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Editorial

EDIÇÃO ESPECIAL: GESTÃO DE BACIAS HIDROGRÁFICAS

SPECIAL EDITION: RIVER BASINS MANAGEMENT

Caros leitores,

É com entusiasmo e satisfação que apresentamos esta edição da Revista Brasileira de Ciências Ambientais dedicada ao tema gestão de bacias hidrográficas. Este número é decorrente das discussões realizadas na III Conferência Participativa em Gestão de Reservatórios e Bacias Hidrográficas, ocorrida em 2019 no Centro de Tecnologia e Geociências da Universidade Federal de Pernambuco, ocasião em que foi lançado o livro *Gestão de bacias hidrográficas e sustentabilidade*, publicado pela Editora Manole. O evento reuniu pesquisadores e profissionais de diversas instituições e suscitou o debate em torno da necessidade de divulgação científica de pesquisas acadêmicas qualificadas sobre o tema. A partir de então, fez-se um esforço coletivo a fim de disponibilizar à comunidade acadêmica e aos profissionais que atuam na área uma edição especial com experiências que abordassem múltiplos aspectos da sustentabilidade em bacias hidrográficas.

Nessa perspectiva, as análises desenvolvidas nos artigos contemplados nesta edição partem do viés interdisciplinar e apresentam pesquisas de várias partes do país, formando um mosaico de experiências envolvendo os recursos hídricos e seus usos múltiplos. Considerando a bacia hidrográfica como unidade de planejamento e gestão, os textos discutem questões que transitam entre políticas ambientais, gestão integrada de recursos hídricos, governança, previsão de cenários considerando as mudanças climáticas, incluindo apresentações de estudo de casos. Não se pretende esgotar a temática, mas evidenciar o que tem sido produzido no âmbito das ciências ambientais, que pode contribuir na otimização dos trabalhos de instituições do poder público, de ensino e pesquisa, juntamente com organizações não governamentais.

Discutir essa questão de modo interdisciplinar, como nos propusemos a fazer, poderá trazer grandes avanços para as ciências ambientais e, particularmente, à gestão de recursos hídricos no contexto atual, em que caminhamos visando ao horizonte postulado pelos Objetivos de Desenvolvimento Sustentável propostos na Agenda 2030, estabelecida pela Organização das Nações Unidas em 2015. Nesse sentido, a ciência é basilar e tem muito a contribuir.

Desejamos a todos proveitosa leitura,

Maria do Carmo Sobral
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THE LOCAL DIMENSION IN WATER RESOURCES GOVERNANCE: THE EXPERIENCE OF INTER-MUNICIPAL CONSORTIA AND COMMITTEES ON RIVER BASINS

A DIMENSÃO LOCAL NA GOVERNANÇA DE RECURSOS HÍDRICOS: A EXPERIÊNCIA DOS CONSÓRCIOS INTERMUNICIPAIS E DE COMITÊS DE BACIAS HIDROGRÁFICAS

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ABSTRACT

Integrated water resources management is advancing in Brazil as decentralized and participatory governance gains more prominence. However, local actions need to be better understood since several public policies are effectively implemented at this level. The present article aims to present the current debate about the local dimension in water resources governance. The paper analyzes empirical cases of water resources management in semi-arid Brazil, based on the performance of inter-municipal consortia and São Francisco's River Basin Committee. Research shows that municipalities do not ignore the need to adopt new management models in response to their known financial and technical limitations. Cases of inter-municipal consortia and river basin committees have proven to be opportunities for greater visibility and action of local participants. Inter-municipal consortia assist in sanitation management, because they increase the access of municipalities to the services provided. On the other hand, dynamics of the river basin committee expanded the possibilities of participation of local actors, allowing the debate and shared decision-making. Nevertheless, identifying factors and strategies for the successful organization of local participation and cooperation in these new governance arrangements is needed.

Keywords: water resources governance; local level; inter-municipal consortia; river basin committees.

RESUMO

A gestão integrada de recursos hídricos no Brasil tem avançado à medida que se amplia a governança descentralizada e participativa. Contudo, há uma necessidade de melhor entendimento sobre a atuação do nível local, tendo em vista que é nesse nível que diversas políticas públicas são efetivamente implementadas. Nesse sentido, este artigo teve por objetivo apresentar o debate contemporâneo sobre o nível local em relação à governança de recursos hídricos no Brasil semiárido, com base no desempenho de consórcios intermunicipais e do comitê de bacia hidrográfica do rio São Francisco. A pesquisa demonstrou que os municípios não ignoram a necessidade de adotar novos modelos de gestão como resposta às suas conhecidas limitações financeiras e técnicas. Os casos dos consórcios intermunicipais e dos comitês de bacia têm se apresentado como oportunidades para maior visibilidade e atuação dos atores locais. Os consórcios intermunicipais têm auxiliado na gestão do saneamento conforme ampliam o acesso de municípios aos serviços prestados. Já a dinâmica do comitê de bacia hidrográfica tem aumentado as possibilidades de participação de atores que atuam em nível local na mesma arena, possibilitando o debate e a tomada de decisão compartilhada. Porém, evidencia-se uma clara necessidade de identificar fatores e estratégias que possibilitem uma organização bem-sucedida de participação e cooperação de níveis locais nesses novos arranjos de governança.

Palavras-chave: governança de recursos hídricos; nível local; consórcios intermunicipais; comitês de bacias hidrográficas.

INTRODUCTION

The last two decades were marked by intense global and institutional changes in regulatory frameworks of water resources (CONCA, 2006). Efforts for the implementation of systems inspired on principles of integrated water resources management (IWRM), both in developed and developing countries, led to the creation of a plethora of new institutions for water resources management (WOODHOUSE; MULLER, 2017). The creation of national and state regulatory agencies, as well as river basin committees, was an important institutional innovation for the governance model adopted in Brazil (ABERS; KECK, 2013).

Academic literature has extensively analyzed the processes of implementation and operation of these new institutions in different international, national, and regional contexts. A quick search on Google Scholar shows, for instance, that 16 academic papers with the term *water governance* were published in 1999. In 2018, 4,080 individual articles including the term were published, with an annual average of 1,469 publications during this period. As a result of this growth, methodological and conceptual approaches, as well as the levels of analysis used, were diversified.

Despite this diversity, some topics are recurrent. The first is the description and analysis of how water resources governance is organized. How are conflicts resolved and how are interests between countries (in the case of cross-border water resources), between different political-administrative entities of the same country (for instance, between central government and states or between municipalities of the same state), between productive sectors and consumers, and between technical and political bodies coordinated? What system of governance is more inclusive and considers the greatest number of voices? How is the process of consolidation of new instances created to manage water resources? These are some of the questions posed in this first topic. The second recurrent discussion is the prescriptive and normative debate on governance. Whereas the first theme has a more descriptive nature, seeking to understand the workings of governance bodies and actors, this second discussion addresses the characteristics of "good" governance, which objectives it should prioritize, and the best ways to reach these goals.

The interaction between these two — completely intertwined — approaches and the knowledge produced by the analysis of numerous cases have gradually led to a consensus: the importance of the local level for understanding the organization of water resources governance (MANCILLA-GARCÍA *et al*., 2019; SHARMA-WALLACE; VELARDE; WREFORD, 2018; WHALEY; CLEAVER, 2017). The local level does not have a self-evident meaning. It can involve political-administrative units, such as municipalities, or even smaller areas, like neighborhoods or communities of a municipality. As a space, the local level also has no natural representation since it encompasses a great variety of actors. Municipal administrators, rural producers, companies, and neighborhood associations are examples of local actors. Simultaneously, settings with high population density and urbanization exponentially increase the local complexity level. In other words, the governance of large metropolitan areas is much more elaborate than that of small rural municipalities.

The growing interest in the local dimension results from the fact that the policies formulated in higher political and administrative spheres, such as federal and state governments, are effectively implemented at the local level. Therefore, systematic and detailed analyses of local dynamics are crucial to understanding the reasons for the success or failure of governance models. In Brazil, for instance, although municipalities are not directly responsible for the management of river basins, they oversee water supply, and sewage collection and treatment, in addition to being the main regulators of local land use – with direct impact on existing water resources.

Moreover, Goal 6 of the United Nations 2030 Agenda for Sustainable Development (UN, 2015) defends the need to "Ensure availability and sustainable management of water and sanitation for all", with one of its targets declaring the importance of supporting and strengthening the participation of local communities in improving water and sanitation management. In this perspective, local governance becomes paramount, and its improvement, an urgent demand.

According to Philippi Jr., Sobral and Carvalho (2019), reaching the targets of Goal 6 and having instruments for environmental and water resources planning require the creation of governance structures that will lead the implementation of the 2030 Agenda throughout the national territory at the river basin level.

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In Brazil, different governance arrangements involving the local level can operationalize the IWRM. In this regard, the present paper aims to present and analyze the current debate about the local dimension in water resources governance, based on the characterization developed by Hooghe and Marks (2003), detailed in the following topic. After a literature discussion, the study assesses the performance of inter-municipal consortia in providing sanitation services and of São Francisco River Basin Committee (*Comitê da Bacia Hidrográfica do Rio São Francisco* — CBHSF). We chose these examples because they detail how the local level can have a differentiated role in water resources management. In conclusion, municipal performance has some gaps, and these local actors need to be consistently engaged. We also suggest the development of some lines of research on the relation between the local dimension and water resources governance in Brazil.

TYPES OF GOVERNANCE AND THE LOCAL LEVEL

The multifaceted debate on water resources governance reflects the existing diversity in the broader theoretical debate on governance. Ansell and Torfing (2016) discuss, for instance, the different disciplinary backgrounds of the concept. Therefore, a necessary first step is to define the concept of what governance is. In general, when it comes to public policies, governance can be defined as a set of rules that determines which organizations will manage one or several policies/programs in a specific jurisdiction.

Le Galès (2004) defines governance as the process of coordinating actors, social groups, and institutions to achieve goals defined and discussed collectively. Governance refers to a set of institutions, networks, policies, regulations, standards, and political and social practices, as well as public and private actors, which contribute to the stability of a society and political regime, its orientation, its ability to manage and provide services, and its capacity of ensuring its very legitimacy.

Jacobi and Spínola (2019) declare that the concept of governance focuses on the notion of social power, which measures the relations between the State and civil society as a space to build alliances and cooperation. The authors report that governance can be understood as a strategy that stresses the need for social participation in political-decision processes, decentralization of power, and compilation of many interests, goals, and values for common good.

The binary typology developed by Hooghe and Marks (2003) is quite informative in illustrating these definitions (Table 1). According to these authors, Type I governance is inspired by a traditional federal model, in which clearly established geographical jurisdictions are responsible for a combination of programs and public policies (*general-purpose jurisdictions*). Brazilian federalism would be a typical example of Type I governance, in which federal government encompasses state administrations, which, in turn, include municipal administrations, with well-defined geographical boundaries. At the same time, these government spheres — despite having exclusive competence in many cases — are responsible for the management of programs related to different areas. Water resources management is just one of the tasks under the control of these jurisdictions.

Table 1 – Types of governance and their main characteristics.

	Type I	Type II
Geographical coverage	Defined	Fluid
Criteria for membership and participation	Clearly defined and compulsory (e.g., citizenship)	Flexible and voluntary
Thematic jurisdiction	Multiple	Specific
Diversity of interests	High	Low

Source: adapted from Hooghe and Marks (2003).

In contrast to Type I, Type II model is characterized by a thematic focus and a geographical jurisdiction that is more fluid or intersects pre-existing jurisdictions. In the international context, many river basin committees created with the dissemination of IWRM principles are examples of Type II governance. Given that river basins do not usually respect the geographical boundaries of states and municipalities (or countries), governance solely based on state and municipal administrations, typical of Type I model, has clear limitations. The need to coordinate the interests of different actors scattered over various political-administrative jurisdictions is better fulfilled by a new institution. Therefore, river basin committees provide these actors with a specific jurisdiction for coordinating their interests as to the use of water resources.

An important debate about these typologies is the one involving the participation of citizens and organized groups — mainly in democratic societies. In Type I governance, the most common and explicit form of participation is the election of and interaction with local politicians, whereas the form of participation in Type II models tends to be less evident. Considering these organizations have a specific purpose, they usually attract only actors interested in the subject. As a result, whereas Type I models have clear membership criteria (*e.g.*, individuals living in a jurisdiction), the participation and representation criteria in Type II models are often more nuanced. When observing the constitution of Brazilian river basin committees, a complex effort to include representatives from different interested groups can be identified. Public sectors (municipal, state, and federal), civil society, and user representatives are mandatory. Nonetheless, the profile of civil society and user representatives changes drastically from one committee to another, as does the internal dynamics of each committee (ABERS; KECK, 2013).

Given that the civic participation and engagement of individuals are quite heterogeneous during the elections and in the interaction with politicians, the mere possibility of participation in new arenas and institutions does not automatically lead to effective participation (COHEN; DAVIDSON, 2011). Type II organizations, like committees, can be easily seized by specific organized interests, such as those of large companies or even of environmental groups that oppose the interests of users in increasing the water supply coverage (BRANNSTROM, 2004). However, national government interests are usually more predominant in these instances (EMPINOTTI, 2011).

A second better-understood debate based on these typologies addresses the thematic scope and territorial scale under the responsibility of a jurisdiction. Type II governance models are specialized in one area to overcome the difficulty of Type I models in providing satisfactory coordination in contexts of multiple priorities. If we look beyond the issue of water resources, authorities or regional committees that manage public transport and solid waste collection or establish quality criteria for certain products are examples of Type II models that are more effective than traditional Type I models. However, specific issues managed by Type II organizations can easily prove to be complex, leading to pressures for expanding the scope of work of these organizations.

Conceptually, a gradual transformation of Type II models into reformed Type I versions is possible by redefining new geographical jurisdictions with the growth of their specific original purposes. As to the issue of water resources management, river basin committees could slowly increase their responsibilities to manage a series of policies that directly affect the availability and quality of water resources in an area. Topics such as sanitation, urban zoning, collection and processing of solid waste, economic development, environmental regulation, among many other related themes, could be easily included in the jurisdiction of a river basin committee. After all, everything is connected to water. As a result, the normative conceptual debate on water resources governance has started to think about the *nexus* among different sectors, instead of focusing on activities that affect water resources. According to Benson; Gain; Rouillard (2015), the argument in favor of the concept of *nexus* is to consider the management of resources and economic activities holistically to achieve systemic sustainability more easily.

In practical terms, however, this scenario usually leads to a new coordination problem, because the effectiveness of a Type II organization requires the commitment of Type I organizations. In other words, due to the huge legal and organizational barriers involving the expansion of the scope of work of a Type II organization dealing with complex issues, they need to coordinate their activities with Type I organizations, forming a cross-governance. The example of Brazilian river basin committees can be used once more. Even in committees that are working effectively, a vast number of issues that directly affect the water resources of a region are managed by states and municipalities. For instance, important issues such as urban zoning (especially in river banks), standards of construction, water supply, and sewage collection and treatment are under the responsibility of municipalities. As a result, Type II governance arrangements are often incorporated into Type I arrangements.

This responsibility for different areas, essential for a holistic approach to environmental issues, puts municipalities in a privileged position. In the current debate, municipalities are identified as one of the main potential innovation hubs for environmental policy and for facing the challenges posed by climate change (FUHR; HICKMAN; KERN, 2018). Besides that, municipalities are intersection points between Type I and Type II governance models, acting as possible bridges between them (BETSILL; BULKELEY, 2004; ANDONOVA; HALE; ROGER, 2017). Nevertheless, this advantage is, at the same time, a disadvantage, since diverging priorities and pressures at the local level often create incentives to prevent the adoption of holistic strategies. Another typical disadvantage of municipalities is their financial and human resource limitations due to their subordinate political-administrative position in national States. In any case, the success of river basin committees — or any other Type II arrangement — in the sustainable management of water resources is, therefore, directly connected to the success of municipalities.

Hooghe and Marks (2003) emphasize that Type I and Type II governance are suitable for different issues, and coexist because they are complementary. A result is the variable number of independent and operationally differentiated Type II jurisdictions, alongside a more stable number of general Type I jurisdictions.

DIVERSITY OF LOCAL ARRANGEMENT

One of the greatest inventions that have enabled the development of modern science was the microscope, built by the Dutch merchant Anton van Leeuwenhoek, known as the father of microbiology, in the 17th century. Studies based on his invention revealed to the world aspects of the physical and biological world until then belonging only to the realm of fantasy. If the previous section has helped us understand the tensions between Type I and Type II governance models and the central role of low-scale political-administrative units like municipalities, we must now adjust the focus of our analysis, just as with a microscope, to grasp better the dynamics inherent to this scale.

Analytically, we should bear in mind that municipalities can be regarded both as spaces/arenas for interaction between different actors, and as agents acting in governance systems.

This distinction becomes evident when considering the enormous socio-spatial heterogeneity existing in the universe of municipalities. In Brazil, for instance, when we speak of municipalities, both megalopolises such as São Paulo and its more than 12 million inhabitants, and the small Serra da Saudade in Minas Gerais State, with less than 800 residents, can be addressed. The scale and complexity of challenges faced in metropolises with millions of inhabitants are, doubtlessly, greater than those of small- and medium-sized cities. In large cities, historical patterns of urbanization and economic activity lead to different socio-spatial settings. Brazilian metropolises, in particular, have socioeconomic inequalities and processes of reconfiguration of the capitalist system that clearly shape the urban infrastructure, interacting with organizational capacities and patterns of relationship with the public sector, and directly affecting the priorities of residents from different regions of the same city (ROLNIK, 2015).

This internal heterogeneity of large cities represents a unique source of studies on local factors that affect the implementation of programs and public policies in both Type I and Type II governance contexts. The comparison between different sub-regions or neighborhoods of a large city allows an easier identification of the elements that influence the success or failure of policies or programs. A recent example of this potential is given by Silva-Sánchez and Jacobi (2016) in their analysis of satisfaction with linear parks, adopted as a strategy to recover urban rivers in São Paulo City. After evaluating data from interviews with municipal authorities and local community leaders involved in implementing the 16 linear parks in the city, the authors listed a series of factors that contributed to greater or lesser satisfaction with these new parks, such as local infrastructure, community organization, urban and environmental laws, competence of local administrators, among others. A limitation of the study, however, was not systematizing these differences to identify the conditions needed for a high level of satisfaction.

Although more evident, the heterogeneity of local dynamics is not exclusive to large municipalities. Small- and medium-sized municipalities, including those with more rural characteristics, are also marked by internal differences that affect the implementation of programs. For instance, Cooperman (2019) shows how even small municipalities in the inland of Ceará State present a huge diversity in water supply between rural communities only a few kilometers apart. According to the author, this difference reflects a historical pattern of local community organization, in which better-organized communities with stable leadership can coordinate their votes and elect politicians committed to the operation of the water supply system. Contrary to a purely clientelistic logic, the author reveals that organized communities often punish incompetent politicians by voting for other candidates. The perverse effect of this dynamic, however, is the persistence of precarious water supply conditions in less organized areas. This dynamic is not particular to Brazil. Carlitz (2017) investigated processes of decentralization of investments in water supply in Tanzania, and identified that communities with stronger organization and contacts with local politicians had better services.

