurrences)	115		81	

AL: SHPP 1; SM: SHPP 2.

With 35% similarity, the NMDS analysis grouped the abundance and composition of ant assemblages from the sites sampled in the two DIA into four groups. Site 2 of the DIA of SHPP 2 was similar to sites 1, 2, 3, and 4 of the DIA of SHPP 1, while Site 5 of this DIA was isolated from all others. Sites 1 and 5 and sites 3 and 4 of the DIA of SHPP 2 formed two separate groups (Figure 3). The difference between the sites was confirmed by the PERMANOVA analysis ($F = 1.87$; $p = 0.04$). Ecologically, this difference indicates the heterogeneity and the mosaic of different land uses that make up the sites sampled in the DIA of the two SHPP.

Discussion

The biodiversity (subfamilies and genera) of ants sampled reflects the accumulated knowledge of the ant fauna occurring in southern Brazil (Ulysséa et al., 2011; Franco and Feitosa, 2018). The most species-rich subfamilies in the samples, Myrmicinae, Formicinae, Ponerinae, and Dolichoderinae, corroborate the study of Lutinski et al. (2018). The richness of the subfamily Myrmicinae predominates in samples from southern Brazil (Ulysséa et al., 2011; Franco and Feitosa, 2018; Rizzotto et al., 2019). The richness, abundance, and composition sampled will serve as a parameter for evaluating the impacts caused during the implementation of the two projects. The difference in the evaluated parameters of the ant fauna sampled at different sites reflects the mosaic of environments and land uses that compose them.

Myrmicine ants perform various ecosystem functions, occupy different niches, colonize strata from the subsoil, and litter to the top of the canopy (Baccaro et al., 2015; Cuautle et al., 2020). Some species establish relationships with fungi, plants, and even other ants (Baccaro et al., 2015). The richness of the genera *Pheidole* (S = 11), *Acromyrmex* (S = 2), and *Solenopsis* (S = 2) also corroborates the literature on this

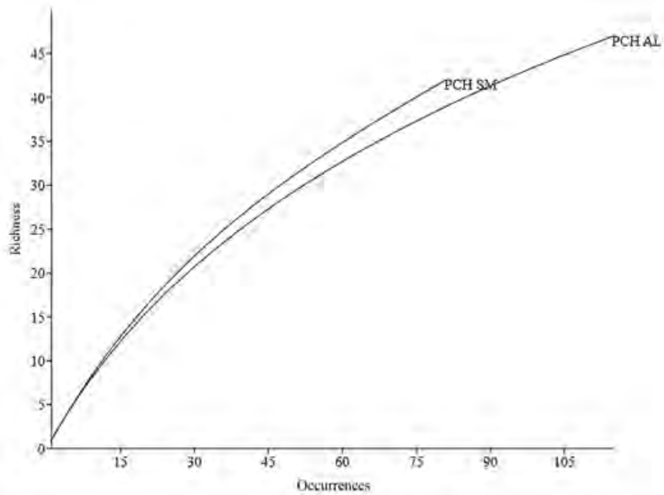

Figure 2 – Comparison, using the rarefaction method, of the richness of ant assemblages sampled in DIA, in the pre-implementation of two SHPP in the municipality of Cascavel, state of Paraná, July 2016 (winter) and March 2017 (summer).
AL: SHPP 1; SM: SHPP 2.

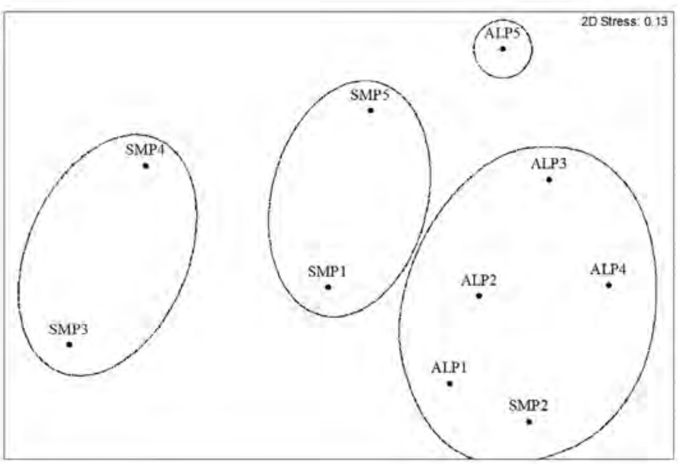

Figure 3 – Distribution, according to NMDS of the abundance and composition of ant assemblages sampled in DIA, in the pre-implementation period of two SHPP in the municipality of Cascavel, state of Paraná, July 2016 (winter) and March 2017 (summer).
AL: SHPP 1; SM: SHPP 2; P1-5: sampling sites.

subfamily in southern Brazil (Ulysséa et al., 2011; Franco and Feitosa, 2018; Dröse et al., 2019). While *Acromyrmex*, *Apterostigma*, *Atta*, and *Mycocepurus* ants feed on fungi grown on plant material, *Crematogaster*, *Monomorium*, *Pheidole*, *Solenopsis*, and *Wasmannia* are generalists (Baccaro et al., 2015). Some species of *Pheidole* and *Solenopsis* are predators and can contribute to biological control (Abeijon et al., 2019). The mosaic of conserved or recovering environments, surrounded by agricultural environments and pasture areas, can explain the occurrence of myrmicine ants in the DIA of the two SHPP, since, among the sampled species, some are tolerant to environmental disturbances, while others require more conserved environments.

The subfamily Formicinae is the second most species-rich among Formicidae in the Neotropical region (Martins et al., 2020). Species-rich genera such as *Camponotus* belong to this subfamily. These are easily sampled ants, usually with arboreal habits; however, some can be found in the soil or litter (Baccaro et al., 2015). The genus *Camponotus*, most species-rich in the samples (S = 15), is constant in the records of the southern Atlantic Forest (Franco and Feitosa, 2018; Lutinski et al., 2018; Dröse et al., 2019). This genus includes generalist ants, although they can establish close relationships with other insects, such as aphids (Hemiptera, Aphididae) (Baccaro et al., 2015), and can also be found in urban environments (Lutinski, 2017). Also highlighted in the samples were the genera *Brachymyrmex* (S = 3) and *Myrmelachysta* (S = 1), ants associated with litter and vegetation, respectively (Baccaro et al., 2015). It is also worth highlighting the records of *Nylanderia fulva* and *Paratrechina longicornis*, ants known for their invasive, generalist, and tolerant habits in disturbed environments (Zenner de Polanía, 2019). As with myrmicine ants, the richness and abundance of Formicinae ants can be explained by the heterogeneous preservation conditions verified in the sampling sites.

The subfamily Ponerinae stands out for its richness and abundance in samples taken in conserved environments in southern Brazil (Franco and Feitosa, 2018; Lutinski et al., 2018; Dröse et al., 2019). The richness of the genera *Hypoponera* (S = 3) and *Pachycondyla* (S = 3) agrees with the literature since these genera stand out in richness among the Ponerinae ants of the neotropical region (Bolton, 2021). Ants of these genera, as well as *Neoponera* and *Odontomachus*, are the specialized predators found in soil and litter, where they prey on small arthropods. It is worth noting that the richness of Ponerinae ants sampled in the two DIA allows us to infer that, despite the anthropogenic disturbance verified from the agricultural and grazing activities practiced in the surroundings, the existing forest remnants harbor a specialized ant fauna.

Dolichoderinae ants are constantly recorded in samples taken in the Atlantic Forest Biome (Freitas et al., 2014). In general, they usually have relationships with some plants, on which feed on sugary liquids from floral nectaries (Baccaro et al., 2015), with an emphasis in this study on the richness of *Linepithema* (S = 5). *Dorymyrmex* and *Linepithema* are the generalist ants and support fragmentation and anthropic environments (Lutinski et al., 2017b), which may explain the richness and abundance in the samples from the two DIA.

The subfamily Ectatomminae was represented in the samples by the records of only one species, *G. striatula*. It is a specialized species of predatory ant that colonizes and forages the litter, where it also finds its prey (Camacho and Feitosa, 2015). The records of this species in the two DIA are associated with the remaining forest fragments.

Pseudomyrmecinae ants are frequent in surveys that were already carried out in southern Brazil (Ulysséa et al., 2011; Franco and Feitosa, 2018; Dröse et al., 2019). Two species belonging to the genus *Pseudo-*

myrmex were sampled, and *Pseudomyrmex flavidulus* was recorded in the two DIA. These ants, although they have already been recorded in urban (Lutinski, 2017) and agricultural (Rizzotto et al., 2019) environments, depend on the vegetation where they find their prey. In this sense, the role of DIA forest fragments in the conservation of this fauna and the biodiversity associated with it is highlighted.

Although 41.3% richness was sampled simultaneously in the two DIA, most species occurred exclusively in one or the other DIA. Myrmecofauna samples are influenced by abiotic factors such as temperature and humidity (Hölldobler and Wilson, 1990) that regulate the foraging activities of these insects. Biotic factors, such as the presence of vegetation that provides them with nesting and food sites, in many cases, and the presence of other animal species, especially other arthropods, with which they interact and obtain food (Baccaro et al., 2015), determine their presence or absence in a given environment. In this sense, the richness shared by the two DIA can be explained by the sharing of biotic and abiotic factors, as they are located in the same hydrographic basin of a small river. The occurrence of unique species in each DIA, in contrast, can be explained by the status of conservation or impact in which each sampling site is. These variations in the status of conservation in which each sampling site is found may also explain the similarity in composition and abundance verified from the NMDS and PERMANOVA. Sites 1 and 2 of each DIA stood out in terms of richness, abundance, and composition, which may be associated with better conditions of native vegetation cover. Sites occupied by crops and pastures showed lower richness and abundance (Sites 3, 4, and 5 of each DIA).

The ant assemblage richness of the DIA of SHPP 1 was 11.9% higher than that of the DIA of SHPP 2. However, Chao 1 estimate for the ant assemblage of DIA of SHPP 2 indicated that the richness of this can be 28.9% higher than the DIA of SHPP 1. These results, associated with the values of the Shannon (H′) and Evenness (J′) indices, do not allow us to infer that the ant richness of the two DIA is different from each other and that the variations found are small and due to chance. Estimates such as Chao 1 help in the analysis of sampling sufficiency (Lemes and Köhler, 2017) and represent a useful tool when the sampling effort is limited.

Final Considerations

The relevance of biodiversity surveys in environments to be impacted by impoundments such as SHPP lies in establishing a basis from which it is possible to carry out further studies and compare the results. In this way, it was contributed to more assertively measure the environmental impacts of these projects. Ants, recognized as bioindicators, allow an inference about the condition of the environment, especially regarding the succession or degradation of the vegetation and, therefore, of the terrestrial invertebrate fauna, with which the ants maintain a close relationship with many taxa.

In this sense, this study fulfills its objective of contributing information about ant assemblages occurring in environments subjected to impacts by the implementation of two SHPP. First, the survey contributes to the expansion of knowledge about the ant fauna occurring in the state of Paraná, and, second, it will serve as a basis for monitoring impacts caused by the implementation of these and other projects.

The ant fauna surveyed here is mostly constituted by genera and species that are abundant in the southern region of Brazil and frequently sampled in anthropized environments. These are resilient species, whose richness and local abundance will be less affected by the implementation of SHPP, in short and medium term. Nevertheless, the occurrence of species of the genera *Gnamptogenys*, *Hypoponera*, *Mycocepurus*, *Myrmelachista*, *Odontomachus*, and *Pseudomyrmex* in the samples stands out. These ants, although abundant in the region, are associated with litter, vegetation, and/or prey (other invertebrates) that serve as food. These species tend to disappear locally as the changes resulting from the implementation of SHPP take place.

Contribution of authors:

Lutinski, J.A.: Conceptualization, Data curation, Investigation, Formal analysis, Methodology, Resources, Software, Writing — original draft, Writing — editing and review, Supervision, Validation, Visualization. Filtro, M.C.: Funding acquisition, Project administration. Baucke, L.: Funding acquisition, Project administration. Dorneles, F.E.: Investigation, Writing – editing and review. Lutinski, C. J.: Investigation, Writing – editing and review. Guarda, C.: Conceptualization, Investigation, Writing – editing and review.

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Effects of a recent urbanization event on coastal groundwater in the southeastern coast of Brazil: a case study of the Macaé municipality

Efeito da urbanização recente em águas subterrâneas costeiras na Região Sudeste, Brasil: um estudo de caso do município de Macaé

Jones Henrique Carvalho da Silva[1], *Emmanoel Vieira da Silva-Filho*[2], *Analy Machado de Oliveira Leite*[1], *Mauricio Mussi Molisani*[1]

ABSTRACT

Coastal groundwater is extremely vulnerable to land-based human activities and seawater intrusion. In Brazil, a developing country, several coastal cities are undergoing recent urbanization with no planning, giving rise to problems such as groundwater overexploitation, sanitation, and chemical contamination. This study provides seasonal and spatial groundwater chemical and microbiological characterization of a recently urbanized coastal region, discussing contamination and salinization. The recent urbanization event affected both shallow and deep wells represented by the extensive presence of *Escherichia coli* on groundwater and nitrate, ammonium, arsenic, and lead (NO_3^-, NH_4^+, As and Pb) levels above groundwater safety guidelines. In contrast, iron and manganese (Fe and Mn) concentrations above the safety limit were associated with lithological enrichment, but might also restrict groundwater consumption. In addition to chemical and microbiological contamination, salinization of coastal aquifers did not pose a threat in this shoreline, but brackish groundwater was found in one well influenced by a coastal lagoon sandbar opening that allowed seawater to enter the aquifer.

Keywords: hydrochemistry; contamination; metal; *Escherichia coli*; salinization

RESUMO

As águas subterrâneas costeiras são extremamente vulneráveis a atividades localizadas no continente e à intrusão salina. Em países em desenvolvimento, a recente urbanização de muitas cidades costeiras ocorreu sem planejamento, levando a problemas como a sobre-explotação das águas subterrâneas, ausência de saneamento e contaminação química. Este estudo apresenta uma caracterização espacial e sazonal de aspectos químicos e microbiológicos das águas subterrâneas em uma região costeira urbanizada recentemente, discutindo a contaminação e a salinização desse recurso hídrico. A urbanização recente afeta tanto poços rasos quanto profundos pela presença extensiva de *Escherichia coli* e alguns valores de NO_3^-, NH_4^+, As and Pb superiores aos de referência da legislação. Em contraste, concentrações de ferro e manganês acima dos valores de referência foram relacionadas a um enriquecimento litológico, embora possam restringir o consumo da água subterrânea. Ao lado da contaminação química e microbiológica, a salinização dos aquíferos costeiros não representou uma ameaça para essa área, embora águas subterrâneas salobras tenham ocorrido em um poço, influenciado pela abertura de barra de uma lagoa costeira, que promoveu a intrusão salina no aquífero.

Palavras-chave: hidroquímica; contaminação; metais; *Escherichia coli*; salinização.

[1]Universidade Federal do Rio de Janeiro – Rio de Janeiro (RJ), Brazil.

[2]Universidade Federal Fluminense – Niterói (RJ), Brazil.

Correspondence address: Jones Henrique Carvalho da Silva – Alameda da Lagoa 769/3 – Granja – CEP: 27930-000 – Macaé (RJ), Brazil. E-mail: jones.carvalhobio@gmail.com

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Introduction

Groundwater is an important resource for human society (Graaf et al., 2019). However, groundwater quantity and quality have been increasingly vulnerable to pollution, overexploitation, and salinization (UNICEF and WHO, 2017). Coastal aquifers might be vulnerable to an intensification of land use and land cover changes, mainly associated with an increasing number of people settling in coastal cities. Coastal cities are expected to host around 800 million people by 2050, while being vulnerable to sea-level rise of 0.5 m (WEF, 2019). Consequently, urbanization, especially rapidly developing cities, has increased coastal aquifer exploitation and the emission of a myriad of untreated effluents (Machiwal et al., 2018). In addition, coastal groundwater salinization may occur by intensive groundwater withdrawal, land subsidence, and seawater intrusion, allowing hydraulic saline gradients into aquifers (Hoover et al., 2017; Gomes et al., 2019).

The Brazilian coast is 8,698 km long with an area of 388,000 km^2. Along the coastal plain, aquifers have important storage capacity, which might be influenced by surface and marine waters (Hu et al., 2017). However, the literature shows scarce data characterizing coastal groundwater pollution and salinization (Silva-Filho et al., 2009; Godoy et al., 2013; Mirlean et al., 2014; Bertrand et al., 2016; Paim et al., 2018; Gomes et al., 2019). Urbanization in several coastal cities has been intensified over the last 40 years, induced by the oil and gas industry, tourism, the naval industry, general services, and others. With no urban planning, such as a waste treatment system, the intensification of urbanization overloaded the carrying capacity of coastal ecosystems, resulting in groundwater vulnerability, for example, due to pollution, giving rise to problems related to sanitation, chemical contamination, and overexploitation (Silva-Filho et al., 2009; Lins-de-Barros, 2017). In addition, the permeability of coastal sandy soils and civil construction works along the shoreline have turned groundwater into a potential source of chemicals for coastal waters (Godoy et al., 2013).

Although some coastal cities in Brazil have moderate groundwater demand (Vilar, 2016), the recent population increase tends to intensify groundwater exploitation. Besides, more than half of the aquifers in Brazil are not regulated, adding unknown pressure on groundwater exploitation and water quality (Vilar, 2016). In this context, many studies have addressed the impact of megacities on groundwater (Bertrand et al., 2016; Gomes et al., 2019), but no studies have been described for small coastal cities, in which urbanization has been recently intensified, with unknown impacts on groundwater. Therefore, this study provides a seasonal and spatial groundwater chemical and microbiological characterization of coastal shallow and deep wells from sedimentary and fissured aquifers in a recently urbanized coastal region. It discusses contamination and salinization of aquifers, identifying patterns that might be occurring in many recently urbanized coastal regions in Brazil.

Material and Methods

The region studied is located on the coast of the Macaé municipality, state of Rio de Janeiro, Brazil. Over the last 40 years, urbanization increased to support the operational activities of the oil and gas industry in the Campos Basin (Figure 1). During this period, the population along the coastal plain increased from 40,000 to over 250,000 inhabitants. Unfortunately, urbanization occurred without any housing waste treatment, in addition to other pollution sources, such as those related to the oil industry. As a result, the anthropogenic sources are responsible for most of the nitrogen, phosphorous, and metal loads cycling in the region (Molisani et al., 2013).

The coastal wells are inserted in the fissured and sedimentary aquifers. Fissured aquifers are characterized by basement rocks represented by the Pre-Cambrian metamorphic sillimanite-biotite gneiss and orthogneiss with granitic crystals of potassium feldspar. Sedimentary aquifers are in the alluviate deposits composed of silty-clay, organic-rich sediment, and beach-ridge terraces constructed along the Pleistocene and Holocene (Barreto et al., 2000; CPRM, 2012). The climate of the region is subtropical, with hot summers and mild dry winters, with an annual rainfall of 1,000-1,500 mm, having the highest volume of 180 mm in December (summer) and the lowest in August, 40 mm on average (winter).

Groundwater samples were collected monthly during 2016 and 2017. Eleven wells were monitored, being six shallow wells (depth from 1.0 to 11 meters) and five deep ones (depth from 16 to 85 meters). Wells were sampled along the fissured (D1, D2, D3, S1, S3) and sedimentary (D4, D5, S2, S4, S5, S6) aquifers (Barreto et al., 2000), and encompassing the industrial (S3, D1, D5) and high-density urban (D2, D3, D4, S1, S2, S4, S5, S6) areas of the municipality (Figure 1). The distance between the wells and the coastal line varied from 0.36 to 8.50 km.

Before sampling, the initial static water levels were measured with an electric sounder, considering that the wells had not been pumped 24 hours before water collection. The water was sampled using a pump coupled to a polyethylene hose cleaned with 70% alcohol to avoid previous microbial contamination. The pump flows were adjusted at the lowest and continuous rate. The wells were purged to remove any stagnant water in the line before water collection was initiated. The water was stored in polyethylene bottles previously cleaned with acid and kept in a thermal box (Brasil, 2013).

Wells were analyzed *in situ* using a portable instrument for the following parameters: temperature (°C), electrical conductivity (EC), and pH. The EC and dynamic water depth were also hourly measured in one well at 0.25 km offshore to trace the influence of marine saltwater intrusion during a semidiurnal spring tidal cycle (0 to 1.3 m) in the dry season (September 2017). Major ions fluoride, bromide, sodium, potassium, calcium, magnesium, chloride, ammonium, nitrate, nitrite, phosphate, sulfate (F^-, Br^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{-2}) were analyzed by ionic chromatography (Metrohn 850 Professional IC). Dissolved organic carbon (DOC) was determined

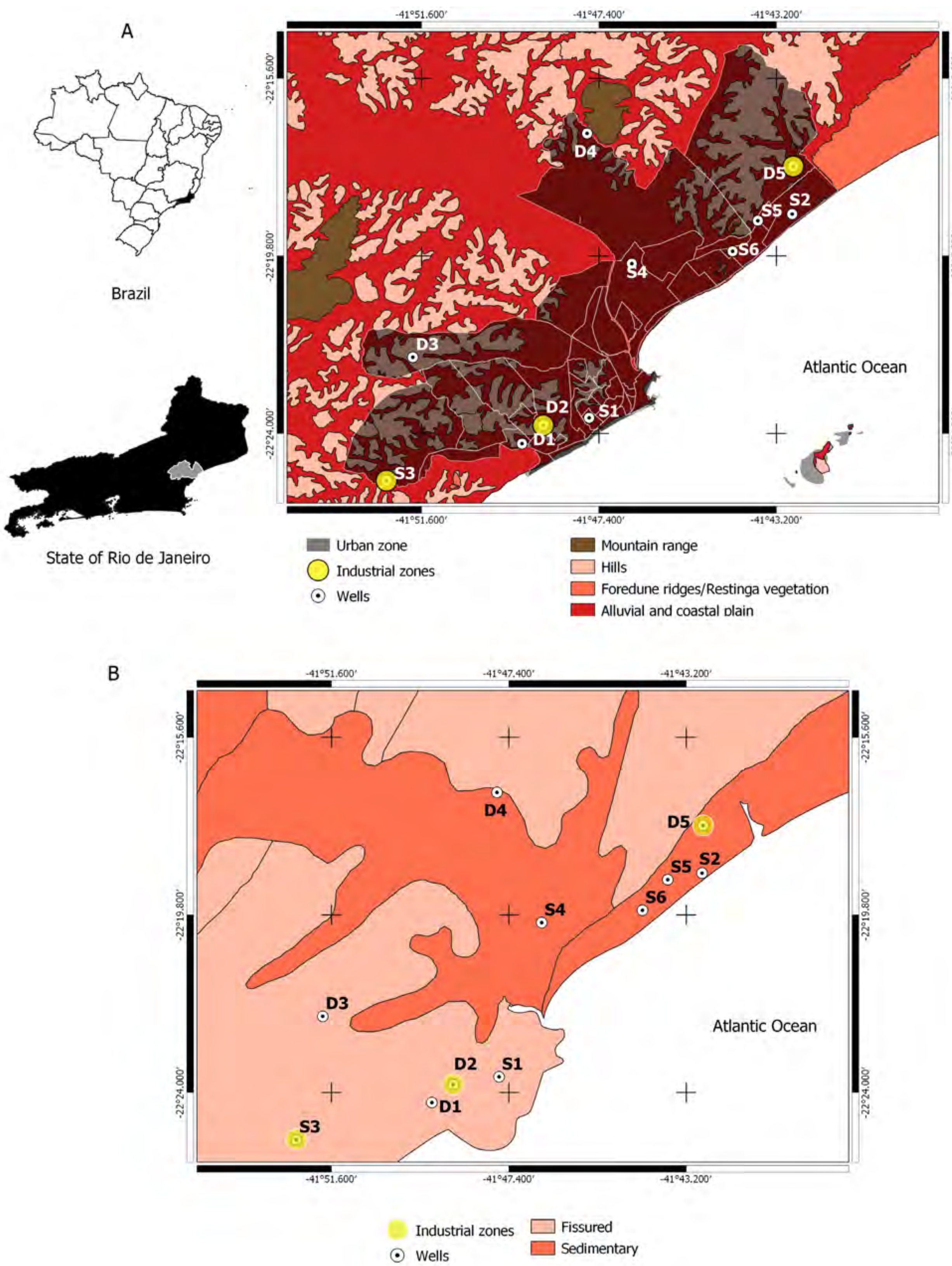

Figure 1 – Map of the studied area, including the (A) location of the monitored shallow (S) and deep (D) wells at the fissured and (B) sedimentary aquifers in the Macaé municipality.

by pyrolytic combustion (Shimadzu TOC analyzer). Metals were analyzed by inductively coupled plasma-mass spectrometry (Thermo Fisher Scientific, model X-Series 2). All samples were analyzed using replicates (coefficients of variations were less than 15%) and analytical blanks. Accuracy was checked using a certified reference solution (AccuTrace™ reference Standard) with recoveries ranging from 92% (Cr) to 106% (Ni). Detection limits were calculated as three times the standard deviation of repeated blank measurements.

For microbiological analysis, water samples were collected according to the standard guidelines, using 250 ml sterile bottles stored in an icebox and processed in the laboratory within four hours after collection (APHA, 2018). The presence or absence of *Escherichia coli* (*E. coli*) was checked using the Defined Substrate Technology (DST) with Colitag® medium and incubation for 24 hours at 37°C. The *E. coli* ATCC 29522 strain was used as a positive control and sterile water as a negative control. After incubation, the presence of *E. coli* was observed by exposing the positive samples to UV light, showing a blue fluorescence and comparing them to the control samples.

D'Agostino–Pearson omnibus normality test was previously used for the one-way analysis of variance (ANOVA) followed by Dunnett's (parametric) test or the Kruskal–Wallis test followed by Dunn's (non-parametric) test to obtain statistically significant differences ($P < 0.05$) of concentrations among wells and between the wet and dry season. A correlation matrix was used to determine data inter-correlations.

Results and Discussion

Groundwater microbiological contamination was the most important problem related to the recent urbanization in the coastal region. About 64% of 143 groundwater samples had *E. coli* (Figure 2). The shallow wells had 69% of the samples contaminated by *E. coli*, while deep wells had 57% of the samples with this pathogen, which is a sanitary indicator of groundwater fecal contamination. Shallow wells had more *E. coli* in the rainy season (72% of the samples) than in the dry season (67% of the samples). In contrast, deep wells had more contaminated samples (66%) in the dry season than in the rainy period (47%). According to the Brazilian Legislation and WHO Guidelines, for every 100 ml of water tested, no *E. coli* should be detected (Brasil, 2008, 2017; WHO, 2017). Thus, part of this coastal urban groundwater was contaminated, preventing direct water consumption. This result suggests poor well management during drilling or sealing and/or cross-contamination of aquifers by the untreated sewage, reported mainly in shallow wells, which are still common in developing countries (Vilar, 2016; Ferrer et al., 2020).