Regarding municipalities as arenas allows a better perspective of potentials (and limitations) of civil society at the local level. As the studies mentioned above show, the organizational capacity of communities or neighborhoods is a determining factor for the success of policies and, consequently, of both Type I and Type II governance models. Understanding how this capacity is organized in each context is essential.

From the point of view of governance models, municipalities are also important actors, usually associated to their local administrations. Many of the governance systems classified by Hooghe and Marks (2003) as Type II are organized by municipal administrations. Recent studies show how global metropolises are leading transnational initiatives to combat climate change, or how large cities are coordinating metropolitan areas to provide public services of common interest. Administrations of small- and medium-sized cities are also potential catalysts of regional processes, such as planning water resources management of river basins crossing the borders of several municipalities (OLIVEIRA-ANDREOLI *et al*., 2019).

Data from the Organisation for Economic Co-operation and Development (OECD, 2015) indicate that the level of participation of municipalities in water resources collegial bodies depends on local conditions, the importance given to water issues, the motivation of mayors and collaborators, and the specific interests at stake. In general, this level of participation is considered low.

Thus, if on the one hand, understanding the central role and possible actions of municipal administrations in alternative Type II governance models is important, on the other hand, identifying the reasons for failures and inaction is equally relevant. Whereas the fragility of local civil society and the incompetence of municipal administrations are often indicated as reasons for the lack of effective public policies, numerous tasks under the responsibility of municipalities create practical difficulties for their implementation. The lack of trained staff and financial resources leads to a significant discrepancy between expectations and the ability to deliver results. In this regard, finding specific mechanisms that can facilitate or hinder the implementation of programs requires a systematic comparison between success and failure cases. If discussions on more comprehensive governance levels usually detect structural barriers to be addressed in the long term, local analyses produce precise diagnoses more easily and with greater potential for replication in other local contexts. Particularly in our case, Type II governance models can be considered options for the limited municipal participation in Type I models. The next section will illustrate this potential for water resources management.

PATHS FOR LOCAL ACTION IN WATER RESOURCES MANAGEMENT: EXPERIENCES OF INTER-MUNICIPAL CONSORTIA AND RIVER BASIN COMMITTEES

The formulation and implementation of water resources policies are, by nature, highly fragmented, and involve a multitude of interested parties and authorities from different levels of government and political areas (OECD, 2015). Several governance arrangements, with varying degrees of local leadership, are possible in water resources management. According to Philippi Jr., Sobral and Carvalho (2019), governance is a mechanism of democratization and advancement of shared management, mitigating conflicts between the multiple users spread over the different geographical jurisdictions present in a river basin. For municipal administrations, governance arrangements different from the traditional hierarchy of Type I models also allow economies of scale in administrative and financial terms.

In this context, this section intends to present cases of different types of organizations with Type II governance that municipal administrations can use for water resources management: inter-municipal consortia and river basin committees. Both cases deal with organizational arrangements that attempt to make water resources management feasible, be it by focusing on the power of municipalities or by favoring several instances of local power and decision-making. These analyses can help us understand the difficulties and potentials of local governance in Brazil.

Inter-municipal consortia for water resources management

With the process of decentralization of public policies started with the redemocratization of the country, a known challenge in Brazilian cities lies in providing the numerous services under their responsibility. Especially in small- and medium-sized cities, the scarcity of financial and human resources created opportunities for the establishment of new forms of governance. A model designed to try alleviating these deficiencies was the inter-municipal consortium. Originally developed in the 1980s for the health sector, consortium is a type of formal cooperation between municipalities from the same region to provide a service (RIBEIRO; COSTA, 2000; CUNHA, 2014). In general, its function is to share the cost of services provided while generating financial and administrative resources for investments that could not be done by any participant alone. Thus, inter-municipal health consortia can be considered Type II organizations voluntarily coordinated by municipalities.

The relative success of this governance model can be seen in its dissemination beyond the provision of health services. Currently, inter-municipal consortia are established in the most diverse fields of activity, especially those related to environmental and water resources management. Sanitation and environmental licensing services are some of the thematic areas linked to the creation of consortia, and they show a huge growth potential (CARDOSO; CARVALHO, 2016). Recognizing the interrelation between these themes, we can observe a recent expansion in the scope of work of existing consortia or the construction of new multi-purpose ones, focused on the development of collective sustainable strategies. The process of creating these consortia also presented different catalysts. In some cases, they result from bottom-up dynamics, in which municipalities take initiative in the process, just like in the case of consortia in the north of Minas Gerais State; in others, state governments encourage the implementation of these organizations, just like in the case in Bahia State.

The National Water Agency (*Agência Nacional das Águas* — ANA, 2019c) highlights that the feasibility of shared options usually requires coordinated actions of greater technical, institutional, economic, and environmental complexity. Therefore, the public sector has a strategic role in the organization of these actions, and in the integrated analysis of the effects and benefits of interventions. However, as demonstrated previously, Type I governance models, such as municipal governments, have several kinds of limitations. In the case of inter-municipal consortia, the collective municipal management attempts to mitigate the issue of financial shortage. This fact emphasizes the need to rethink the federative pact, taking into account the multiple uses of water, since many public services of common interest, such as those related to environmental sanitation, are under municipal jurisdiction, as declared Philippi Jr., Sobral and Carvalho (2019).

Nonetheless, after analyzing data from the Survey of Basic Municipal Information (*Pesquisa de Informações Básicas Municipais* — MUNIC), conducted by the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística* — IBGE) in 2017, we found that the percentage of Brazilian municipalities that participate in inter-municipal public consortia in areas related to water resources management is still relatively small (Table 2). Particularly with respect to sewage, the use of consortia is incipient, reflecting the general precarious situation of the country and the scarcity of financial resources for the infrastruc-

Table 2 – Percentage of municipalities participating in public consortia according to the field of activity.

	Water Supply (%)	Sewage (%)	Solid Waste Management (%)
Brazil	12.8	8.3	22.6
North	7.8	4.2	11.1
Northeast	9.2	4.7	26.6
Alagoas State	4.9	1.0	51
Bahia State	12.7	8.6	18.2
Ceará State	7.6	7.1	41.8
Maranhão State	6.5	2.3	4.1
Paraíba State	3.6	3.1	32.7
Pernambuco State	21.1	8.1	36.8
Piauí State	5.4	5.4	1.8
Rio Grande do Norte State	9.0	4.2	36
Sergipe State	6.7	1.3	76
Southeast	13.6	11.2	20.4
South	20.2	11.5	22.1
Midwest	9.6	7.7	27

ture projects needed. Inter-municipal consortia for solid waste management — an area directly related to the quality of water resources — have become more widespread. Although some of them are expanding their scope to include environmental management and urban planning themes, many seem to be limited to waste collection and landfill management. This scenario possibly results from the requirements provided in the National Solid Waste Policy, established by Federal Law No. 12.305/2010 (BRASIL, 2010).

When we assess the distribution of these consortia between states of the same region, such as the Northeastern, we can easily identify a great heterogeneity. Whereas states such as Maranhão and Piauí have practically no inter-municipal consortia, Pernambuco shows the highest percentage of municipalities with water supply consortia. In general, however, solid waste management is the main issue that mobilized these municipalities due to the sharing of costs and infrastructure for collection and final disposal.

As shown by Hooghe and Marks (2003), Type II governance models, which match the profile of inter-municipal consortia, have among their characteristics a flexible design and the possibility of acting in specific jurisdictions with certain themes or activities. In this case, there can be a very fluid institutional arrangement to facilitate sanitation services, according to the interests and financial investment availability of the parties.

Interest in academic research on inter-municipal consortia is in solid development, mainly for the several decentralization efforts promoted in European countries in recent decades. A volume organized by Hulst and van Montfort (2007) analyzes various experiences of inter-municipal cooperation in European countries. The obvious difficulty in comparing these experiences lies in the different legal and institutional frameworks of each country, which directly shape the possible format of these local governance arrangements. Typical governance challenges, such as building effectiveness and legitimacy, are the most frequent diagnoses, especially in countries with weak traditions in autonomy and local cooperation (SILVA; TELES; FERREIRA, 2018). Nonetheless, analyses of waste collection and sewage treatment services carried out in European countries suggest that these inter-municipal cooperative arrangements are effective ways of improving coverage and reducing operational costs (SOUKOPOVÁ; VACEKOVÁ, 2018).

In Brazil, OECD data (2015) underline the performance of inter-municipal consortia for water resources management in Paraná State by means of "decentralized executive units" (*unidades executivas descentralizadas* — UEDs), which have executive power and responsibilities intrinsic to river basin agencies. Paraná shows an alternative governance model precisely because of the prominent role given to users and municipalities.

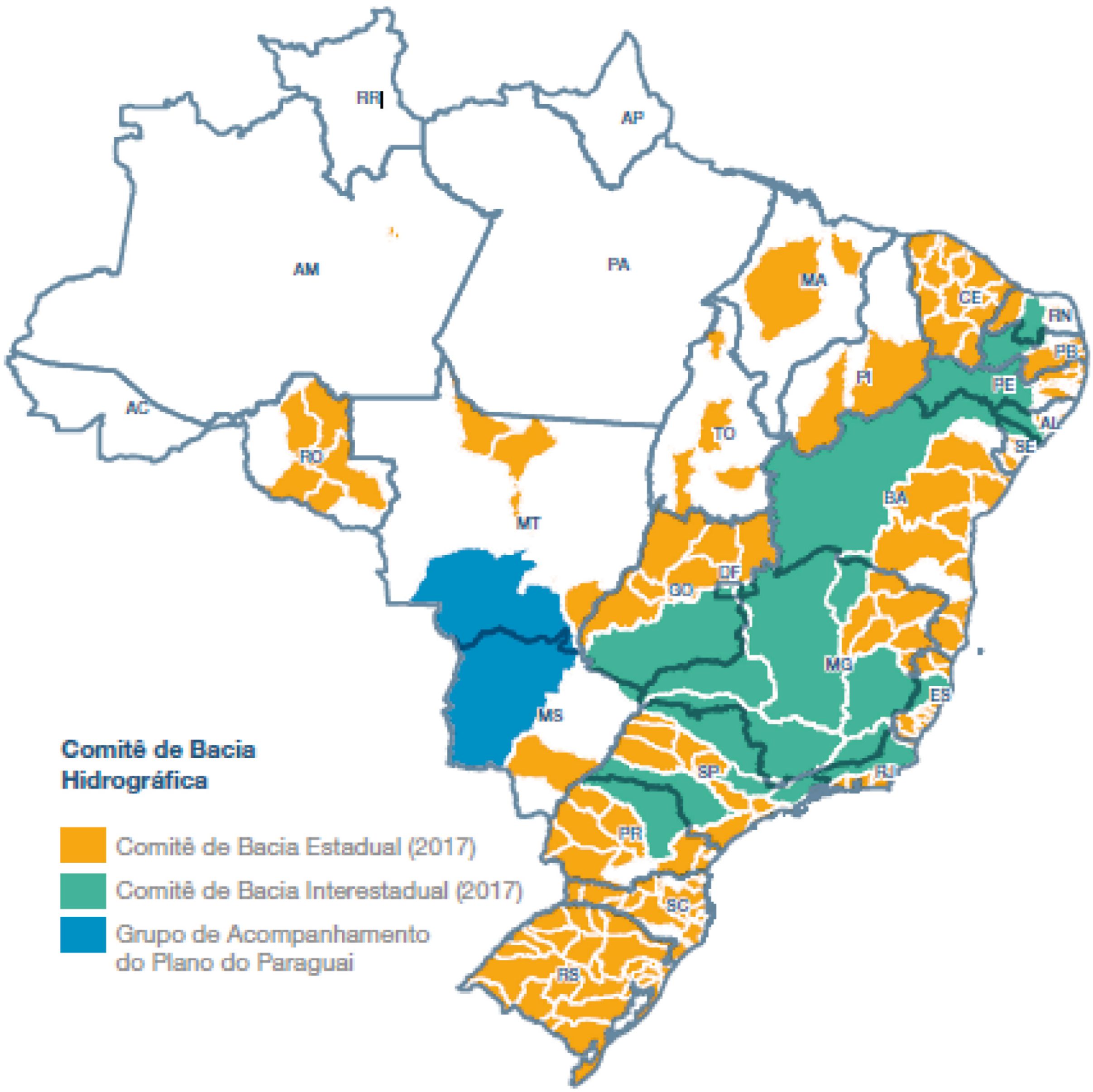
In Brazil, understanding the factors that contribute to the success (or lack thereof) and influence the performance of these arrangements is still limited. Whereas existing studies focus on metropolitan areas (MEZA *et al*., 2019), very little is known about inter-municipal consortia in small- and medium-sized cities. With the gradual increase in these governance models for the provision of services related to water resources, there is a huge research agenda to be developed.

River basin committees for water resources management

The establishment of the National Water Resources Policy in 1997 represented progress both in the conceptual sense and in the institutionalization of an integrated, participatory, and decentralized management, based on the integration among management bodies, users, and other institutions in river basin committees (SOBRAL *et al*., 2017). However, even though legislation addressed the space for expansion of social participation in IWRM, ANA data (2019b) indicate that the fulfillment of the Goal 6 target referring to the *proportion of local administrative units with established policies and procedures aimed at local participation in water and sanitation management* is not satisfactory in Brazil, because it corresponded to 49% in 2017. This low percentage reflects the challenges and difficulties of the institutionalization of Type II governance models when made from top-down on a national scale. The mere creation of governance spaces does not automatically generate engagement, decision-making and organizational best practices of the actors involved. Just like Abers and Keck (2013) argue, the institutionalization of river basin committees has yielded very heterogeneous results, particularly regarding the participation of municipalities.

According to ANA (2011), river basin committees are collegial bodies formed by the public sector, representatives of users and civil society with regulatory, deliberative, and advisory power in the river basin of their jurisdiction. This context automatically leads to the creation of groups with distinct constitutions, practicing not only the interdisciplinarity but also the interinstitutionality of water resources management. River basin committee is a discussion forum that decides on issues related to water resources management of a specific river basin (ANA, 2019a). According to Philippi Jr., Sobral and Carvalho (2019), water resources management occurs at the federal level in river basins that cross state and national borders, and at the state level in river basins belonging to only one state. No specific institutional structure has been established at the municipal level; municipalities only have a representative role in river basins committees. This fact makes the activities of the committee and its representation even more relevant, because it is one of the only structures that guarantee municipal participation. Besides that, the committee structure allows the participation of bodies that are even more local, such as user associations, cooperatives, among others. This Type II governance model arrangement poses many challenges precisely because it places actors from different origins and interests in the same debate arena.

On the other hand, the more "local" role of the committee as an advisory and deliberative body is extremely complex, given the diverse interests and representation of its members. Until 2018, Brazil had 235 river basin committees — 10 federal committees (inter-state) and 225 state committees (Figure 1).



Source: ANA (2019b).

Figure 1 – River basin committees in Brazil.

Although late, the inherent difficulties of institutionalizing a complex Type II governance system, such as river basin committees, were recognized and inspired federal actions. In 2016, the National Program for Strengthening River Basin Committees (*Programa Nacional de Fortalecimento dos Comitês de Bacias Hidrográficas* — PROCOMITÊS) was created to support state committees operationally and institutionally by providing financial aid for their operation (ANA, 2019a). This action aims to cover the lack of financial resources whose nature is usually voluntary in Type II organizations.

CBHSF illustrates governance with committees, with a significant role in semi-arid Brazil.

Experience of São Francisco River Basin Committee

São Francisco river basin covers part of six states (Alagoas, Bahia, Goiás, Minas Gerais, Pernambuco, and Sergipe) and the Federal District, crosses 507 municipalities, and has a drainage area of 639,219 km², which corresponds to 8% of the country's territory. Its main river — São Francisco — is 2,863 km long (CBHSF, 2019). Among its multiple uses, water supply for the population, irrigation, power generation, mining, fishing, and navigation are highlighted.

Created in 2001, the committee operates with 62 members, divided among users, who represent 38.7% of the total members; the public sector (federal, state, and municipal), 32.2%; civil society, 25.8%; and traditional communities, 3.3% (CBHSF, 2019). The total number of members per representation is defined in the internal rules of CBHSF (CBHSF Deliberation No. 106/2019), as shown in the Figure 2.

National representatives correspond to the institutions:

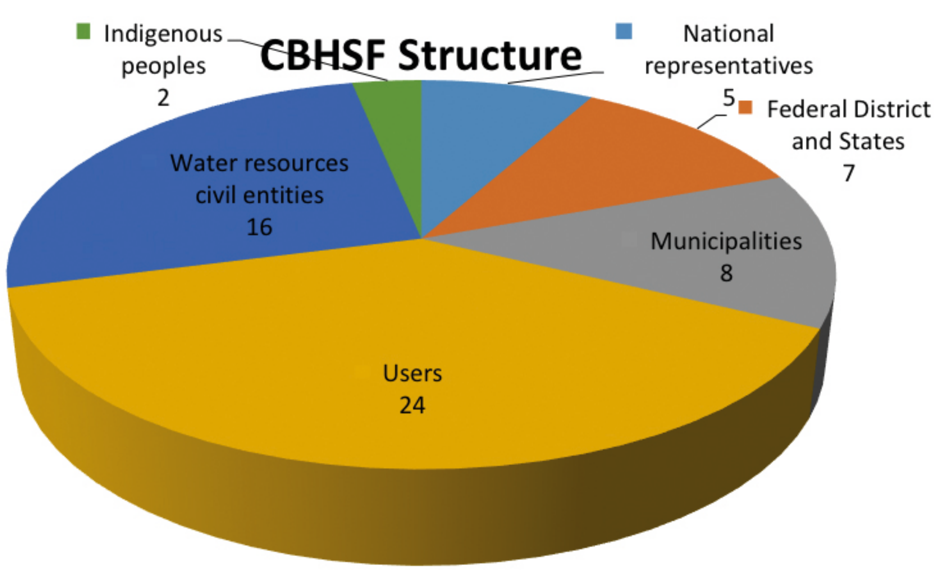
- Ministry of the Environment;
- Ministry of Regional Development;
- Ministry of Economy;
- Ministry of Mines and Energy;
- National Indian Foundation.

The Federal District and each of the six states that compose the basin have a seat on the Committee. The distribution of municipal representatives is:

- three for Minas Gerais;
- two for Bahia;
- one for Pernambuco;
- one for Alagoas;
- one for Sergipe.

Users of water resources of the basin have 24 representatives:

- six for urban water supply;
- five for industry, collection, and dilution of industrial and mining effluents;



Source: adapted from the CBHSF Deliberation No. 106/2019 (CBHSF, 2019).
Figure 2 – Structure of São Francisco River Basin Committee.

- six for irrigation and agriculture use;
- one for fluvial transport;
- four for fishing, tourism, and leisure activities;
- two for companies with concession or authorization to generate hydroelectric power.

The 16 representatives from water resources civil entities are:

- two for inter-municipal or user consortia and associations;
- five for technical organizations for education and research or other organizations;
- eight for non-governmental organizations;
- one for traditional *quilombola* communities (settlements with descendants of enslaved Africans), within the basin context.

The diversity of CBHSF participants is an attempt to ensure the balance in decisions and benefits to all areas, be it geographical or thematic. However, given the complexity and socio-environmental heterogeneity of the river basin, the committee's performance is often inefficient and does not meet the most urgent needs of the basin, favoring the wishes of groups of users. Rodorff *et al*. (2015) highlight that, despite the implementation of IWRM with the creation of a participatory committee, the challenging scenario for its establishment and operationalization is evident. In Brazil, legal framework and policy for water as a natural resource — primarily at the federal level, followed in greater detail by the state level — are implemented in municipalities, which have their own specificities, adopting the principle that water management and access to clean water are significant criteria at all levels. Bearing in mind that each of these levels has a web of interests of various multiusers, as well as the need to contemplate distinct social, economic, and institutional interests, according to a policy of social and economic growth, the challenge lies in providing transparency for each of these roles, and perceiving methods of strategic and tactical management.

This committee meets twice a year, besides the meetings of several technical chambers and four regional groups. Despite being a top-down participatory institution, the committee is a unique opportunity for the various interested parties to meet, exchange experiences, and build the foundations for a common understanding on water resources management (KÖPPEL; SIEGMUND-SCHULTZE, 2019).

The importance of tributary committees is also emphasized, which operate on an even more specific scale and can aid the committees of the broader geographical area to which they belong. In this perspective, research conducted by Souza Junior *et al*. (2017) on São Francisco river basin identified 44 water planning units for tributary rivers within the region of São Francisco, of which 26 — a little over 59% of the existing units — have no committee representation. The authors also underline the lack of guarantees that all implemented committees are representative and active.

Nonetheless, CBHSF recognized the central role of municipal administrations for a successful river basin management. In recent years, for instance, CBHSF funded the elaboration of sanitation plans in 63 of the 270 municipalities that comprise São Francisco river basin. In addition to providing information for municipal administrations to identify priority areas for action, the preparation of these plans is essential for municipalities to obtain federal resources for investing in water supply and a network for sewage collection. Thus, the interaction of a Type II organization with the structure of a Type I organization is clear, with municipalities as a common link.

Although considered a reasonably institutionalized committee with capacity for coordination, the studies cited above show the challenges that still exist for disseminating this governance model at the local level. An important reason for the difficulty in integrating municipalities in a more consistent way in these new multilevel governance structures is the predominance of interests of federal or state governments, often funders of local actions. Moreover, the lack of systematized knowledge about what makes some experiences and organizations successful and which of these elements can be replicated in other contexts are pointed out.

On the other hand, there is an understanding that the intense engagement of interested parties and the wide social mobilization must not overlap solid tech-

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nical knowledge and the exercise of public authority. The need to complement or even integrate bottom-up approaches with a top-down process to ensure the fulfillment of national targets and long-term goals is also known (OECD, 2015).

Empinotti (2011) emphasizes that participatory institutions require commitment and time to negotiate, besides mastering the technical language that prevails in this area. Even with dedication and effort in participating in discussions and arguments, many variables can neutralize the entire negotiation. In this regard, Ostrom (2011) declares the need for valuing the knowledge about realities of local governance structures and the trust among decision-makers, highlighting that these two attributes related to individual decisions are not often included in current analyses.

CONCLUSION

The present article aimed to present a brief and non-exhaustive summary of the current debate about water resources governance, stressing the importance given to the local level by the international literature. As argued, Brazil is no exception. Most challenges faced by water resources governance in Brazil require some level of action from municipal governments. Nonetheless, given that municipalities are multi-purpose districts, they need to split their scarce human and financial resources between other demands beyond the water issue. The main challenge for the new forms of governance created for water resources management is consistently engaging these local actors.

The role of the local level in water resources management, presented as committees and inter-municipal consortia — examples of Type II governance arrangements —, reveals the expansion of local representative action in the decision-making process. In consortia, municipalities are protagonists and collectively define their priorities. On the other hand, municipalities need a more effective way of increasing their participatory space in river basin committees. At the same time, in these spaces, the local level can have other representations. These participatory spaces demand greater governmental support to ensure their full operation and autonomy of action. In addition, the functioning of these bodies requires ongoing training for participants, as well as financial support.

The review of official and national literature data shows that municipalities do not ignore the need to adopt new management models in response to their known financial and technical limitations. Type II governance structures, such as inter-municipal consortia and river basin committees, are considered opportunities to meet these needs due to their flexibility, multilevel scale, and polycentric nature. However, the scarcity of knowledge of which factors and strategies can lead to the successful organization of local participation and cooperation in these new governance arrangements is evident. Identifying which factors are behind the success of inter-municipal consortia or better planning of water resource management by local governments is of utmost importance for the development of actions and programs that can encourage the replication of these effective cases. One way of overcoming criticism related to the *lack of political will* from municipal authorities is knowing the reasons for successful cases.

Engagement of municipal leaders is obviously crucial. So are financial resources. International literature shows that these two elements walk together. The availability of resources is a beacon for local authorities and a clear incentive for their engagement. However, as Termeer, Dewulf and Biesbroek (2017) state, an important element for the success of cases of adaptive changes related to climate change is the establishment of feasible and achievable goals, and action plans within a relatively short period. Namely, the elaboration of small projects, so municipal authorities can see concrete results faster, is an effective way of building trust and foundations for larger-scale projects.

Another aspect highlighted by the authors is the usual tendency of central authorities to dirigisme, resulting in an underestimation of local actors. Top-down processes, typical of Type I governance models, are also likely to occur in Type II models. Thus, river basin committees dominated by groups insensitive to the challenges experienced by local governments and their possible contributions to finding alternative solutions weaken the legitimacy and transformative potential of new governance models. In addition to institutional spaces, the communication between parties must be perceived as an effective dialog, rather than a monologue.

The recent Brazilian academic production is particularly valuable in identifying and describing the processes of institutionalization of new forms of water resources governance. Systematic comparisons focused on local experiences, such as tributary basin committees, are a still unexplored and rich source of knowledge. Further research in this field should consider that interdisciplinary analysis is essential. Attempting to broaden the theoretical and analytical concept to understand how local organizations work and change is a necessary step to improve water resources governance.

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ENVIRONMENTAL SUSTAINABILITY AND INTEGRATION IN WATER RESOURCES POLICY IN BRAZIL: INSEPARABLE ISSUES

SUSTENTABILIDADE AMBIENTAL E INTEGRAÇÃO NA POLÍTICA DE RECURSOS HÍDRICOS NO BRASIL: QUESTÕES INSEPARÁVEIS

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ABSTRACT

The article deals with factors considered to guide Brazil's water resources management policy, integration and articulation, aspects that are included in the legal basis of national policy (Law no. 9,433/1997; chapter III). It emphasizes the evaluation of the discussion of water policy and its interface with other sectorial policies. To understand the scope of the concepts of integration and articulation, and dialogue with practice, the perspectives of integrated management adopted by the Global Water Partnership, entitled "Integrated Water Resources Management", will be presented, as well as the one developed by the New Water Culture Foundation, associated with an ecosystem perspective. It evaluates how the issues of integration between policies and perspectives are taking place within the framework of the Brazilian National Water Resources Council, the central forum for discussions on the country's water policy. The systematization of data is based on the survey and analysis of the minutes and guidelines within the 20 years of existence of this Council. The minutes were systematized with the statistical Program R to evaluate the frequency of terms cited during the meetings. The themes of the agendas were organized into six major topics: rules of operation, management tools, integrated water management, sector articulations, environmental education, presentations. It became clear that the guidelines in greater numbers deal with the operating rules that aggregate administrative issues and general rules.

Keywords: integration of public policies; water resources governance; integrated water resources management; National Water Resources Council; water management tools.

RESUMO

O artigo trata de fatores considerados orientadores da política, da integração e da articulação da gestão de recursos hídricos do Brasil, aspectos que constam da base legal da política nacional (Lei nº 9.433/1997; capítulo III). Ele enfatiza a avaliação da discussão da política de água e sua interface com outras políticas setoriais. Para entender o alcance dos conceitos de integração e articulação, e dialogar com a prática, serão apresentadas as perspectivas da gestão integrada adotada pela Parceria Mundial da Água (Global Water Partnership), intitulada "Gerenciamento Integrado de Recursos Hídricos" (Integrated Water Resources Management), e também aquela fundamentada pela Fundação Nova Cultura da Água, quando trata da perspectiva ecossistêmica. Avalia-se como as questões da integração entre políticas e perspectivas estão ocorrendo no âmbito do Conselho Nacional de Recursos Hídricos brasileiro, fórum central das discussões da política de águas do país. A sistematização dos dados se apoia no levantamento e na análise das atas e pautas tratadas durante os 20 anos de existência do conselho. As atas foram analisadas com o Programa estatístico R para avaliar a frequência de termos citados durante as reuniões. Os temas das pautas foram organizados em seis grandes tópicos: regras de funcionamento, instrumentos de gestão, gestão integrada da água, articulações setoriais, educação ambiental e apresentações. Tornou-se claro que as o maior número de pautas versam sobre as regras de funcionamento que agregam questões administrativas e normas gerais.

Palavras-chave: integração de políticas públicas; governança de recursos hídricos; gestão compartilhada de recursos hídricos; Conselho Nacional de Recursos Hídricos; instrumentos de gestão da água.

INTRODUCTION

Theme, objective, procedures

The theme of this article is the analysis of the Brazilian water resources public policy, instituted by Law no. 9,433/1997 (BRASIL, 1997) on the issues of integration and articulation. This law has foundations, objectives, guidelines for action and technical and financial instruments to implement the policy through of the National Water Resources Management System, whose highest decision making body is the National Water Resources Council (Conselho Nacional de Recursos Hídricos — CNRH).

The focus of the article is on these two action guidelines, integration and articulation, defined in Chapter III of the Law nº 9,433/1977, considered strategic to the extent that water is the main element and transversal to various public policies, as it will be detailed below, as well as its management and consequent environmental sustainability, to comply with the aforementioned guidelines. We will conceptualize these two guidelines and investigate how they are approached within the CNRH. We will also explore the development of the management instruments provided by law.

Thus, the objectives of this article are, firstly, to present how these guidelines are expressed in the law and the concepts underlying them, taking as reference the literature on integrated management and the management models. Secondly, the focus is on the dynamics of the CNRH, characterizing its composition and the themes discussed. The guidelines and minutes of the 81 meetings held are the basic reference material, identifying those themes that had more emphasis over the 20 years, the frequency they were addressed, and the debate on management instruments and the relationship between water policy and other public policies. The text addresses how the integration and articulation guidelines are presented and which technical and financial instruments are given greater attention.

The theoretical framework is based on the approach concerning integrated management, formulated by the Global Water Partnership (GWP), and we also include the one developed by the New Water Culture Foundation (Fundación Nueva Cultura del Agua — FNCA). The GWP is an international umbrella organization that promotes network action in order to develop knowledge and expand capacity for water management at all levels — local, national, regional and global — and disseminates the concept of Integrated Water Resources Management (IWRM). The FNCA is an organization composed of Iberic professionals from various areas, who, based on scientific knowledge and social sensitivity, seek to promote changes in water policies emphasizing sustainability. For FNCA (2020), the ecosystem management model is also based on an integrated vision. Besides these two perspectives, we also include the water management paradigms identified by Allan (2003).

The theoretical aspects regarding integration and articulation are presented, as well as the outcomes of the research on the translation of these guidelines into effective action, having the CNRH as the scenario. The source material, the agenda and minutes of its activities, was systematized and analyzed as it follows. Initially, all the agendas of the 81 meetings of the CNRH held between 1998 and 2018 were collected and tabbed in order to identify a thematic pattern for the proposed agendas, taking as a guide the concern with integration and articulation and the management instruments. These agendas were read individually and organized and registered; repetitions were then checked, and a pattern was defined. Six recurrent themes were identified: rules of operation; management tools; integrated management (management without natural barriers, including fresh, brackish and saltwater, surface and underground, and factors that lead to commitment); sectorial articulations (articulation between public policies transversal to water); environmental education (activities aimed at training for the management and valorization of the resource) and other specific themes on strategic issues. This theme will be detailed below, and the tabulation presented in Table 1.

The second process developed with the issues addressed by the 81 minutes was through the R software, a statistical computing system that facilitates account for information and generates frequency graphs that, in this case, pointed out the frequency of strategic themes, previously determined by the researchers, and guided by the concerns of the research.

The themes previously determined to organize through the R system are environmental education, water management, management tools, environment, land-use planning, cross-border relations, sanitation, health, sectors involved in water management and management unit. They were chosen as they encompass both sectoral policies and the environment.

Problematization and legal basis

The terms "integration" and "articulation" are part of the general action guidelines of the Brazilian National Water Resources Policy. They are associated with environmental management and multiple uses of water, as well as its relation with the territory, estuarine and coastal zones. The term articulation is associated with the relationship between levels of federal entities, *i.e.*, the Union and the States (JACOBI 2009). From this emerges the first question that we seek to address: do integration and articulation occur? The second question, which derives from the first, aims to analyze whether the management instruments, which should theoretically guide policy action, are developed for this purpose and induce the intended integration. We are dealing with the instruments provided by law, such as the Water Resources Plans, the classification of water bodies into classes according to their predominant uses, the granting of the right to use water, the information system and the charging for water use.

As water is a cross-cutting theme in several areas and contemplated by other policies, as it will be presented below, we assess whether and how often discussions on other sectoral policies take place during CNRH meetings (JACOBI, 2009).

Fundamentals of integrated management and sustainability of development

According to Agudo (2009 p. 101), professor at the University of Zaragoza and one of the mentors of the FNCA, it is necessary to change our way of thinking: water management must be carried out from the perspective of the ecosystems, rivers and aquifers where they are inserted. It represents a much more complex approach than the predominant still being practiced today in several countries, as water is considered only in the river trough.

Ituarte (2003) highlights the concept of integration as fundamental to protect water and associated ecosystems. It characterizes the integration not only by the way water becomes available — be it surface or underground, by its quality or quantity — but also points to the need to integrate the subjects that through an articulated and interdisciplinary dialogue (JACOBI, 2009) with hydrology, hydraulics, ecology, chemistry, agronomy, economics, sociology and law, as well as with different approaches and experiences that improve the management process. The concept also involves cooperation and coordination between different sectors and levels of government (national, regional and local) and strengthens the premises regarding the integration of users and social groups that should participate in the decision-making process, in order to boost the social learning process (JACOBI; BUJAK; SOUZA, 2018; WALS, 2007) and thus lead to the implementation of commitments.

Still, according to Agudo (2015), management should be based on three ethical categories that relate water to life, citizenship and economy. First, water and life — concern the survival of all living beings, ecosystems and communities, as well as traditional forms of production, emphasizing the need to promote water sharing, as this is a principle that guides UN Resolution nº 16/02, that proclaims that water and sanitation are human rights. The second in importance and connected to the first relates water to citizenship and concerns the role of health and social cohesion, *i.e.*, the precautions and care of population linked to water supply services, collection and treatment of sewage. It also includes the characteristics of management that should bind the rights and duties of the citizenry through the implementation of participatory public management, a tariff system under control and social criteria that allow the financing of efficient universal services. Water linked to economic issues is a point related to productivity issues and the generation of benefits to improve the lives of users, which have to follow criteria of economic rationality. This category represents the water that is used and that generates problems related to pollution, and in which criteria of social and inter-territorial equity must be applied.

The concept of IWRM, a method developed between 1997 and 2000 and disseminated by the GWP, is to be considered. It is characterized as

> a process that seeks to promote coordinated development and management of water, soil and related resources in order to maximize social and economic welfare, also committed to the sustainability of ecosystems and the environment. Within the principles, it provides for broad participation of all social sectors, social equity, economic efficiency and ecological sustainability (GWP, 2019).

It should be noted that the concept of IWRM "was approved by the European Water Resources Directive, to realign its water management strategies at basin scale in all of its member countries" (RODORFF *et al*., 2015 *apud* MOLLE, 2008).

This management model breaks away with the hydraulic paradigm, emphasized by engineers until the early 1980s. Allan (2003) considers IWRM as a response to the inefficiency of old policies, and the approach recognizes competitive demands, such as that of irrigated agriculture versus environmental services, and the relationships between upstream and downstream properties of the same watercourse. The author also highlights that this is a political discursive process, and not just a planning process. This perspective seeks to consider within water management not only the environmental issues but also the economic ones, and its essential aspects for its allocation and management.

The process of allocation and management differs between countries due to social, political and economic constraints. Thus, North and South, from Allan's (2003) point of view, manage water under different perspectives and policies. Moreover, IWRM is subject to variations in terms of its incorporation, depending on its capacity to assume innovations, whether in conceptual or technological sense (ALLAN, 2003). Allan highlights the role of the Green Movement (decades of 1970/1980), which helped to raise awareness of water scarcity in society.

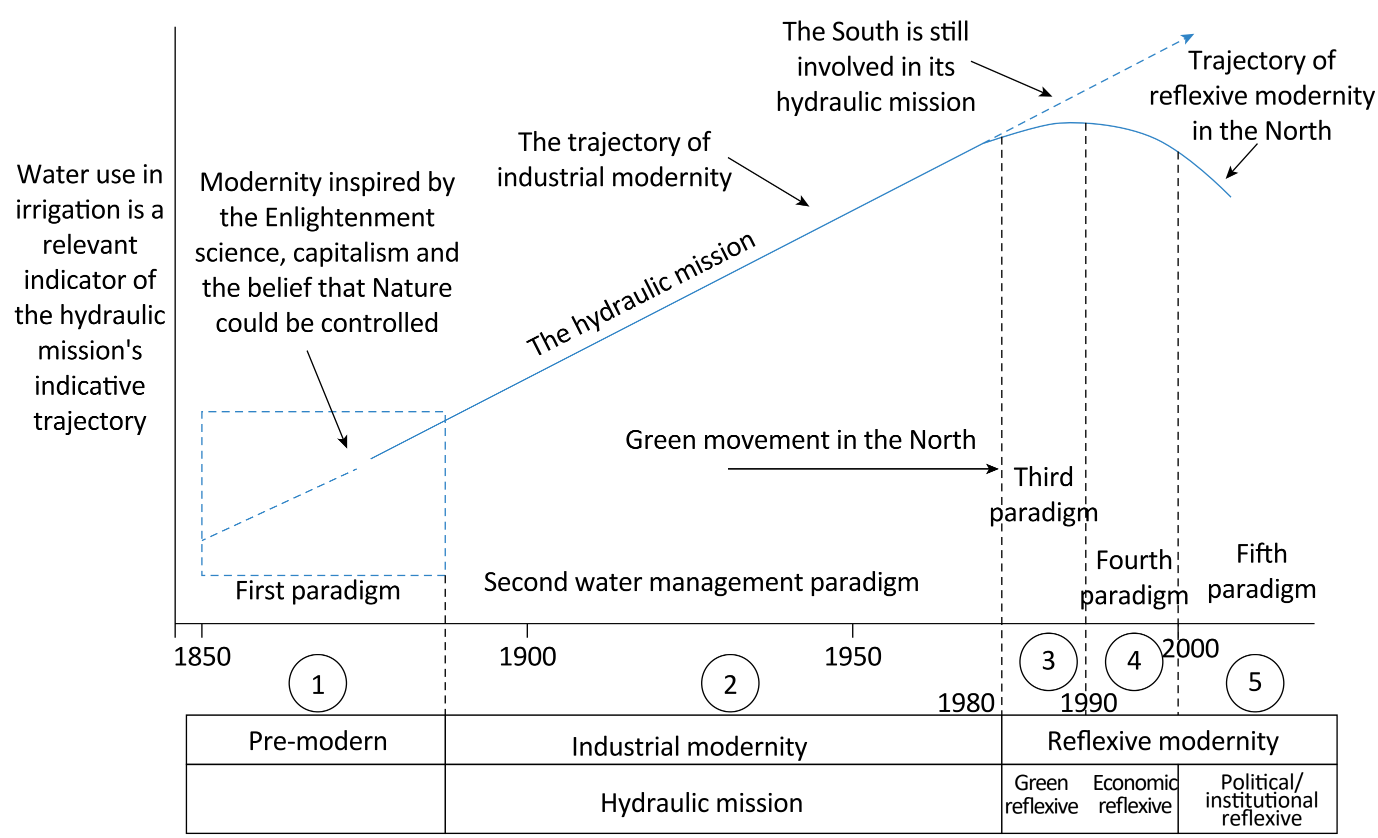
Allan presents a conceptual framework in which he shows the changes in water use trends for irrigation between 1850 and 2000, and defines five paradigms for water management, considering the technical and organizational capacity, which can be seen in Chart 1.