The systematic review and meta-analysis performed by Genter et al. (2021) showed that groundwater is vulnerable due to fecal contamination in low- and middle-income countries, where 36% of the monitored samples were contaminated by *E. coli*. Such results showed that self-supply shallow groundwater was more vulnerable to fecal contamination, mainly in low-income countries. In the coastal area studied, located in a middle-income country, 64 and 57% of the samples from shallow and deep wells, respectively, were contaminated by *E. coli*. Microbiological contamination was more extensive than that reported by the above-mentioned review, including a coastal area in low-income Ghana (Africa) where 33% of the groundwater samples were contaminated by *E. coli* (Lutterodt et al., 2021). Such comparisons indicated the deleterious effects of recent urbanization and untreated domestic sewage emission on groundwater in a region that has been receiving a lot of money in royalties from oil exploration, but its groundwater sanitary conditions are worse than that of low-income African countries.

Table 1 shows the physical and chemical groundwater parameters for shallow and deep wells in the studied area. Comparing the major ion composition with the Brazilian Groundwater Guidelines (BRASIL, 2008), it was observed that 10% of the samples had higher NO_3^- concentrations than the proposed limit for drinking water. According to Zhang et al. (2020), high groundwater nitrate concentrations in newly urbanized regions was two or more times higher than those in long-standing urbanized areas, and have a relationship to inadequate wastewater systems (Boumaiza et al., 2020). When comparing the NO_3^- values in wells from the fissured and sedimentary aquifers, higher values (8.9 mg L^{-1}) were observed in fissured aquifers than in sedimentary ones (1.2 mg L^{-1}). The predominance of NO_3^- on groundwater over NH_4^+ in the wells monitored was also attributed to the nitrification process, which also enhances NO_3^- contamination in recently urbanized coastal zones (Shi et al., 2018).

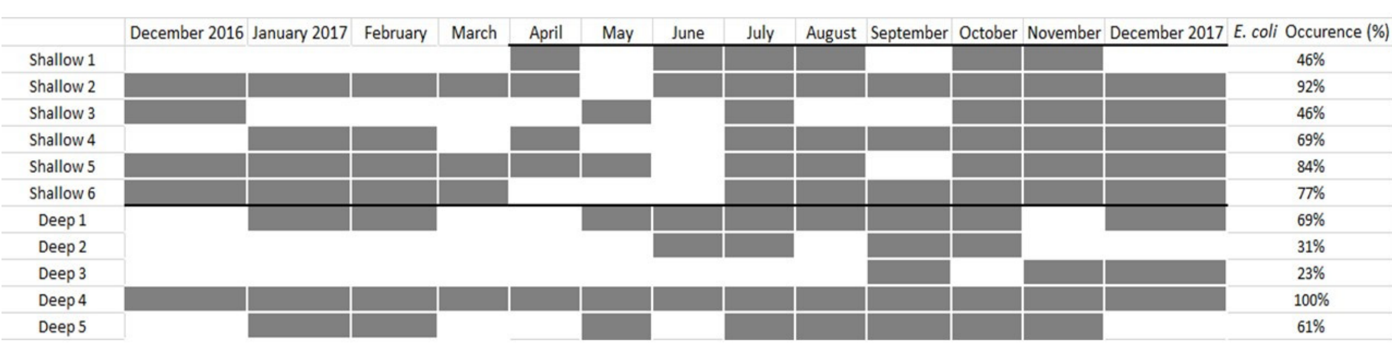

Figure 2 – Presence (grey) and absence (white) of Escherichia coli in shallow and deep wells monitored during the sampling period.

The relationship between nitrate and chloride (NO_3^- and Cl^-) is widely applied to trace nitrate pollution sources (Li et al., 2010). The correlation between NO_3^- and Cl^- from the shallow well that had higher nitrate values than the Brazilian Groundwater Guidelines showed a significant positive correlation ($r^2 = 0.62$, $P = 0.01$) (Figure 3), which suggested that nitrate could be originated from untreated sewage and residential buildings (Li et al., 2010; Güller et al., 2012; Boumaiza et al., 2020; Zhang et al., 2020). Similarly, the high variability of chloride on groundwater should be attributed to the widespread use of chlorine in the wells for water disinfection, as corroborated by extensive groundwater microbiological contamination. To obtain effective chlorine disinfection, the pH should be lower than 8 (WHO, 2017). However, the maximum pH values measured at some of the wells studied were higher than 8 (Table 1), which is more likely to be ineffective for chlorine disinfection, for example, for the *E. coli* measured on groundwater.

Table 1 – Minimum, maximum, and mean (coefficient of variation) values of the physical and chemical parameters for shallow and deep wells and comparison to the Brazilian Groundwater Guidelines (Brasil, 2008) and International Standards for Drinking-water (WHO, 2017)*.

Parameter	Shallow			Deep			Brasil (2008)	WHO (2017)
	Min.	Max.	Mean (CV)	Min.	Max.	Mean (CV)		
Water depth (m)	1.0	11	4.5 (48)	16	85	47 (63)	-	-
Temperature (°C)	22	31	26 (6.0)	21	29	26 (7.0)	-	-
Conductivity (mS cm^{-1})	0.14	1.02	0.39 (58)	0.059	1.06	0.39 (76)	-	1.7
pH	5.0	8.8	6.7 (14)	5.4	8.1	6.9 (10)	-	6.5-8.5
F^- (mg L^{-1})	0.01	0.67	0.12 (154)[a]	0.01	2.21	0.23 (167)[b]	1.0	1.5
Br^- (mg L^{-1})	0.03	0.30	0.12 (60)	0.03	5.2	0.87 (190)	-	-
Ca^{+2} (mg L^{-1})	0.25	41	14 (8.9)	0.68	57	18 (90)	-	150-300
Mg^{+2} (mg L^{-1})	0.1	9.8	3.8 (57)	0.26	23	5.4 (97)	-	150-300
Na^+ (mg L^{-1})	3.2	162	33 (91)	2.3	73	25 (66)	200	200
K^+ (mg L^{-1})	0.63	21	5.6 (73)[a]	0.40	11	3.6 (74)[b]	-	-
Cl^- (mg L^{-1})	2.9	166	37 (88)	1.0	225	41 (123)	250	250
SO_4^{-2} (mg L^{-1})	3.0	272	43 (119)[a]	1.0	67	15 (88)[b]	250	250
NO_3^- (mg L^{-1})	0.10	50	4.9 (231)	0.10	50	5.8 (196)	10	50
NO_2^- (mg L^{-1})	0.01	0.01	0.01	0.02	0.04	0.03	1.0	3.0
NH_4^+ (mg L^{-1})	0.01	2.6	0.45 (139)[a]	0.01	1.1	0.21 (129)[b]	1.5	1.5
PO_4^{-3} (mg L^{-1})	0.11	0.87	0.08 (203)	0.12	1.2	0.10 (185)	-	-
DOC (mg L^{-1})	0.41	15	6.7 (52)[a]	0.16	10	4.2 (67)[b]	-	-
Al (µg L^{-1})	0.92	162	65 (66)[a]	0.86	127	42 (87)[b]	200	200
Fe (µg L^{-1})	0.35	1,841	223 (174)[a]	0.16	225	55 (126)[b]	300	1,000
Mn (µg L^{-1})	8.0	1,583	140 (220)	0.1	818	78 (178)	100	400
Zn (µg L^{-1})	0.75	76	22 (92)	3.5	217	44 (58)	500	400
Cu (µg L^{-1})	0.17	19	5.5 (83)	0.51	12	4.1 (81)	2000	2000
Cr (µg L^{-1})	0.02	48	4.1 (10)[a]	0.03	2.5	0.54 (117)[b]	50	50
Ba (µg L^{-1})	8.4	293	72 (92)	8.4	211	79 (63)	700	700
Ni (µg L^{-1})	0.06	19	2.3 (183)	0.06	3.3	1.2 (77)	20	70
As (µg L^{-1})	0.11	4.7	1.8 (1.4)[a]	0.74	32	9.6 (13)[b]	10	10
Sr (µg L^{-1})	23	372	90 (87)	6.0	357	89 (106)	-	-
Pb (µg L^{-1})	0.10	12	2.5 (116)	0.24	4.3	1.9 (70)	10	10
Cd (µg L^{-1})	0.02	0.11	0.05 (63)	0.03	0.10	0.04 (28)	5.0	3.0
V (µg L^{-1})	0.001	15	2.7 (136)	0.07	7.5	2.3 (2.0)	50	-
Co (µg L^{-1})	0.01	6.5	1.4 (122)[a]	0.01	1.0	0.22 (133)[b]	-	-

*Upper case letters indicated that means are statistically different for a probability of 95%.

In another shallow well, in a recent large population settlement without sewage treatment in the municipality, all samples monitored during the sampling period had NH_4^+ values above the safety limits. In this shallow well, dissolved oxygen (%) had the lowest average (± SD) concentration measuring 63 ± 31%. Ammonium in wells from the sedimentary aquifer was higher (0.59 mg L^{-1}) than in the wells sampled in the fissured aquifers (0.1 mg L^{-1}). Ammonium is released into groundwater via landfill, septic tanks, and sewage disposal, or even produced *in situ* by anaerobic organic matter decomposition (Zhang et al., 2020). Because of a possible NO_3^- loss through denitrification and retention of NH_4^+ not oxidized to NO_3^-, NH_4^+ may be enriched in urban wells located at lowlands. The measured concentrations of NO_3^- and NH_4^+ in this study were lower than the values reported for highly urbanized coastal regions (> 20 mg L^{-1} and > 1 mg L^{-1}, respectively) (Shi et al., 2018; Zhang et al., 2020), indicating small to moderate enrichment of the nitrogen forms associated with the recent urbanization event.

On average, the shallow and deep wells were similar for most ions, except for F^- which was significantly higher in the deep wells. In contrast, K^+, SO_4^{-2}, NH_4^+, and DOC had significantly higher concentrations in the shallow wells. When comparing wells from fissured and sedimentary aquifers, only Br^- and F^- were significantly higher on groundwater from the fissured aquifers, while DOC was higher in the sedimentary aquifer. The results showed groundwater chemical heterogeneity, with a larger coefficient of variation for nitrate, phosphate, fluoride, and sulfate in the shallow wells; and for nitrate, bromate, phosphate, fluoride, and chloride in the deep wells (Table 1). Heterogeneity may reflect the influence of anthropogenic emission (Santucci et al., 2017), although the lithological diversity has been considered at chemical concentrations in such coastal region (Silva-Filho et al., 2009).

Higher DOC and nitrogen concentrations in the shallow wells in the sedimentary aquifer should confirm the connection of groundwater to the runoff (Barbosa and Silva Jr., 2005), including the urban runoff carrying organic matter from anthropogenic sources, including untreated sewage. A potentiometric survey indicated that aquifers in the study area have a strict connection to surface waters, being recharged by adjacent upstream areas and discharged seaward (Barbosa and Silva Jr., 2005). Thus, groundwater contamination may be linked to infiltration of contaminated surface water (Engström et al., 2015; Siqueira, 2017; Soares et al., 2020). In the study area, Molisani et al. (2013) estimated that the anthropogenic loads represented 90% of the total nitrogen input in the coastal plain where the wells are located. Livestock, mainly cattle, and untreated domestic sewage were both the major nitrogen sources, contributing to 620 ton $year^{-1}$ and 550 ton $year^{-1}$, respectively, for surface waters and soils of the coastal plain.

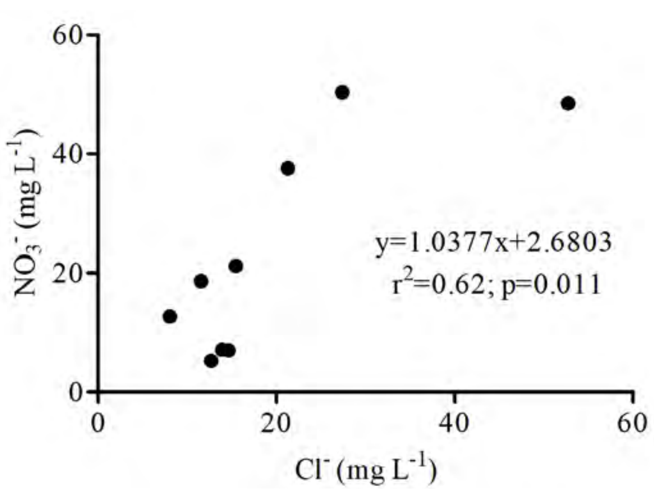

Figure 3 – Relationship between NO_3^- and Cl^- in a nitrate-contaminated well.

In addition to the human influence on the chemical features of the coastal groundwater, natural processes also determine such conditions. The pH and electrical conductivity were similar among the wells during the monitoring period. Such values were reported for coastal aquifers from the granitic-gneiss lithology and diverse regional geochemical facies, as also related to marine-derived atmospheric deposition and anthropogenic contamination (Silva-Filho et al., 2009; Gomes et al., 2019). For major ions, coastal groundwater from the shallow and deep wells had a predominance of Cl^-, SO_4^{-2}, Na^+, Ca^{2+} (Table 1) that should be attributed not only to the local granitic lithology and weathering, but also to the marine droplet atmospheric deposition, seawater intrusion and soil organic matter decomposition (Silva-Filho et al., 2009; CPRM, 2012). As a result, the groundwater samples were grouped into four dominant facies:

- Group 1: sodium chloride facies;
- Group 2: sodium bicarbonate facies;
- Group 3: calcium bicarbonate facies;
- Group 4: sulfate magnesium facies.

This classification was also reported for another survey in the study area which described the predominance of sulfate and chlorine on the groundwater, explained by the coastal proximity and potential salinization of the aquifers (Bento, 2006). The range of Na^+, Ca^{2+}, Mg^{2+}, and Cl^- concentrations for the shallow wells were similar to other adjacent coastal aquifers in the state of Rio de Janeiro, in which the groundwater was influenced by sea salts (Silva-Filho et al., 2009). However, assuming that Cl^- in the seawater is about 536 mEq L^{-1}, the contribution of marine chloride on the groundwater of the shallow wells of this study is 0.8%, which is lower than the 1.5% reported by Silva-Filho et al. (2009).

Ionic ratios have been applied to trace the hydrochemistry dynamic of groundwaters, based on the following ratios, rMg^{+2}/rCa^{+2}, rK^+/rNa^+, rNa^+/rCl^- (Chidambaram et al., 2018). Such ratios were calculated for the wells in the sedimentary and fissured aquifers along with the coastal municipality. The results indicated that wells inserted in the sedimentary and fissured aquifers, respectively, had the following ratios: rMg^{+2}/rCa^{+2} (0.30 and 0.60), rK^+/rNa^+ (0.11 and 0.07), rNa^+/rCl^- (1.35 and 1.08). The interpretation of the calculated ionic ratios indicated that groundwater in the studied coastal region has a continental source and a relationship with water circulation in the granitic crystalline rocks. This analysis corroborates the assumption that aquifers in the study area have a strict connection to surface waters, being recharged by adjacent upstream areas (Barbosa and Silva Jr., 2005), where the lithology is composed of gneiss and orthogneiss with granitic crystals (CPRM, 2012).

Comparing the metal concentrations with the Brazilian Groundwater Guidelines (BRASIL, 2008), higher values for Fe, Mn, As, and Pb were observed in the monitored wells. Similarly, Pb was observed at higher concentrations than that provided for in the Brazilian Groundwater Guidelines (BRASIL, 2008) for one sample in a well in the industrial zone. The As values were higher than the safety limit in three sampling events of a well located in the industrial region of the municipality, where metal framework manufacturers are located. High concentrations of this metalloid were described in a deltaic shallow aquifer near the study area and were related to the long-term atmospheric fall out over the sediments (Mirlean et al., 2014), similarly to other coastal areas influenced by anthropogenic As sources (Mirlean et al., 2003). Thus, considering the atmospheric As a pathway for some areas of the Brazilian coast, the high values in one well located in the industrial area suggested the anthropogenic source of this metalloid in the municipality.

On the contrary, Fe and Mn concentrations in some shallow and deep wells were higher than the concentrations proposed by the guidelines, but were related to natural processes. Fe and Mn are common elements found in the regional granitic-gneiss lithology. Their values range from 1 to 7% of Fe_2O_3 and from 0.02 to 0.17% of MnO (CPRM, 2012). Consequently, the weathering of Fe and Mn-rich minerals is responsible for mobilizing such metals and their high concentrations on groundwater are controlled by the redox potential and dissolution of such minerals found in aquifers (Güller et al., 2012). A maximum Fe concentration of 2.3 mg L^{-1} was reported for intensive anthropogenic coastal areas, being this level considered a moderate-to-heavy pollution risk level (Wen et a., 2019) and similar to those measured in some shallow wells in this study (1.8 mg L^{-1}). In contrast, elevated Mn levels (> 0.4 mg L^{-1}) were measured in coastal aquifers from rapidly urbanized regions and related to untreated sewage and industrial wastewater, as well as decomposition of organic matter, reduction of Fe (hydr)oxides, and Mn-rich runoff (Hou et al., 2020). Maximum values of 1.5 mg L^{-1} measured in the study area highlight the enrichment of such metal, mainly in the sedimentary aquifer (mean of 0.16 mg L^{-1}), compared to the fissured aquifer (mean of 0.07 mg L^{-1}). In addition, the recent human occupation of the coastal lowlands of our study requires, in many cases, an extensive embankment foundation, which consists of a series of compacted layer soils removed from local hills to raise ground height, thus enhancing the weathering of Fe and Mn minerals. No matter their origin, Fe and Mn excess on groundwater may cause taste deterioration, staining of laundry, and potential effects to the human health (WHO, 2017). Fe, Mn, and As enrichments in aquifers were also found in recently urbanized coastal regions and such metals may be indicators of the recent human occupation on the coastal zone (Huang et al., 2018; Wen et al., 2019; Hou et al., 2020; Islam et al., 2020).

During the sampling period, concentrations were more detectable for Al, Fe, Mn, Zn, Cu, Ba, Sr than for Cr, Ni, As, Pb, V, Co, Cd. On average, higher values of Al, Fe, Cr, and Co were found in the shallow compared to the deep wells. In contrast, deep wells had higher values for As only (Table 1). The wells located in the sedimentary aquifer had significantly higher Fe, Cu, and Al values than those in the fissured aquifer (255 and 48 μg L^{-1} for Fe; 6.2 and 3.6 μg L^{-1} for Cu, 73 and 32 μg L^{-1} for Al, respectively for the sedimentary and fissured aquifers). Most of the chemical data had a high deviation, which did not provide a statistical differentiation between the dry and rainy seasons (Table 2). The large variability of metal and major ions concentrations

Table 2 – Seasonal variation of physical and chemical parameters (mean ± standard deviation) measured in the shallow and deep wells*.

Parameter	Shallow		Deep	
	Dry	Rainy	Dry	Rainy
Water depth (m)	4.9 ± 2.2	3.8 ± 1.9	47 ± 29	47 ± 31
Temperature (°C)	25 ± 1.5	26 ± 1.7	25 ± 2.1	26 ± 1.4
Conductivity (mS cm^{-1})	0.36 ± 0.2	0.43 ± 0.27	0.40 ± 0.3	0.40 ± 0.3
pH	6.6 ± 0.8	6.8 ± 1.3	6.9 ± 0.7	7.0 ± 0.7
F^- (mg L^{-1})	0.08 ± 0.13	0.05 ± 0.05	0.23 ± 0.41[a]	0.13 ± 0.06[a]
Br^- (mg L^{-1})	0.12 ± 0.10	0.13 ± 0.10	0.97 ± 1.9	0.66 ± 1.2
Ca^{+2} (mg L^{-1})	15 ± 10	13 ± 7.0	19 ± 17	18 ± 16
Mg^{+2} (mg L^{-1})	4.7 ± 2.3	5.4 ± 5.8	3.5 ± 2.1	5.5 ± 4.4
Na^+ (mg L^{-1})	36 ± 35	30 ± 23	26 ± 18	22 ± 14
K^+ (mg L^{-1})	6.1 ± 5.0	4.7 ± 3.0	4.3 ± 3.2	2.5 ± 1.2
Cl^- (mg L^{-1})	35 ± 31	41 ± 37	44 ± 56	36 ± 41
SO_4^{-2} (mg L^{-1})	53 ± 62	28 ± 22	19 ± 16	10 ± 6.0
NO_3^- (mg L^{-1})	4.1 ± 11	6.0 ± 12	5.5 ± 11	6.3 ± 12
NH_4^+ (mg L^{-1})	0.42 ± 0.63	0.46 ± 0.61	0.16 ± 0.24[a]	0.39 ± 0.33[a]
PO_4^{3-} (mg L^{-1})	0.04 ± 0.05	0.16 ± 0.26	0.08 ± 0.12	0.14 ± 0.28
DOC (mg L^{-1})	6.7 ± 3.6	6.8 ± 3.4	4.2 ± 3.0	4.1 ± 2.3
Al (μg L^{-1})	76 ± 32	68 ± 51	52 ± 40	33 ± 32
Fe (μg L^{-1})	304 ± 505	136 ± 171	86 ± 86	38 ± 57
Mn (μg L^{-1})	213 ± 420	66 ± 72	112 ± 197	49 ± 47
Zn (μg L^{-1})	25 ± 21	15 ± 17	48 ± 59	39 ± 59
Cu (μg L^{-1})	7.0 ± 4.5[a]	3.1 ± 3.3[a]	6.1 ± 3.2[b]	1.8 ± 1.4[b]
Cr (μg L^{-1})	7.0 ± 14	1.6 ± 1.8	0.73 ± 0.70	0.24 ± 0.30
Ba (μg L^{-1})	77 ± 72	65 ± 58	90 ± 56	63 ± 35
Ni (μg L^{-1})	3.3 ± 5.2	0.78 ± 0.80	1.5 ± 1.0	0.75 ± 0.60
As (μg L^{-1})	2.2 ± 1.4[a]	0.34 ± 0.1[a]	7.6 ± 12	Nd
Sr (μg L^{-1})	118 ± 90[a]	54 ± 38[a]	121 ± 106	46 ± 51
Pb (μg L^{-1})	2.5 ± 3.2	2.7 ± 2.5	2.4 ± 1.2	0.71 ± 0.5
V (μg L^{-1})	2.9 ± 3.8	2.7 ± 4.2	2.2 ± 2.3	1.6 ± 1.6
Co (μg L^{-1})	1.6 ± 1.8	1.3 ± 1.5	0.2 ± 0.3	-

*Upper case letters indicated that means are statistically different for a probability of 95% (n = number of samples).

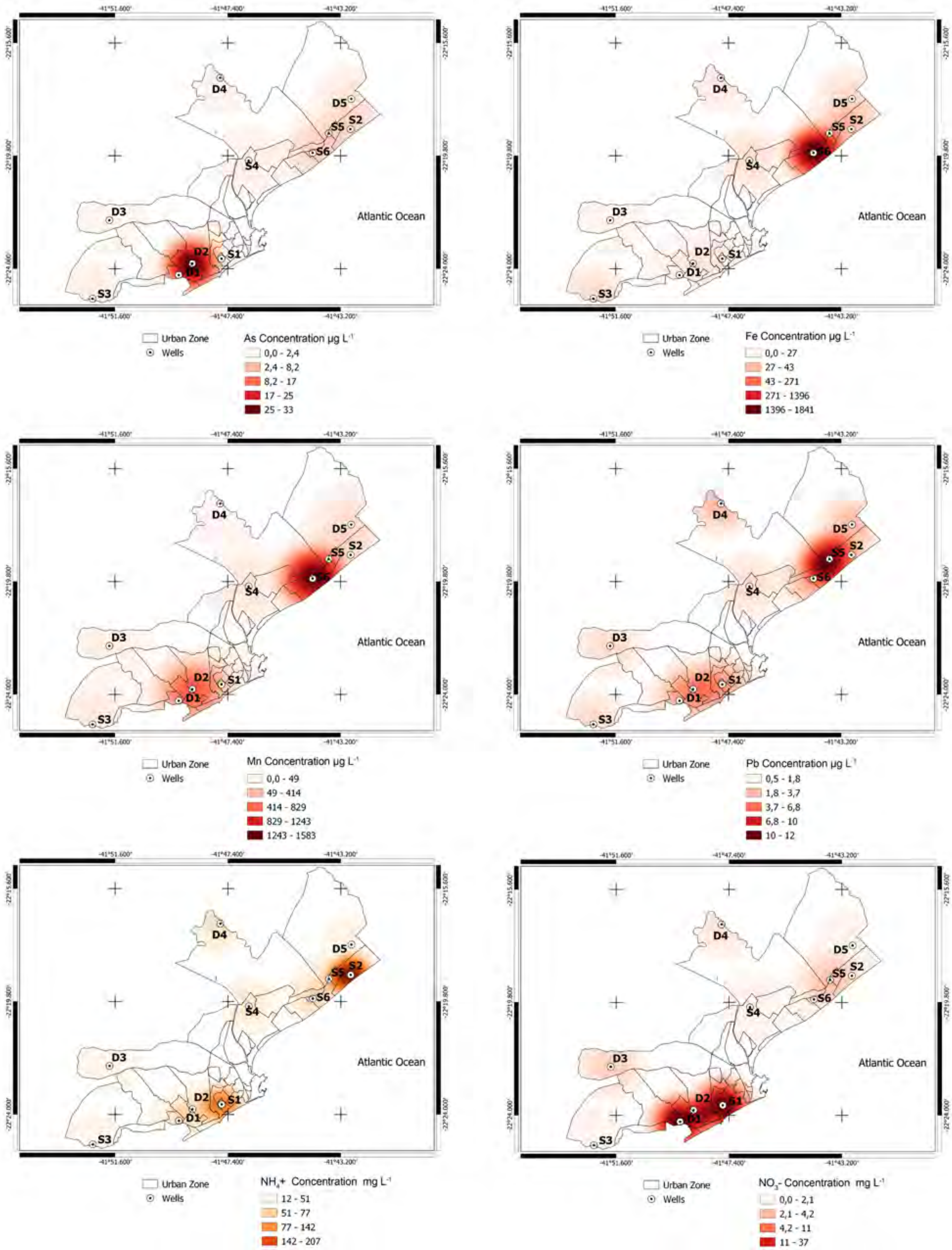

Figure 4 – Spatial variation of maximum concentrations of the critical parameters measured on the groundwater of the recently urbanized coastal municipality.

on groundwater has been attributed to the human influence, mainly to the leaking of effluents, although the aquifer also influenced such variability (Santucci et al., 2017). In contrast, the shallow wells had higher Cu, As, and Sr values during the dry season, while the deep wells had higher F^- and Cu concentrations in the dry season, and higher NH_4^+ levels during the rainy season. Increased chemical concentration in the rainy season may be a result of the desorption from organic matter or aquifer minerals, as observed for NH_4^+, while dilution may also occur mainly in the shallow coastal sand aquifers (McDonough et al., 2020). Thus, higher groundwater Cu, As, Sr, F^- enrichments in the dry season may indicate a reduced dilution capacity due to the lower water volume of aquifers, mainly reported for shallow wells, intensifying the effects of the recent urban occupation on the coastal zone.