- Pre-modern (1850–1900): drinking water, food production, livelihoods. Low technical and organizational capacity;
- Industrial modernity (1900–1980): Hydraulic Mission (infinite water to meet demands; support in engineering works; low population and demand). Economic priority;
- Green reflective modernity (1980–1990): the risks are now considered. Valued environmental services;
- Reflective economic modernity (1990–2000): economic value. Charging for water use;
- Reflexive political and institutional modernity (2000–present): political process. Consider the demands of various sectors of society. IWRM model.

Brazilian policy is still partly based on the hydraulic paradigm (ALLAN, 2003), as it operates based on engineering works, with the construction of hydraulic works of great magnitudes, such as the transposition of the São Francisco River. The granting process is still carried out from the perspective of meeting demand and the assumption that water is infinite, not supply management, which is considered more ecologically and economically sustainable (PATO, 2013).

The policy proposes the valuation of water as an economic good, which can be charged — as may be assessed below, from the discussion of the issue in plenary sessions — and evaluates the risks of its poor quality or the effects of climate change on the general water dynamics since it is the point of argumentation at CNRH. However, it still needs to be guided by environmental concern and the maintenance of ecosystems.

When thinking about sustainability (ALLAN, 2003), the two main challenges of integrated water resources management are precisely sustainable development and intersectoral planning, which must be achieved through different approaches. For management, water should be thought of as a whole, not just like a river in its course, and should involve the participation of different stakeholders in the issue, from the most qualified — either technically or in government functions — to those affected by the problems. This has to be without necessarily having a specific qualification; moreover, among other strategic issues, water should be recognized as an economic good, and its equitable allocation should be emphasized.



Source: Allan, 2000.

Chart 1 – The five paradigms of water management (1850–2000).

Sectoral articulation: water in the various policies

Since this is a natural resource within the public domain, available on the surface of rivers, lakes or seas, or underground in aquifers, and must meet the multiple demands of society, the water resources policy, according to Law nº 9,433/97, aims to ensure that all social and economic demands are met by the water of adequate quality and quantity, and must also take steps to prevent critical events (floods, for example), misuse (excessive) or poor conditions (polluted water). Thus, this policy is focused on water in its natural environment, the river basin, the aquifer or in its other forms of availability.

The national sanitation policy, foreseen in Law nº 11,445 of 2007 (BRASIL, 2007), aims to ensure that citizens, especially in urban environments, are served by sanitation services that include water supply, collection, treatment and final disposal of sanitary sewage, urban cleaning and solid waste management, in addition to drainage. The focus here is on services and sanitation, a fundamental factor for the supply of water in proper quality. Thus, it is understood that both policies must be in constant dialogue.

The national environmental policy, provided by Law nº 6,938/1990 (BRASIL, 1990), aims to preserve, improve and restore environmental quality, in order to ensure adequate conditions for socioeconomic development. This policy involves the natural elements: water, air, soil and subsoil. Its focus is on avoiding pollution, disciplining activities, for example, through the licensing of potentially polluting activities. The policy also defines quality standards, including water and spaces that must be protected, among other action instruments and guidelines. Thus, it is understood that the environmental policy should not conflict, but be associated and coordinated with the two previous policies in order to achieve its objectives.

The relationship between water and health dates back to the Federal Constitution of 1988, which, in its article 200, establishes, among the competencies of the Unified Health System (Sistema Único de Saúde — SUS), to develop actions in the area of sanitation and control of water for human consumption (BRASIL, 1988). This article is the motto for Law no. 8,080/90 (SUS Organic Law), which details these competencies (BRASIL, 1981). The Organic Law opens the gap for Decree no. 5,440/2005 (BRASIL, 2005), which establishes definitions and procedures on water quality control of supply systems and places the Ministry of Health among those involved directly in the matter. This Decree establishes the standards of potability, control and monitoring of water quality, currently in force through the Ordinance of the Ministry of Health No. 2,914/11 (BRASIL, 2011).

Thus, while Water Resources and Environment policies are focused on water in the natural environment, the sanitation policy is focused on capturing and treating this water, meeting the requirements of intended use, health and safety for this water to be consumed by the population. With this description, it is relevant that these policies need to be coordinated and in dialogue in order for water to be, in fact, well managed.

As to the issue of land use planning, which, in the absence of a national policy establishing objectives and actions to achieve a balance in land use and occupation, it usually ends up being the main vector of environmental impacts, particularly on the water, the case of pollution and silting up of water bodies, as examples (SANDER; MAIORKI, 2012). The lack of a national policy does not prevent states and municipalities from taking initiatives and using environmental policy instruments, such as Economic Ecological Zoning and the creation of conservation units, in an attempt to organize the space of their territories, but, unfortunately, there is still no generalized action to reduce the impact of the various uses that are given to the territory and the effects on the water before its misuse.

The National Water Resources Council: a scenario for policy debate

In Brazil, the framework for the creation of public policy councils is the 1988 Federal Constitution, which "defined social participation as necessary for some specific policies" (IPEA, 2013), opening space for power-sharing. Public Policy Councils are understood as public spaces linked to bodies of executive power. Their purpose is to allow the participation of society in the "definition of priorities of the political agenda, and to support the formulation, monitoring and control" (IPEA, 2013). The Councils can be "considered hybrid institutions since the State and civil society share decision-making power and constitute public forums that capture demands and agree on specific interests of various groups involved in a given policy area" (MANCINI, 2019).

Until December 2018, CNRH was composed mostly of representatives of the public sphere, either federal or state, with 29 ministerial representatives and 10 representatives of state water resources councils, represented by members of the State Secretariats that coordinate water policy agenda. There is also the participation of 18 members of civil organizations, 12 of which represent users (irrigators; public service providers of water supply and sanitary exhaustion; concessionaires and authorized hydroelectric generation; hydro-way/port sector; mining-metallurgic sector; fishermen and users of water resources for leisure and tourism) and 6 represent civil organizations of water resources (committees; consortiums and inter-municipal associations of hydrographic basins; technical teaching and research organizations; environmental entities).

Representatives of public authorities are appointed by their own institutions and those of civil society through an electoral process as the constituency of the sectors represented. The renewal process takes place every two years, in accordance with the bylaws of CNRH.

During the last 20 years, the Council and its 10 Technical Chambers that deal with specific issues related to Water Resources Policy have been active in Brazil until recently.

It is worth noting that this interruption is justified by the fact that, in early 2019, administrative reform was carried out that still extends in many respects through the Provisional Measure no. 870/2019 that recently created Ministry of Regional Development (MDR) and aggregated the attributions of the then existing Ministry of Cities, the Ministry of National Integration, the Departments of Water Resources and Revitalization of Watersheds and Access to Water of the Ministry of Environment (MMA), besides attributions of the National Water Agency (ANA). The MDR is presently responsible for the integration and coordination of the water agenda within the Federal Government (BRASIL, 2020). The Decree no. 9,666/2019, created the National Secretariat of Water Safety (Secretaria Nacional de Segurança Hídrica — SNSH), define its competencies in article 16. Thus, the CNRH is no longer linked to the Ministry of Environment, but to the Ministry of Regional Development.

Guidelines and themes of the CNRH

The theoretical model used for the analysis of the dynamics of the CNRH, through the evaluation of the issues of guidelines on integration and articulation, is based on Archon Fung (2006), a theoretician of participatory democracy, who proposes dimensions to be considered in the evaluation of the effectiveness of policies. The three dimensions are: who participates in the Council (already presented above); what is discussed, with focus on the agendas; and the proposal to be evaluated and if the debate leads to public action.

In order to identify whether the existing sectoral policies and instruments promote some type of discussion on the integration and articulation of water policy with other policies, detailed documental research of the agendas discussed at the CNRH in its 20 years, and its 81 ordinary and plenary meetings, the last one being held in 2018. The Executive Secretariat of the CNRH and the coordination of its Technical Chambers defined the majority of the agendas.

As follows, we present a summary of the themes discussed at the CNRH and a quantitative systematization of the incidence of related sub-themes that constitute the guidelines. The thematic systematization based on the agenda addresses:

- Rules of operation of the Council and related bodies inserted in the National Water Resources System, such as: regulation, mission and composition of the Council and Technical Chambers; creation of management bodies such as River Basin Committees and Management Agencies (delegating entities); agenda and work plan for the system; related legal issues;
- Management Instruments (what are the instruments and how often these instruments are discussed): National Plan or Water Resources Plan; environmental granting and licensing; framework of water bodies in a class of predominant use; information

system for the management of water resources; national hydrographic division, classification of watercourses; collection for the use of water; monitoring;

- Integrated water management: correlation between surface, groundwater and coastal water; issues of quality and quantity; mineral water; sustainability in the use of water resources, dominance;
- Sectoral articulations: identify which sector policies related to water management have been addressed in the CNRH: sanitation; environment (impact assessment); food security; water security; territory and mining;
- Environmental education: definition of commemorative dates; training of members; insertion of postgraduate programs in universities (emphasis on hydrogeology);
- Lectures/presentations on strategic themes, such as transposition of the São Francisco River, extraction of shale gas, drought in the Northeast and Southeast, and rupture of the dams of Fundão in Mariana (2015) and Brumadinho (2019), both in the State of Minas Gerais.

Considering the themes, we also detail the contents discussed under each of them, as can be seen in Table 1.

What can be observed is that the agendas prioritize the rules of operation that aggregate mostly administrative issues, representing a total of 201, while 174 are linked to other themes. The aspects related to rules of operation are mostly forwarded by the Legal Technical Institutional Chamber. The significant number, which demands more time and work from the plenary, due to the constant revisions made to the CNRH's bylaws, adapts its rules of operation to the demands of the members and their segments or sectors; also, to a large number of Technical Chambers, which maintain their own bylaws and rules for operation; and to feedback these issues to the agenda in subsequent meetings, since they are rarely approved in their first session.

The management instruments are the main tools related to water policy to be implemented, with the consequent improvement of water conditions, whether in terms of quality or quantity. Water Resources Plans allow the diagnosis of the situation of a certain portion of the territory (basins, states or nation) and the actions to be developed and prioritized there. Through the Regulatory Water Framing, goals are established to achieve the improvement of water conditions, in order to meet the various current and future projected demands. With the water charges, prices are established for the withdrawal, release and consumptive demands, and simultaneously an instrument of planning and economic/financial strategy.

Considering the themes included in the guidelines, the debates on Water Use Charging have been predominant, as most Water Basin Committee's demand and depend on these resources to implement their actions. In second place, in the debates, arise issues associated with the National Water Resources Plan (24), indicating the role and showing the effort of CNRH in its formulation. Notwithstanding, the legal water framing, an essential tool to promote an integrated approach to water and its environment as to its relationship with the territory, is inexpressive, having only four inclusions in the agenda during 20 years.

In continuity to the themes addressed by the CNRH, those classified as inducers of the debate on integrated management are those based on the categories developed by Ituarte (2003), integration of the discussion of surface and groundwater, quality and quantity aspects, consideration of associated ecosystems and different degrees of salinity. Adding all these themes, they are part of the debate 32 times, being 11 linked to groundwater, one of the most active Technical Chambers of the CNRH, that having as its framework integrated management, is part of an active network of hydrogeologists in Brazil.

The issue of coastal water is only mentioned six times, and the approach, integrating freshwater with coastal water, suffered strong resistance to its approval from the government sectors and the productive sector, mainly due to an understanding that the inclusion of coastal waters would disfigure the Council, thus causing legal insecurity for the private sector when requesting the water allocation grant. This is due to the fact that it is not yet foreseen for saline water and even for water charging (in the case of releasing load or desalination). The coastal issue is also included in the agenda when related to the integration of Water Resources Plans in Water Basin Committees meetings these issues, what never occurred.

On the other hand, the themes of pollution and degradation appear only five times (pollution four and degradation one), and the counterpoints protection (2)

Table 1 – Themes and sub-themes discussed at Conselho Nacional de Recursos Hídricos (CNRH) meetings between 1998 and 2018/Number of times they have been on the agenda

Themes	Number of times they have been on the agenda	Sub-themes
1. Operational Rules	201	Rules of operation that apply to the Council and the Technical Chambers, defined throughout the activities of the CNRH itself, mostly regulations and composition. Also included Work Plans and Budget of the Management System, which are approved annually.
2. Management Tools	100	National Plan or Watershed Plan of Union domain – 24 Framework – 4 National Information System – 4 Water Allocation – 18 Water Charges – 39 National Hydrographic Division, coding, classification – 6 Monitoring – 3
3. Integrated Water Management	32	An approach that strengthens that water management should take place without physical barriers, being thought in an integral way, whether in its superficial, underground, freshwater, brackish or saline (coastal) availability: Groundwater – 11 Coastal water – 6 Pollution – 4 Protection – 2 Degradation – 1 Sustainability/integrated management – 4 Relationship between basins – 2 Minimum remaining flow – 1 Dominiality – 1
4. Sectoral Articulations	19	Focus on other policies interrelated with water management, such as: Sanitation – 5, Spatial Planning (mining and works that go beyond the domain of a state) – 8 Food Safety: Zero Hunger, Zero Headquarters – 2 Aquaculture and fishing – 1 Dam Safety – 3
5. Environmental Education	7	Celebration of environmental facts, capacity building of water basin committees' representatives and specific educational activities.
6. Scenarios	16	Presentation of a scenario where specific subjects are included, such as droughts, shale gas exploration, dam ruptures, transposition of São Francisco River, government programs and the National Water Plan.

Source: adapted by CNRH (2019).

and sustainability (4) altogether, six mentions. The reduced presence of these themes indicates little interest in environmental and ecosystem issues.

As to sector articulations, which seeks to evaluate the incidence of discussion on public policies related to water within the CNRH, 19 insertions were found, and basic sanitation is mentioned only 5 times in the agenda, and not as policy integration, but in information, or in initiative or approval of another law. The territorial issue is presented 8 times, mainly from the perspective of mining exploration or impact of construction works between more than one state. The topic of food security comes as a presentation of national programs or demands of the aquaculture and fishing sector (once), and these were occasional discussions that did not lead to joint action between ministries or policies.

To conclude this topic, environmental education arises with a certain regularity, but not from the perspective of a National Program that mobilizes the plenary and the States. We categorize as "presentations" those themes of extreme importance, which were not deepened or even forwarded to the Technical Chambers to be analyzed — as the cases of the transposition of the São Francisco River, exploration of shale gas, actions to minimize the effects of the rupture of dams and the drought in the Southeast (2014/2015) and Northeast.

It is also relevant to consider that the Council is a deliberative forum (article 1st of its Internal Rules), so its decisions are supposed to become effective after approval. The guidelines, or themes to be discussed and deliberated, are proposed by the representatives of the Executive, and the choice is for those issues of technical-administrative nature, excluding most controversial and with a political type. What is to be observed, alongside the documents raised, is that those issues were the Executive does not have full autonomy to conduct the process, is not taken to deliberation. Thus, the discussion of strategic issues, such as water crisis, are not debated in its importance, as alternatives or emergency action plans are not discussed within the Council.

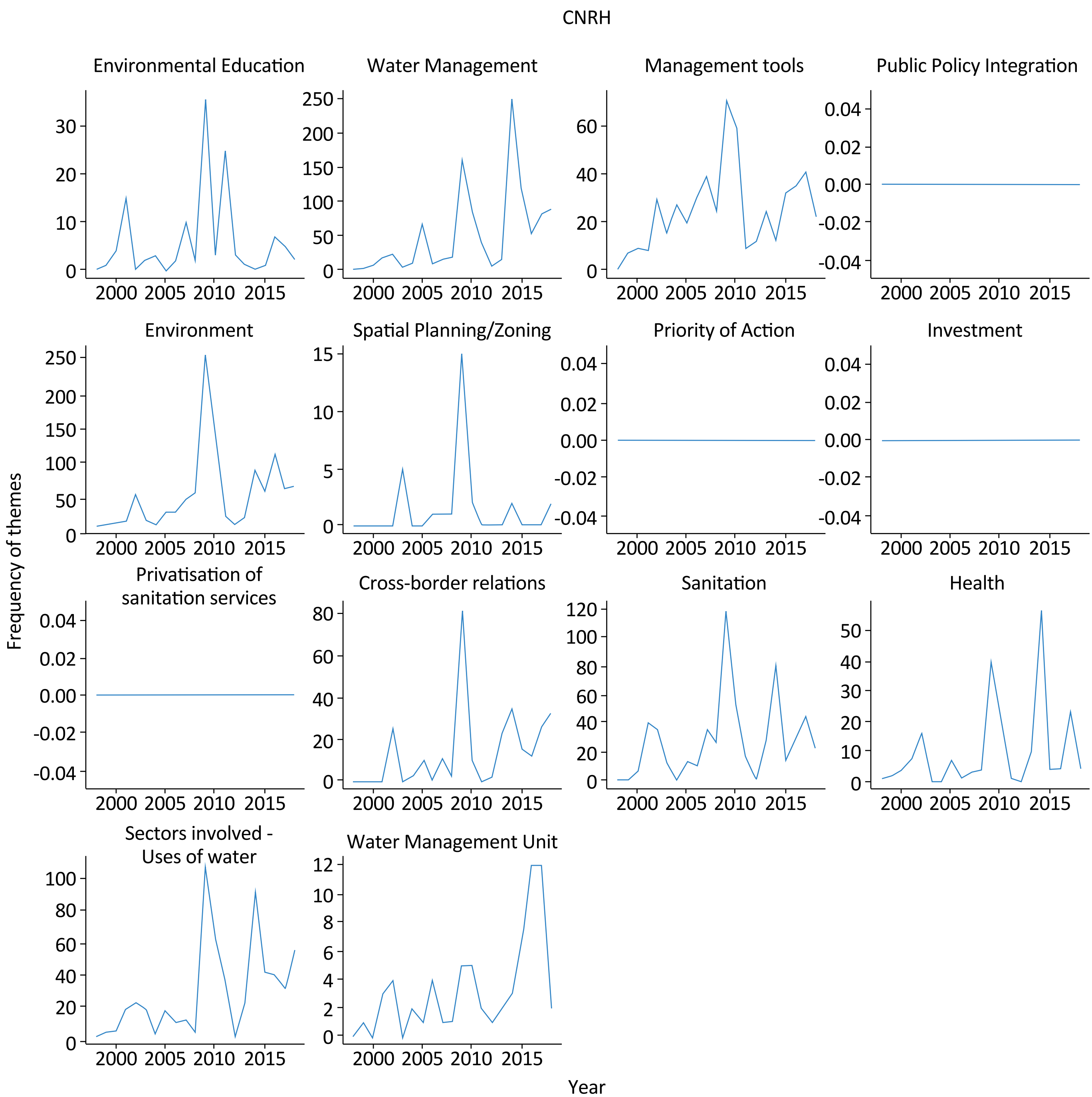
As a complement to Table 1, we can see several graphs (Figure 1) that demonstrate in quantitative and temporal approach, the incidence of those themes related to integration and sectorial policies in the discussions, that identified by Program R, which processed all 81 minutes of CNRH from 1998 to 2018 and obtained this set of graphs:

Considering these outcomes, it is observed that "integration of public policies" does not express itself, only at the moments when sectoral policies are cited nominally. The incidence of discussions on the environment is very low or non-existent, having its peak in 2010, when the guidelines of CNRH were focused on deliberations linked to integrated qualitative and quantitative monitoring for groundwater; management of the Guarani Aquifer; Water Resources Plan on the right bank of the Amazon River; minimum remaining flow or ecological flow. Land use planning was highlighted in 2009, focusing on mining issues. Sanitation is a recurring theme, with an emphasis in 2007, when the Law no. 11,445, that establishes the guidelines for basic sanitation, was approved. The health issue is expressive in the debates that took place between 2013 and 2014 when the guidelines on artificial recharge of aquifers, extraction of shale gas and drought in the Southeast and Northeast were prevailing.

Thus, what emerges is that most discussions at CNRH are focused on administrative issues and on the regulation of the system itself, not effectively discussing means to articulate policies that have a common focus, such as water. It is worthwhile to explore and identify the existence of a relationship between members of different portfolios and public policies, which within the Council may become closer and stimulate articulations between policies.

The systematization of the themes discussed in sessions of CNRH converges with aspects raised by Senra on IWRM. The author highlights:

> Despite the importance given to the principle of integrated management of public policies, in practice, it occurs little in Brazil, regardless of the level of government. IWRM is still little effective and its governance process, in 20 years of its implementation, it needs to improve significantly, as well as the whole process of social control of other policies and sector plans (SENRA, 2018).



Source: adapted by CNRH (2019).

Figure 1 – Representation of the frequency of discussion of strategic issues and public policies related to water during Conselho Nacional de Recursos Hídricos (CNRH) meetings.

Need for improvement and case studies

The outcomes obtained raise two major questions. The first is related to the need to break with the trend of insulation of the different policies. The second is how to improve water management so that Councils can promote more openly dialogues, encouraging a collaborative perspective of different angles.

One cannot ignore that the current situation as to environmental and water policy in Brazil is not the most promising, since the most strategic spaces for debate of guidelines and actions, the Councils, are under scrutiny by other vested, that confront those on environment and water. Recently, the structure of the Council was modified by Federal Decree No. 10,000 of September 3, 2019. The number of seats on the Council has been reduced to 37, with ministries going from 27 to 19 incumbent representatives and, according to data presented by the Water Governance Observatory — OGA (4/9/2020), the new composition reduces the participation of 10 to 9 representatives of the State Councils, the user sector from 12 to 6, and civil society organizations from 6 to 3, linking the representativeness of Non-Governmental Organization (NGOs) to those who are members of river basin committees under the Federal control. In addition, distortions are maintained, such as the representation of River Basin Committees being foreseen in the list of civil society representations and the maintenance of the majority of the Federal Government, which now can deliberate a*d referendum* without any review by the plenary.

This indicates that, if with the recently existing representation there has been already a reduced agenda, with this intervention, the tendency is to have an even greater impact on the effectiveness of the policy, with fewer debates on issues that should be on the agenda, such as water safety, which has become increasingly relevant, both from the point of view of water quality and quantity, due to the ever-growing effects of climate change (JACOBI; TORRES; GRESSE, 2019).

The recent water crisis experienced by the population of several municipalities of Paulist Macrometropolis, composed of 174 municipalities within the State of São Paulo, brought evidence of the fragility of the current water management system. The lack of integration of actions in response to the region's water vulnerability indicates that water management has not been effective and that new forms of participation and collaboration among sectors and stakeholders are needed. In addition, the water management system has shown not to be prepared for the impacts of climate change.

Transforming water-social relations to pursue water security implies allowing people and organizations to become significantly involved in water governance, not only as water users but also as political actors (EMPINOTTI; BUDDS; AVERSA, 2019). As Jepson *et al*. (2017) point out, this implies a shift in the focus of water security interventions far from water supply and towards the nature of water-social relations. According to Linton and Budds (2014), this indicates the need to rethink the structures and decision-making processes for water security interventions, and to focus on the interventions and their impacts on social structures and orders at different scales (LINTON; BUDDS, 2014).

In understanding governance as a process that involves decision-makers and non-decision-makers with a common purpose, it is necessary to promote strong decentralized and co-responsible participation as the main point of the process. This requires network performance, integrated collaboration and empowerment of those actors involved in management, interacting with decision-makers in the negotiation spaces. At the same time, educational practices and the participation of civil society should be widely considered, contributing to the process of building shared decision-making (JACOBI, 2012; PAHL-WOSTL *et al*., 2012).

CONCLUSION

If the guidelines are limited and if the planned management tools, as well as principles of integrated management and articulation, are not sufficient to stimulate effective action and discussions on real problems that each region of the country experiences, new strategies must be thought to improve management. This implies either to deal with the usual themes, which are related to what is foreseen in the policies, or to reduce the impacts of uncertainties and the scope of the recurrence of extreme events.

This raises a fundamental issue related to the demand for greater proactivity from all board representatives. The various sectors of society and the State represented at the CNRH will need to join efforts to strengthen global agendas consistent with their institutional or sectoral, and concerns in an integrated manner with water policy. For this, it will be necessary promoting effective progress in the democratic governance of water, emphasizing policies that reduce liabilities and deficits, encouraging policy articulations in a transparent way with accountability.

The various representatives of State Councils, in turn, need to be committed to discussing those most pressing issues they face in their territories, so that CNRH becomes an effective national forum and a space to exchange experiences, that lead to solving problems and deficits, rather than a forum of agendas that emphasize rules with very little dialogue with the major problems that arise from the disarticulation of policies.

On the other hand, entities representing organized civil society need to be better prepared and strategically articulated to follow the debates and stimulate agendas that include as well the environmental and business perspectives in an explicit and non-reactive way.

Thus, it is understood that the possibility of developing integrated programs and with joint budgets can result in an efficient process to integrate, articulate and define the best coordination for water governance, and also emphasize its adaptive and participatory dimension.

From the perspective of water security, there is a need to promote a new paradigm for water governance, in which the articulation of actions based on a new strategy of integrated, adaptive and participatory management prevails. This requires considering society as a key player both in decision making and in social control of the decisions to be implemented.

One of the greatest challenges of water governance is to ensure an open and transparent, inclusive, communicative, equitable and ethical approach. Thus, the creation of conditions for a new proposal of dialogue and co-responsibility must be increasingly supported in educational processes oriented to “public deliberation”.

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GESTÃO AMBIENTAL, LEGISLAÇÃO E OS RECURSOS HÍDRICOS NA CIDADE DE FORTALEZA (CE), BRASIL

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RESUMO

Este trabalho discute a importância da gestão ambiental e da legislação de controle urbano para a proteção dos recursos hídricos. Destaca, também, a importância da lei de uso do solo para a conservação ambiental, devendo o zoneamento urbano considerar as características do ambiente natural. É feita uma avaliação da legislação de uso e ocupação do solo de Fortaleza (CE), constatando-se que ela nem sempre segue as exigências do código florestal do Brasil, no que concerne às Áreas de Preservação Permanente (APP). A última alteração da legislação municipal (lei complementar nº 250/2018) resultou na redução de 961.185,34 m^2 das APP às margens dos recursos hídricos de Fortaleza (CE). Utilizando a sobreposição de mapas e visitas de campo, foram identificadas as alterações ocorridas nas APP em duas bacias hidrográficas da cidade de Fortaleza (CE), Brasil, ocorrendo reduções após a lei complementar nº 250/2018.

Palavras-chave: áreas de preservação permanente; áreas ribeirinhas; uso do solo; controle urbano; zoneamento urbano.

ABSTRACT

This paper discusses the importance of environmental management and urban control legislation for the protection of water resources. It also highlights the importance of land use law for environmental conservation and that urban zoning should consider the natural environment characteristics. It was evaluated the Fortaleza (CE) legislation about land use and it was noted that it does not observe Forest Code of Brazil requirements with regard to Permanent Preservation Areas (PPA). The latest legislation amendment (Complementary Law No. 250/2018) resulted in a reduction of 961,185.34 m^2 of permanent preservation areas on water resources margins in Fortaleza, Ceará. Using map overlays and field visits, the changes occurred in preservation areas in two river basins of the city of Fortaleza, Ceará, Brazil, were identified. After Complementary Law No. 250/2018, there were reductions in the areas of permanent preservation in the two river basins.

Keywords: permanent preservation areas; riparian areas; land use; urban control; urban zoning.

INTRODUÇÃO

Os recursos hídricos constituem a base que sustenta todo o sistema de vida da Terra. Especialmente para bacias severamente afetadas pela crise hídrica, o manejo integrado dos recursos hídricos é importante para a reabilitação dos ecossistemas aquáticos, suas funções e para a garantia do desenvolvimento sustentável das bacias hidrográficas (ZHANG; JIN; YU, 2018).

O crescimento da população urbana, no Brasil e no mundo, tem resultado em alterações ambientais significativas, incluindo, entre elas, as modificações nos recursos hídricos tanto em termos de qualidade como de quantidade.

Por outro lado, os recursos hídricos desempenham importante papel na condução da evolução urbana. A água é um elemento crítico para a vida sustentável em áreas urbanas, nas quais as questões relacionadas aos recursos hídricos serão cada vez mais importantes no futuro (KAUSHAL *et al*., 2015).

Os corpos de água são ecossistemas ecológicos cultural e economicamente importantes que fornecem muitos serviços valiosos à humanidade. No entanto, à medida que as atividades humanas se intensificam (por exemplo, o aquecimento global, o uso da terra, as mudanças na cobertura vegetal, a explosão populacional e outros fatores antropogênicos), ocorrem alterações na quantidade e na qualidade da água, que exigem soluções desafiadoras (WANG; HO; LU, 2019).

A expansão mundial das áreas urbanas tem resultado em marcadas alterações nos processos naturais, na qualidade ambiental e no consumo dos recursos naturais. O espaço urbano tem influência na infiltração e na evapotranspiração. As superfícies impermeáveis tornam mais intenso o processo de escoamento superficial da água. Nas áreas urbanas são produzidos poluentes que impactam a qualidade da água, em que novos contaminantes continuam a representar desafios para seu monitoramento e tratamento (MCGRANE, 2016).

Segundo Sun e Caldwell (2015), o aumento da população e o desenvolvimento constituem a maior ameaça ao suprimento de água de boa qualidade. Essa ameaça é aumentada em áreas com secas periódicas e com maiores faixas de temperatura e precipitação associadas às mudanças climáticas causadas pela ação humana. Uma área urbanizada é mais suscetível aos impactos negativos das mudanças climáticas, por causa da perda da capacidade de proteção dos ecossistemas naturais.

Para o equacionamento desta questão, é fundamental uma efetiva modificação na relação entre as políticas urbanas e de recursos hídricos, visando a integração e a cooperação entre esses dois sistemas, sobretudo quando se trata de bacias intensamente urbanizadas, cuja gestão está intimamente ligada aos processos de uso e ocupação do solo urbano (GASPAR; KLINK, 2008).

O atual modelo de desenvolvimento observado, principalmente nas cidades, com a crescente demanda por recursos naturais e espaço físico, tem ocorrido com áreas que deveriam servir como suporte à preservação ambiental, como as margens de córregos e rios (APP), sendo ocupadas de forma desordenada e sem planejamento, o que resulta em diversos problemas ambientais urbanos como inundações, proliferação de doenças veiculadas pela água, despejos de efluentes sanitários nos corpos hídricos, deslizamentos de terra, enchentes, aumento do escoamento superficial, entre outros (SILVA; SANTOS; GALDINO, 2016).

As cidades precisam de água para diversas atividades e, ao mesmo tempo, geram resíduos resultantes dos diversos usos, os quais têm como destino os recursos hídricos, muitas vezes, poluindo-os.

A expansão das áreas urbanas tem sido feita à custa de desmatamentos, alterações no relevo, impermeabilização do solo, aterramento de cursos de água e lagoas, retiradas excessivas de águas superficiais e subterrâneas, entre outras intervenções as quais resultam na degradação dos recursos hídricos.

As diferentes fontes de poluição em um ambiente urbano, desde o escoamento das águas pluviais até o lançamento de efluentes de estações de tratamento de esgotos e a poluição industrial, entre outras, causam impactos sobre os recursos hídricos. Ao mesmo tempo, a capacidade suporte natural de corpos hídricos, pântanos e aquíferos é comprometida por meio da implantação do sistema viário e da impermeabilização do solo, resultando na diminuição da infiltração da água e no aumentando do escoamento das águas pluviais. O impacto cumulativo dessas e de outras atividades ainda não é totalmente compreendido (RIEMANN *et al*., 2017).

A qualidade das zonas ribeirinhas está inversamente relacionada ao grau de urbanização das áreas adjacentes, observando-se que os usos da terra com maior cobertura florestal garantem uma condição menos degradada e maior diversidade de espécies (DÍAZ-PASCACIO *et al*., 2018).

Uma das principais ferramentas de proteção dos recursos hídricos, no Brasil, é o Código Florestal (Lei Federal nº. 4.771, de 25 de maio de 2012), que regulamenta a definição de APPs para as faixas marginais dos corpos de água (BRASIL, 2012).

Segundo Campagnolo *et al*. (2017), o Código Florestal brasileiro, em todas suas versões, tem como essência a manutenção da qualidade de vida de toda a sociedade brasileira, pois entende que a conservação dos ecossistemas e a proteção dos recursos naturais são de interesse comum. No entanto, ressaltam que o Novo Código Florestal carece de muitos estudos técnicos para que sua efetividade seja confirmada, bem como os benefícios propostos.

Os recursos hídricos não podem ser considerados como ambientes isolados, mas associados aos outros componentes do meio como um todo. Uma alteração em um dos meios pode causar modificações nos ambientes aquáticos, tanto sob os aspectos quantitativos como qualitativos (MOTA, 2019).

Os recursos hídricos têm grande interação com os demais componentes de suas áreas adjacentes que compreendem a bacia hidrográfica. Assim, a administração dos recursos hídricos deve integrar uma gestão ambiental mais ampla, que compreenda toda a bacia hidrográfica.

As ações de gestão ambiental de determinada área têm grande repercussão nos recursos hídricos que a integram.

A qualidade e a quantidade de um recurso hídrico dependem dos usos da água e das atividades desenvolvidas na bacia hidrográfica. Para que se garanta o uso adequado do solo e da água, é necessária uma legislação com enfoque no controle ambiental.

Este trabalho teve como objetivo destacar a importância da gestão e da legislação ambiental para a proteção dos recursos hídricos e realizar, como estudo de caso, utilizando a sobreposição de mapas e visitas de campo, uma avaliação da legislação de uso e ocupação do solo de Fortaleza (CE), Brasil, comparando com a legislação federal em vigor

MATERIAIS E MÉTODOS

Este trabalho foi desenvolvido em duas etapas: na primeira são discutidas as ferramentas de gestão ambiental e de legislação de controle ambiental, com ênfase para a proteção dos recursos hídricos; na segunda, faz-se uma análise da situação das APPs de recursos hídricos urbanos, no contexto da legislação municipal da cidade de Fortaleza.

O município de Fortaleza é composto por quatro Bacias Hidrográficas: Cocó, Maranguapinho/Ceará, Pacoti e Vertente Marítima. Neste trabalho, foram avaliadas as alterações provocadas pelas mudanças na legislação nas Bacias do Rio Cocó e do Rio Maranguapinho.

Os métodos adotados foram: pesquisa bibliográfica, pesquisa documental, sobreposição de mapas e visitas de campo.

Inicialmente, realizou-se uma revisão bibliográfica sobre o tema central. Posteriormente, foram estudadas e discutidas as legislações pertinentes por meio de pesquisa documental.

Sá-Silva, Almeida e Guindani (2009) apontam a principal diferença entre a pesquisa bibliográfica e documental, afirmando que a bibliográfica remete para as contribuições de diferentes autores sobre o tema, como as fontes secundárias, enquanto a documental recorre aos materiais que ainda não receberam tratamento analítico, ou seja, as fontes primárias.

O método de construção e sobreposição de mapas promove a integração de informações e permite a visualização espacial mais didática dos dados. Segundo Cremonez *et al*. (2014), essa metodologia consiste na montagem de uma série de mapas temáticos, no qual cada mapa indica uma característica cultural, social e física que reflete um impacto.

Os mapas apresentados neste trabalho foram construídos por meio do Sistema de Informações Geográficas (SIG), *software* QGIS na versão 2.14.16 (Essen), que permite a edição de mapas dos arquivos em formato KML e *Shapfile*. Os arquivos utilizados para elaboração dos mapas encontram-se disponíveis nos *sites* da Prefeitura de Fortaleza (PMF), na plataforma Fortaleza em Mapas, no Infocidades, ano 2019 (https://mapas.fortaleza.ce.gov.br).

GESTÃO AMBIENTAL URBANA E OS RECURSOS HÍDRICOS

De acordo com Philippi Jr. e Bruna (2013), gestão ambiental é o ato de administrar, de dirigir ou reger os ecossistemas naturais e sociais em que se insere o homem, individual e socialmente, em um processo de interaçao entre as atividades que exerce, buscando a preservação dos recursos naturais e das características essenciais do entorno, de acordo com padrões de qualidade. Os objetivos últimos são estabelecer, recuperar ou manter o equilíbrio entre natureza e homem.

Mota (2016) enumera as seguintes atividades de gestão ambiental: caracterização e valoração ambiental; estudos de impacto ambiental; licenciamento ambiental; auditoria ambiental; análises de riscos; manejo de recursos ambientais; planejamento ambiental / zoneamento ambiental; gestão de bacias hidrográficas; gestão de áreas de valor ambiental / unidades de conservação; gestão de resíduos; gestão ambiental em empresas / ISO 14000; legislação ambiental; educação ambiental; outras atividades visando a conservação ambiental.