Our findings showed that urban groundwater from several shallow and deep wells were not suitable for proper human consumption. However, the extension of groundwater contamination was lower than those measured in recently-urbanized larger coastal cities with over one million inhabitants (Zhang et al., 2015; Bertrand et al., 2016; Huang et al., 2018; Shi et al., 2018; Wen et al., 2019; Islam et al., 2020; Zhang et al., 2020), in contrast to small and medium-sized cities such as the Macaé municipality and others (Samantara et al., 2017). However, similar qualitative groundwater contamination by NO_3^+, NH_4^+, As, Pb, Fe, and Mn was reported for such large cities, as for this recently urbanized coastal municipality, mainly in the industrial zone and low-income urban settlements without sanitation (Figure 4).

Besides the chemical and microbiological contamination of recently urbanized coastal areas, salinization may risk groundwater consumption (Hoover et al., 2017; Gomes et al., 2019). During the monitoring period, the electrical conductivity ranged from 130-1,010 µS cm^{-1} for the shallow and 590-1,060 µS cm^{-1} for the deep wells, with significant differences between the dry and wet seasons (Tables 1 and 2). The average values for the shallow and deep wells were plotted against the distance to the seashore, which showed that the wells close to the seafront had the highest conductivity values (Figure 5). However, the conductivity range showed relatively low or even no groundwater salinization for the study area (Cary et al., 2015; Gomes et al., 2019). In contrast, the hourly monitored well during the semi-diurnal spring tidal cycle showed higher electrical conductivity, typical of brackish water. The initial measurement at the low tide presented a conductivity of 14,000 µS cm^{-1}, with the peak tide indicating maximum values of 26,000 µS cm^{-1}. During the tidal cycle, the dynamic depth of the well varied by 20 cm (Figure 5). The presence of brackish groundwater in this well is apparently associated with the proximity to a coastal lagoon that had its sand barrier artificially opened in the previous rainy season for urban flood control. Thus, the sand barrier opening induced seawater inflow into the lagoon, salinizing the adjacent aquifer. Groundwater salinity and mixing processes with adjacent surface water are complex, with shallow wells being more susceptible (Das and Mukherjee, 2019).

Conclusion

This study concluded that the intensification of urbanization over the last 40 years, with no domestic waste treatment, has compromised the sanitary and chemical aspects of coastal groundwater, as shown by extensive *E. coli* contamination of both shallow and deep wells of this coastal municipality. The recent urbanization also compromised the coastal groundwater with NO_3^+, NH_4^+, As, and Pb, but to a lower extent compared to microbiological contamination, represented by one-time concentrations higher than that provided for by the Brazilian Groundwater Guidelines in wells in the industrial zone and urban settlements. The large spatial and temporal heterogeneity of the chemical concentrations may reflect not only the lithological diversity of the coastal region, but also confirm the influence of anthropogenic emissions on groundwater. Furthermore, Fe and Mn concentrations above the Brazilian Groundwater Safety Limits indicated the influence of a natural lithologic

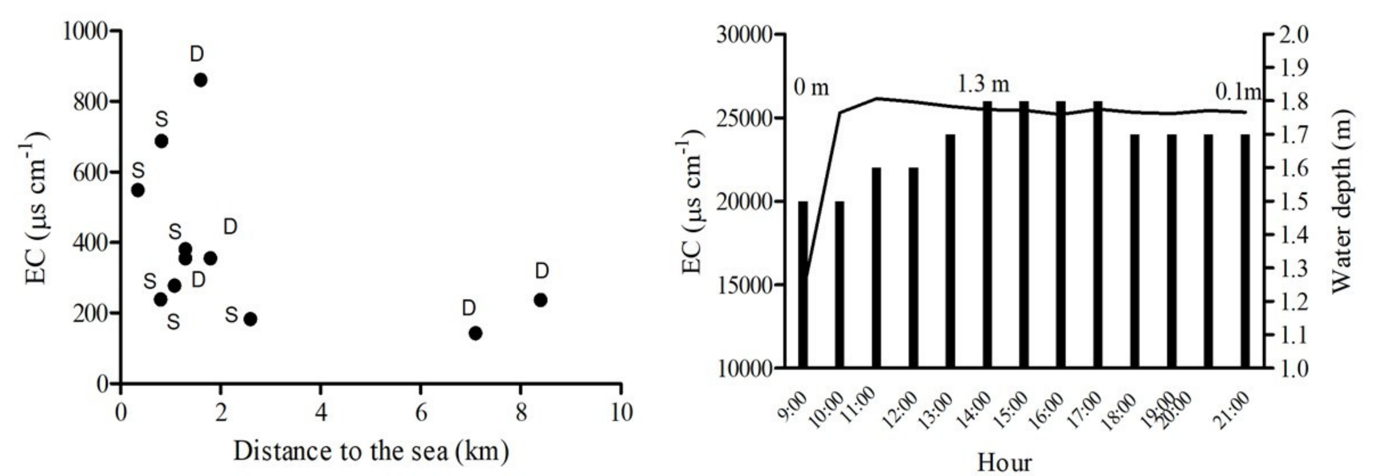

Figure 5 – Mean electrical conductivity (EC) in the shallow (S) and deep (D) wells relative to seafront distance (left) and hourly electrical conductivity and water depth of one well monitored during a semi-diurnal tidal cycle (numbers on top indicate the tidal range) (right).

enrichment that may synergically affect groundwater consumption. Corroborating the literature, this study proposes that *E. coli*, NO_3^+, NH_4^+, As, and Pb are indicators of the influence of recent urbanization on the coastal groundwater, in synergism with the geochemical processes, as exemplified by the high Fe and Mn content on groundwater.

In general, shallow wells located at the urban settlement were more intensively impacted than deep wells, usually drilled in industrial zones. Well drilling and water withdrawal in industrial areas are legally regulated by protocols and standards. On the contrary, domestic wells, mainly in low-income urban settlements, are usually drilled without any regulation and inspection, and thus shallow wells (1 to 11 m) sitting at a short distance from septic tanks are affected by cross-contamination, represented by the widespread presence of *E. coli*. Furthermore, both industrial and domestic wells in the studied municipality have extensive water withdrawal, which influences the contamination scenario and the well conditions, for example, reducing the water dilution capacity and intensifying water recharge from the urban area.

Besides the chemical and biological aspects of urban groundwater, salinity did not pose a threat to the monitored coastal wells. In contrast, brackish groundwater was measured in a well from an aquifer that was salinized by seawater intrusion during a sandbar opening of a coastal lagoon for urban flood control.

Contribution of authors:

SILVA, J.H.C.: Conceptualization, Formal Analysis, Investigation, Resources, Writing — Original Draft, Writing — Review and Editing.; MOLISANI, M.M.: Conceptualization, Formal Analysis, Investigation, Resources, Writing — Original Draft, Writing — Review and Editing.; SILVA-FILHO, E.V.: Methodology, Validation, Formal Analysis, Resources, Writing — Review and Editing.; LEITE, A.M.O.: Methodology, Validation, Formal Analysis, Resources, Writing — Review and Editing.

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Vegetation dynamics and precipitation sensitivity in three regions of northern Pantanal of Mato Grosso

A dinâmica da vegetação e a sensibilidade à chuva em três regiões do norte do Pantanal mato-grossense

Tonny Jader de Moraes[1], Nadja Gomes Machado[2], Marcelo Sacardi Biudes[1], Nelson Mario Banga[3], Laís Braga Caneppele[4]

ABSTRACT

The wet areas of the Pantanal provide important services such as water and carbon storage, improved water quality, and climate regulation. Analysis and monitoring of vegetated land and precipitation on a regional scale using remote sensing data can provide important information for the preservation of the landscape and biodiversity of the region. Thus, the purpose was to analyze characteristics of the green cycle of the vegetated surface and to what extent the vegetated surface responds to the variability of precipitation in the Pantanal. The areas include the regions of Cáceres (CAC), Poconé (POC), and Barão de Melgaço (BAM) in Mato Grosso. Time series of accumulated precipitation (PPT) and NDVI (Normalized Difference Vegetation Index) were used for the period from 2000 to 2016, obtained on NASA's Giovanni platform (National Aeronautics and Space Administration). The analysis of the wavelet transform was applied for NDVI data and there was cross-correlation analysis for PPT and NDVI data. The results showed that the highest correlation between PPT and NDVI was positive with a 1-month lag, but was significant with a lag of up to 3 months. The wavelet analyses showed that the largest wavelet powers occurred at the frequency between 0.5 and 1.3 years, i.e., the NDVI series presented the main variances on the approximately annual scale, indicating that these characteristics are important aspects of local phenology variability, such as cumulative green throughout the year and generalized senescence.

Keywords: NDVI; wavelet; cross-correlation; seasonality.

RESUMO

As áreas úmidas do Pantanal fornecem importantes serviços, como armazenamento de água e carbono, melhoria da qualidade da água e regulação do clima. A análise e o monitoramento da superfície vegetada e da precipitação em escala regional, com uso de dados de sensoriamento remoto, podem oferecer informações importantes para a preservação da paisagem e da biodiversidade da região. Assim, o objetivo deste estudo foi analisar características do ciclo do verde da superfície vegetada e em que medida a superfície vegetada responde pela variabilidade da precipitação no Pantanal. As áreas analisadas compreendem as regiões de Cáceres (CAC), Poconé (POC) e Barão de Melgaço (BAM), em Mato Grosso. Foram usadas séries temporais de precipitação acumulada (PPT) e índice de vegetação *Normalized Difference Vegetation Index* (NDVI) para o período de 2000 a 2016, obtidos na plataforma Giovanni da *National Aeronautics and Space Administration* (NASA). Foram aplicadas a análise da transformada *wavelet* para os dados de NDVI e a análise de correlação cruzada para os dados de PPT e NDVI. Os resultados mostraram que a maior correlação entre a PPT e o NDVI foi positiva com defasagem de um mês, mas foi significativa em até uma defasagem de três meses. As análises *wavelet* mostraram que as maiores potências ocorreram na periodicidade entre 0,5 e 1,3 anos, isto é, as séries de NDVI apresentaram as principais variâncias na escala aproximadamente anual, indicando que essas características são aspectos importantes da variabilidade da fenologia local, como o verde cumulativo ao longo do ano e a senescência generalizada.

Palavras-chave: NDVI; *wavelet*; correlação cruzada; sazonalidade.

[1]Universidade Federal de Mato Grosso – Cuiabá (MT), Brazil.
[2]Instituto Federal de Mato Grosso – Cuiabá (MT), Brazil.
[3]Zambeze University – Beira, Moçambique.
[4]Universidade do Estado de Mato Grosso – Cuiabá (MT), Brazil.
Correspondence address: Tonny Jader de Moraes – Rua 20, 16 – Santa Terezinha – CEP: 78089-758 – Cuiabá (MT), Brazil. E-mail: tonny@fisica.ufmt.br
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Introduction

The Pantanal, considered the largest tropical wet area in the world, has numerous rivers and is predominantly covered by different types of savannas and forests characterized by seasonal floods with varying intensities (Junk et al., 2006; Junk et al., 2014). The heterogeneity of the Pantanal is represented, according to Silva and Abdon (1998), by 11 sub-regions based on the flood, relief, soil, and vegetation aspects. The swamp plain has a periodic cycle of droughts and flooding (flood pulse), which plays an essential role in nutrient cycling and carbon sequestration, by preserving organic matter in flooded soils (Erwin, 2009; Hiraishi et al., 2014). These cycles govern all biodiversity and facilitate the development of animal and plant species in the Pantanal (Muniz et al., 2017).

The flood pulse of the Pantanal is controlled not only by local precipitation but also by precipitation in the headlands, where the Paraguay River has access to the Pantanal mainly from the North, in the subregions of Baron de Melgaço and Poconé (Lázaro et al., 2020). The disposition and diversity of species vary in and between different habitats, arranged along the flood gradient, from non-flooding to seasonal and permanently flooded (Junk et al., 2011). Thus, the interannual variability of precipitation also affects the vegetation of these regions differently near the flooded areas, with weaker and defaced responses to precipitation due to local water storage (de Deus et al., 2020).

However, several changes have impacted the biodiversity of the Pantanal, such as the expansion of agricultural activities and hydroelectric development (Bergier, 2013; Ioris et al., 2014), and recent studies based on predictive models also indicate a gradual growth in the frequency of intense precipitation and long periods of stress (Hirabayashi et al., 2013; Marengo et al., 2015, 2021). In addition to these disturbances, the vegetation is highly sensitive to the ocean-atmosphere climatic phenomena El Niño and La Niña, which cause changes in the hydrological cycle (Vicente-Serrano et al., 2013; Hilker et al., 2014; Penatti et al., 2015; Li et al., 2016). Thus, extreme events show that climate change poses a high risk of environmental degradation for the Pantanal and many other wet areas around the world (Thielen et al., 2020).

Knowledge of the current behavior and the possible changes of the cycle of increase and decrease of the green of the vegetation, in response to climatic changes, is fundamental to the understanding of the ecosystem dynamics of the Pantanal. For example, precipitation availability and periodicity are key factors controlling biogeochemical cycles, primary productivity, and vegetation growth and reproduction phenology, while regulating agricultural production (Feng et al., 2013; Baptista et al., 2018). However, more studies are needed, with greater scope, over several long time scales (> 10 years) to understand the complex relationship between precipitation regimens and vegetation, as well as the system's responses to different magnitudes of human and climate pressures (Schulz et al., 2019).

Monitoring of regional environmental data in the Pantanal at a reasonable cost is a challenge due to difficulties in representing the spatial heterogeneity of precipitation and some parameters of vegetation (Penatti et al., 2015). However, orbital remote sensing is an efficient source of data to observe potential impacts that climate change can cause on the Pantanal (Miranda et al., 2018a).

Due to the spectral response characteristic of the vegetation, it is possible to use geoprocessing techniques for its identification and evaluation, which allows obtaining information, such as those of complexity and heterogeneity of the vegetation (Miranda et al., 2018a), changes in the use and coverage of the land (Paranhos Filho et al., 2014; Corrêa et al., 2017), classification of vegetation types (Bispo et al., 2013), the relationship between vegetation indices and soil water content (Danelichen et al., 2016), hydrological dynamics (Penatti et al., 2015) and spatial-temporal variability of vegetation (de Almeida et al., 2015).

Among the vegetation indices we can highlight the Normalized Difference Vegetation Index (NDVI), which is widely used in the evaluation of various biophysical parameters (Tartari et al., 2015; de Morais Danelichen and Biudes, 2020), proving suitable for monitoring phenological changes in plant formations (Miranda et al., 2018a). In addition, NDVI time series are generally non-stationary, i.e. they have different frequency components, such as seasonal variations, long-term and short-term fluctuations, whose analysis of these components cannot be limited to just the average of the series, as these components affect their general structure of variance (Qiu et al., 2013).

In addition to the trend analysis for a time series of vegetation index, the interannual changes may also contain significant information on the response of vegetation to forced weather (Zoffoli et al., 2008; Martínez and Gilabert, 2009). Therefore, different mathematical techniques and statistics can be used to monitor vegetation dynamics from multi-temporal data, among which the analysis of main components (de Almeida et al., 2015) and curve adjustment (Zhang et al., 2006), self-correlating function (Zoffoli et al., 2008) and spectral frequency techniques, such as Fourier analysis (Quiroz et al., 2011; Vourlitis and Rocha, 2011), and, recently, the wavelet decomposition (Soto-Mardones and Maldonado-Ibarra, 2015), which was also used to identify the phenological dynamics of vegetation (Martínez and Gilabert, 2009; Kuplich et al., 2013; Qiu et al., 2013). However, the wave analysis is an efficient resource to expose many characteristics of a time series, such as trends, periodicity, discontinuities, and points of change (Nikhil Raj and Azeez, 2012; Joshi et al., 2016).

The analyses carried out in this study may show whether the green increase of the vegetated surface will respond positively to precipitation on a monthly scale, whether these vegetation responses differ based on local characteristics of the areas, and lastly whether the wavelet analysis can provide relevant information on the vegetation dynamics of northern Pantanal, such as the essential aspects of the temporal variability of surface phenology, that is, the characteristics of the phenological cycle of the vegetated surface.

To understand the different key characteristics related to the phenology of the vegetated surface and to what extent the vegetated surface responds to the variability of precipitation in the northern region of the Pantanal, the objective was: analyzing the periodicity and intensity of the phenology of the vegetated surface at various time scales using the transformed wavelet applied to the NDVI (Normalized Difference Vegetation Index) time series and analyzing the green response of the vegetation of the surface in reaction to the variability of the precipitation through the analysis of cross-correlation, i.e., measuring the degree of association between the monthly average of NDVI and the monthly accumulated precipitation in the region of CAC, BAM, and BAM in the Pantanal.

Materials and methods

Description of the study area

The study areas are in the north of the Pantanal, comprising the southern region of the state of Mato Grosso, located in the central west of Brazil (Figure 1), in the municipalities of Cáceres, Poconé, and Barão de Melgaço. Three quadrants were selected, one quadrant in each of the municipalities of Cáceres, Poconé, and Baron de Melgaço for seasonal monthly NDVI analysis and monthly accumulated precipitation (Figure 1).

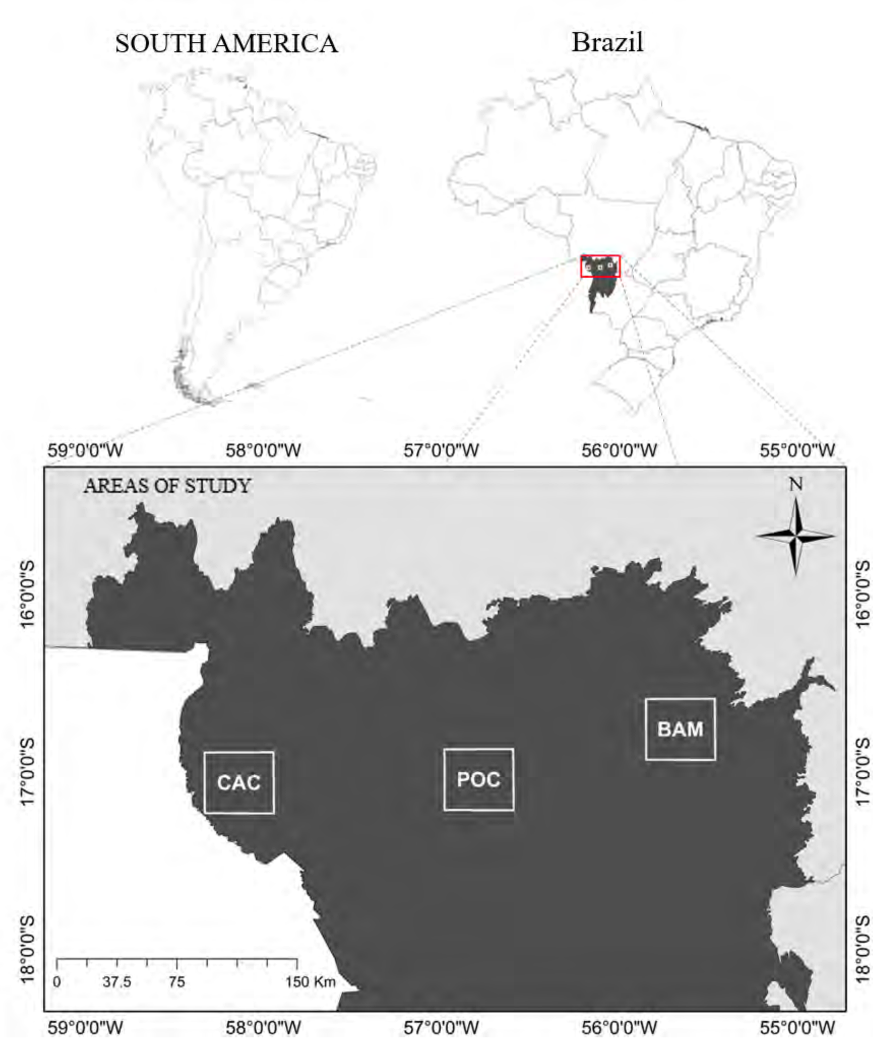

Figure 1 – Location of the Pantanal in Brazil and the areas of study (line in white color) selected respectively in the municipalities of Cáceres (CAC), Poconé (POC) and Barão de Melgaço (BAM).

According to the Köppen classification, the climate of the study area, in the north of the Pantanal, is the Aw, characterized by being warm and humid with precipitation in summer and dry in winter. The annual precipitation is approximately 1,400 mm and there is a marked dry season between May and September. The average air temperature ranges from 29 to 32°C, and the minimum from 17 to 20°C (Machado et al., 2015).

The characteristics of the predominant types of vegetation, soil, location, and sizes of the selected areas in each of the municipalities of Cáceres, Poconé, and Baron de Melgaço (respectively, CAC, POC, and BAM) are described in Table 1.

Products derived from orbital remote sensors used

The analysis of the dynamics of vegetative vigor was based in a monthly NDVI time series from 2000 to 2016, derived from the product MODIS-TERRA MOD13C2, obtained on the platform Giovanni National Aeronautics and Space Administration (NASA), through the link http://giovanni.gsfc.nasa.gov/. NDVI data have a spatial resolution of 0.05° X 0.05° (5600 m) and monthly temporal resolution (Didan, 2015).

Vegetation indices are generally calculated from remote detection data based on the fundamental optical characteristics of vegetation that are strongly absorbent in the red, but highly reflective in the near-infrared (NIR) regions of the solar spectrum (Rouse Jr. et al., 1974; Tucker, 1979). This is possible because vegetation has low reflectance in the visible band (as a function of the absorption of electromagnetic radiation by photosynthetically active leaf pigments) and high in the near infrared (due to the spread of electromagnetic radiation in the internal leaf structure) (Rosemback et al., 2013).

The product (TRMM 3B42 7) of the TRMM (Tropical Rainfall Measuring Mission) mission from NASA's Giovanni platform (site: https://giovanni.gsfc.nasa.gov/giovanni/) was used for the study. The precipitation data have a spatial resolution of 0.25° X 0.25° and monthly temporal resolution (from 2000 to 2016).

Subsequently, cross-correlation analysis was performed on a monthly scale for the monthly average precipitation and NDVI series for the same precipitation data period 2000-2016. Cross-correlations reveal the degree of interconnection between two variables in certain time series (Derrick and Thomas, 2004). The coefficient was used to measure the degree of association between the monthly mean of NDVI and the monthly accumulated precipitation in the region of CAC, POC, and BAM in the Pantanal.

The transformed wavelet

The temporal variations of the NDVI were evaluated using wave analysis, which allows the decomposition of the series as a function of time and frequency, that is, it allows the identification of the main modes of variability and the way they vary over time, as well as analyzes the periodicity at different time scales (Santos et al., 2013). The wavelet transform implements the decomposition of a signal at different spatial or temporal scales into a set of basic functions. It has been widely applied in remote sensing data analysis (Galford et al., 2008; Martínez and Gilabert, 2009; Quiroz et al., 2011; Kuplich et al., 2013; Shihua et al., 2014; Fontana et al., 2015).

The set of basic functions {ψ a, b (t)}, can be generated by translating and staggering the so-called parent wave (t), according to the Equation 1:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi(\frac{t-b}{a}) \quad (1)$$

where a is the "dilation" parameter used to change the scale, and b is the translation parameter used to slide in time. The spectral frequency technique of the wavelet transform (or wavelet) is a relatively recent tool in trend detection studies and there are few studies based on the wavelet technique (Pandey et al., 2017). The main idea of the wave transformation is to analyze a signal or time series according to different scales or resolutions (Martínez and Gilabert, 2009), so the main advantage in using this technique concerning time methods is to investigate the variability of variables in a range of time and frequency scales (Rhif et al., 2019).

In this study, the wavelet transform was applied through the DOG (Derivative of Gaussian) parent function with parameter 2 and a significance level of 0.05. The DOG function was chosen for greater precision in the time domain as compared to frequency (Farge, 1992;

Table 1 – Areas of study and types of vegetation and soil.

Área	Sub-Region	Coordinates of studied polygons	Study Area (Km²)	Vegetation	Soil
Cac	Cáceres	17°13' S; 58°22' W 16°52' S; 57°56' W	1580	Savana, with pioneering formations of river influence near the Paraguay River, grassy savannah, shrubby savannah and forest formations	sandy
Poc	Poconé	17°13' S; 56°59' W 16°51' S; 56°35' W	1580	Cerrado, vegetation under river influence and forest formations	clay
BAM	Barão de Melgaço	16°56' S; 56°51' W 16°34' S; 55°27' W	1580	Shrubby cerrado, wooded savanna and vegetation under river influence	sandy

Source: adapted from Silva and Abdon (1998) and Paranhos Filho et al. (2014).

Torrence and Compo, 1997; Santos et al., 2013), and also made it possible to represent a time series through a time-frequency diagram called a scalogram (Mallat, 2008). The coefficients are defined by the color scale, the blue color representing less intensity of the wave coefficient, energy, or power, and the red color representing greater power. Thus, the wave analysis was applied using the algorithm available in http://paos.colorado.edu/research/Wavelets, for the code, and the Matlab Software was used.