Gestão ambiental urbana é definida por Nolasco e Silva Filho (2010) como o conjunto de rotinas e procedimentos que permite uma organização ou comunidade urbana administrar adequadamente as relações entre suas atividades humanas e o ambiente que as abriga, atentando para as expectativas das partes interessadas com objetivo de atenuar ou anular os efeitos negativos sobre os ecossistemas e a qualidade de vida, advindos dessas atividades.

De acordo com Global Water Partnership (2017), gestão integrada de recursos hídricos é o processo coordenado de desenvolvimento e gestão da água, solo e recursos relacionados, com o objetivo de maximizar o bem-estar econômico e social de forma equitativa, sem comprometer a sustentabilidade de ecossistemas vitais nem o meio ambiente. A gestão deve ter como objetivo o uso equânime, eficiente e sustentável da água, considerando que é um recurso natural, parte integrante de um ecossistema, um bem social e econômico, cujas quantidade e qualidade determinam a sua utilização.

Segundo Kumar, Kumar e Khosla (2016), a gestão dos recursos hídricos deve constituir um conjunto de medidas, regras operacionais e incentivos (economia, regulação, judicial, social) aplicados à água e aos recursos terrestres a ela associados, por meio de um arranjo institucional envolvendo entidades relacionadas à água, ou não, públicas e privadas, e suas regras e regulamentos.

A gestão de recursos hídricos deve estar associada à gestão ambiental como um todo, compreendendo os outros componentes do meio físico, solo e ar, do meio biótico, fauna e flora, e do meio antrópico.

Dois instrumentos de gestão são fundamentais para a proteção dos recursos hídricos: o Plano de Bacia Hidrográfica e o Plano Diretor de Desenvolvimento do Município.

De acordo com a Política Nacional de Recursos Hídricos, estabelecida pela Lei nº 9.433, de 8 de janeiro de 1997 (BRASIL, 1997), os Planos de Recursos Hídricos são planos diretores que visam fundamentar e orientar a implementação da Política Nacional de Recursos Hídricos e o gerenciamento dos recursos hídricos. A referida lei considera a bacia hidrográfica como a unidade territorial para implementação da Política Nacional de Recursos Hídricos e atuação do Sistema Nacional de Gerenciamento de Recursos Hídricos.

O Plano de Bacia Hidrográfica, instrumento central de articulação entre o planejamento e a gestão, tem como objetivo geral definir ações de gestão, programas, projetos, obras e investimentos prioritários para esse território, em um contexto que inclua os órgãos governamentais, a sociedade civil, os usuários e as diferentes instituições que participam do gerenciamento dos recursos hídricos. Tal plano também deve levar em consideração todos os demais programas, projetos e estudos que incorporem a proteção dos recursos hídricos na área de abrangência das respectivas bacias hidrográficas, articulando-se com os planejamentos municipais, setoriais e regionais existentes (PERES; SILVA, 2013).

Em nível de planejamento municipal, ressalta-se o Plano Diretor, que, de acordo com a Constituição Federal de 1988 (BRASIL, 1988), é o instrumento básico da política de desenvolvimento e da expansão urbana, devendo ser aprovado pela Câmara Municipal e obrigatório para cidades com mais de vinte mil habitantes.

Conforme Pizella (2015), o Plano Diretor de uso e ocupação do solo constitui o principal instrumento de gestão territorial e municipal, definindo os parâmetros para o cumprimento da função social, ambiental e econômica da propriedade. Nesse sentido, os municípios possuem grande responsabilidade na proteção dos recursos hídricos, e, sem seu apoio, não é possível integrar a gestão territorial e hídrica no âmbito da bacia hidrográfica.

Ressalta-se que os limites das bacias hidrográficas quase sempre não coincidem com os dos territórios municipais, o que constitui uma dificuldade para a implementação das políticas de proteção dos recursos hídricos. Carneiro, Cardoso e Azevedo (2008) levantam a questão de como relacionar a gestão de recursos hídricos por bacias hidrográficas e a gestão do território municipal, ou seja, como a questão do uso do solo deve se inserir nos planos de bacia hidrográfica e como a gestão dos recursos hídricos se inserir nos planos diretores municipais.

Pizella (2015) destaca a necessidade de uma participação mais expressiva do município no Comitê de Bacia, com a qual é possível que as formas de ocupação e uso do solo municipal sejam consideradas no momento de elaboração e execução dos Planos de Bacia. Assim, a gestão dos recursos hídricos pode se dar integradamente.

A integração entre os Planos de Bacia Hidrográfica e os Planos Diretores de Desenvolvimento Urbano municipais é indispensável para que sejam propostas, em ambos, medidas integradas e complementares visando à proteção dos recursos hídricos.

Além do Plano de Gestão de Bacia Hidrográfica e do Plano Diretor de Desenvolvimento do Município, outros instrumentos de gestão ambiental são importantes para a gestão ambiental dos recursos hídricos.

Entre outras atividades da gestão ambiental, podem ser destacadas as que têm maior relação com a gestão dos recursos hídricos urbanos: manejo de outros recursos ambientais — solo, ar, meio biótico, meio antrópico; gestão de áreas de valor ambiental — encostas, áreas de preservação permanente, áreas de recarga de aquíferos, áreas de solos suscetíveis à erosão, áreas de amortecimento de cheias, unidades de conservação, entre outras; gestão de resíduos sólidos, líquidos e gasosos; legislação ambiental; educação ambiental.

Palavizini (2012) ressalta que deve ser concebido e realizado um processo de avaliação complexa permanente, que contemple todas as etapas do planejamento e da gestão, o qual deve prever indicadores e meios de verificação de processos, resultados e impactos.

LEGISLAÇÃO E OS RECURSOS HÍDRICOS

Ferramentas legais e administrativas são requeridas para permitir e aplicar a gestão ambiental da água em todos os níveis. Uma estrutura de administração para a gestão ambiental dos recursos hídricos é necessária para apoiar os seus objetivos e deve ser entendida e implementada por todas as partes interessadas (AITHER, 2018).

O conjunto de órgãos e colegiados federais, estaduais e municipais, responsáveis pela concepção e implementação das ações de gestão de recursos hídricos, constituem a estrutura administrativa para garantir o uso adequado da água.

Como ferramentas legais, incluem-se leis, decretos, resoluções, normas, portarias e outros documentos em nível federal, estadual e municipal, que garantem a conservação dos recursos hídricos.

Duas leis federais são importantes: a Lei nº 6.938, de 31 de agosto de 1981, que estabeleceu a Política Nacional do Meio Ambiente (BRASIL, 1981), e a Lei nº 9.433, de 8 de janeiro de 1997, que instituiu a Política Nacional de Recursos Hídricos.

A lei da Política Nacional do Meio Ambiente inclui como um dos seus princípios a racionalização do uso do solo, do subsolo, da água e do ar. A lei referida considera como um dos seus instrumentos o zoneamento ambiental.

Entre os fundamentos da Política Nacional de Recursos Hídricos, encontram-se: a gestão dos recursos hídricos deve sempre proporcionar o uso múltiplo das águas; a bacia hidrográfica é a unidade territorial para implementação da política; a gestão dos recursos hídricos deve ser descentralizada e contar com a participação do poder público, dos usuários e das comunidades.

De acordo com a Lei nº 9.433/97, constituem diretrizes gerais de ação para implementação da Política Nacional de Recursos Hídricos: a gestão sistemática dos recursos hídricos, sem dissociação dos aspectos de quantidade e qualidade; a adequação da gestão de recursos hídricos às diversidades físicas, bióticas, demográficas, econômicas, sociais e culturais das diversas regiões do País; a integração da gestão de recursos hídricos com a gestão ambiental; a articulação do planejamento de recursos hídricos com o dos setores usuários e com os planejamentos regional, estadual e nacional; a articulação da gestão de recursos hídricos com a do uso do solo; a integração da gestão das bacias hidrográficas com a dos sistemas estuarinos e zonas costeiras.

Conforme disposto na lei da Política Nacional de Recursos Hídricos tem que haver a articulação entre a gestão de recursos com a do uso do solo. Assim, os controles do uso e da ocupação de uma bacia hidrográfica devem ser disciplinados, de forma a garantir a proteção dos recursos hídricos que a integram.

As normas de proteção às florestas e recursos hídricos brasileiros são fundamentadas na Lei nº 4, de 1965, com atualizações baseadas na Lei nº 7.803, de 1989, e Medida Provisória nº 2.166-67, de 2001, responsáveis pelo atual código florestal (ZANDER *et al*., 2010).

A preservação das margens dos recursos hídricos é exigida pelo Código Florestal — Lei nº 4.771, de 25 de maio de 2012. Essa lei dispõe sobre a vegetação nativa e considera como APP: as faixas marginais de qualquer curso de água natural perene e intermitente, excluídos os efêmeros, desde a borda da calha do leito regular; as áreas no entorno dos lagos e lagoas naturais; as áreas no entorno dos reservatórios de águas artificiais, decorrentes de barramento ou represamento de cursos de águas naturais; as áreas no entorno das nascentes e dos olhos de água perenes.

A preservação das áreas situadas nas margens dos corpos hídricos, embora tenha como objetivo principal proteger a vegetação, constitui importante medida de proteção da água. De acordo com Kusler (2016), as áreas situadas às margens de recursos hídricos constituem uma variedade de funções e valores, como indicado a seguir: contribuem para o controle de inundações, armazenando e liberando lentamente a água; reduzem a formação de ondas antes de chegar à costa, diminuindo a força das águas; constituem áreas de recarga e descarga de águas subterrânea; contribuem para reduzir a erosão do solo; constituem áreas com vegetação natural; previnem a poluição dos corpos hídricos; constituem *habitat* para peixes e mariscos; constituem *habitat* para anfíbios, répteis, mamíferos e insetos; formam *habitat* para aves aquáticas; constituem *habitat* para diversas espécies de aves; constituem *habitat* para animais e vegetais ameaçados de extinção; contribuem para a retenção de carbono e a consequente redução das mudanças climáticas; têm influência no microclima, evitando o aumento da temperatura; podem ser usadas como áreas de recreação e para práticas de ecoturismo; podem proporcionar oportunidades para experiências históricas, arqueológicas, patrimoniais e estéticas; podem constituir áreas para realização de atividades de educação ambiental; podem ser utilizadas como áreas para o desenvolvimento de pesquisas científicas.

O disciplinamento do uso do solo é competência do poder público municipal, o qual, conforme a Constituição do Brasil, é responsável pela política de desenvolvimento urbano, que tem por objetivo ordenar o pleno desenvolvimento das funções sociais da cidade e garantir o bem-estar de seus habitantes.

Os instrumentos das políticas urbanísticas municipais estão fixados nos termos do artigo 30, inciso VIII, da Constituição Federal, no qual dispõe à competência dos municípios promover, no que couber, adequado ordenamento territorial, mediante planejamento e controle do uso, do parcelamento e da ocupação do solo urbano (*apud* SANTOS, 2011).

Os dispositivos constitucionais foram regulamentados pela Lei nº 10.257, de 10 de julho de 2001 (Estatuto da Cidade) (BRASIL, 2001), que estabelece normas de ordem pública e interesse social que regulam o uso da propriedade urbana em prol do bem coletivo, da segurança e do bem-estar dos cidadãos, bem como do equilíbrio ambiental.

O Estatuto da Cidade inclui entre os seus instrumentos o planejamento municipal, em especial: plano diretor; disciplina do parcelamento, do uso e da ocupação do solo; zoneamento ambiental; instituição de unidades de conservação; instituição de zonas especiais de interesse social.

Outra lei federal relacionada ao uso do solo urbano é o Estatuto da Metrópole — Lei nº 13.089, de 12 de junho de 2006, alterada pela Lei nº 13.683, de 19 de junho de 2018. A referida lei estabelece diretrizes gerais para o planejamento, a gestão e a execução das funções públicas de interesse comum em regiões metropolitanas e em aglomerações urbanas instituídas pelos estados, normas gerais sobre o plano de desenvolvimento urbano integrado e outros instrumentos de governança interfederativa, e critérios para o apoio da União às ações que envolvam governança interfederativa no campo do desenvolvimento urbano (BRASIL, 2018).

A possibilidade de se alcançar uma sustentável gestão de recursos hídricos deve, necessariamente, passar por uma clara articulação com o planejamento do uso do solo. O que se observa no Brasil, entretanto, é uma desarticulação entre os instrumentos de gestão de recursos e os de planejamento do uso do solo, refletindo, possivelmente na ausência de legitimidade do planejamento e da legislação urbana nas cidades brasileiras, marcada por um alto grau de informalidade, e mesmo de ilegalidade, na ocupação do solo (CARNEIRO; MIGUEZ, 2012).

Dois instrumentos legais municipais importantes para o controle do uso e ocupação de áreas urbanas são: a Lei de Uso e Ocupação do Solo e a Lei do Parcelamento do Solo. O primeiro define os parâmetros norteadores da ocupação do solo urbano, incluindo o zoneamento, e constitui um importante instrumento para ordenar o desenvolvimento da cidade e garantir a proteção dos recursos hídricos.

Em uma lei de uso do solo elaborada, visando à conservação ambiental, o zoneamento da cidade deve considerar as características do ambiente natural e deve ser proposto visando a proteção de áreas especiais (ou potencialmente frágeis) como: corpos hídricos e suas planícies de inundações, encostas, áreas de recarga de aquíferos, áreas de amortecimento de cheias, dunas, manguezais, entre outras, cuja ocupação inadequada pode prejudicar os recursos hídricos.

Existem duas formas de proteger uma propriedade: por meio de sua desapropriação, transferindo-a para o domínio público, ou pela limitação de usos, restringindo-se sua ocupação. A Lei de Uso e Ocupação do solo é o meio legal de definir os usos e restrições de ocupação de uma área.

Na definição do zoneamento de uma área urbana podem ser estabelecidas: áreas a serem preservadas (de acordo com a legislação vigente); áreas com ocupação restrita (áreas potencialmente frágeis); e áreas a serem ocupadas com maior intensidade. No estabelecimento dessas áreas devem ser consideradas as características do ambiente, definindo-se menor ocupação para as áreas de valor ambiental.

As áreas que devem ter baixas taxas de ocupação, garantindo grandes áreas permeáveis com vegetação, são: áreas adjacentes às faixas de preservação de recursos hídricos; encostas (o Código Florestal considera como de preservação permanente terrenos com declividade igual ou superior a 45º; áreas com inclinação entre 25 e 45º são consideradas como de uso restrito); áreas de recarga de aquíferos; áreas alagáveis / de amortecimento de cheias; áreas de solos suscetíveis à erosão; estuários; manguezais; apicuns e salgados; dunas (eram consideradas como de preservação permanente na versão anterior do Código Florestal).

Também deve ser considerada a existência, ou não, de infraestrutura sanitária. Em áreas onde não existem redes coletoras de esgotos não devem ser permitidas atividades que resultem na geração de grandes vazões de águas residuárias, pois não será possível a adoção de soluções individuais tipo fossa / sumidouro (ou valas de infiltração).

Para a proteção dos recursos hídricos, deve ser definida uma faixa de uso com baixa taxa de ocupação, adjacente à faixa de preservação exigida pelo Código Florestal. Mota (2019) propõe que sejam estabelecidas duas faixas:

- APP às margens dos corpos de água, definida no Código Florestal;
- Faixa de proteção adjacente à área de preservação permanente a ser utilizada com baixas taxas de ocupação, de modo que seja garantida a proteção de grande parte da vegetação, a infiltração da água e o escoamento adequado das águas superficiais.

Nas áreas adjacentes à faixa de preservação permanente somente devem ser permitidos usos como: parques, áreas de lazer, unidades de conservação de uso sustentável, residencial unifamiliar ou outro uso urbano, desde que seja garantida uma área permeável no mínimo igual a 50% da área do lote.

Na Figura 1, apresenta-se uma proposta de uso e ocupação às margens de um curso de água, em que foram adotadas algumas medidas visando à proteção do corpo hídrico: faixa de preservação permanente às margens do curso de água; na faixa adjacente à área de preservação permanente foram propostos os usos residenciais unifamiliares com baixa e média densidades, em função do afastamento para o corpo hídrico.

Outro exemplo de ocupação às margens de um curso de água está apresentado na Figura 2, observando-se uma área de lazer adjacente à faixa de preservação permanente.

O controle do parcelamento do solo para fins urbanos é um dos itens de maior relevância no que se refere ao ordenamento da cidade, principalmente na organização espacial de novas áreas urbanas. Tem como objetivo garantir que a expansão física dos municípios obedeça às regras e normas de cunho técnico e jurídico, promovendo a distribuição equilibrada de atividades e pessoas no município, estimulando seu desenvolvimento (GOVERNO DO ESPÍRITO SANTO, 2006).

A Lei Federal nº 6.766, de 19 de dezembro de 1979, modificada parcialmente pela Lei nº 9.785, de 29 de janeiro de 1999, dispõe sobre o Parcelamento do solo urbano, e expressa em seu texto requisitos urbanísticos que objetivam melhor ordenamento das novas áreas urbanas dos municípios brasileiros (GOVERNO DO ESPÍRITO SANTO, 2006).

Área de preservação permanente	Residencial baixa densidade	Residencial média densidade

Fonte: adaptado de Randolph (2011).

Figura 1 – Exemplo de ocupação às margens de um curso de água.

Com o advento do Estatuto da Cidade (Lei nº 10.257/01), a disciplina do parcelamento do solo passa a compor o rol de instrumentos que devem ser utilizados para atender aos seus fins. Assim, sendo instrumento útil à execução da política urbana, nenhum parcelamento do solo deverá ser realizado de forma a contrariar as diretrizes insertas nos termos do art. 2º, também da aludida lei federal (MPSC, 2010). O art. 2º da Lei nº 10.257/01 estabelece que a política urbana tem por objetivo ordenar o pleno desenvolvimento das funções sociais da cidade e da propriedade urbana.

Cabe aos municípios elaborarem a Lei de Parcelamento do Solo, também conhecida como Lei de Loteamentos. Esta lei é um valioso instrumento para o controle da ocupação de áreas urbanas, a qual pode estabelecer exigências visando garantir o escoamento e a infiltração da água em determinada gleba urbana e o seu parcelamento.

Segundo Mota (2019), o melhor projeto de parcelamento é aquele cuja distribuição das vias públicas e dos lotes considera a topografia do terreno e os caminhos naturais de escoamento das águas; que preserva as áreas marginais aos recursos hídricos; que protege áreas de valor ecológico; que prevê lotes maiores e com menor ocupação para as áreas ambientais especiais, tais como áreas adjacentes à faixa de preservação, locais com vegetação, encostas, áreas de recarga de aquíferos, áreas de amortecimento de cheias, terrenos mais suscetíveis à erosão.