Results and Discussion

Seasonal dynamics of precipitation and NDVI

Seasonal trends were observed in the monthly accumulated precipitation time series and the monthly average of NDVI, with approximately coincident maximum and minimum values for the analyzed regions (Figure 2). The monthly precipitation accumulated during the wet season represented approximately 63% of the annual total sum in

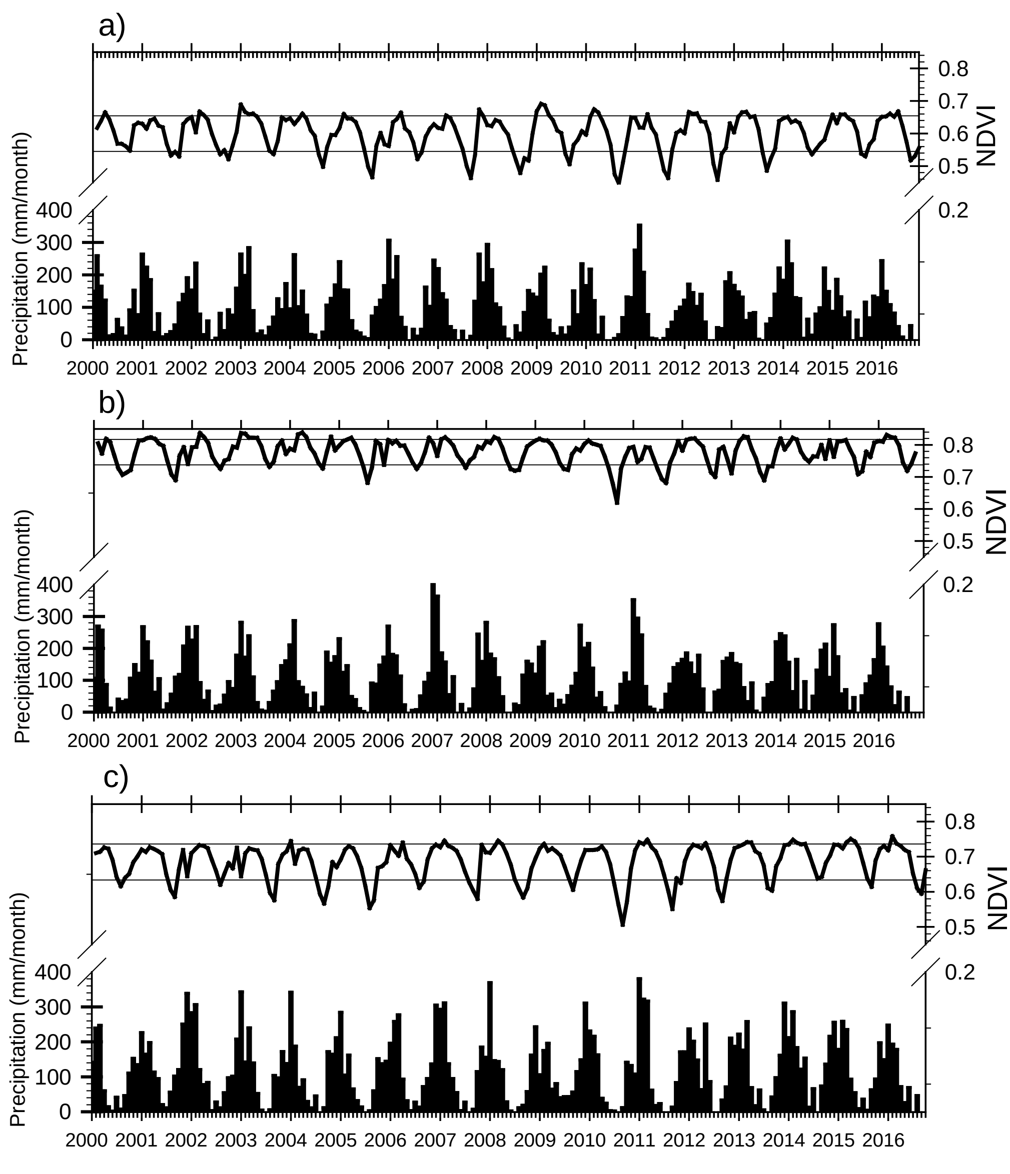

Figure 2 – Monthly seasonal change of NDVI and Precipitation of the period 2000-2016, the line (in black) represents the lower and higher limits of the standard deviation of the period average. (A) Cáceres – CAC, (B) Poconé – POC, and (C) Barão de Melgaço – BAM, in the northern region of the Pantanal in the State of Mato Grosso.

the BAM, 73% in the CAC, and POC (Figure 2). These seasonal patterns occurred synchronously for the regions analyzed and were consistent with the climatology of the region (Biudes et al., 2012; Machado et al., 2015; Novais et al., 2015; Penatti et al., 2015).

The synchronicity of the seasonal pattern of precipitation is associated with a unimodal pattern with precipitation occurring throughout the Upper Paraguay basin (Ivory et al., 2019). During the wet period, the South Atlantic Convergence Zone (ZCAS) is associated with a convergent moisture output from the Amazon to the Brazilian Southeast, which is responsible for extreme precipitation events (Rao et al., 1996).

Moreover, as observed in Figure 2, the seasonal cycle of vegetation follows the pattern of annual variability of precipitation in the Pantanal, with the river line and greenness coinciding with the beginning of the rains (de Almeida et al., 2015). These patterns indicates that vegetation phenology tends to follow relatively well-defined temporal patterns (Fontana et al., 2015; Schwieder et al., 2018). Also, according to de Almeida et al. (2015), the cycle of vegetation observed by the NDVI of the Pantanal regions can be explained by two factors together, the seasonal pattern of precipitation and the seasonal pattern of floods.

Observing the variability of the average monthly precipitation between the regions, the CAC values corresponded to the maximum value of 212.19 mm in February and a minimum of 15.4 mm in June (Figure 2A), while the mean value is 99.9 ± 11.4 (mean ± standard deviation). In the POC area, the average monthly precipitation was 229.7 mm/month in January (Figure 2B), a minimum of 16.5 in August, and an average of 107.6 ± 12.3 (average ± confidence interval). Finally, in the BAM area the average monthly precipitation was the maximum of 252.4 mm/month in January (Figure 2C), a minimum of 11.9 in August, and the mean value was 116.2 ± 13.5. These differences observed in the monthly precipitation values between the regions analyzed CAC and POC, POC and BAM may be related to the difference in the amount of precipitation over the Upper Paraguay watershed, where the largest precipitated amounts occurred in the northern and eastern regions of the basin (Penatti et al., 2015; Macedo et al., 2019), strongly influenced by regional differences (Bergier et al., 2018).

There was greater standard deviation and greater predominance of below-average values (observing the bottom line of the standard deviation of Figure 2A) in the minimum NDVI phase (average September 0.51 ± 0.02) in CAC (2005, 2007, 2008, 2010, 2011, 2012 and 2013) as compared to BAM areas (0.59 ± 0.02) (2004, 2005, 2010 and 2011) and POC (0.71 ± 0.02) (2005, 2010, 2011 and 2013) (Figure 2). Higher variability (standard deviation) and higher predominance of lower-than-average NDVI values (0.51 ± 0.02) of CAC can be explained by the greater sensitivity of planted, natural and arable pasture areas to rainfall, although precipitation and NDVI are approximately synchronous in the region, vegetation responses differ based on the geographic location of the flooded areas (Ivory et al., 2019). However, the lowest standard deviation of the NDVI and the lowest prevalence of extreme values (Figure 2B) in POC may be related to local characteristics, such as being close to river flows and bodies of water (Miranda et al., 2018a; Ivory et al., 2019). The lower mean NDVI in the CAC may also be related to high ligneous mortality rates, which favors the development of grass species (Lehmann et al., 2011; Miranda et al., 2018b), and human interference (Wessels et al., 2004; Jacquin et al., 2010). On the other hand, the highest NDVI value in POC may be related to the influence of precipitation, as the highest precipitated values occurred in the northern and eastern regions of the Upper Paraguay basin (Penatti et al., 2015; Macedo et al., 2019).

The temporal patterns of NDVI were approximately sinusoidal with the maximum value in March and April, an intense decline from the end of April until the phase of minor NDVI in August, and resuming the increase in October completing the formation of the cycle (Figure 3). According to Zhang et al. (2006), these points of change in the curvature of the monthly NDVI averages of Figure 3 correspond to the transition dates of a phenological cycle of the vegetated surface, which does not change abruptly, but gradually, such as senescence, Greenup, dormancy, and maturity. This vegetative development is determined by the continuous increase of green biomass until reaching a maximum quantity (Fontana et al., 2015). For example, in deciduous vegetation in many crops, the emergence of leaves tends to be followed by a period of rapid growth, followed by a relatively stable period of maximum foliar area (Dalmolin et al., 2015; Schwieder et al., 2018).

Based on the standard deviation to the second of the year (period of 2000-2016) in Figure 3, the greatest variabilities occurred in the phase of decrease and increase of the NDVI (dry period and beginning of wet period). However, the smallest deviations occurred in the phase of maximum NDVI (March, April, and May). The greater variability of NDVI in the dry period may be related to the change in the availability

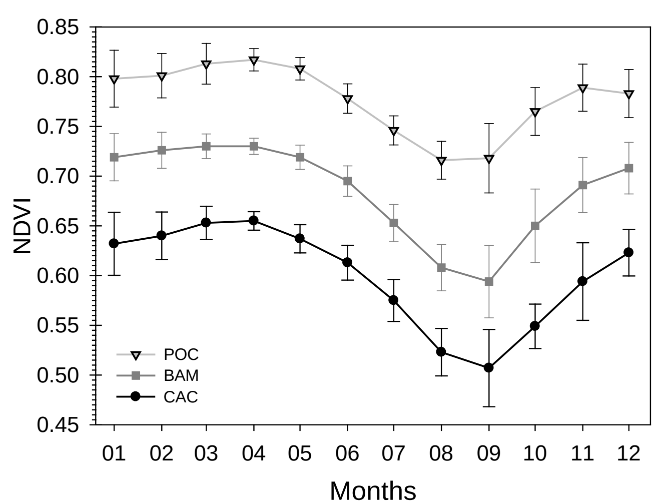

Figure 3 – Monthly average and standard deviation of the NDVI from the period 2000-2016, in three areas of study, Cáceres (CAC), Poconé (POC) and Barão de Melgaço (BAM), in the northern region of the Pantanal in the State of Mato Grosso.

of soil water due to the difference in the amount of precipitation between years (Miranda et al., 2018b). Due to the lower water availability during dry season, early senescence may occur causing more severe and longer dormancy period, as an artifice to maximize the carbon gain, increasing the rates of carbon assimilation of vegetation when the first rains begin (Franco et al., 2005; Rossatto et al., 2009).

So, the biggest difference in the intensity and the variability of the NDVI in the regions of CAC, POC, and BAM can be associated with strategies of use of the water, in other words, gramineous like those in the CAC region are considered intensive explorers, while in the trees and shrubs of forests of POC and BAM, explorers are spread out (Burgess, 1995). Therefore, grasses with dense and shallow root systems make use of provisional water available in the upper layer of the soil, while trees, which have root systems that enter the shallow and deep layers of the soil, have a more constant supply of water in the soil (Scanlon et al., 2002).

The data from the analysis of the cross-correlation between monthly accumulated precipitation and monthly mean NDVI are provided in Table 2 for CCS, POC, and BAM regions for the period from 2000 to 2016. The correlation coefficients of the sites were positive and significant in up to a 3-month lag, however, the maximum correlations occurred with a one-month lag between precipitation and NDVI (Table 2). The greatest correction between precipitation and NDVI was for the BAM region ($\beta = 0.71$, $p < 0.001$), followed by CAC and CDVI (respectively, $\alpha = 0.69$ and $\beta = 0.64$ $p < 0.001$). Thus, the results of Table 2 indicate the strong synchronicity of precipitation between CCS, POC, and BAM regions. In addition, vegetation productivity is out of phase with a delay of at least one month regarding precipitation (Ivory et al., 2019). The higher coefficient of CAC and BAM, as mentioned above, may be related to the greater dependence of vegetation on precipitation, since in the Pantanal, differences in vegetation type and soil cover can result in a strong dependence on climate or local conditions (Viana and Alvalá, 2011; Ivory et al., 2019).

Other studies (de Almeida et al., 2015; Penatti et al., 2015; Ivory et al., 2019) indicate that the seasonal pattern of vegetation productivity in the Pantanal is heterogeneous and complex in its relation to the regional climate, such as Penatti et al. (2015), as compared to the time series of EVI, precipitation and water storage in the Pantanal in the Upper Paraguay basin, and observed a strong relationship between precipitation and vegetation variability, and, in addition, water storage time in different regions of the basin varies based on geomorphology, soil type and plain drainage (Ivory et al., 2019).

NDVI analysis by wavelet transformation

Figures 4A, 5A and 6A show that the highest concentrations of wave powers (ranging from -1 to 1, from light blue to dark red) of NDVI in the Wave Power Spectrum (WPS) were significant, as they occurred within the line-delimited region (blue) representing the level of significance. These major wavelet powers occurred periodically between 0.5 and 1.3 years, indicating that the CAC NDVI series, POC, and BAM have a strong annual variation throughout 2000 – 2016. It is also observed (Figures 4B, 5B, and 6B) that the time series of the average scale (selected for the period range of 0.3 to 1.3 years) has a Gaussian distribution, centered on the peak of the drought, coincident with the generalized senescence.

The annual periodicity observed in Figure 4A, also observed in Figures 2A and 3A, may be associated with the essential aspects of the spatial-temporal variability phenology of the vegetated surface of these sites, that is, the cumulative green throughout the year (Fontana et al., 2015; Schwieder et al., 2018). The higher power intensity (Figure 6A) and the higher variance (Figure 4B) in CAC, as compared to POC and BAM, may be associated with greater variability of vegetation productivity due to a greater influence of the climax of the drought season (de Almeida et al., 2015).

It was observed in Figures 4B and 6B that there was greater variance and greater predominance of higher power intensities for CAC and BAM (in the years 2005, 2007, 2008, 2010, 2011, 2012, and 2013) as compared with the area of POC (Figure 5B). The higher mean-variance and higher predominance of higher power intensities of CAC and BAM, as mentioned above, may be related to the greater dependence of vegetation on precipitation, but other authors also attribute the higher sensitivity of these areas to extreme weather events such as El Niño, for example. Gris et al. (2020) analyzed the influence of precipitation on an arboreal species (*Erythrina fuscano*) in the Cáceres region and

Table 2 – Cross-correlation between Precipitation and NDVI.

lag (month)	Places		
	CAC	POC	BAM
All correlations are significant for p < 0.001			
0	0.66*	0.59*	0.68*
1	0.69*	0.64*	0.71*
2	0.57*	0.50*	0.55*
3	0.29*	0.22*	0.27*

*p ≤ 0.001

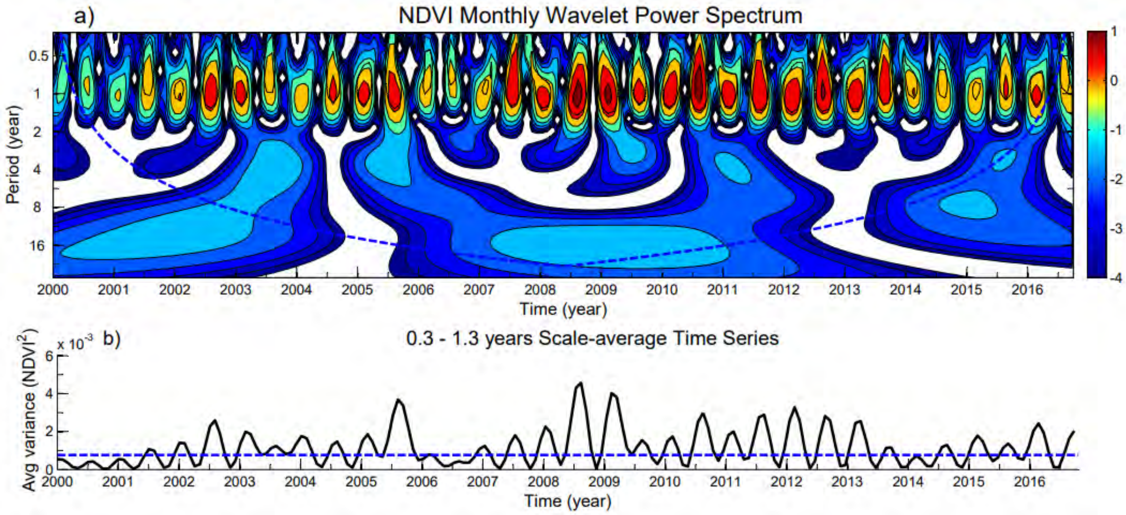

Figure 4 – (A) The wave power spectrum of NDVI for the Cáceres region (C) from 2000-2016. The region bounded by the U-shaped curved line represents the cone of influence (level of 5% significance). (B) Time series of the average band scale 0.3-1.3 years. The line dashed in blue is the 95% confidence level.

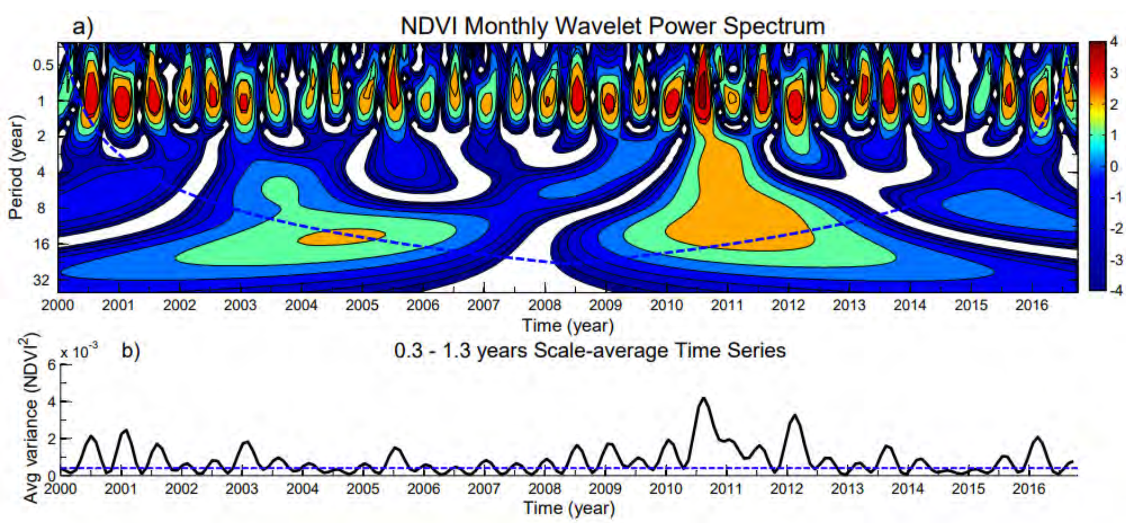

Figure 5 – (A) The wave power spectrum of NDVI for the Poconé region of 2000-2016. The region bounded by the U-shaped curved line represents the cone of influence (level of 5% significance). (B) Time series of the average band scale 0.3-1.3 years. The line dashed in blue is the 95% confidence level.

observed that El Niño events reduce precipitation in the Pantanal, and in turn result in a decrease in the growth of individuals.

Also, Fortes et al. (2018) identified that El Niño events significantly reduced precipitation in the Pantanal and resulted in a drop in trunk diameter increment for arboreal species *V. divergens*. Thus, the occurrence of El Niño may result in a decrease in precipitation compared to the neutral period (Moura et al., 2019) and, consequently, with the reduction of precipitation, the ecosystems respond in a highly plastic way to the availability of water (Hilker et al., 2014).

Average variance values on the 0.3 to 1.3 positive years scale have a Gaussian distribution (Figures 4B, 5B, and 6B) starting approximately in May, peaking in September, and ending in October. This temporal variation of the series, centered on the peak of the drought, coincides with the generalized senescence, the rift, and the greening of the vegetation of the regions, as seen in Figures 2 and 3. Thus, the series also exhibits an annual cycle and may be associated with a phenological variation of the vegetated surface (Penatti and Almeida, 2012).

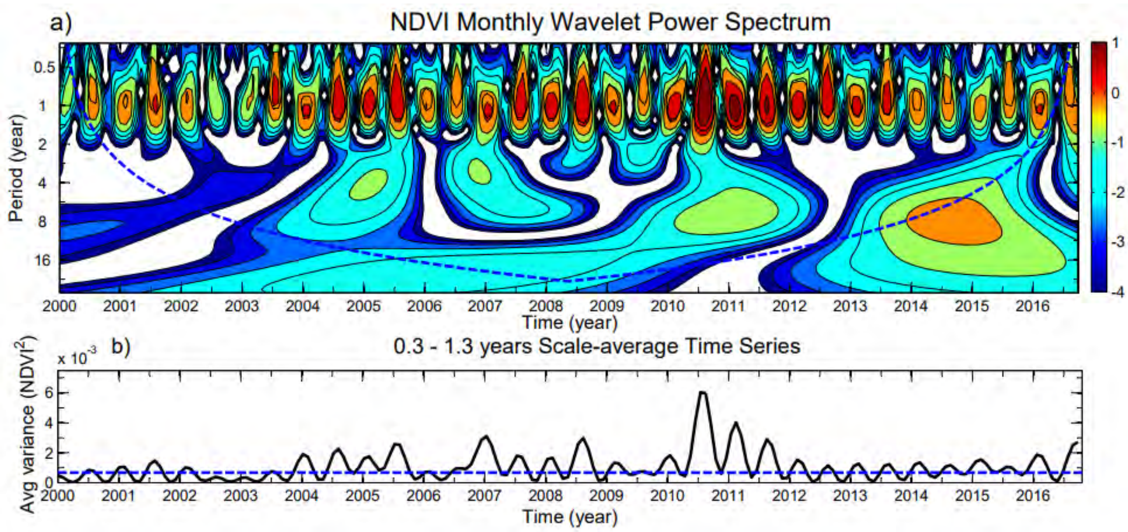

Figure 6 – (A) The wave power spectrum of NDVI for the Barão de Melgaço (BAM) sub-region 2000-2016. The region bounded by the U-shaped curved line represents the cone of influence (level of 5% significance). (B) Time series of the average band scale 0.3-1.3 years. The line dashed in blue is the 95% confidence level.

Conclusion

The cycle of increase and decrease of the green of the vegetation follows the pattern of annual variability of precipitation in the Pantanal and the rift and greenness (greenness) coincident with the beginning of the rains. In addition, it was observed that the seasonality of precipitation is synchronized and is related to a strongly unimodal pattern with precipitation occurring throughout the Upper Paraguay basin.

In the NDVI time-series Profiles, of CAC, POC and BAM, an intense decline occurred from April until the phase of lower NDVI in August., These points of change in the curvature of the monthly averages of NDVI may correspond to the transition dates of a phenological cycle of the vegetated surface, which changes gradually, such as senescence, Greenup, numbness, and maturity.

The correlation between precipitation and NDVI for CAC, POC, and BAM was positive and significant in up to 3 months of lag. However, maximum correlations occurred with a 1-month lag. The greatest correction between precipitation and NDVI was for the BAM region, followed by CAC and POC, respectively. Thus, the results indicate the strong synchronicity of precipitation between CAC, POC, and BAM regions. In addition, vegetation productivity is out of phase with a delay of at least one month regarding precipitation. These results may be indicative that the seasonal relationships between precipitation and vegetation productivity differ based on the position relative to flooded areas.

The largest wavelet powers occurred periodically between 0.5 and 1.3 years, indicating that the NDVI time-series for CAC, POC, and BAM has a strong annual variation throughout the 2000-2016 period. The annual periodicity observed in CAC, such as those of POC and BAM, may be associated with the essential aspects of spatial-temporal phenology variability of the vegetated surface of these sites, i.e., cumulative green throughout the year. And the higher power intensity and the higher variance in CAC as compared to POC and BAM may be associated with greater variability in vegetation productivity due to a greater influence of the climax of the drought season.

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Contribution of authors:

Moraes, T.J.: Formal Analysis, Methodology, Resources, Software, Writing – Original Original Draft, Writing – Review and Editing. Machado, N.G.: Funding Acquisition, Project Administration. Biudes, M.S: Supervision, Validation, Visualization, Writing – Review and Editing. Banga, N.M.: Conceptualization; Data Curation; Investigation. Caneppele, L.B.: Conceptualization; Data Curation; Investigation.

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Trend in hydrological series and land use changes in a tropical basin at Northeast Brazil

Tendência em séries hidrológicas e de mudanças no uso e cobertura da terra em uma bacia tropical do Nordeste do Brasil

Lorena Souza da Silva[1], *Lorena Lima Ferraz*[2], *Lucas Farias de Sousa*[2], *Carlos Amilton Silva Santos*[3], *Felizardo Adenilson Rocha*[3]

ABSTRACT

Flow is one of the hydrological variables of greatest interest due to its connection with water availability and its multiple uses. However, in recent years this resource has been threatened by intense land use and climate change, affecting patterns previously considered to be stationary. The goal of this study was to evaluate trends in changes of patterns of flow, precipitation, and land use in a basin located in the Brazilian Cerrado. 33 years of rainfall, fluviometric, and land use data were used, covering the period of 1985 to 2018 on an annual scale. Mann-Kendall and Sen Slope's nonparametric test was applied to evaluate the trends in temporal series, as well as the Spearman Rho and Pettit, which were used to analyze the correlations between variables and detect the point of change in the series, respectively. The results show statistically significant trends in flow reduction over time. At the same time, a considerable reduction in natural areas occurred, with an increase of +750% in agricultural areas. The results also show that although a tendency to reduce precipitation was detected, its magnitude was not significant, with land use changes being the main factor for the negative changes in the flow of the Rio Grande tributary.

Keywords: stacionariety; flow; nonparametric tests; Rio Grande river.

RESUMO

A vazão é umas das variáveis hidrológicas de maior interesse por sua importância econômica e ligação direta com a disponibilidade para os usos múltiplos da água. Nos últimos anos, no entanto, esse recurso tem sido ameaçado pelas grandes alterações no uso e ocupação do solo e pelas mudanças climáticas, com alterações nos padrões antes tido como estacionários. O objetivo deste estudo foi avaliar as tendências de mudança nos padrões de vazão, precipitação e de uso e ocupação do solo e sua correlação ao longo do tempo na bacia do Alto Rio Grande. Foram utilizados 33 anos de dados pluviométricos, fluviométricos e mapas de uso e ocupação do solo para o período de 1985–2018, em escala anual. Para indicar a presença ou não tendências nas séries históricas, foi aplicado o teste não paramétrico de Mann-Kendall; para avaliar a magnitude dessas tendências, foi utilizado o coeficiente Sen's Slope, além dos testes de Spearman Rho e Pettitt para correlacionar as variáveis e detectar o ponto de mudança nas séries, respectivamente. Os resultados inferem tendências de redução no posto fluviométrico verificado, estatisticamente significante a 5% de probabilidade. Concomitantemente, houve considerável redução das áreas naturais e ascensão de +750% das áreas agrícolas. Os resultados mostram ainda que, embora tenha sido detectada uma tendência de redução na precipitação, sua magnitude não foi relevante quando relacionada à vazão, sendo as mudanças do uso e ocupação do solo o principal fator para as mudanças negativas na vazão do afluente Rio Grande.

Palavras-chave: estacionariedade; vazão; testes não paramétricos; rio Rio Grande.

[1]Universidade Estadual do Sudoeste da Bahia – Itapetinga (BA), Brazil.

[2]Universidade Estadual de Santa Cruz – Ilhéus (BA), Brazil.

[3]Instituto Federal da Bahia – Vitória da Conquista (BA), Brazil.

Correspondence address: Lorena Souza – Rodovia 415, Km 3, s/n – Recanto da Colina – CEP: 45700-000 – Itapetinga (BA), Brazil. E-mail: loriesouza@hotmail.com

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Introduction

Recently, trend analysis in hydrological series has received attention in the scientific community (Rosin et al., 2015; Pousa et al., 2019; Salehi et al., 2020; Alifujiang et al., 2021). This concern has been largely attributed to climate change, due to its impact on the hydrological cycle such as pandemics, low food productivity, reduced availability and quality of water, imbalance in ecosystems such as loss and fragmentation of habitats inducing the loss of biodiversity (Campbell et al., 2016; Das et al., 2018; Sharma et al., 2018; Moraci et al., 2020).

According to Poorheydari et al. (2020), although water availability is attributed to climate change, factors such as land use changes are among the most relevant factors for variations in the hydrological behavior of the basin. Changes occurring in a region influenced by the rainfall regime can affect the management of water resources, as well as the availability of drinking water and food production, which can cause conflicts (Hu et al., 2017). Although this scenario is associated to climate change and rainfall patterns, factors such as land use changes may also be connected (Lamichhane and Shakya, 2019).

Land use changes are among the most relevant factors behind alterations in the hydrological behavior of the basin. Since changes in previously natural surfaces cause alterations in the components of the water balance, they create an increase/decrease in evapotranspiration, surface runoff, and consequently, in the recharge of confined waters, infiltration and interception (Medeiros et al., 2019; Poorheydari et al., 2020).

These changes affect the water cycle beyond the river flows, causing a series previously considered stationary to become non-stationary (Jehanzaib et al., 2020). When a hydrological series does not reproduce the same statistical parameters (mean and constant variance) over time, it is considered non-stationary (Naghettini and Pinto, 2007). However, identifying the changing patterns in a hydro-meteorological series at the local level is complex, due to several active factors that can contribute, jointly or separately, for variations in stationarity patterns (Milly et al., 2008), in addition to the specific characteristics of the region, such as the size of the basins (Chagas and Chaffe, 2018).

Given these facts, it is necessary to understand the impact of climate change on the hydrology, as well as evaluate trends and their magnitude in the temporal series. Many researchers have used classic trend detection models, such as the Mann-Kendall test; for correlating the magnitude of trends using the Rho Spearman test; and the Pettitt test, widely used for the analysis of abrupt changes in a hydroclimatic series (Tamagnone et al., 2019; Ferreira et al., 2020; Mirdashtvan et al., 2020; Salehi et al., 2020). These studies report urbanization, population growth, and the rise of agricultural land as the main factor behind the changes in the statistical patterns of the hydro climatological series.

Western Bahia is one of the most active agricultural frontiers in Brazil. In the last decades, the region has developed an extreme extension of agricultural activities and pastures, a process that occurred in an accelerated way under modern bases with permanent and mechanized irrigation mainly for the cultivation of beans, soybeans, cotton, and corn (Santos et al., 2018). Due to the intense agricultural development combined with the constant conflicts between multiple uses of water, this region may be suffering the effects of stationarity changes in the hydrological series.

The authors Nascimento and Santos (2019) also report the accelerated growth of +100% in agricultural areas in the Fêmeas River basin for irrigated agriculture and +100% for rainfed agriculture, mainly stimulated by governmental actions, in addition to the region's physical characteristics, such as flat relief and rainfall, which can reach 1,265 mm/year.

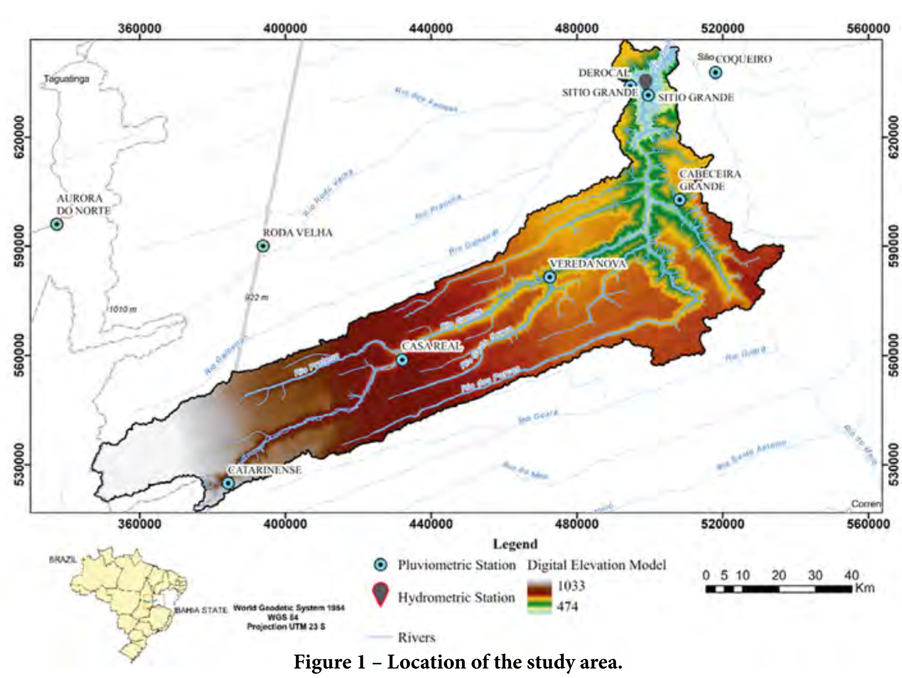

Figure 1 – Location of the study area.

This accelerated rise in agricultural areas to the detriment of deforestation can cause future damage to the water supply and the maintenance of local agriculture, since conflicts over supply and demand are already a reality. These factors raise the importance of studying the possible impacts on the statistical patterns of the hydrological series in the region for better management of water resources.

Given the reasons above, the current work aims to evaluate trends in changes in patterns of flow, precipitation, and land use, as well as their correlation over time in the Upper Rio Grande basin.

Materials and Methods

Study area

The study area (Figure 1) comprises a sub-basin of the Alto Rio Grande, totaling 5,193 km². The main river is one of the tributaries of the Rio Grande, a watercourse in Bahia, located in the northeastern portion of the state. It starts in the Serra Geral in Goiás and runs through the city of São Desiderio until it flows into the mouth of the São Francisco River.

According to the Koppen classification, the region's climate is classified as Aw-tropical with summer rains (Beck et al., 2018) with an average annual temperature of 22.3°C, a minimum of 15°C and a maximum of 40.9°C. The average annual precipitation corresponds to 1,100 mm per year and relative air humidity ranges between 45 and 79%. The region is located in one of the most extensive and important aquifers in Brazil, the Urucuia Aquifer System (SAU), being of great importance in the regulation of the rivers in the São Francisco River basin. This aquifer is responsible for the perpetuity of water bodies in the region, especially in the dry periods corresponding to the months of June to August (Gonçalves et al., 2018).

Data acquisition and processing

Fluviometric data

The fluviometric daily data were used to calculate average rainfall and were acquired from the online platform Hidroweb, made available by the National Water Agency (ANA, 2020). The monitoring station (code 46415000) is located at the lowest altitudes in the region (Figure 1). The monitoring period for the station is 1977-2020, using 33 years of measured data (1985-2018).

Rainfall data

The rainfall data were acquired from ANA's hydro-meteorological network and corresponds to 7 stations within the perimeter of the study area as well as 3 more stations to fill in rainfall gaps. The data is described in Table 1 and serve as a basis for calculating the annual average rainfall volume in the region.

The analyzed period corresponds to the same one used for the flow data (1985-2018). To fill the gaps, the regional weighting method was used based on the average precipitation of neighboring stations, described in Equation 1:

$$P_Y = \frac{P_{Ym}}{3}\left(\frac{P_{X_1}}{P_{Xm_1}} + \frac{P_{X_2}}{P_{Xm_2}} + \frac{P_{X_3}}{P_{Xm_3}}\right) \quad (1)$$

In which:

PY = Precipitation of the post to be corrected;

PYm = Average precipitation of the post Y;

Px1 to Px3 –= precipitation of posts x1 to x3;

PMx1 to PMx3 = average precipitation of posts x1 to x3.

This method is widely disseminated in the literature, being used by several authors (França et al., 2019; Ferreira et al., 2020; Fistarol and Santos, 2020; Junqueira et al., 2020), mainly for trend statistical analysis, since short period series can signal non-stationarity, when in fact they are natural fluctuations of the analyzed hydrological series. Of the seven stations that make up the basin perimeter, four had faults: Catarinense, Casa Real, Cabeceira Grande, and Vereda Nova during 1985 to 2000. These gaps were filled by the regional weighting method, whose filling scale was the monthly average data, with the aid of three other rainfall stations. These stations were incorporated into the study with the purpose of filling gaps (according to Table 1), as they contain a complete historical series and are close to the stations with missing data.

Table 1 – Location of rainfall stations.

Name	Code	Latitude	Longitude	Elevation
Sitio Grande	1245007	-12.43	-45.08	507
Catarinense	1346010	-13.28	-46.02	867
Casa Real	1345002	-13.01	-45.63	751
Cabeceira Grande	1245016	-12.66	-45.01	657
Sitio Grande	1245001	-12.43	-45.08	527
Derocal	1245005	-12.41	-45.12	511
Vereda Nova	1245030	-12.83	-45.30	690
Stations used to fill in faults				
Aurora do Norte	1246001	-12.71	-46.40	464
Roda Velha	1245015	-12.76	-45.94	820
Fazenda Coqueiro	1244019	-12.38	-44.93	607

Land use mapping

To evaluate land use changes, 33 maps covering the period of 1985 to2018 were used, available on the Annual Mapping Project for Land Use in Brazil Mapbiomas online platform, collection 4. The land use mapping was carried out through pixel-by-pixel classification of mosaics of Landsat images (spatial resolution of 30 m). Each mosaic was prepared according to the different scenes contained in each card and calculated from the median, pixel by pixel within a time interval. The general accuracy of the maps used was 82.9%, allocation disagreement was 12.5%, and area disagreement 4.7% (MapBiomas, 2020).

The mapbiomas were inserted in ArcMap 10.5, where they were redesigned for UTM datum SIRGAS 2000 and cut according to the morphometric characteristics of the basin as area and perimeter. The land use classes were reclassified into 5 categories:

- Forest: tree species, with the formation of a continuous canopy;
- Savannah: areas with a predominance of tree and shrub species, spread over a grassy substrate, without the formation of a continuous canopy;
- Grassla–d: the predominance of herbaceous species and some shrubs, without the occurrence of trees in the landscape;
- Agriculture: area for the cultivation of crops, mainly grains such as soybean, corn, and cotton;
- Past: pasture areas for livestock, dirty fields;
- Urban areas: man-made areas, urban infrastructure, constructions, access roads, and buildings.

Statistical tests

The statistical tests used in this study are described in the sections below. The significance level α = 0.05 (5% probability) was adopted for all three applied methods. If the probability (p) of the test is $p > \alpha$, the test is statistically insignificant. All tests were processed in *software R*.

Mann-Kendall test

The Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) is a non-parametric test used to detect the presence or absence of trends in historical series. The null hypothesis (H0) points to the absence of a trend over time, against the Alternative Hypothesis (HA) that there are increasing or decreasing trends. It is a widespread test in the literature, being used for the analysis of hydro-meteorological series (Karmeshu, 2012; Ahmad et al., 2015; Mudbhatkal et al., 2017; Alifujiang et al., 2021). This test is recommended by the World Meteorological Organization for detecting long-term trends in natural series (Liang et al., 2011).

The value of S is described by Equation 2 and calculated from the signs of the difference sgn, pair by pair, involving all values of the series (xi) and the values they will assume in the future (xk)In which the time series x_i proceeding from $i = 1, 2, ..., n - 1$ and x_k coming from $k = i + 1, ..., n$ is described in Equation 3.

$$S = \sum_{i=1}^{n-1} \sum_{k=t+1}^{n} sgn(x_k - x_i) \quad (2)$$

$$sgn\ (\theta) = \begin{Bmatrix} +1, \theta > 0 \\ 0, \theta = 0 \\ -1, \theta < 0 \end{Bmatrix} \quad (3)$$

Where:
xj = the estimated sequence of values'
n and the length of the time series and the sign (xi - xj) is equal to -1 for (xi - xj) < 0, 0 for (xi - xj) = 0, and 1 for (xi - xj) > 0 (Equation 4).

$$Z_c = \begin{Bmatrix} \frac{S-1}{\sqrt{var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{var(S)}}, & S < 0 \end{Bmatrix} \quad (4)$$

Z_c is the statistical test and when $|Z_c| > Z_{1-a/2}$, which $Z_{1-a/2}$ are the standardized normal variables and α is the level of significance to the test, *Ho* will be rejected. The magnitude of the trend is described in Equation 5:

$$\beta = Median\left(\frac{x_i - x_j}{i - j}\right), \forall_j < i \quad (5)$$

In which:
$1 < j < i < n$.

The positive value of β indicates an increasing trend, while the value of β negative indicates a decreasing trend.

Sen's slope

Although effective in detecting trends in hydro-meteorological series, the Mann-Kendall test does not represent the magnitude of the trend (Moreira and Naghettini, 2016; Salehi et al., 2020).

Therefore, the model proposed by Sen (1968) was used in this study as an aid to the Mann-Kendall test to estimate the slope or change rate and it is described by Equation 6:

$$Q_{ij} = \left(\frac{x_j - x_i}{j - i}\right), com\ i < j \quad (6)$$

In which:
X_i e X_j = the variable values in years *I* e *j* in question.

The values of Q vary positively or negatively, as positive values indicate the magnitude of the increasing trend, and the Sen Slope indicator is the value of this rate of change, while negative values represent the magnitude of the decreasing trend. The Sen's slope estimator is the median of N values of *Qij* (Tao et al., 2014). The Sen Slope's non-parametric test applied in this study infers that the null hypothesis (H0) affirms the absence of the rate of variation of increasing or decreasing trend in the hydroclimatic series, while the alternative hypothesis infers the rate of variation in the presence of trends in the series.

Pettit test

The Pettit test (Pettitt, 1979) uses a version of the Mann-Whitney test and serves to complement the Mann-Kendall and Sen's slope tests. Pettit's inference is non-parametric and checks whether two samples belong to the same population. The statistical test counts the number of times that the first sample exceeds the second, therefore, the result is what defines whether two samples are statistically different. Thus, this test was used in order to identify points of abrupt changes in the historical flow series, precipitation, and land use. The null hypothesis of the Pettit test (H0) admits the absence of a turning point in the historical series while the alternative hypothesis admits the presence.

This arbitrary point is given by the Equations 7, 8 and 9:

$$K_T = max_{1 \le t \le T} \left| U_{t,T} \right| \quad (7)$$

In which:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn\left(X_i - X_j\right) \quad (8)$$

In which:

$$sgn\ (X) = \begin{cases} 1\ se\ x > 0 \\ 0\ se\ x = 0 \\ -1\ se\ x < 0 \end{cases} \quad (9)$$

Therefore, the statistical test is calculated for values of $1 \le t \le T$, and *KT* statistics of the test is the maximum absolute value of *Ut*, *T*. Thus, the test reports the presence or absence of two samples in the same population, indicating the location in the time series of the turning point (Penereiro and Ferreira, 2012). When reporting the absence of change, the hypothesis is null.

The critical value to be adopted is given by the Equation 10:

$$P \cong 2\ exp\left(\frac{-6K_T^2}{T^3 + T^2}\right) \quad (10)$$

In which:
P = the level of significance;
KT = the critical value;
T = the number of years in the historical series.

Rho Speaman test

The Spearman test was used to evaluate the correlation between two quantitative variables (Zhang et al., 2015). In this test, the proposition is based on the fact that the time series data are independent and equally distributed. The null hypothesis (H0) reports the lack of a trend over time and in contrast, the alternative hypothesis (HA) points to increasing or decreasing trends in the series (Kale and Sönmez, 2018). It is described by Equations 11 and 12.

$$D_{sr} = 1 - \frac{6\sum_{i=1}^{n}(R_i - i)^2}{n(n^2-1)} \quad (11)$$

$$D_{sr} = D_{sr}\sqrt{\frac{n-2}{1-D_{sr}^2}} \quad (12)$$

Where:
Ri = the classification of the observations of *i*;
n = the size of the historical series.

The results range between 1 and -1. The positive ρ value suggests an increasing trend while the negative value suggests a negative trend. In this study, the flow was the variable used as a parameter for the correlation. Therefore, value 1 was accepted for this data, which was used in the relationship between land use x flow and precipitation x flow. The variables of land use and precipitation can vary negatively or positively,either decreasing or increasing impact on the flow, respectively.

Results and Discussion

Trend in the series of annual average flow

The historical series of average annual flows in the Rio Grande affluent during the measured period is shown in Figure 2.

A downward trend is noticeable in the flow data, with the lowest flow values detected in recent years. This behavior indicates possible non-stationarity in the historical series of flow through the strong tendency to decline, indicated by the trend line. The results of the statistical tests for analysis of stationarity are shown in Table 2. The results of Mann-Kendall tests applied to the flow variable showed significance at 5% of probability. The null hypothesis was rejected, and the series cannot be considered stationary. The value of tau (-0.74) infers a downward trend in the fluviometric series, which is confirmed by the magnitude of the decline in the Sen Slope test (-0.59).

Change point of the average annual flow

After identifying a decreasing trend in the flow series, the Pettit test was applied to detect the breaking point (change) of the temporal

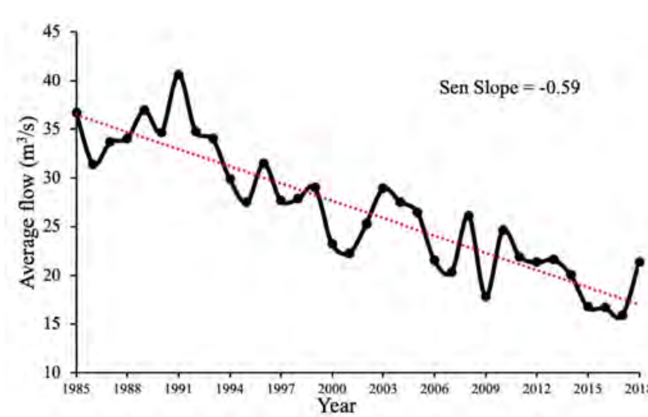

Figure 2 – Average annual flow for the Sítio Grande monitoring station.

Table 2 – Results of Pettitt change-point analysis, Kendall's tau and Sen's slope tests for streamflow, precipitation and land use classes (annual).

Parameter	Pettitt Change Year	*p* for change point	Mann–Kendall test		*Sen Slope*
			tau	*p*	
Streamflow	1999	2.288e-05	-0.74	7.612e-10	-0.59
Precipitation[a]	2011	0.1049	-0.27	0.02074	-11.74
Agriculture	2001	9.102e-06	0.96	2.698e-10	51.69
Past	1998	8.356e-06	0.84	9.369e-16	5.132
Urban areas	1999	1.786e-05	0.82	2.113e-12	0.0008
Forest	2002	0.0001203	-0.76	1.242e-13	-1.48
Savanna	2002	8.356e-06	-0.89	1.517e-15	-24.87
Grassland	2001	1.175e-05	-0.96	8.075e-10	-31.52

[a]Average annual precipitation for the entire basin.

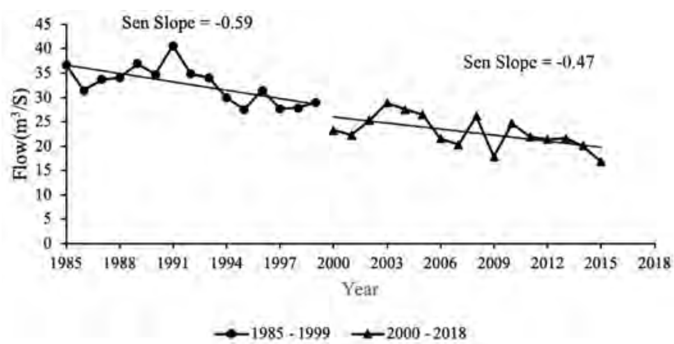

Figure 3 – Change point in the average annual flow of the Sítio Grande monitoring section.

series. The test showed significance at 5% probability and indicates the point of change within the series in 1999. According to the results, it is possible to verify two different hydrologic periods (Figure 3).

After the separation of the hydrological periods, it is observed that the average annual flow was 32.69 m^3/s during the 1985-1999 period and in the second period, it becomes 22.11 m^3/s, a reduction of 32.33% in the average annual flow. The negative trend in the reduction of the flow is statistically proven in the MK test and the conflicts that emerge in the area reinforce the need to investigate the possible causes of this reduction.

Trends in the precipitation series

The results of the MK test for rainfall data showed a decreasing and statistically significant trend. Although the null hypothesis is rejected, with the inference that a decreasing trend was detected, this trend has little magnitude (tau = -0.27), also confirmed by the Sen Slope test (-11.75).

The visual analysis of the graphics presented in Figure 4, shows the declining behavior in the annual average of rainfall in four seasons: Vereda Nova (1245030), Casa Real (1345002), Sítio Grande (1245007), and Fazenda Catarinense (1346010). The trend line in red, declining from right to left, indicates a decreasing behavior, although without much inclination magnitude. The magnitude of the changes by season was analyzed separately to better understand the precipitation decline trends. The MK and Sen slope tests were applied for the 4 seasons and are described in Table 3.

The tests were applied to understand the level of changes in these four seasons, and although this trend is evident, its magnitude does not reach variations of 20 mm/year. The spatial distribution of the rainfall regime was shown in Figure 5A and the magnitude of the changes in (mm/year) in Figure 5B.

The average data of pluviometry in the Rio das Fêmeas sub-basin ranges from 970 mm to 1,200 mm and the trends of change were detected throughout the entire basin, from the head to the executory, the biggest change occurring in the headland region (-14.40 mm/year).

Land use changes

Authors report that one of the main factors that can lead to non-stationarity in hydrological series are land use changes (Bayazit, 2015; Deb et al., 2019). The results from the analysis of the spatial-temporal variation of land use in Rio das Fêmeas (Figure 6), culminated in a considerable alteration on the landscape in the last 34 years of study.

Between the period of 1985 to 2018, there was an increase of 635.86% in anthropized areas (pasture, agriculture, and urban areas). The changes and percentages are described in Table 4. The accelerated growth in the region was driven by public policies between the late 1980s and early 1990s, especially in agricultural areas. The federal and state government made agriculture extensive in the region, through the concession of lands prone to low-cost agriculture, making it promising from an economic point of view and attractive to farmers across the country (Oliveira and Vieira, 2018).

This immigration occurred not only in the western region of Bahia but also in the central-western region of the country, which was the locus for the expansion of agriculture and the creation of a frontier in the country, known as MATOPIBA – an acronym for Maranhão, Tocantins, Piauí e Bahia, considered by many to be a newly mechanized northeast (Reis et al., 2020).

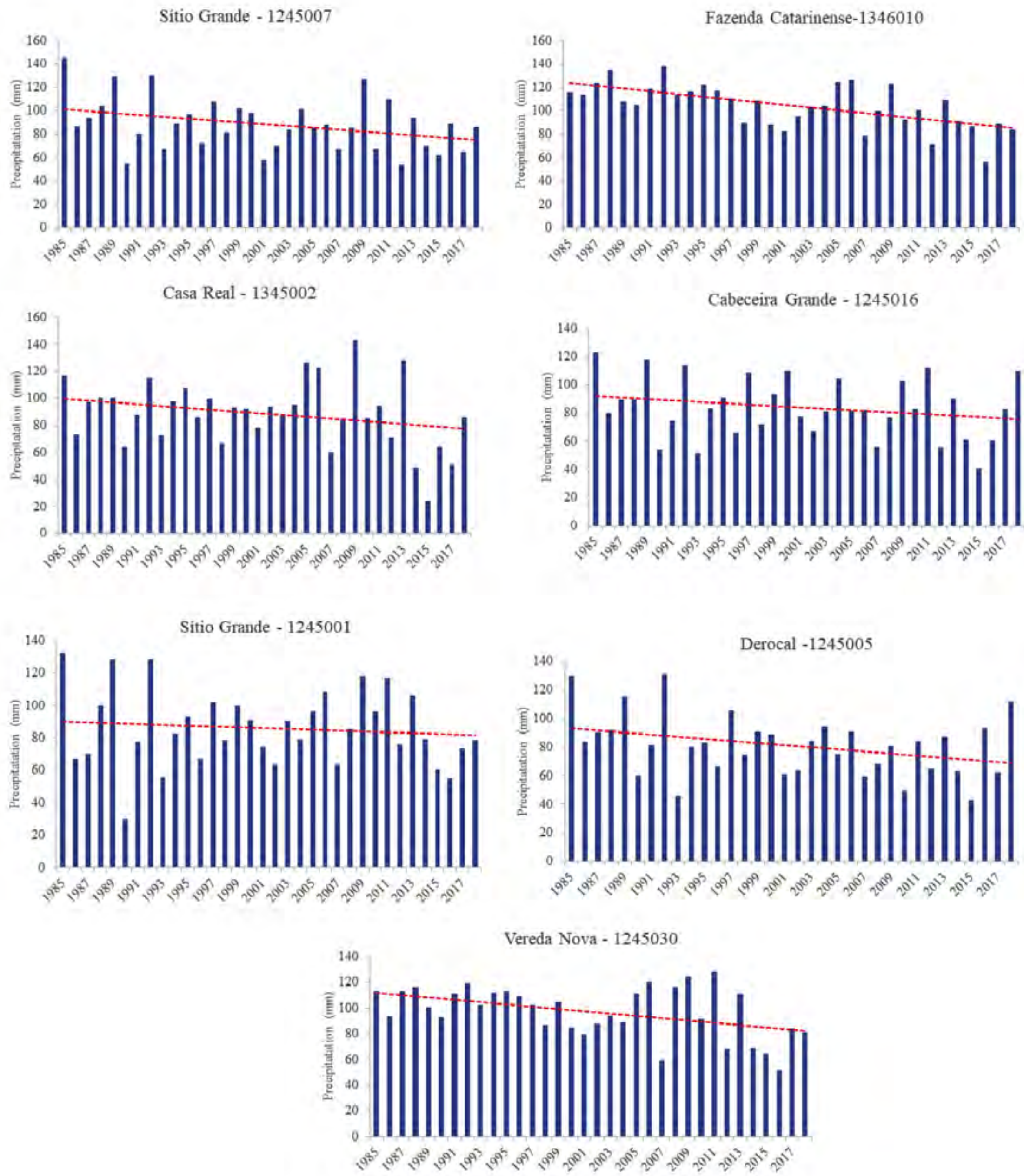

Figure 4 – Average annual precipitation study for each sub-basin in the period of 1985-2018.