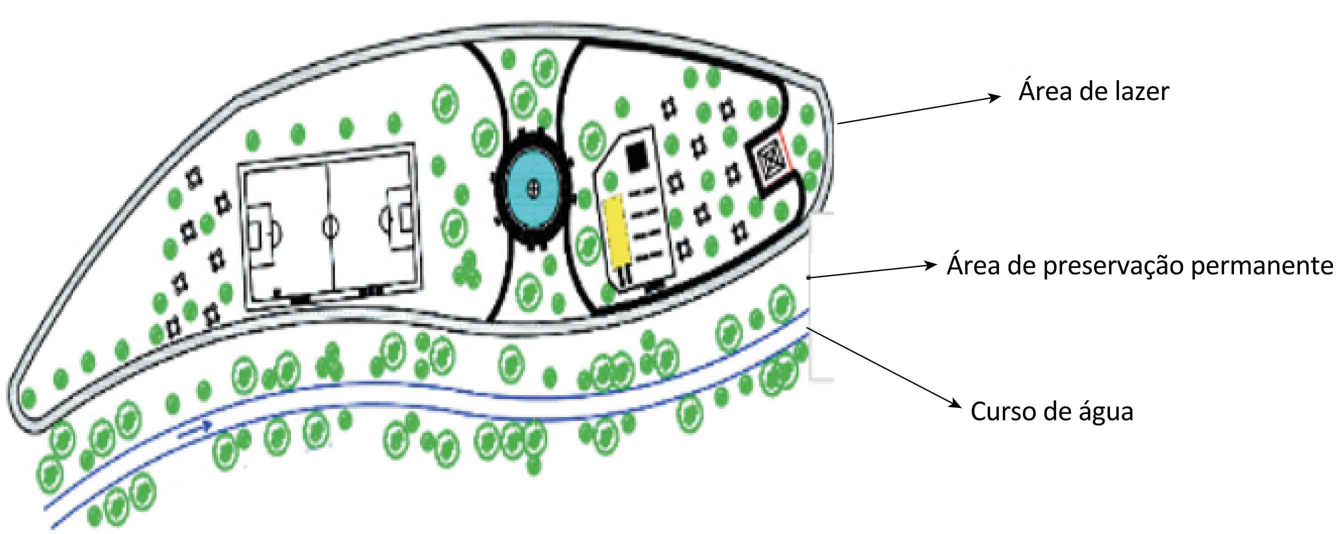
Na Figura 3, mostram-se dois tipos de parcelamento do solo: parcelamento tradicional, com arruamento na forma xadrez, sem considerar as características naturais do terreno; parcelamento respeitando a topografia do terreno (arruamento principal acompanhando as curvas de nível) e a drenagem natural das águas (adotando uma área verde no fundo do vale).

Da Figura 4, consta um exemplo de parcelamento do solo com baixo impacto ambiental, comparando-se com um projeto tradicional de parcelamento.

O CENÁRIO INTERNACIONAL

As ações de gestão ambiental e as leis de proteção de recursos hídricos dependem da história de cada país e refletem as heranças das relações entre sociedade e natureza.

Se compararmos o Brasil com países da Europa, por exemplo, constata-se que a transformação da natureza em espaços socialmente apropriados é recente na maior parte do país. Quando se pretende comparar os



Fonte: adaptado de Carneiro e Miguez (2012).

Figura 2 – Faixa de preservação e área de lazer às margens de um curso de água.

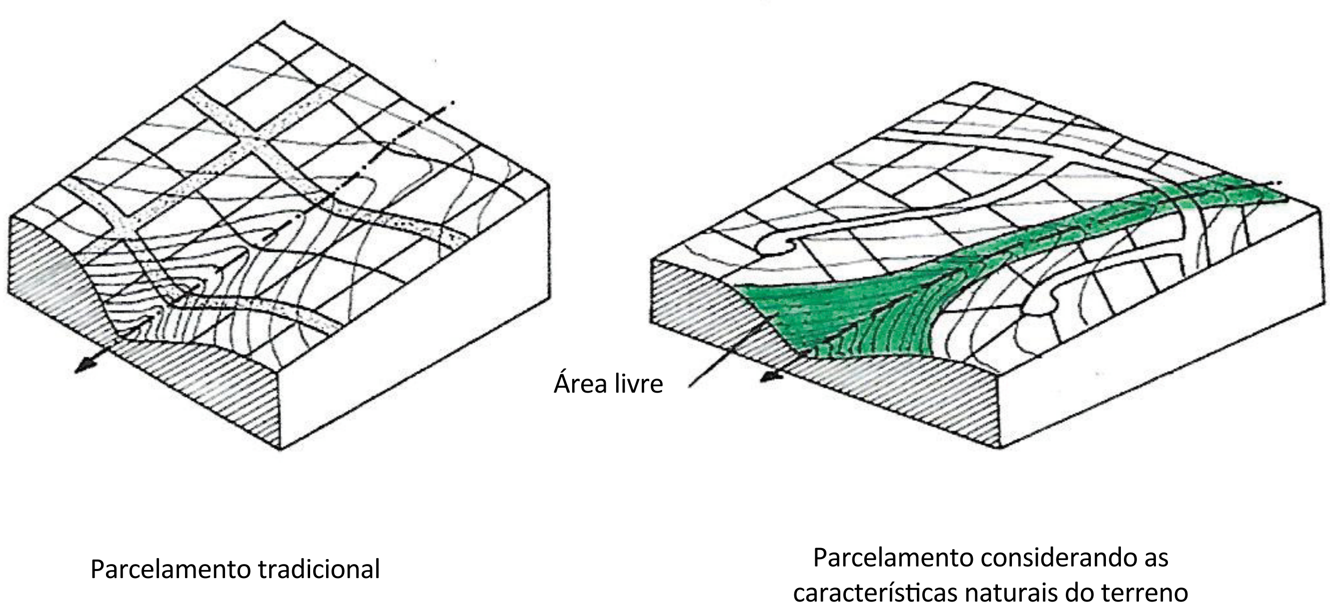
modelos de legislação e sua aplicação no Brasil com os de outros países, quanto às APPs, observa-se que há características diversas do meio, de legislação ambiental e diferentes necessidades de gestão, que dependem da realidade de cada país, as quais resultam dos processos históricos de uso e ocupação do solo.

Na França, por exemplo, as áreas naturais praticamente desapareceram, em 2010, elas representavam 1,2% do território (núcleos dos parques nacionais; áreas municipais de proteção da biota, reservas naturais nacionais e regionais na Córsega, reservas biológicas integrais e implementadas). Em outros espaços nacionais, os ambientes foram modificados pelas intervenções humanas profundamente e em um passado distante. Os leitos fluviais na França foram consideravelmente modificados e é difícil encontrar segmentos intocados, exceto em trechos próximos às nascentes ou de montanha. Eles foram transformados para a navegação fluvial, geração de energia hidrelétrica, mineração de depósitos aluviais, drenagem de bacias hidrográficas, proteção contra as inundações, abastecimento de água etc. Estas transformações têm produzido muitas perturbações, nas quais os instrumentos legais têm procurado objetivar na busca de ações de remediação (GASS *et al*., 2016).

De acordo com Gass *et al*. (2016), as faixas de vegetação herbácea ou florestal são definidas pela Lei nº 788, de 2010, que obriga os proprietários rurais a estabelecerem sua largura em pelo menos cinco metros. Suas funções semelhantes às de zonas úmidas (regulação do fluxo, purificação da água etc.) são claramente entendidas como uma forma de reduzir os fluxos de poluentes e de sedimentos que vêm das parcelas agrícolas. É a única norma que se impõe nos cursos d'água do espaço nacional.

Embora não exista na França um código florestal que defina limites para faixas de preservação, deve-se considerar que esse país é referência na gestão das águas, atuando fortemente na gestão territorial e de bacias hidrográficas, de forma integrada, visando à proteção dos mananciais.

Segundo Pedroso Júnior *et al*. (2015), nos Estados Unidos, a regulação das APPs é descentralizada. Assim, ela varia conforme o estado em que a área está localizada, o ente competente para normatizar o uso daquele local e a titulação (pública ou privada) da propriedade em que a APP está inserida. Diante dessa variedade, foi desenvolvida uma série de instrumentos para proteger áreas equivalentes às APPs brasileiras.



Fonte: adaptado de Mota (2011).

Figura 3 – Parcelamento tradicional do solo e parcelamento ambientalmente adequado.

O Committee on Riparian Zone Functioning and Strategies for Management, Water Science and Technology Board do National Research Council dos Estados Unidos estabeleceu algumas estratégias legais de proteção, a serem observadas pelos diferentes entes em diversos contextos (NATIONAL RESEARCH COUNCIL, 2002):

- Exigir identificação e análise de impactos a serem causados, com base em políticas de abrangência nacional e/ou estatal. Embora essa estratégia não se aplique apenas às florestas ripárias, ela é útil para que alternativas menos danosas sejam consideradas quando há intervenção nessas áreas;
- Limitar as atividades que o poder público pode desenvolver em florestas ripárias;
- Regular as atividades em florestas ripárias privadas, resguardando equilíbrio entre os direitos do proprietário e o interesse público;
- Incentivar em termos econômicos e capacitação técnica para a preservação de áreas ripárias, combinados a uma política de educação ambiental;
- Comprar (ou receber como doação) áreas privadas pelo poder público. Particularmente, essa estratégia tem sido muito utilizada no contexto urbano para criar corredores verdes (*greenways*) tanto com objetivos preservacionistas quanto recreativos.

Pedroso Júnior *et al*. (2015) ressaltam que essas estratégias estão baseadas em instrumentos normativos de abrangência federal, estadual e local. Embora a Federação seja competente para tratar de alguns aspectos específicos da proteção de áreas ripárias, em regra a competência sobre a matéria é dos estados. Porém, tradicionalmente, os estados delegam esse poder para as autoridades locais, de modo que grande parte da normatização dos Estados Unidos sobre a matéria é dotada de pequena abrangência. A maioria dessas normas desencoraja ou proíbe construções próximas aos lagos e cursos de água.

São exemplos de exigências feitas por estados americanos, de acordo com Pedroso Júnior *et al*. (2015):

Projeto tradicional de parcelamento do solo | Projeto de parcelamento do solo com baixo impacto

Fonte: CMAP (2003).

Figura 4 – Projeto tradicional de parcelamento e projeto de parcelamento com baixo impacto.

- · Massachusetts: as APPs têm uma extensão de cerca de 60 metros medidos a partir de cada margem do rio, entretanto essa largura diminui para 8 metros em determinados municípios urbanizados (como Boston e Chelsea, por exemplo), assim como em áreas densamente desenvolvidas (que assim forem designadas pelo órgão de meio ambiente competente). Além disso, os tipos de atividades e projetos permitidos na área de proteção variam conforme sua localização, a depender dos impactos do projeto e das características naturais locais;

- · New Hampshire: designa como área de proteção especial áreas localizadas até cerca de 80 metros de "águas públicas" (que incluem rios, a costa, e outros corpos de água). Nessas áreas, são proibidas determinadas atividades (como utilização para ferro-velho, por exemplo). Os demais usos urbanos, industriais ou agrícolas devem obedecer a *standards* mínimos de proteção;

- · Maryland: as APPs são classificadas entre áreas intensamente desenvolvidas, áreas desenvolvidas de modo limitado, ou áreas de conservação de recursos. A regulação das atividades a serem autorizadas nesses locais depende desta classificação.

Por causa do papel ecológico fundamental desses ambientes, a sua fragilidade e os serviços ecossistêmicos que prestam à sociedade, a União Europeia ressalta a necessidade de uma avaliação ampla da cobertura ribeirinha na Europa. Conhecer a sua distribuição pode fornecer a base para uma caracterização abrangente e uma análise ecológica em escala continental, para identificar as principais zonas ripárias, manter a conectividade paisagística, monitorar as tendências de mudança e avaliar os serviços ecossistêmicos que essas zonas podem fornecer (CLERICI *et al*., 2011).

Clerici *et al*. (2011) desenvolveram um modelo piloto de zoneamento das áreas ripárias para a Europa continental. Com base nos resultados do modelo, 2% da Europa continental é vista como áreas ripárias. A alta densidade dessas áreas é encontrada em territórios montanhosos, onde a densa rede hidrográfica e os *habitats* naturais estendidos criam as condições para a sua abundância. Em áreas simples, a presença de zonas agrícolas é a principal causa da baixa densidade das ripárias e da alta fragmentação. Uma primeira caracterização mostra que uma grande parte das zonas ripárias europeias (cerca de 70%) está associada ao *habitat* florestado, enquanto em menor medida às outras formas de vegetação. Esse resultado é importante, uma vez que fornece localização e uma indicação quantitativa de *habitats* florestais na Europa, que também têm significado ecológico como zonas ripárias.

Estudando a situação de várias cidades do Canadá, Ibrahim e Patrick (2017) concluíram que decisões políticas constituem o fator mais significativo para o planejamento e a gestão das ações de proteção dos recursos hídricos, sendo a capacidade técnica o segundo aspecto mais importante.

LEGISLAÇÃO E ÁREAS DE PRESERVAÇÃO PERMANENTE EM FORTALEZA, CEARÁ

Aspectos legais

O Plano Diretor participativo de Fortaleza instituído em 2009 definiu o macrozoneamento da cidade de Fortaleza em duas macrozonas: macrozona de proteção ambiental e macrozona de ocupação urbana. Essa classificação foi reconhecida pela Lei de Uso e Ocupação do Solo (Lei Complementar nº 62/2009 e alterações), na qual foi especificada a composição da macrozona de proteção ambiental (FORTALEZA, 2009).

A macrozona de proteção ambiental é constituída de ecossistemas de interesse ambiental, bem como por áreas destinadas à proteção, preservação, recuperação ambiental e ao desenvolvimento de usos e atividades sustentáveis, e é composta das seguintes zonas:

- Zona de preservação ambiental (ZPA), subdividida nas seguintes zonas: faixa de preservação permanente dos recursos hídricos (ZPA 1); faixa de praia (ZPA 2) e Parque Natural Municipal das Dunas de Sabiaguaba (ZPA 3);

- Zona de recuperação ambiental (ZRA);

- Zona de interesse ambiental (ZIA), subdividida nas seguintes Zonas: ZIA Coco, ZIA Praia do Futuro e ZIA Sabiaguaba.

O Capítulo III da Lei de Uso e Ocupação do Solo trata das normas específicas para ocupação das ZPA. Destaca-se o artigo 103: "Não será permitido o parcelamento do solo, tampouco a edificação, na Zona de Preservação Ambiental (ZPA), sendo permitido apenas o uso indireto dos recursos naturais" (FORTALEZA, 2017). O artigo 103 estabelece que nas áreas que estejam totais ou parcialmente em ZPA não se permite nenhum tipo de construção, até mesmo parcelamento do solo, o que reforça a necessidade de manter esses espaços preservados.

O parágrafo único do artigo 106 da Lei de Uso e Ocupação do Solo estabelece*:* "A execução de quaisquer obras, planos, atividades ou projetos de atividades públicas ou de interesse social será consoante o art. 8º da Lei nº 12.651/2012 (código florestal)" (FORTALEZA, 2017). O art. 8º do Código Florestal trata da supressão vegetal nas APPs, admitindo: "A intervenção ou a supressão de vegetação nativa em Área de Preservação Permanente somente ocorrerá nas hipóteses de utilidade pública, de interesse social ou de baixo impacto ambiental previstas nesta Lei" (BRASIL, 2012). Ou seja, a Lei de Uso e Ocupação do Solo faz menção ao Código Florestal no que tange à supressão de mata nativa, equiparando as ZPA e APP, admitindo que ambas possuam as mesmas funções ambientais.

Neste contexto, entende-se que as APP dos recursos hídricos do município de Fortaleza estão amparadas pela legislação municipal por meio das ZAP-1. Quando se consideram as diretrizes e gestão dessas áreas, o plano diretor municipal assemelha-se ao Código Florestal brasileiro, no entanto as distâncias e os limites mínimos estabelecidos pela legislação federal para as APP nem sempre são observados na legislação municipal para as ZPA.

A seguir, faz-se uma análise da situação das APP dos recursos hídricos urbanos, no contexto da legislação municipal da cidade de Fortaleza.

Alterações na legislação e as zonas de preservação ambiental de Fortaleza

O Plano Diretor de Fortaleza sofreu alterações durante sua vigência, sendo a última decorrente da Lei Complementar nº 250, de 3 de julho de 2018, que afetou diretamente as APP dos recursos hídricos, atingindo 18 sub-bacias hidrográficas de Fortaleza (FORTALEZA, 2018). Vários limites de ZPA 1 foram alterados por essa lei complementar.

Utilizando-se os arquivos disponíveis no *site* da Prefeitura de Fortaleza, e usando a superposição de mapas em programa de SIG, foram determinadas as alterações nas ZPA 1 decorrentes da referida lei complementar.

Antes da vigência da Lei Complementar nº 250/2018, o município de Fortaleza possuía 45.459.564,24 m^2 de ZPA 1. Com a vigência dessa lei, foram acrescidos 3.701.792,03 m^2 e suprimidos 4.662.977,37 m^2, resultando na redução de 961.185,34 m^2 (2,11%) de áreas das ZPA 1.

Ressalta-se que a legislação municipal nem sempre observa o Código Florestal na definição das áreas de preservação permanente, tendo estabelecido faixas com larguras inferiores ao mínimo de 30 metros exigido na legislação federal. Além disso, em vários casos, as ZPA 1 não devem corresponder somente aos 30 metros nas margens dos recursos hídricos urbanos, pois as medidas mínimas a serem adotadas devem variar em função das larguras das calhas do leito regular dos cursos d'água, como exige o código florestal, o que não ocorreu em Fortaleza. Assim, o total de APP às margens dos recursos hídricos de Fortaleza, se fosse observada a lei federal, seria bem superior ao que é exigido pela legislação municipal em vigor (Lei Complementar nº 250, de 3 de julho de 2018).

Como exemplo de alterações ocorridas nas áreas de preservação dos recursos hídricos de Fortaleza, elaborou-se o mapa constante da Figura 5, no qual é possível observar, na bacia do Rio Cocó, as áreas de ZPA 1 acrescidas, suprimidas e mantidas pela Lei Complementar nº 250/2018, comparando-se com as áreas anteriores, definidas na Lei de Uso e Ocupação do Solo de Fortaleza (Lei Complementar nº 62/2009, alterada pela Lei Complementar nº 101/2011) (FORTALEZA, 2011).

Na Bacia do Rio Maranguapinho também foram observadas algumas supressões de áreas de ZPA 1, como indicado na Figura 6.

Vê-se que ocorreram reduções nas APP das duas bacias hidrográficas (indicadas nas legendas com cinza escuro), principalmente nos trechos mais urbanizados.

A fragmentação das ZPA 1 constitui um dos principais problemas, pois as APP de recursos hídricos fragmentadas tornam-se mais vulneráveis à ocupação.

A ocupação de APP é um problema recorrente nas cidades brasileiras densamente urbanizadas. Ressalta-se que, como no caso de Fortaleza, as legislações municipais que definem as APP nem sempre observam as exigências do código florestal, pois estabelecem faixas com larguras inferiores às exigidas na legislação federal.

Em Fortaleza, muitas áreas das ZPA são ocupadas por assentamentos precários, residências, serviços, indústrias, equipamentos públicos, entre outros. A maioria das ocupações ocorre por edificações e vias, ou seja, essas áreas encontram-se impermeabilizadas, o que influencia diretamente na drenagem das águas pluviais, sendo comum a ocorrência de enchentes.

CONCLUSÕES

O crescimento das áreas urbanas tem ocorrido, geralmente, de forma desordenada, com a ocupação de áreas que deveriam ser preservadas, como as margens de recursos hídricos (APP), resultando em diversos problemas ambientais.