Table 3 – Results of Kendall's tau and Sen's slope tests for precipitation.

Station	Z	p-value	Sen's slope
Casa Real	-1.77893	0.0376	-6.42375
Fazenda Catarinense	-3.64681	0.0001	-14.4085
Sítio Grande 5007	-1.74948	0.0401	-6.18794
Vereda Nova	-2.31261	0.0103	-11.8394

Areas known for agriculture increased from 3.95% (62.99 km2) in 1985 to 33.56% (232.24 km2) in 2018 and sum up a change of 750,34% of the total evolution of agricultural areas. The second class of major changes was pasture (from 62.99 km² - 1.23% in 1985, to 232.24 km² - 4.54% in 2018). The smaller magnitude of changes in pasture areas can be justified by the economic change in western Bahia, initially founded in extensive agriculture then gradually changed to mechanized (Santos et al., 2018).

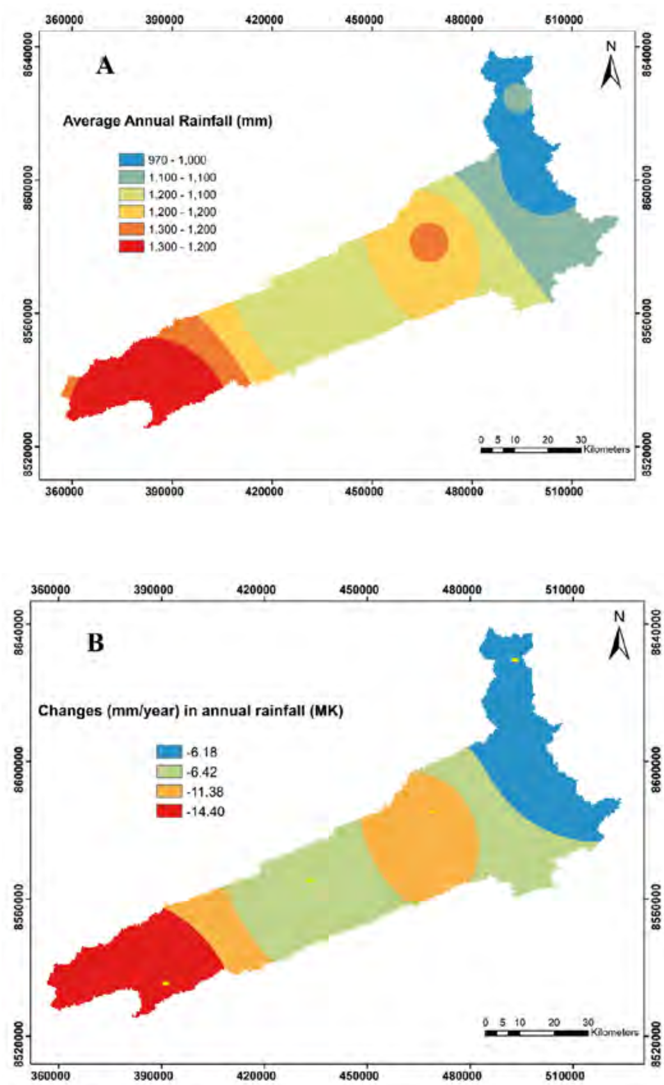

Figure 5 – (A) Spatial distribution of average annual rainfall (mm/year); (B) trends in average annual rainfall (mm/year) for the period of 1985–2018 using MK and Sen'Slope.

Urban areas grew by 0.004%, representing a small evolution and defining the region as strictly agricultural. As for natural areas, all changes signaled a reduction. The rural formations are the class that presents the smallest reduction in area, encompassing three main phytophysiognomy types: Dirty, Clean and Rupestrian Field. These formations do not present a formed canopy and few herbaceous-shrub substrates, facilitating the transformation of these areas into agricultural fields, without any legal restrictions as it is not a dense forest area.

Even so, the areas with denser natural formations such as forests and savanna formations, suffered reductions in smaller magnitudes (-22.29 e 23.17% respectively).

Statistical tests were applied for each class of use and occupation. The reduction in forested areas corroborates with the results of the tests (Table 2). The MK test signals a decreasing and statistically significant trend. The magnitude given by the Sen's slope test indicates deforestation patterns in the forest, field, and savanna series (-1.48, -24.87, -31.52, respectively).

According to Sen Slope, the greatest magnitude of change is statistically proven in agricultural areas (51.69) and the second highest magnitude occurs in the field class with a negative trend (-31.52), mainly proving the replacement of savanna areas for other types of land use classes. The Pettit test indicates that the point of change in the flow coincides with the point of change in urban areas (1999), as well as the turning point for the classes of forest and savanna (2002), agriculture and field (2001), which confirms the magnitude of land use changes, as well as in the flow.

The impacts associated with sudden changes in the landscape are reported by recent studies (Acheampong et al., 2019; Doggart et al., 2020) which highlight that deforestation and the rise of agricultural areas affect the hydrological regime directly, due to the use of groundwater for irrigation. The use of confined water can damage the longevity of rivers in the region. According to Pimentel et al. (2000), the contribution of the Urucuia complex (which supplies the region's hydrogeological refills) is 258.50 mm.year-1 estimated for the period (1984 – 1995), which represents only 20% of the precipitated rainfall volume. Over-exploration of this complex can lead to bankruptcy in the supply of rivers in the region, as is the case with the Rio Grande tributary.

Correlation analysis between the variables flow, land use and rainfall

The results of the Rho Spearman test (Table 5) showed a high correlation between the variables land use and flow: above 73%, except for the precipitation variable, which presented a low correlation (-0.44).

The areas anthropized by agriculture, pasture, and urban infrastructure showed a negative correlation (-0.91, -0.90, -0.88, respectively to Spearman Rho and 0.96, 0.84, 0.82, to MK), representing a high correspondence with the decline in the flow, while the natural areas presented 0.81, 0.78, 0.92 (SR) and 0.76, -0.89, -0.96 (MK) to forest, savanna and fields, respectively. These changes have a high correlation with the flow, indicating that the drop in the flow is related to the drop in the values of these classes.

The low correlation indicated by the Spearman Rho test in the rainfall data corroborates that although there is a negative trend, it does not present a significant magnitude and it cannot be considered as the cause in the decline of the flows to the Rio Grande tributary .

The correspondence between the rise of agricultural areas and the decrease in flow, without detecting changes in behavior in the rainfall regime was also reported by Ferreira et al. (2020), from 1985 to 2014, the variables were independent and point out that precipitation did not impact the flow.

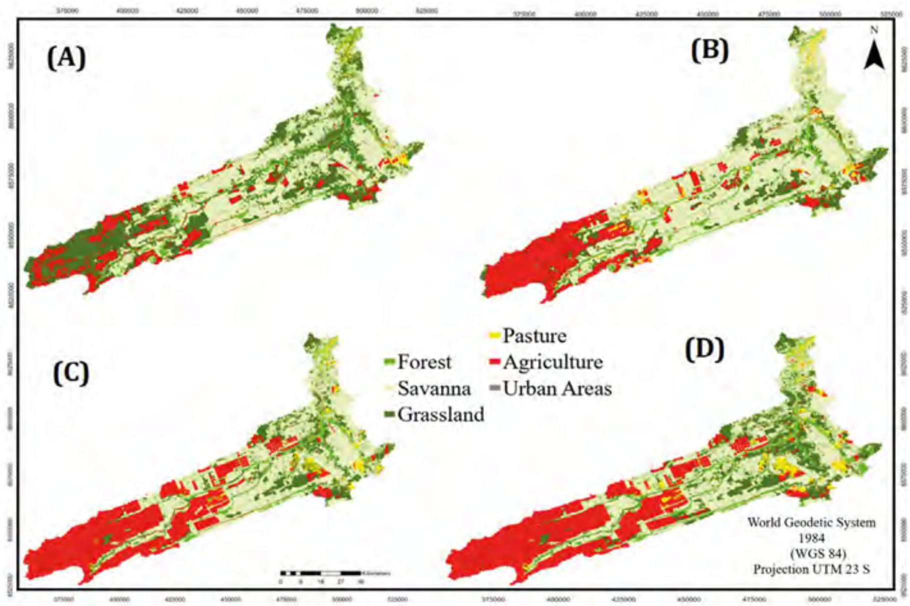

Figure 6 – Map of temporal evolution of land use and occupation in Rio das Fêmeas. (A) Period of 1990; (B) Period of 2000; (C) Period of 2015; (D) period of 2018.

Table 4 – Area of each class of land use (km²) and percentage of the total area of the basin.

Year	Forest	Savanna	Grassland	Pasture	Agriculture	Urban areas
			Km²			
1985	205.298	3,314.85	1,328.98	62.9913	201.84	0
1990	218.14	3,212.3	1,097.19	87.809	538.78	0
2000	181.239	3,127.9	931.976	129.996	742.829	0.01
2015	157.688	2,623.89	478.144	193.304	1,660.84	0.09
2018	159.53	2,546.88	458.75	232.24	1,716.32	0.22
			Percentage of areas (%)			
1985	4.01	64.82	25.99	1.23	3.95	0.000
1990	4.27	62.81	21.45	1.72	10.54	0.000
2000	3.54	61.16	18.22	2.54	14.53	0.000
2015	3.08	51.31	9.35	3.78	32.48	0.002
2018	3.12	49.80	8.97	4.54	33.56	0.004
Changes	-22.29	-23.17	-65.48	268.69	750.34	0.004

Table 5 – Spearman's rho tests results for streamflow, precipitation and land use classes (annual).

Parameter	Spearman test	
	rho	*p*
Streamflow	1	1
Precipitation	-0.28	-0.44
Agriculture	-0.80	-0.91
Past	-0.82	-0.90
Urban areas	-0.83	-0.88
Forest	0.83	0.81
Savanna	0.82	0.78
Grassland	0.82	0.92

The impact of these changes in the water regime is also reported by Silva (2019), who pointed out the replacement of forested areas by pastures and agricultural areas change the physical-chemical composition of the soils, making it more compact, indicating that water tends to travel with more difficulty and consequently the water table is lowered. This fact significantly reduces the recharge of rivers by lateral flow and base runoff, mainly threatening the minimum flows in dry periods. Thus, the reduction in flow is related to the increase in the catchment for irrigated agriculture, which had a great development in the region over the period considered in this study.

Conclusion

Statistical tests pointed out that the average annual flow of the Sítio Grande fluviometric station located in the Rio Grande tributary is not stationary, since a decreasing trend was detected over the 34 years analyzed, with an abrupt changing point in 1999 which is also the breaking point for urban areas.

In the rainfall series, declining trends were detected. Only four rainfall stations presented a drop and they are located along the basin. However, these changes do not reach 20 mm/year.

The Rho Spearman test corroborates with the low correlation in changes in the average annual flow with the precipitation data (rho -0.28) and strong correlation with the changes in the landscape (rho -0.80, -0.82, -0.83, 0.83, 0.82, 0.82). Anthropized areas showed greater correspondence with the declining inflow, which allows us to infer that the changes in the flow regime are a consequence of the changes in land use over the 34 years analyzed in the study area. These evidences reinforce that public policies must be implemented so that there is no compromise in the local public supply as well as in agricultural activities, the multiple uses must be reviewed so that no sector is harmed. In addition, water use permits must be revised in light of the current conditions of water bodies in the region, which already point to considerable declines, and at this rate of water retention, they are vulnerable.

In general terms, the provision of historical data on rainfall and fluviometric series is an important subsidy for robust statistical analyses, new studies should apply statistical treatments to new variables in the region to provide a more solid scientific understanding incorporated into monitoring programs for better resource management of rivers in the region.

Contribution of authors:

Silva, L.S: Data acquisition, Writing – Original Draft, Writing – Review and Editing. Ferraz, L.L.: Formal analysis, Writing – Review and Editing. Sousa, L.F.: Methodology, Formal Analysis, Supervision. Santos, C.A.S.: Conceptualization, Formal Analysis, Validation, Writing – Review and Editing. Rocha, F.A: Validation, Formal Analysis, Investigation, Supervision.

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Overview of studies on stemflow chemistry effect on soil: systematic review of the literature

Panorama dos estudos acerca da influência da composição do escoamento pelo tronco sobre o solo: revisão sistemática da literatura

Marcelle Teodoro Lima[1], *Kelly Cristina Tonello*[1], *Julieta Bramorski*[2], *Marcia Magalhães de Arruda*[1], *Gregorio Nolazco Matus*[1]

ABSTRACT

The study systematically analyzes the literature in order to identify the main contributions of the trunk runoff study on the soil nutrient flux in recent years. The review included 47 articles published from 2015 to 2019. The aim of the present study is to correlate the main stemflow research subtopics that have contributed to chemical soil enrichment. Correlation analysis was performed in Iramuteq software with the aid of R software, based on keywords in the selected articles. There has been an overall upward trend in research related to stemflow impact on soil nutrient flux, mainly in Asia, whose publications have significantly increased over the latest years. Based on the keyword co-occurrence map, "stemflow" and "throughfall" were the main used terms because they established strong correlation to other keywords, mainly to "concentration", "composition", "biogeochemical cycle", "nutrient cycling" and "dissolved organic matter". These terms, in their turn, were correlated to and co-occurred with several other keywords, such as "soil", "nitrogen", "water chemistry", "nutrient dynamics" and "cations".

Keywords: nutrient cycling; nutrient concentration and composition; forest hydrology; nutrient enrichment.

RESUMO

Este trabalho analisa sistematicamente a literatura com o intuito de identificar as principais contribuições do estudo de escoamento pelo tronco sobre o fluxo de nutrientes no solo nos últimos anos. A revisão contemplou 47 publicações do período entre 2015 e 2019. Com base nas palavras-chave das publicações encontradas, aplicou-se a análise de similitude no *software* Iramuteq, com o auxílio do *software* R. Observou-se que há uma tendência geral de crescimento das pesquisas nesse tema, principalmente na Ásia, onde houve aumento de publicações nos últimos anos. Por meio do mapa de coocorrência, as palavras "*stemflow*" e "*throughfall*" aparecem como termos principais que criam relações de ocorrência com outras palavras, principalmente "*concentration composition*", "*biogeochemical cycle*", "*nutrient cycling*" e "*dissolved organic matter*". Estas, por sua vez, trazem diversas palavras que se relacionam e coocorrem com elas, como "*soil*", "*nitrogen*", "*water chemistry*", "*nutrient dynamics*" e "*cations*".

Palavras-chave: ciclagem de nutrientes; concentração e composição de nutrientes; hidrologia florestal; enriquecimento de nutrientes.

[1]Universidade Federal de São Carlos – São Carlos (SP), Brazil.

[2]Universidade Federal do Amapá – Macapá (AP), Brazil.

Correspondence address: Marcelle Teodoro Lima – Praça Brasil, 16 – Santa Helena – CEP: 18117-720 – Votorantim (SP), Brazil. E-mail: marcelleteodoro@yahoo.com.br

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Introduction

In forested areas, canopies play an important role in the partitioning of rainfall. During this process there is also a redistribution of particulate matter that is deposited from the atmosphere on vegetative surfaces and transported to soil layers by throughfall and stemflow (Cayuela et al., 2019). Tree canopy chemistry undergoes quantitative and qualitative changes as they intercept the incident rainfall and react with it. These changes are mainly caused by both dry deposition washoff and canopy exchange processes due to leaching and leaf absorption (Liu et al., 2019). Throughfall (TF) and stemflow (SF) are two canopy-derived flow paths of precipitation as it is transferred to the forest floor. Stemflow has historically been considered to be a minor component of forest canopy water budgets compared with throughfall, and it was neglected in early studies of forest water and nutrient balances (Llorens and Domingo, 2007). Tonello et al. (2021) summarized the main contributions of stemflow (SF) studies from recent years through a systematic review of the literature, including 375 scientific articles published between 2006 and 2019. The authors identified that few studies have related the stemflow effects in biogeochemical cycle more broadly. Stemflow is of biogeochemical importance in forested ecosystems because it is a spatially localized point input of water and nutrients at the plant stem (Levia and Herwitz, 2000; Levia and Frost, 2003). The knowledge of the various interactions of the stemflow in biogeochemical cycle leads to more assertive conservation and restoration actions.

Stemflow is the rain absorbed by forest canopy and channeled through woody surfaces until it reaches forest ground. The hydrological process of connecting the canopy to the soil has strong impact on the biogeochemical cycle of forest ecosystems. Stemflow (SF) is arguably the longest path a rain drop can travel to reach the soil surface, requiring lengthy interaction between rainfall and canopy surfaces (Van Stan and Gordon, 2018). SF stays much longer on tree surfaces than other rainfall processes; thus, it is an important nutrient cycling step (Levia and Germer, 2015).

The ability of SF to wash off dry deposition and stimulate ion exchange capacity leads to more nutrient-rich water flows than those driven by total rainfall and throughfall (Su et al., 2019). Kumar Gautam et al. (2017) argue that such a process helps replenishing soil nutrient pools, which are a bioavailability zone for plants.

The edaphic properties varied in different below-canopy infiltration areas (Aboal et al., 2015); in this way, the water intercepted by plant stems or trunks can contribute to "fertile islands" growth due to its effect on the area surrounding the trunk base. SF can either leach large nutrient concentrations under certain conditions or not make significant contributions to nutrient flux. Atmospheric components tend to accumulate in canopies and stems during drought periods. Based on total rainfall and throughfall, the first rainfall event makes the accumulated components flow through the trunk and it increases their concentration (Zhang et al., 2016).

Research conducted by Suescún et al. (2019) in Colombia concluded that changes in weather conditions, such as drought and natural forest degradation increase and worsening, can affect the ecohydrological and biogeochemical cycles of tropical forest canopies. Chen, S. et al. (2019) studying stem hydrology and dissolved organic matter flux in perennial forests in an urban area in Japan concluded that the tree size is an important factor influencing the heterogeneity of spatial patterns of chemical solution near the tree trunks.

The aim of the present study was to perform a systematic review of literature comparing the main subtopics on research with stemflow contributions to soil nutrient enrichment.

Materials e Methods

The present study is a systematic literature review based on a thorough analysis of the matching literature and on the selection of the most relevant articles regarding the assessed topic (Guitart et al., 2014). The keywords "stemflow" (flow of intercepted water down the trunk or stem of plants), "nutrients", "nutrient flux" and "nutrient cycling" were entered into ScienceDirect and Scopus databases in order to analyze articles that have associated stemflow with nutrient flux (Chart 1). Scientific articles, review articles, books and book chapters published from 2015 to 2019 were selected. The query was limited to publications in English. The articles found in both databases were identified.

The selected articles were screened, and the ones focused on agricultural plant stemflow were excluded from the research.

The main topic of each research was determined based on Title, Keywords and Abstract sections. The keyword analysis of each selected article was performed in Iramuteq software with the aid of R software

Chart 1 – Parameters of the query carried out at Scopus and ScienceDirect databases.

Scopus:	(TITLE-ABS-KEY (stemflow) AND TITLE-ABS-KEY (nutrients) OR TITLE-ABS-KEY (nutrients AND fluxe) OR TITLE-ABS-KEY (nutrient AND cycling) AND LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "re") AND (LIMIT-TO (EXACTKEYWORD, "Nutrient Cycling") OR LIMIT-TO (EXACTKEYWORD, "Leaching") OR LIMIT-TO (EXACTKEYWORD, "Nutrients") OR LIMIT-TO (EXACTKEYWORD, "Atmospheric Deposition") OR LIMIT-TO (EXACTKEYWORD, "Nutrient Dynamics") OR LIMIT-TO (EXACTKEYWORD, "Biogeochemistry") OR LIMIT-TO (EXACTKEYWORD, "Precipitation Chemistry") OR LIMIT-TO (EXACTKEYWORD, "Chemical Composition") OR LIMIT-TO (EXACTKEYWORD, "Nutrient") OR LIMIT-TO (EXACTKEYWORD, "Soil Chemistry") OR LIMIT-TO (EXACTKEYWORD, "Nutrient Fluxes") OR LIMIT-TO (EXACTKEYWORD, "Water Chemistry") OR LIMIT-TO (EXACTKEYWORD, "Positive Ions") OR LIMIT-TO (EXACTKEYWORD, "Interception") OR LIMIT-TO (EXACTKEYWORD, "Nutrient Leaching") OR LIMIT-TO (EXACTKEYWORD, "Ions") OR LIMIT-TO (EXACTKEYWORD, "Stemflow Chemistry") OR LIMIT-TO (EXACTKEYWORD, "Nutrient Enrichment") OR LIMIT-TO (EXACTKEYWORD, "Cations") AND (LIMIT-TO (LANGUAGE, "English")).
ScienceDirect:	"stemflow" AND "nutrients" OR "nutrients fluxe" OR "nutrient cycling"

(R Core Team, 2018). Statistical data were treated to show the correlation among the articles' keywords — this correlation was represented by spatial distance, wherein each word is a point in space. Therefore, keywords separated by shorter distances and connected by thicker lines showed the strongest correlation. The most representative keywords were highlighted in a word cloud presenting smaller words next to them (Iramuteq, 2013).

The main topic frequency of each article was summarized in a word cloud, wherein word size was proportional to how often words were identified as the main topic. The duplicate articles found in both databases were considered only once.

The articles were subsequently clustered and assessed based on their publication year and continent of origin.

Results and Discussion

Current status of stemflow and soil dynamics research

Forty-seven (47) articles were published between 2015 and 2019: 37 articles into Scopus and 10 articles into ScienceDirect databases. Five (5) articles are listed both in Scopus and SicenceDirect databases. Thus, the total number of distinct articles is 42: 32 articles in Scopus and 5 articles in ScienceDirect databases (Table 1).

Table 1 – Articles listed and published (2015-2019) into selected databases.

	Authors	Title	Journal
Scopus			
1	Álvarez-Sánchez et al. (2016)	Inorganic nitrogen and phosphorus in stemflow of the palm Astrocaryum mexicanum Liebm. located in Los Tuxtlas, Mexico	*Tropical Ecology*
2	Bade et al. (2015)	Chemical properties of decaying wood in an old-growth spruce forest and effects on soil chemistry	*Biogeochemistry*
3	Bigelow and Canham (2017)	Neighborhood-Scale Analyses of Non-additive Species Effects on Cation Concentrations in Forest Soils	*Ecosystems*
4	Bittar et al. (2018)	Estimation of throughfall and stemflow bacterial flux in a subtropical oak-cedar forest	*Geophysical Research Letters*
5	Cayuela et al. (2019)	Particulate matter fluxes in a Mediterranean mountain forest: interspecific differences between throughfall and stemflow in oak and pine stands	*Journal of Geophysical Research: Atmospheres*
6	Chen, L.C. et al. (2019)	Mediation of stemflow water and nutrient availabilities by epiphytes growing above other epiphytes in a subtropical forest	*Ecohydrology*
7	Chen, S. et al. (2019)	Stemflow hydrology and DOM flux in relation to tree size and rainfall event characteristics	*Agricultural and Forest Meteorology*
8	Deng et al. (2017)	Effects of canopy interception on epikarst water chemistry and its response to precipitation in Southwest China	*Carbonates Evaporites*
9	Duval (2019)	Rainfall partitioning through a mixed cedar swamp and associated C and N fluxes in Southern Ontario, Canada	*Hydrological Processes*
10	Fukushima et al. (2015)	Influence of strip thinning on nutrient outflow concentrations from plantation forested watersheds	*Hydrological Processes*
11	Levia and Germer (2015)	A Review of Stemflow Generation Dynamics and Stemflow-Environment Interactions in Forests and Shrublands.	*Reviews of Geophysics*
12	Li et al. (2017)	Abiotic processes are insufficient for fertile island development: A 10-year artificial shrub experiment in a desert grassland	*Geophysical Research Letters*
13	Limpert and Siegert (2019)	Interspecific Differences in Canopy-Derived Water, Carbon, and Nitrogen in Upland Oak-Hickory Forest	*Forests*
14	Liu et al. (2019)	Base Cation Fluxes from the Stemflow in Three Mixed Plantations in the Rainy Zone of Western China	*Forests*
15	Lombardo et al. (2018)	Organic carbon fluxes by precipitation, throughfall and stemflow in an olive orchard in Southern Spain	*Plant Biosystems*
16	Lu et al. (2016)	Nutrient characteristics of throughfall and stemflow in the natural forest of Pinus densata in the Tibetan plateau	*Phyton*

Continues...

Table 1 – Continuation.

	Authors	Title	Journal
17	Lu et al. (2017)	Nutrient Fluxes in Rainfall, Throughfall, and Stemflow in Pinus densata Natural Forest of Tibetan Plateau	*Clean - Soil, Air, Water*
18	Michalzik et al. (2016)	Effects of aphid infestation on the biogeochemistry of the water routed through European beech (Fagus sylvatica L.) saplings	*Biogeochemistry*
19	Rehmus et al. (2017)	Aluminum cycling in a tropical montane forest ecosystem in southern Ecuador	*Geoderma*
20	Rice et al. (2016)	Role of riparian areas in atmospheric pesticide deposition and its potential effect on water quality	*Journal of the American Water Resources Association*
21	Rosier et al. (2016)	Seasonal dynamics of the soil microbial community structure within the proximal area of tree boles: Possible influence of stemflow	*European Journal of Soil Biology*
22	Rossi and Ares (2016)	Overland flow from plant patches: Coupled effects of preferential infiltration, surface roughness and depression storage at the semiarid Patagonian Monte	*Journal of Hydrology*
23	Siegert et al. (2017)	Do storm synoptic patterns affect biogeochemical fluxes from temperate deciduous forest canopies?	*Biogeochemistry*
24	Su et al. (2019)	Hydrochemical Fluxes in Bulk Precipitation, Throughfall, and Stemflow in a Mixed Evergreen and Deciduous Broadleaved Forest	*Forests*
25	Suescún et al. (2019)	ENSO and rainfall seasonality affect nutrient exchange in tropical mountain forests	*Ecohydrology*
26	Sun et al. (2015)	Variation characteristics of nitrogen concentrations through forest hydrologic subcycles in various forests across mainland China	*Environmental Technology*
27	Thieme et al. (2019)	Dissolved organic matter characteristics of deciduous and coniferous forests with variable management: different at the source, aligned in the soil	*Biogeosciences*
28	Türtscher et al. (2019)	Reconstructing Soil Recovery from Acid Rain in Beech (Fagus sylvatica) Stands of the ViennaWoods as Indicated by Removal of Stemflow and Dendrochemistry	*Water, Air and Soil Pollution*
29	Van Stan and Stubbins (2018)	Tree-DOM: Dissolved organic matter in throughfall and stemflow	*Limnology and Oceanography Letters*
30	Vandecar et al. (2015)	Phosphorus input through fog deposition in a dry tropical forest	*Journal of Geophysical Research: Biogeosciences*
31	Yuan et al. (2017)	Comparisons of stemflow and its bio-/abiotic influential factors between two xerophytic shrub species	*Hydrology and Earth System Sciences*
32	Zhang et al. (2016)	Variations of Nutrients in Gross Rainfall, Stemflow, and Throughfall Within Revegetated Desert Ecosystems	*Water, Air, and Soil Pollution*
ScienceDirect			
1	Attarod et al. (2019)	Replacing an oriental beech forest with a spruce plantation impacts nutrient concentrations in throughfall, stemflow, and O layer	*Forest Systems*
2	Rosier et al. (2015)	Forest canopy precipitation partioning: an important plant trait influencing the spatial structure of the symbiotic soil microbial community	*Advances in Botanical Research*
3	Jian et al. (2019)	Retracted: Study on the throughfall, stemflow, and interception of two shrubs in the semiarid Loess region of China	*Agricultural and Forest Meteorology*
4	Wilcke et al. (2019)	Temporal Trends of Phosphorus Cycling in a Tropical Montane Forest in Ecuador During 14 Years	*Journal of Geophysical Research: Biogeosciences*
5	Wang et al. (2019)	Dissolved Organic Matter Characteristics and Important Site Factors in a Subtropical Mountain Forest in Central China	*Forest Science*
Scopus and ScienceDirect			
1	Berger et al. (2016)	A slight recovery of soils from Acid Rain over the last three decades is not reflected in the macro nutrition of beech (Fagus sylvatica) at 97 forest stands of the Vienna Woods	*Environmental Pollution*
2	Schooling et al. (2017)	Stemflow chemistry in relation to tree size: A preliminary investigation of eleven urban park trees in British Columbia, Canada	*Urban Forestry & Urban Greening*
3	Schwendenmann and Michalzik (2019)	Dissolved and particulate carbon and nitrogen fluxes along a Phytophthora agathidicida infection gradient in a kauri (Agathis australis) dominated forest	*Fungal Ecology*
4	Türtscher et al. (2017)	Declining atmospheric deposition of heavy metals over the last three decades is reflected in soil and foliage of 97 beech (Fagus sylvatica) stands in the Vienna Woods	*Environmental Pollution*
5	Van Stan and Pypker (2015)	A review and evaluation of forest canopy epiphyte roles in the partitioning and chemical alteration of precipitation	*Science of the Total Environment*

Main topic analysis based on publication year and continent of origin

Although there was upward trend in Scopus articles from 2015 to 2017, it dropped sharply in 2018. Yet, the number of published articles increased in 2019. The number of ScienceDirect articles remained stable from 2015 to 2017; it was followed by a decrease in 2018 and an increase in the last analyzed year (2019) (Figure 1).

Moreover, both Scopus and ScienceDirect databases showed that Asia was the continent accounting for the largest number of publications on the topic addressed herein over the last 5 years; it was followed by North America (Figure 2). Conversely, Oceania and South America recorded the lowest number of published articles.

Keyword analysis

The Graph Theory-based keyword analysis allows identifying the frequency of a given word and the signs of connection among words, which helps identifying the text corpus content structure (Figure 3). "Stemflow" and "throughfall" were the two words that have stood out the most among the selected articles and they are highlighted in the middle of this structure. They branch off in the structure for being highly correlated to other terms, such as "forest" and nutrient".

Overall, it can be inferred that the literature discussed herein, in addition to presenting references inherent to the stemflow and throughfall process, also acknowledged stemflow as an important channel for nutrient input into forest soil. Yet, there are other essential aspects for the broad understanding of the topic addressed herein. The "stemflow" cluster was correlated to terms such as "concentration", "chemistry", "biogeochemical cycle" and "nutrient dynamics", whereas the "throughfall" cluster encompassed words such as "ecohydrology" and "interception".

Thus, both stemflow and throughfall take part in nutrient dynamics, since they alter the chemistry of rainwater that flows down tree canopies and contribute to biogeochemical cycling by carrying nutrients into the soil. Zhang et al. (2016) and Schooling et al. (2017) have shown that throughfall and stemflow water cycles are key drivers of ecosystem processes, mainly of nutrient cycling. Su et al. (2019) argue that rainfall is one of the main chemical input sources in forest ecosystems; therefore, understanding nutrient cycling and hydrochemical fluxes of forest ecosystems is essential to manage their dynamics. Attarod et al. (2019), demonstrated that changing from a natural beech forest to a spruce plantation significantly alters nutrient fluxes leached from the canopy and that provides essential information on how planting exotic species affect nutrient cycles.

The "stemflow" cluster was also made up of words such as "leach", "ion" and "water chemistry", since stemflow is rich in leachate solutions from leaves, branches and stems (Aboal et al., 2015). Moreover, its water residence time in tree surfaces lasts much longer than that of other interception processes. Therefore, stemflow is a key process in nutrient cycling (Levia and Germer, 2015).

Several factors can affect the concentration and flow of nutrients from tree canopies and stems to the soil, such as the following: rainfall volume and intensity; dry seasons preceding rainfall; seasonality. These factors are important because they can change the dilution and leaching processes of the minerals accumulated in tree canopies and stems (Siegert et al., 2017). Yet, soil chemistry can also affect the cycling of nutrients by trees and, consequently, affect the leaching rates of the same nutrients in plant tissue (Aboal et al., 2015). Chen, L.C. et al. (2019) suggest that the tree size is also an important factor affecting the heterogeneity of the spatial patterns of the soil solution chemistry near tree trunks.

The "stemflow" cluster comprises the "soil" subcluster, which is made up of words that validate the importance of stemflow to nutrient input into the soil, such as "chemistry", "soil chemistry", among others. Deng et al. (2017) demonstrate that precipitation shows an acid and nutrient enrichment phenomenon after interception by canopy. Levia and Germer (2015) state that SF has been increasingly acknowledged as an important process for providing water and nutrients to spatial areas of forest ground. SF particles stay on tree surfaces for much longer than particles carried by other rainfall interception processes; therefore, it is a key pathway in the nutrient cycling.

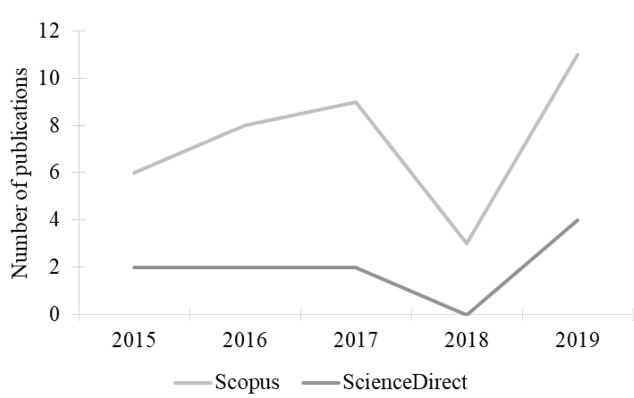

Figure 1 – Distribution of number of publications per year.

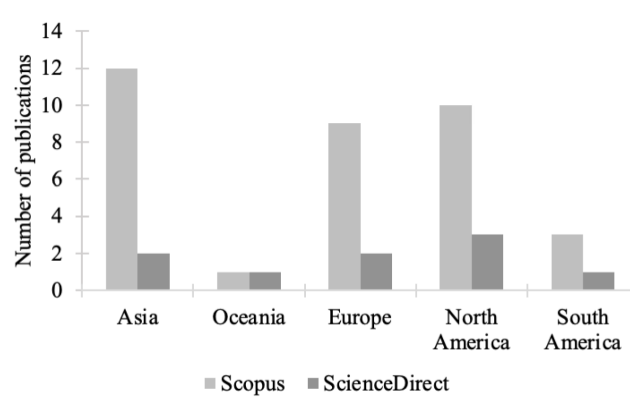

Figure 2 – Distribution of the number of publications by continent.

The term "*fagus sylvatica*" also stands out from the interconnected words belonging to the "stemflow" cluster. *Fagus sylvatica*, *Fagus grandifolia*, *Prunus virginiana*, *Caragana korshinskii* and *Acer rubrum* (Figure 4) were the five most assessed species associated with nutrient cycling; however, the selected articles were mostly focused on species *Fagus sylvatica* (Berger et al., 2016; Michalzik et al., 2016; Thieme et al., 2019; Türtscher et al., 2019). *Fagus sylvatica*, also known as European beech, is one of the most common tree species in Europe; it is distributed in Central and Western Europe.

There was no study providing an overview of the stemflow importance for nutrient cycling in both existing Brazilian plant species and biome diversity. *Tabebuia chrysantha*, *Cedrela odorata*, *Ocotea aciphylla* and *Larrea divaricata* were the most widely distributed species in Brazil; yet, the other species were either missing or difficult to find (Table 2).

The term "atmospheric deposition" stood out in the "stemflow" word cluster. Cayuela et al. (2019) argues that the atmospheric particulate matter is redistributed and deposited on plant leaves before they are carried into soil layers through SF and TF (throughfall). Lu et al. (2017) assessed the components and features of both SF and TF solutes from the *Pinus densata* forest in Tibet Plateau; their results suggested

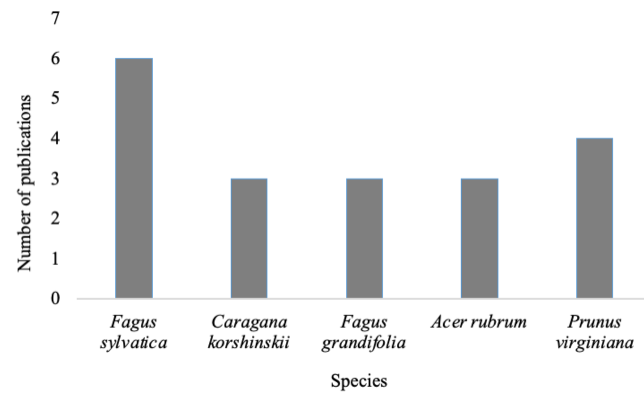

Figure 4 – Five most assessed species based on stemflow and nutrient cycling.

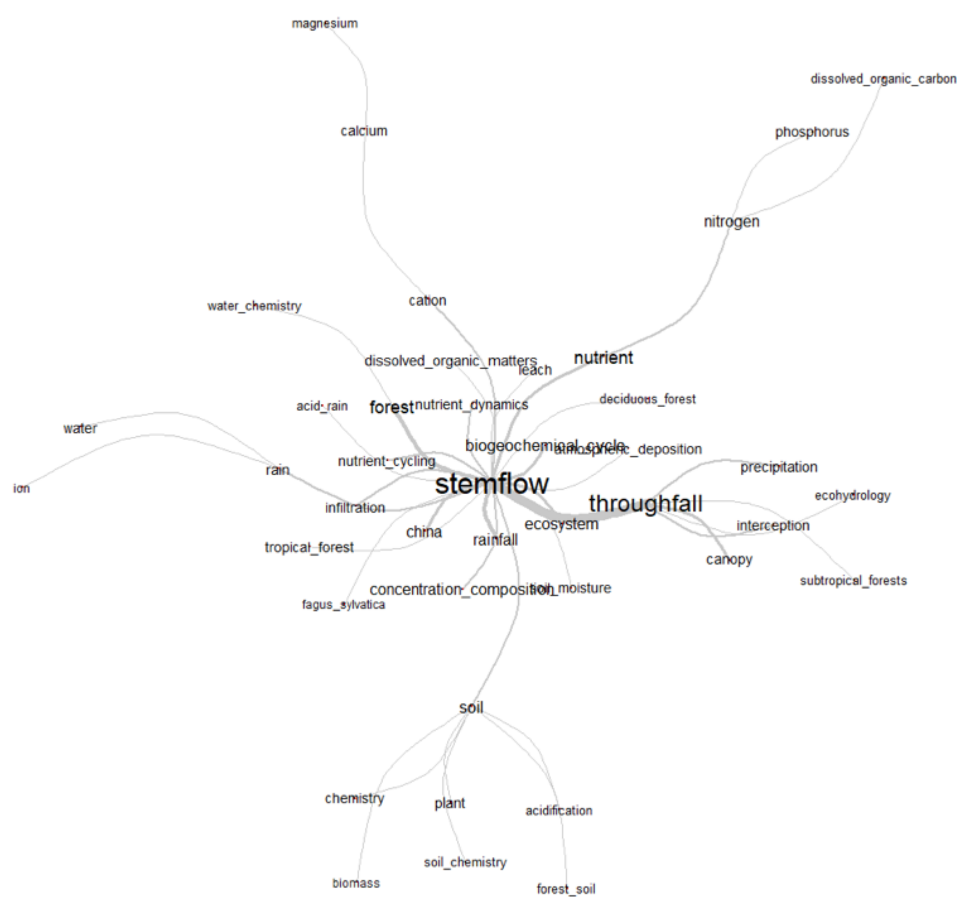

Figure 3 – Cluster of keywords from research about stemflow effect on soil nutrient flux, based on co-occurrence analysis.

that atmospheric deposition plays an important role in nutrient supply to the soil surrounding the trees. Türtscher et al. (2017) used SF to study the legacy of high atmospheric heavy metal deposition. Results of measurements taken from heavy metal contamination in *Fagus sylvatica* trees in Vienna have shown critical heavy metal levels in microsites affected by SF.

Yet, the term "soil moisture" in the "stemflow" cluster indicated that SF becomes a source of moisture to the soil. Research by Jian et al. (2019) in arid regions have confirmed that SF has positive effect on soil moisture balance in the root zone; moreover, it can improve soil moisture and structure in deeper layers. Studies conducted by Rosier et al. (2016) suggest that SF enhances and alters edaphic conditions

Table 2 – Species searched based on the keywords presented herein.

Author	Species
Cayuela et al. (2019)	*Quercus pubescens, Pinus sylvestris*
Chen, S. et al. (2019)	*Castanopsis cuspidata*
Duval (2019)	*Thuja occidentalis, Abies balsamea, Populus balsamifera, Fraxinus nigra, Picea mariana, Betula papyrifera, Alnus glutinosa*
Limpert and Siegert (2019)	*Quercus alba, Quercus stellata, Quercus pagoda, Quercus shumardii, Carya ovata, Carya glabra*
Liu et al. (2019)	*Cryptomeria fortunei, Quercus acutissima, Phoebe zhennan, Camptotheca acuminate, Padus racemosa, Pterocarya stenoptera, Michelia wilsonii, Cryptomeria fortune, Alnus remastogyne*
Schwendenmann and Michalzik (2019)	*Agathis australis*
Su et al. (2019)	*Cyclobalanopsis multinervis, Cyclobalanopsis oxyodon, Fagus engleriana, Quercus serrata*
Suescún et al. (2019)	*Quercus humboldtii*
Türtscher et al. (2019)	*Fagus sylvatica*
Attarod et al. (2019)	*Fagus orientalis, Picea abies*
Thieme et al. (2019)	*Fagus sylvatica, Picea abies, Pinus sylvestris*
Jian et al. (2019)	*Caragana korshinskii, Hippophae rhamnoides*
Chen, L.C. et al. (2019)	*Phoebe formosana, Machilus zuihoensis, Neolistea, konishii, Pasania hancei*
Bittar et al. (2018)	*Quercus virginiana, Juniperus virginiana*
Bigelow and Canham (2017)	*Acer saccharum, Fraxinus americana, Fagus grandifolia, Acer rubrum, Quercus rubra, Tsuga canadensis, Acer pensylvanicum, Malus pumila, Carpinus caroliniana, Crataegus brainerdii, Ostrya virginiana, Hamamelis virginiana, Prunus virginiana, Carya ovata, Prunus serotina, Picea rubens, Pinus strobus, Betula populifolia, Betula alleghaniensis, Betula papyrifera*
Lu et al. (2017)	*Pinus densata*
Rehmus et al. (2017)	*Purdiaea nutans, Alchornea pearcei, Graffenrieda emarginata, Podocarpus oleifolius, Alazatea verticilata, Clusia ducoides, Hyeronima moritziana, Ocotea aciphylla, Ocotea bentamiana, Miconia, Elaeagia, Matayba inelegans, Prunus opaca, Cedrela odorata, Heliocarpus americanus, Tabebuia chrysantha*
Siegert et al. (2017)	*Fagus grandifolia, Liriodendron tulipifera*
Schooling et al. (2017)	*Cercidiphyllum japonicum, Tilia cordata, Prunus virginiana, Acer rubrum, Fraxinus pennsylvanica, Quercus macrocarpa, Acer freemanii, Prunus padus, Fagus sylvatica, Quercus palustres*
Türtscher et al. (2017)	*Fagus sylvatica*
Kaushal et al. (2017)	*Morus alba*
Michalzik et al. (2016)	*Fagus sylvatica*
Zhang et al. (2016)	*Caragana korshinskii, Artemisia ordosica*
Rice et al. (2016)	*Acer rubrum, Symplocarpus foetidus, Impatiens pallida*
Álvarez-Sánchez et al. (2016)	*Astrocaryum mexicanum*
Berger et al. (2016)	*Fagus sylvatica*
Lu et al. (2016)	*Pinus densata*
Rosier et al. (2016)	*Fagus grandifolia, Liriodendron tulipifera*
Rossi and Ares (2016)	*Schinus johnstonii, Pappostipa speciosa, Chuquiraga avellanedae, Larrea divaricata*
Fukushima et al. (2015)	*Chamaecyparis obtuse, Cryptomeria japonica*
Aboal et al. (2015)	*Morella faya, Laurus novocanariensis, Erica arborea, Persea indica, Ilex perado*
Bade et al. (2015)	*Picea abies*

of the soil surrounding individual tree trunks, such as moisture, pH and mineral nutrients (Al, Cu, K, Mn) available to plants. However, SF effects may specifically vary among species and specimens. This fact assumingly explains the structural differences in the microbial community of the soil surrounding the tree trunks.

The analysis of articles addressing dissolved organic matter (DOM) was based on both "stemflow" cluster and on its subclusters, mainly "cations", "calcium" and "magnesium". Dissolved organic carbon (DOC) is part of the "nitrogen" subcluster. DOM is important for both vertical and horizontal nutrient transport in forest ecosystems (Wang et al., 2019). DOM features during leaching can highly vary depending on forest type; this variability is mostly evident when there are changes in seasonal leaves and rainfall conditions (Van Stan and Stubbins, 2018; Chen, S. et al. (2019); Duval, 2019). DOM is part of the biogeochemical cycles of carbon and nutrients, as it carries ions and encourages soil growth. Both chemical concentration and its properties in the water flow path of forest ecosystems depend on their sampling site and transformation processes (Thieme et al., 2019).

Research conducted by Schwendenmann and Michalzik (2019) has demonstrated that the following data are also measured in order to assess nutrient cycling status during forest restoration processes: water input and output in the ecosystem; DOC leaching and water migration coefficients; nitrogen flux.

The word "phosphorus" stands out in the subcluster "nitrogen". Atmospheric deposition can significantly increase the amount of P available in the soil of many tropical forests — phosphorus (P) is considered a limiting nutrient. This effect takes place due to the increased deposition of P-rich aerosol particles (dry deposition) and fog droplets (wet deposition) on leaf surface (Vandecar et al., 2015). Results of the research conducted by Álvarez-Sánchez (2016) on palm *Astrocaryum mexicanum* implied that its SF is an important pathway for both P and nitrogen input into the soil of this tropical forest of palms.

The terms "subtropical forests" and "tropical forest" make up the "throughfall" and "stemflow" clusters, respectively, and the word "China" is highlighted close to the "stemflow" cluster. Despite the growing number of publications on the topic addressed herein, most of them come from China, whose vegetation consists mostly of subtropical forests. Thus, the number of studies conducted in tropical forests remains insufficient. This statement is supported by the fact that the entered keywords did not show results of studies carried out in Brazil, only in Ecuador and Colombia. Thus, the knowledge gap on the role played by different species in the biogeochemical cycle — mainly the stemflow process — of tropical forests remains.

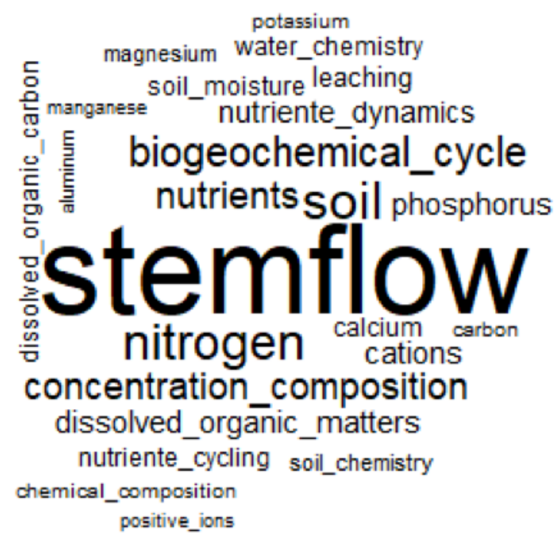

Figure 5 – Word cloud showing the main topics associated with stemflow-driven nutrient dynamics.

The word cloud generated from published articles mainly focused on SF was analyzed in order to substantiate the previous analysis. Results have shown that the most common keywords were "stemflow", "nitrogen", "concentration", "composition", "biogeochemical cycle", "dissolved organic matter", "soil nutrients" and "atmospheric deposition". Such results emphasize the importance of stemflow for nutrient leaching, since SF improves ion availability in the soil (Figure 5).

Conclusions

Stemflow is a fundamental component for nutrient leaching, since SF improves ion availability in the soil. Only a few studies provided an overview of the importance of stemflow for nutrient cycling in Brazilian plant species and biome diversity. Based on the searched databases, forty-seven (47) articles were published between 2015 and 2019, thirty seven (37) in Scopus, and 10 in Science Direct databases. Five (5) articles are listed both in Scopus and Sicence Direct databases. Asia comprised most of the publications related to the aforementioned topic over the last 5 years, whereas South American research on the role played by different species in stemflow — mainly during the biogeochemical cycle — remains scarce. Research regarding the stemflow effect on biogeochemical cycling and soil dynamics is still insufficient, and full understanding thereof still requires many further studies.

Contribution of authors:

Lima, M.T.: Formal Analysis, Methodology, Writing — Original Draft, Writing — Review and Editing. Tonello, K.C.: Formal Analysis, Methodology, Supervision, Validation, Visualization, Writing — Review and Editing. Bramorski, J.: Formal Analysis; Methodology; Validation, Visualization, Writing — Review and Editing. Arruda, M.M.: Formal Analysis; Methodology; Writing — Review and Editing. Matus, G.N.: Formal Analysis; Methodology; Writing — Review and Editing.

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Viewpoint

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Legal Action for Climate Protection — impulses on the international level from the German Federal Constitutional Court: the Court Order from March 2021 on the Unconstitutionality of the Federal German Climate Protection Act

Ação Jurídica para a Proteção do Clima — Impulsos em Nível Internacional do Tribunal Constitucional Federal Alemão: a ordem do tribunal de março de 2021 sobre a inconstitucionalidade da Lei Federal de Proteção Climática da Alemanha

Stephan Tomerius[1]

ABSTRACT

Against the background of the international climate protection aim deriving from the "Paris Agreement" of December 2015, demanding a limitation of global warming to 1,5° Celsius at best, the public discussion and anger on the mid- and longterm consequences of a constantly growing greenhouse effect have clearly risen. Along with that, "climate litigation" has turned into serious means to sue governments for inadequate measures to reach international and domestic climate protection goals. In a line of several legal actions and high court decisions in different countries during the last years is the court order of the Federal German Constitutional Court from March 2021. The judges considered the German Federal Climate Protection Act unconstitutional due to a lack of clearing a reliable legal path to reach the CO_2-reduction goals and this decision was seen as a milestone in climate litigation. Combined with the obligation of the state to protect the natural resources by legislation, the court invented the "advance interference-like effect"on future generations and the "intertemporal guarantees of freedom", two legal figures which could be possibly applied to constitutional law abroad and thus fertilize argumentation in climate litigation outside of Germany, too.

Keywords: Paris agreement of 2015; climate litigation; greenhouse gases; global warming; CO_2-emissions; German federal climate protection act; constitutional law; legislation; sustainability; natural resources; future generations.

RESUMO

No contexto do objetivo internacional de proteção do clima decorrente do Acordo de Paris, de dezembro de 2015, que exige uma limitação do aquecimento global a, no máximo, 1,5° Celsius, a discussão pública e a raiva relativas às consequências em médio e longo prazo de uma estufa em constante crescimento efeito aumentaram claramente. Além disso, o "litígio climático" transformou-se em um meio consistente de processar os governos por medidas inadequadas para atingir as metas internacionais e domésticas de proteção climática. Na linha de várias ações legais e decisões de tribunais superiores em diferentes países durante os últimos anos, está a ordem judicial do Tribunal Constitucional Federal alemão de março de 2021. Os juízes consideraram a Lei Federal de Proteção Climática da Alemanha inconstitucional por não abrir um caminho confiável para se atingirem as metas de redução de CO_2. Essa decisão é vista como um marco no litígio climático. Ela soma-se à obrigação do Estado de proteger os recursos naturais pela legislação que o tribunal criou com "efeito de interferência antecipada" sobre as gerações futuras e às "garantias intertemporais de liberdade" — duas figuras jurídicas que poderiam ser aplicadas ao direito constitucional no exterior e, assim, poderiam fertilizar a argumentação sobre litígios climáticos fora da Alemanha também.

Palavras-chave: Acordo de Paris de 2015; litígio climático; gases de efeito estufa; aquecimento global; emissões de CO_2; lei federal de proteção climática da Alemanha; lei constitucional federal alemã; legislação; sustentabilidade; recursos naturais; gerações futuras.

[1]Berlin School of Economics and Law – Berlin, Germany.

Correspondence address: Stephan Tomerius – Berlin School of Economics and Law – Campus Lichtenberg – Alt Friedrichsfelde 60 – 10315 Berlin, Germany – E-mail: stephan.tomerius@hwr-berlin.de

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Introduction and Background of International Climate Litigation

The ongoing rising emission of greenhouse gases, especially CO_2, in the atmosphere keeps on contributing to accelerated global warming. This has not only generated international protests against insufficient national and international policymaking, strongly expressed by organizations such as "Fridays for future", "Greenpeace", "Extinction rebellion" and other environmental and climate protection groups. In the public discussion, frequently accompanied by frustration and anger, are mid- and longterm consequences of a constantly intensified greenhouse effect such as sea-level rise, shrinking of groundwater restoration, increase of draught etc., foreseeably causing migration and escape from regions in the world severly struck by climate change[1]. Within these dynamics of the climate discussion, initial steps have also been taken in the field of "climate litigation", i.e. attempting to sue governments for inadequate measures to reach official climate protection goals.[2] In the cases mentioned as follows, litigation was mainly targeted at governments and the legal leverage was mostly applied with regard to domestic law. In doing so, it was usually attempting to reflect the goals deriving from agreements on international climate conferences, especially focusing on the aim of limiting global warming to 1,5° Celsius in the "Paris Agreement" of December 12, 2015. In that agreement a global framework was set up to avoid dangerous climate change by limiting global warming to well below 2° Celsius and pursuing efforts to preferably limit it to 1.5° Celsius.[3]

In the meantime, several supreme or highest courts especially in the USA, Australia, New Zealand and in the European Union (EU) have decided on cases of climate litigation, often with great national and international attention. Already in 2007, the US Supreme Court decided on the case "Massachusettes vs. EPA", on the competence of the Environmental Protection Agency (EPA) to rule greenhouse gases as air pollutants (U.S. Department of Justice, 2007).

A climate case of worldwide attention was set in Europe in the year 2015: In the "Urgenda Climate Case", citizens claimed that the Dutch government had a legal duty to prevent dangerous climate change (Urgenda, 2022).[4] In June 2015, the District Court of The Hague ruled that the government must cut its greenhouse gas emissions by at least 25% by the end of 2020 (relative to 1990).[5] The court found the government's existing approach to reduce emissions by 17% insufficient, as a consequence of the Dutch contribution towards the United Nations goal of keeping global temperature rise within 2° Celsius. Due to the severity of the consequences of climate change and the great risk of climate change occurring, the court ordered the government to immediately take more effective actions on climate change.

More recently in the year 2021, several high courts in different nations had to deal with climate protection litigation: For example[6] the Federal Court of Australia (2021) pointed out in the case "Sharma by her litigation representative Sister Marie Brigid Arthur v Minister for the Environment [2021] FCA 774 (No 2) " that the 'government has the duty to take reasonable care under the relevant environmental law to avoid causing personal injury or death to persons who were under 18 years of age and ordinarily resident in Australia arising from emissions of carbon dioxide into the Earth's atmosphere'.In New Zealand the group "Lawyers for climate action" has moved a legal action in the summer of 2021 against the Climate Change Commission to the New Zealand high court, pleading that the country's emission budgets and reduction targets are inconsistent with the Paris Agreement goal to limit global warming to 1,5° Celsius (Corlett, 2021).

As far as the situation in the EU is concerned, the "Conseil d'État", the highest administrative court in France, ordered the French government in March 2021 to take 'all necessary and additional steps to reach its climate targets or face possible sanctions, including substantial fines'[7] in the case of "Notre Affaire à Tous and Others v. France", where the the court finally pointed out that France is not on the right track to meet its CO_2-reduction-goals of 40 % by the year 2030.

Distinctly from the climate lawsuits mentioned above, directed at national governments, another sensational legal action in the Netherlands triggered worldwide attention by changing the target to a big private company: The case of "Milieudefensie et al. v. Royal Dutch Shell plc."[8] was taken up to "The Hague District Court" through an action of more than 17.000 Dutch citizens suing the huge oil enterprise Royal Dutch Shell. To the plaintiff's point of view, Shell's oil-related business was violating its obligation to reduce the aggregate annual volume of CO_{2}- emissions into the atmosphere. Amongst other claims, the plaintiffs demanded the withdrawal of Shell from the fossile energy business. The Hague District Court ordered Shell in May 2021 to reduce its

[1] See the impressive and somewhat frightening description of IPCC (2021).

[2] Find more on climate litigation in courts at Setzer/Bangalore (2017).

[3] See more on the Paris Agreement under (United Nations, 2022).

[4] find a good summary oft he dutch decision under http://climatecasechArticlecom/climate-change-litigation/non-us-case/urgenda-foundation-v-kingdom-of-the-netherlands/

[5] The District Court's decision was upheld both by the Court of Appeal in 2018 and the Dutch Supreme Court in 2019.

[6] For a longer list of climate litigation cases see the blog of the Columbia Law School (2021).

[7] Find a good summary of the French decision in english under http://climatecasechArticlecom/non-us-case/notre-affaire-a-tous-and-others-v-france/?mc_cid=2ee16a4b8f&mc_eid=c70ad85e80

[8] Find a good summary of the Dutch decision in english http://climatecasechArticlecom/climate-change-litigation/non-us-case/milieudefensie-et-al-v-royal-dutch-shell-plc/?mc_cid=e15e769911&mc_eid=c70ad85e80

emissions by 45 % by 2030, relative to 2019, capturing all the company's activities, its subsidiaries and emissions in a broad understanding. Thus, for the the first time a non-state entity has been legally obliged to mitigate climate change in accordance with the goals of the Paris Climate Agreement. Shell will appeal to the decision, but as the Dutch court made its decision provisionally enforceable, the company will be required to meet its reduction obligations right away.

Apart from these court decisions, publications from other social sectors than climate, environmental policies or law reveal a growing perceptance, relevance and impact of climate litigation on other fields.[9] Even adjustments towards climate-awareness in the portfolio of major investment institutes has become visible (BlackRock, 2022).

The international context of the Paris Agreement and its consequences for domestic governmental responsibilties are also decisive when we look at the recent climate litigation in Germany. In order to grasp the content and relevance of the recent key decision made by the *German Federal Constitutional Court (Bundesverfassungsgericht – BVerfG)* on the unconstitutionality of the German Climate Protection Act from March 2021 (Bundesverfassungsgericht, 2021) which gained a worldwide echo, we also need to take a short look on some basic legal framework and principles of constitutional and administrative law in Germany in the following "Climate litigation under German constitutional and administrative law". The court decision itself will be explained in its major considerations and findings in "The decision of the German Federal Constitutional Court". The question if these major considerations of the German court decision are transferable to the international level will be an essential part of a summary and outlook in the final "Summary and outlook".

Climate Litigation Under German Constitutional and Administrative Law

In order to understand the in parts "epochal" oder "revolutionary"[10] findings of the German Federal Contitutional Court, it is necessary to at least outline the basic framework of German constitutional law in which the "climate protection" and "sustainability" topics are set. From the constitutional law perspective, these terms are situated in a surrounding of three important principles and rights of the German constitution, i.e. the "Basic Law" (Grundgesetz – GG): Firstly the "*state objective of protection of natural resources*" *(Article 20a GG)*, secondly the "*state duty of protection of basic constitutional rights*" (especially with regard to Article 2 (2) – right to physical integrity and life – and Article 14 – right to property) and thirdly the common "*principle of proportionality*" for state decisions and regulations.

Article 20a GG provides that the state protects the natural resources and the animals also in responsibility for future generations within the framework of constitutional law through legislation and through executive power and jurisdiction.

As far as the "state duties of protection of basic constitutional rights" are concerned, the Federal Constitutional Court rules in settled case law that the state is required to protect life and physical integrity under Article 2 (2) GG and property under Article 14 (1) GG against impairments, possibly in combination with a duty of care deriving from Article 20a GG.[11]

Finally the "principle of proportionality" (Verhältnismäßigkeitsgrundsatz) as an overall constitutional principle demands that state measures and legislation have to be suitable according to a legitimate aim, necessary as the mildest, equally suitable measure and in fair proportion considering and balancing public interests and losses of freedom rights of the concerned citizens.[12]

Before March 2021, the Federal Constitutional Court had not accepted claims of individuals referring to Article 20 a GG. This regulation was mereley seen as an *objective* duty of the German state to protect natural resources with responsibility for future generations, but not as a *subjective* right, which could be individually claimed in court. In advance of the climate-protection-order of the Federal Constitutional Court in March 2021, the Berlin Administrative Court also made this clear in a well-known decision during the year 2019: In this case, several plaintiffs were attempting to sue the Federal Government to come up with further measures in order to fulfill the goals of the "Federal Action Programme Climate Protection 2020".[13], however the Berlin Administrative Court had already denied the plaintiffs the standing for proceeding at court, arguing that the "Federal Action Programme Climate Protection 2020" was merely a political memorandum and not a legal regulation from which a standing for legal action in court could be derived from (Berlin Administrative Court, 2019).

The Decision of the German Federal Constitutional Court

The order of the German Federal Constitutional Court from March 24, 2021 gained wide-spread attention, both on a national and international levels.[14] The key message that German federal climate protection law was considered insufficient to reduce greenhouse gas emissions and

[9] For the impact of climate litigation on the financial sector, see European Central Bank (2021).

[10] See out of the legal scientific community e.g. *Calliess*, Das "Klimaurteil" des Bundesverfassungsgerichts: "Versubjektivierung" des Article 20 a GG? ZUR 2021, pp. 355 et seq.; *Ekardt/Heß*, Bundesverfassungsgericht, neues EU-Klimaschutzrecht und das Klima-Ziel des Paris-Abkommens, NVwZ 2021, pp. 1421 et seq.

[11] See e.g. the rule on the Genetic engineering Act in Leitsätze (2010).

[12] For basics and principles of German Constitutional Law, see Bumke/Voßkuhle (2019).

[13] Check out the current and revised Federal Climate Protection Programme – now with a view to 2030 – (Germany, 2022).

[14] See also the summary of the court order by Talmon (2021) and Bodle and Sina (2021).

limit climate change especially with respect to future generations was called "epochal", "a milestone" or also "a slap in the face" (i.e. the face of the legislator).[15] According to German constitutional law, the court has the power to declare laws violating constitutional rights void or require legal amendments.

The legislation in focus was the Federal Climate Protection Act ("Klimaschutzgesetz" - KSG). This Federal law roots back to 2019 and established binding climate targets for the first time. As an overall goal, it requires reductions of greenhouse gas emissions of 55% compared to 1990 by the year 2030. Different key economic sectors such as the energy industry, agriculture or building and housing have to contribute to this goal by decreasing annual emission budgets provided for the relevant sector. The law demands greenhouse gas neutrality by the year 2050. However, the provisions taken up to court ruled the climate targets in form of decreasing greenhouse emissions up to 2030 but left the path after 2030 open without any legal concretization regarding the relevant economic sectors. The federal government was only required to set up annually decreasing emission budgets for periods after 2030 by statutory ordinance (and not by formal federal legislation in parliament) in 2025.

The plaintiffs' claims and arguments

The plaintiffs — partly children, adolescents and young adults, some of whom lived in Bangladesh and Nepal and were backed by environmental associations, contested legal inaction and failure of the federal legislator in four complaints. They claimed that several provisions of the The Federal Climate Protection Act ("Klimaschutzgesetz" — KSG) were insufficient to counter climate change, thus violating their fundamental rights in an unconstitutional way.[16] Primarily the complainants stated that Germany has failed to introduce a proper legal framework for the reduction of mainly CO_2 emissions and that current legislation under the Federal Climate Change Act is insufficient to stay within the remaining CO_2 budget that would correspond to a temperature increase of 2°C or preferably 1.5°C.

In the plaintiffs' legal opinion, the state must fulfil its constitutional duties of protection arising from Article 2 (2) GG — right to physical integrity — and from Article 14 (1) GG — right to property. Furthermore, they claimed a fundamental right to a future with human dignity and a fundamental right to an "ecological minimum standard of living" ("ökologisches Existenzminimum"), deriving the latter from Article 2 (1) GG — general freedom of action — in conjunction with Article 20a GG and Article 1 (1) GG — right to human dignity. With one further — and later to be seen as a decisive argument, the plaintiffs put forward that the Federal Climate Protection Act is insufficient in its mechanisms and in its path to distribute the future burdens arising from the obligations to reduce emissions for periods after 2030 in a fair way. Rather the law would lay these burdens on the shoulders of generations to come.

Another crucial point in the plaintiffs' argumentation is connected with Germany's "CO_2 budget"[17]: They claimed that if the emission reduction goal from the Paris Agreement, i.e. to limit the increase in the global average temperature to well below 2°C and preferably to 1.5°C, shall be met and if future burdens shall be distributed in a fair way between the generations, there would have to be an "emergency stop" for CO_2 emissions right now. The plaintiffs added that the state, in leaving the path of CO_2 reduction after 2030 open, the burden of carrying the consequences of costs and restrictions of rights to freedom would be shifted unfairly to the younger generations.

Key considerations of the German Federal Constitutional Court

The constitutional complaints had been partially successful. The key findings of the court order refer to the question of whether the German state neglected its constitutional protection duties, and whether it violated the state objective to protect the natural resources (Article 20a GG). However, the decisive part of the court order which founded the success of the plaintiffs was the invention of new constitutional figures, namely the "*advance interference-like effect*" and the "*intertemporal guarantees of freedom*", combined with the traditional constitutional "*principle of proportionality*", here applied to federal legislation.

The ruling on the constitutional protection duties of the state

After having approved the climate target from the Paris Agreement as a reasonable political goal including the resulting CO_2 budget, the Federal Constitutional Court examined the question of whether the legislator, by adopting the Federal Climate Protection Act, fulfilled its constitutional duties of protection arising from Article 2 (2) GG — right to physical integrity — and from Article 14 (1) GG — right to property. Even though the court acknowledged the scientific findings that an average global warming of more than 1.5°C would have significant climate consequences and even though it stated that the duties of protection include the obligation of the state to protect from the dangers and risks for life and health by climate change, the judges refrained from finding that Germany violated its protection duties.[18] Akin to a

[15] See the report of Deutsche Welle and the echo on the court decision (Deutsche Welle, 2021).

[16] For an overview of Germany's climate protection policies in english see Brohmer (2020).

[17] This residual emission budget was calculated as a "carbon budget" on an international level by the "Intergovernmental Panel on Climate Change (IPPC)" to clarify the necessary contributions to the reduction of greenhouse gases by the countries having signed the "Paris Agreement", for more information see MCC (2022); on the German national level the "Sachverständigenrat für Umweltfragen" (SRU, 2020) has also calculated a residual CO_2 budget which is stricter than the IPCC; find more on SRU (2020).

[18] Para. 148 et seq. of the order.

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number of earlier decisions on constitutional protection duties, the Federal Constitutional Court granted a considerable leeway for the legislator in fulfilling the duty of protecting fundamental rights, especially since it must also reconcile the requirements of health protection with conflicting interests in considerable uncertainty. The court pointed out that the federal national climate protection law may be considered too politically unambitious but could not support the complainants' opinion that the legislator has exceeded this leeway by basing its action on the Paris target.

The judges did not see that Germany would follow a protection strategy that failed to pursue the goal of climate neutrality as a protection required by fundamental rights. The courts also did not consider the German climate protection legislation manifestly unsuitable for the protection against the risks of climate change. It did not judge the relevant German law as an entirely inadequate approach able to allow climate change to "simply run its course" or using nothing but so-called adaptation measures to fulfil the constitutional duty of protection.[19]

As several of the complainants were citizens of Nepal and Bangladesh, it was also at issue if Germany had violated its constitutional duties to protect their life, health, and property due to insufficient climate protection efforts. The Federal Constitutional Court left the question of whether a duty of protection also existed with regard to human beings living abroad. Apart from this, it stated that German climate protection policies would not violate such a duty as the state committed itself to the requirements of the Paris Agreement and is trying to pursue greenhouse gas neutrality by the year 2050.[20] In other words, the court found the serious political and legal approaches in Germany in order to meet the international climate protection aims sufficient with regard to the complainants from abroad.[21]

The ruling on the state objective to protect the natural resources (Article 20a GG)

With regard to Article 20a GG, which obliges the state to protect the natural resources by legislation, mindful of its responsibility towards future generations, the Federal Constitutional Court provides important clarifications: For the first time, the court derives explicitly an objective legal obligation of the state *for climate action* from Article 20a GG, independent of the fact that climate change and global warming can only be solved on a global level. The court attests Article 20a GG a special international dimension, meaning that the constitutional objective forces the German state to grow active with national contributions and international cooperation in order to tackle the global climate challenge.[22] The court ads another important sentence: "The path to globally effective climate protection indicated by Article 20a GG currently leads primarily via the Paris Agreement."[23]

From the constitutional law perspective, this statement actually means a constitutional enrichment and upgrade of the climate protection aims of the Paris agreement incorprated in the state's obligation from Art. 20a GG. But again, the Federal Constitutional Court acknowledges Germany‘s efforts in climate protection policies and law: The court holds that the German legislator adopted the climate target of the Paris Agreement, aiming at a mitigation of the global average temperature increase to a limit of well below 2°C and preferably 1.5°C. The court also grants a wide legislative leeway to the federal legislator combined with a certain prerogative in its mandate to concretize the reduction targets under the obligation of Article 20a GG. Finally, the Federal Constitutional Court judged that by following the climate aims of the Paris agreement, the legislator did not currently exceed its leeway in an unconstitutional way.

Earlier in its order, the court left open a question of whether a basic constitutional right to an "ecological minimum standard of living", as claimed by the plaintiffs, existed in the German "Basic Law", since the court did not hold this aspect relevant for the decision.[24]

What's new: the "advance interference-like effect" and the "intertemporalguarantees of freedom"

After the Federal Constitutional Court had denied both a violation of the state duties of protection of life, health and property as well as a violation of the constitutional order to the state form Art. 20a GG, it was somewhat surprising how the court finally arrived at the result of the unconstitutionality of the Federal Protection Act. The reason why the complainants won the case was at least partially an invention under constitutional law: The Federal Constitutional Court created two new legal figures and combined them with the traditional "principle of propotionality".

In the decisive part of the order, the court held that the legal path of the Federal Climate Protection Act substantially narrows the remaining options for reducing emissions by leaving the concrete mitigation efforts open after 2030. In conjunction with a very small remaining CO_2-budget for the years after 2030 (see above in chapter "The plaintiffs' claims and arguments"), the court found that this legal effect would jeopardise nearly every type of freedom protected by fundamental rights for younger generations to come. In this context, the court invented a new characteristic of fundamental rights: It stated that these

[19] Para. 157 et seq. of the order.
[20] Para. 173 et seq. of the order.
[21] See a similar assessment of the decision from Talmon (2021).
[22] Para. 199 et seq. of the order.
[23] Para. 204 of the order.
[24] Para. 113 et seq. of the order.

rights are to be understood as "*intertemporal guarantees of freedom*", here in form of protection against comprehensive threats caused by the greenhouse gas reduction burdens shifted and loaded upon future generations. According to the obligation of the beforementioned Article 20a GG, the judges pointed out that the legislator should have taken sufficient precautionary steps to ensure a transition to climate neutrality. In doing so, the state must respect fundamental freedom rights of generations to come and must not shift the main burden caused by efforts of greenhouse gas reductions onto the future. The court stated a lack of constitutional respect for these freedom rights in the regulations of the Federal Climate Protection Act.[25]

As the relevant specific climate protection provisions left the concrete path of mitigation efforts after 2030 open, the Federal Constitutional Court noticed — and this is the second invention of the court — an *"advance interference-like effect"* of this law on the freedom rights of the younger generation. This includes and affects the freedom rights of the complainants comprehensively protected by the German constitution, the "Basic Law", *already today*. Then, the court drew the consequence of the described lack of regulations as follows: It acknowledged that any exercise of freedom will directly or indirectly involve CO_2 emissions. However, the more provisions the relevant federal climate protection allow for CO_2 emissions in present time, the bigger the irreversible legal threat to future freedom rights of the younger generations will be. The court clearly speaks out that every amount of CO_2 that is allowed today narrows the remaining options for reducing emissions in compliance with Art. 20a GG later on. Consequently, any exercise of fundamental freedom rights involving CO_2 emissions would have to be subjected to increasingly stringent, and constitutionally required restrictions by the state.[26]

An important factor for these court findings is the reference to the residual greenhouse emission budget assessed by the *IPCC* and the *German Advisory Council on the Environment* in order to meet the Paris Agreement goal to limit the increase in the global average temperature to well below 2°C, preferably 1.5°C (see above under "The plaintiffs' claims and arguments"). Referring to these evaluations, the Federal Constitutional Court held that much of the CO_2-budget will be already depleted by the year 2030. The court pointed out that provisions allowing CO_2 emissions irreversibly led to legal risks for future freedoms. Therefore, the reason was that any amount of emission admitted by law today would minimize the residual CO_2-budget for the future irreversibly and would inevitably lead to stronger freedom restrictions — constitutionally required by order of Article 20a GG — in the future.[27]

Thus, there would be an elevated risk to achieve the transition to climate-neutral behaviour in a way that respects the freedom of future generations in a fair way. There would also be the risk of serious losses of future freedom rights due to an apparently shorter timeframe for the technological and social developments required to compensate today's still heavily CO_2-oriented lifestyle. This risk to the future exercise of fundamental rights – so the court continues to say — has to be seen and treated by the legislator already at current time.[28] This means a legal framework has to be established early enough by taking sufficient precautions in order to ensure that fundamental rights will also be protected in future times.

Considering the described "advance interference-like effect" on the plaintiffs already today, the court demanded that the current federal emission provisions must be compatible with the objective obligation from Article 20a GG to take climate action. The court admitted that federal provisions could of course not rule and solve all the technological and social challenges related to the urgent climate change issue. But against the background of Article 20a GG and the "advance interference-like effect" it demanded from the state to pass a legislation setting up preconditions and giving incentives early enough in all relevant sectors — such as production, service, transport, infrastructure, administration, housing, agriculture, culture, consumption etc. Driven by the state obligation of Article 20a GG, this legislation must ensure a future development allowing the exercise of freedom, albeit increasingly on CO_2-free alternatives of action.[29]

The court stated that the beformentioned "advance interference-like effect" of the federal climate protection provisions on basic freedom rights requires a "constitutional justification". A precondition for this justification is that the provisions on the emission amounts do not lead to disproportionate burdens placed on the future freedom of the complainants. It is the legislator's responsibility on its way to climate neutrality today to set up a legal framework not fostering a strongly CO_2-oriented lifestyle further on for the present generation at the price of continence for future generations facing severe freedom restrictions against the background of a nearly expleted residual CO_2-budget.

Regarding these constitutional requirements, the Federal Constitutional Court finally ruled that the provisions of the Federal Climate Protection Act have an "*advance interference-like effect*" as comprehensive threats to the paintiffs' "*intertemporal guarantees of freedom*". These provisions would violate these fundamental freedom rights today by shifting the burdens of greenhouse gas reduction into the future and loading them upon future generations in a disproportional way. Therefore, the federal legislator violated its obligation rooting

[25] Para. 183 of the order.

[26] Para. 184 et seq. of the order.

[27] Para. 186 et seq. of the order.

[28] Para. 186 et seq. of the order.

[29] Para. 248 et seq. Of the order.

in the *principle of proportionality* to distribute the CO_2 reductions — as a constitutional duty deriving from Art. 20a GG – prospectively over time in a fair and transparent way considering the basic freedom rights carefully.[30]

Consequences of the court order

After the Federal Constitutional Court had declared that the provisions of the Federal Climate Protection Act lack a fair and transparent distribution of CO_2 emissions over time, it wasn't long until the federal legislator grew active. Its task was clear: The legislation had to be corrected in order to fulfill the legal duty to take precautions today in order to protect fundamental freedom rights after 2030. As a consequence from the court order, the altered law had to initiate a transition to climate neutrality early and transparently in order to enable the relevant economic and social sectors to plan ahead. This included — in shape of formal legislation and not merely on the basis of an executive ordinance — the previously lacking decreasing emission levels for the time after 2030 depending on each sector.[31]

The federal legislator also exacerbated the CO_2 emission aims for Germany in the Climate Protection Act: With its amendment already in August 2021, the German Federal Government enshrined in law the goal of achieving greenhouse gas neutrality by 2045. The current aim is to reduce CO_2 emissions by 65 % of the 1990 levels by 2030 and 88 % by 2040 — a very ambitious task for the new Minister of Economic Affairs and Climate Action from the Green Party after the elections in 2021 (Federal Ministry of Economic Affairs and Climate Action, 2022).

Summary and Outlook

The order of the German Federal Constutional Court from March 2021 on the Federal Climate Protection Act is in line with a growing number of other climate litigation cases especially during the last decade. Thus, it also reflects a trend to use the instrument of law to make the legislator sing the song of climate protection with a clearer voice. The Federal Constutional Court picked up the legitimate demands and complaints of the younger generation in the dilemma and crisis of climate change: The older generation has lived a heavily CO_2-oriented lifestyle for far too long. Politics and the law have sustained this way of producing and consuming for far too long as well, while also neglecting the fact that in truth we are exploiting our resources and emitting greenhouse gases in an excessive, unsustainable way — at the cost of younger, future generations. The German Federal Constutional Court — and this is a fascinating aspect of this court order — picked up these legitimate complaints and growing concerns of the civil society, here targeted at insufficient federal climate protection provisions, and poured them into a constitutional form, particularly with the figures of the "*advance interference-like effect*" and the "*intertemporal guarantees of freedom*". Combining these fundamental positions of constitutional law with the traditional "*principle of proportionality*", the road became clear for a substantial and successful action of the plaintiffs in court, considered legally affected in fundamental freedom rights by insufficient legislation.

With the court order from March 2021, the German Federal Constutional Court has taken a path which it probably can't leave or change substantially anymore. It is to be expected that further litigation is to come based on the "*intertemporal guarantees of freedom*" in cases where federal legislation apparently fails to tackle climate protection and global warming issues in a sufficient way. Indeed, this court decision is a milestone in Germany in making the constitutional duties of the legislator clear, as well as fundamental climate protection rights on constitutional grounds. Particularly if it should turn out that one or the other climate target is not met in nearer future, one does not need to be a prophet to foresee: A remarkable and likely growing part of the younger generation will not be willing to accept further failure on the legally required path to climate neutrality. We can be assured: More climate litigation is to come in Germany and likely in other countries, too.

An exciting question — not only for those studying or working in law — is whether this German court order may be transferred to the constitutional framework of other countries. This clearly depends on the system and structures of constitutional law in the relevant countries and the line of jurisdiction, probably often in case law, in their constitutional courts. An important aspect will also be whether domestic constitutional law offers a standing for proceeding at court for the plaintiffs by granting subjective legal claims and constitutional positions with regard to the climate protection issue. However, the decisive constitutional figures of the German court order, i.e. the "*advance interference-like effect*" and the "*intertemporal guarantees of freedom*", in conjunction with the traditional "*principle of proportionality*" are terms of a broad and overall range, which makes them possibly adaptable and manageable in other countries' constitutional law. The "*principle of proportionality*" is definitely a common constitutional principle for legislative, governmental and administrative measures in many countries. Furthermore the "Precautionary Principle" is an internationally accepted, prospective principle in environmental policies, particularly with a view to sustainability and future generations. All things considered, it does not seem so far-fetched that some of the Federal Constitiutional Court findings could be used in climate litigations outside of Germany. For the sake of sufficient climate protection legislation, it would be worth a try. Who knows, perhaps also in Brazil.

[30] Para. 243 et seq. of the order.

[31] See also Bodle and Sina (2021).

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