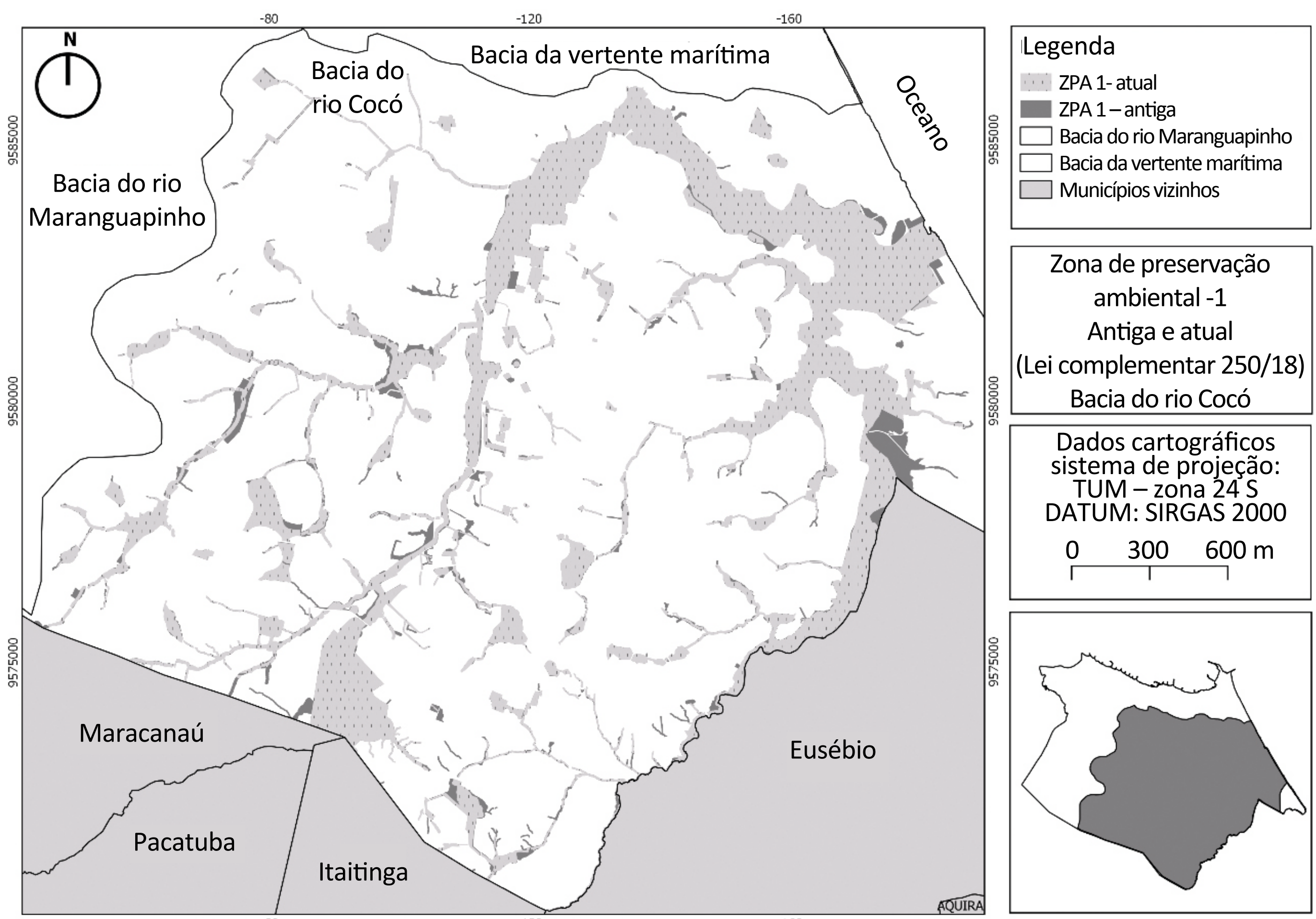


Figura 5 – Zonas de Preservação Ambiental 1 da Bacia do rio Cocó, Fortaleza, Ceará, antes e depois da Lei Complementar nº 250/2018.

É necessário que a ocupação dessas áreas seja controlada, o que ressalta a importância da gestão ambiental e da legislação de controle urbano. As ações de gestão ambiental no município têm grande importância para a proteção dos recursos hídricos. Do mesmo modo, uma legislação de uso e ocupação do solo que tenha como objetivo o uso adequado dos recursos naturais é fundamental para a preservação das áreas situadas às margens dos recursos hídricos, consideradas como de preservação permanente.

A legislação municipal de uso e ocupação do solo deve observar as exigências do código florestal, no que se refere às APP, no entanto isso nem sempre acontece, como no caso da legislação de Fortaleza.

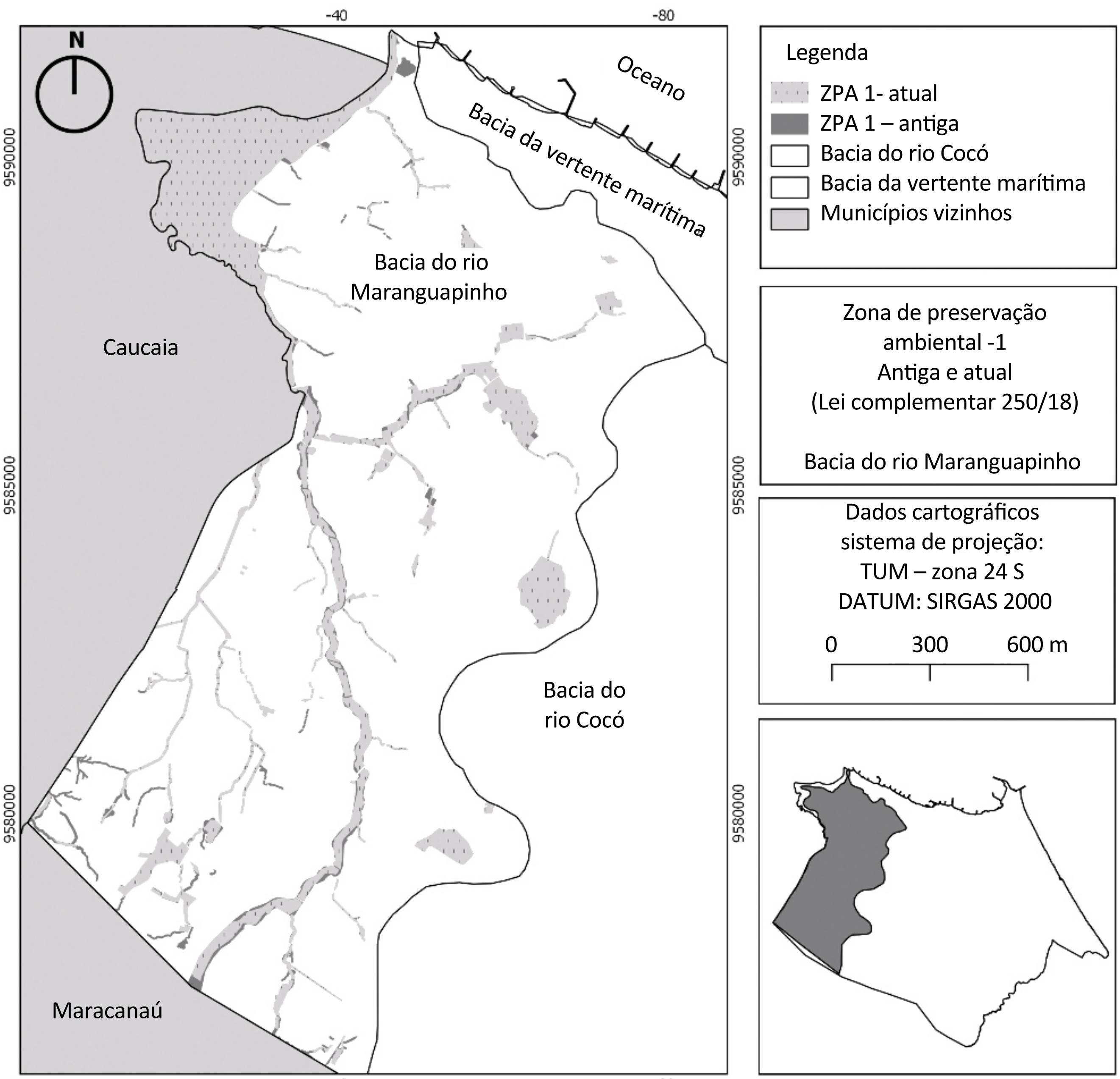


Figura 6 – Zonas de Preservação Ambiental 1 da Bacia do rio Maranguapinho, Fortaleza, Ceará, antes e depois da Lei Complementar nº 250/2018.

A legislação que trata das ZPA 1 em Fortaleza é menos restritiva que o código florestal, definindo, em muitos casos, faixas de preservação com menos de 30 metros às margens dos recursos hídricos, mínimo exigido pela lei federal.

Alterações efetuadas na Lei de Uso e Ocupação do Solo têm resultado na redução das áreas de preservação. As últimas modificações, definidas na Lei Complementar nº 250/2018, resultaram na redução de 961.185,34 m^2 (2,11%) de áreas inseridas nas ZPA 1 de Fortaleza.

Além disso, tem ocorrido a ocupação das áreas consideradas como de preservação pela legislação municipal, o que tem ocasionado sérios problemas de drenagem, com graves consequências para a população.

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THE CAPIBARIBE PARK PROJECT, RECIFE: USING THE RIVER TO REINVENT THE CITY

PROJETO PARQUE CAPIBARIBE, RECIFE: REINVENTANDO A CIDADE A PARTIR DO RIO

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ABSTRACT

Recife is an amphibious city whose urban development does not value its rivers. In the past, the city's main watercourse, the river Capibaribe, was understood to play a key role in structuring urban spaces and providing connectivity. Since then, this understanding has dwindled, and the resulting situation is a cause of great concern. Recife City has turned its back on the banks of its rivers and neglected both their capacity to smooth and shape urban space, and their potential to create a coherent image of the city. Recife is one of those cities in the world that are most vulnerable to climate change, ranking 16th in the list of world hotspots. In order to confront these challenges and rethink the role of the river that runs in the heart of Recife, researchers, architects, engineers, and sociologists from Research and Innovation for Cities — *Universidade Federal de Pernambuco* (INCITI-UFPE) were invited by the Recife City Hall to draw up plans for a park stretching along the river's banks. Capibaribe Park Project attempts to answer one key question: How can we use the river to transform the city? The park project is based on a structural approach to landscape and is guided by the precepts of sustainability and regeneration of public spaces, in line with the emerging paradigm that combines a cross-disciplinary and cross-sector approach with water-sensitive design and social participation. The present article presents an overview of the main characteristics and development of this project, its theoretical and methodological underpinnings, its contribution to society, and the results achieved so far. It shows how, in addition to the planned park, the project also envisages the installation of a much more extensive system of parks, as a first stage towards the creation of park-city by the 500th anniversary of the foundation of Recife, in 2037.

Keywords: sustainability; Recife city; River Capibaribe; urbanism and landscaping; water-sensitive urban design.

RESUMO

Cidade anfíbia, o Recife não valoriza seus rios em seu ordenamento territorial. Principal curso d'água da cidade, o Capibaribe chegou a receber atenção correspondente ao seu papel de articulador e estruturador dos espaços urbanos no passado. Desde então, esse interesse reflui, resultando em um quadro preocupante: o Recife deu as costas ao rio, desprezando tanto sua função de organização e amenização dos espaços urbanos, quanto seu potencial de dar coesão à imagem da cidade. Frente ao processo de mudanças climáticas, a cidade é uma das mais vulneráveis, ocupando o 16º lugar na lista de pontos de acesso mundiais. Para enfrentar essas problemáticas e revalorizar o papel no rio que atravessa o coração da cidade, pesquisadores, arquitetos, engenheiros e sociólogos do Pesquisa e Inovação para as Cidades - Universidade Federal de Pernambuco (INCITI-UFPE) foram convidados pela Prefeitura da Cidade do Recife para projetar um parque linear às suas margens. O objetivo do Projeto Parque Capibaribe era responder à uma questão chave: como transformar a cidade a partir do rio? Fundado em uma abordagem estrutural da paisagem e guiado por preceitos como a sustentabilidade e a requalificação de espaços públicos, o projeto alinha-se com um paradigma em formação, associando aspectos como a integração setorial e disciplinar, a sensibilidade para com as águas e a participação social para efetivação do parque. Este artigo resume o desenvolvimento desse projeto, seus referenciais teórico-metodológicos e resultados, sua natureza e contribuições. Revela-se que, além do projeto de um parque, consolidou-se a perspectiva de estruturação de um sistema de parques, primeiro passo rumo à concepção de uma cidade parque no ano de 2037, ano em que o Recife festeja seus 500 anos.

Palavras-chave: sustentabilidade; Recife; Rio Capibaribe; urbanismo e paisagismo; urbanismo sensível às águas.

INTRODUCTION

Recife is well known as a city intimately related to the waterways that run in it. It is described as such in many poems and literature works. Some of these describe the city in a glowing light, full of civic pride. It is the city "where the rivers Capibaribe and Beberibe meet to form the Atlantic Ocean" (as the local saying goes), or the city that is "part imagination, part robbed from the sea" (CARNEIRO LEÃO, 1999, p. 129). At other times, it has been denigrated: viewed as a "dog without feathers" – an unattractive living being that has lost everything of its own (MELO NETO, 1999, p. 103-116) – the final setting of the peregrinations of the migrant worker Severino (MELO NETO, 1999, p. 103-116), burdened with his whole family by the cruel cycle of the "man who lives like a crab" (CASTRO, 1967, p. 13-14).

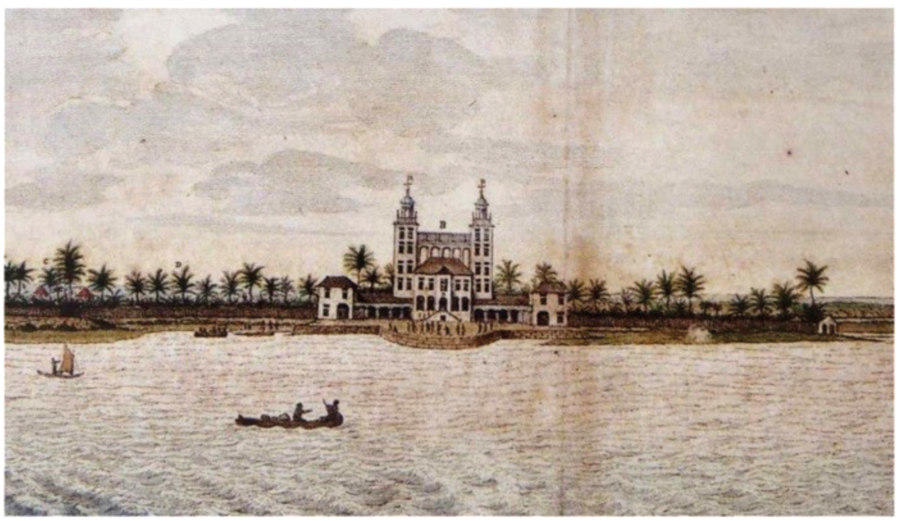
These citations picture Recife as an "amphibious city" (CASTRO, 1954, p. 23), a place where "anything that is not water, either has been or will be water" (OLIVEIRA, 1942, p. 48), in which "it is hard to know where the river begins... and where man, where his skin begins from the mud" (MELO NETO, 1999, p. 103-116). As an estuarine city subject to the vicissitudes of the tides and river currents, Recife was deemed suitable for the construction of a port in the 16th century. At that time, it was a small coastal island sheltered by coral reefs, from which it got the name (from Arabic "ár-raçif", meaning dike, wharf, breakwater, DINIZ, 2010, p. 33), in 1537, of Reef Harbor Estuary.

The development of the city also owes a great deal to the navigable river Capibaribe, along which people and merchandise travelled between sugar mills and the port, connecting the floodplains, in the west, to the Atlantic Ocean, in the east. Throughout its history, Recife developed by way of a series of urban planning, architectural and landscaping interventions, which resulted in a city of stunning landscapes. From the very beginning, the sea, the estuary, the rivers, the streams, and canals have made their presence felt, providing open spaces and broad vistas of varying scales within the hydrographic basin that structures the locale. Recife's history of landscape architecture dates back to the 16th century, with the creation of Count John Maurice of Nassau-Siegen's Freiburg Palace Park, by the architect Pieter Post (Figure 1), and the drawing up of an urban plan in which the waters of the canals and the winding river structured the morphology of the city center in the early stages of its development, in typically Dutch fashion. This tradition consolidated landmarks such as Avenida Martins de Barros, the area surrounding Praça da República and Rua da Aurora, and the State Governor's Palace, near the original site of Nassau's Palace (Figure 2).

Currently listed among the 16 cities in the world most vulnerable to the effects of climate change (IPCC, 2013), Recife no longer respects its rivers. The hydrographic basin of the river Capibaribe — the river of the capybaras, the most important watercourse in the city — is associated to the fragility of the fluvial and estuarine environment, its dynamics and its capacity to withstand the effects of extreme climate events. This underlines the extent to which the environment in which Recife is located is susceptible to these ill effects. Furthermore, factors relating to urban systems and infrastructure, modes of production and urban life, planning tools, projects and management may increase or lower the risk of accidents, underlining the vulnerability of this society and the lands it occupies.

Building resilience in such a society and physical environment, with this hydrological dynamic, requires urgent acknowledgement of the urban and landscape features of the river basin and of the way it has been appropriated and occupied by residents. Resilience is translated into the ability societies and urban structures of reacting to and recovering from accidents and disasters. Good practices in other countries (ROBERTS; GORE; BULKELEY, 2018) show that there is no other way to introduce measures and practices that favor resilience in Recife, especially those related to the effects of extreme weather events, such as flooding and torrential rain.

A recent experience of the development of Capibaribe Park Project (INCITI-UFPE, 2019) testifies to the scale of the challenge posed. The initial aim of the project was to ascertain the physical-environmental and socio-spatial patterns of occupation of riverbank spaces



Source: INCITI-UFPE (2019).
Figure 1 – Freiburg Palace (17th century).

Source: INCITI-UFPE (2019).
Figure 2 – Campo das Princesas Palace (19th century).

to transform them. The overall objective, from a managerial point of view (as a collaboration between municipal government and university), was to draw up intervention/action guidelines for changes based on the idea of a linear park along river banks. In terms of scientific research, the aim was to investigate the object of research in more depth, building up methodologies and new knowledge for the purpose of urban land use planning, guided primarily by the relation between water and the city, and the key question of how to use the river to transform the city.

Adapting to the complexity of the inter-related issues involved, the methodology adopted was based on urban ecology, which studies "the interactions between organisms, built structures and the natural environment, in which people congregate within the city" (FORMAN et al., 2014, p. 312). Thus, the physical features (the natural and built environment), and social and environmental dynamics (the economy, mobility, management, the biome, water resources, the climate, and so forth) are compared as a way of guiding development at an acceptable level of sustainability as to the ecosystem, economic and social balance.

With the aid of strategic planning tools, the project provides a vision of the future for Recife on its 500th anniversary (in 2037), based on a refoundation of the city and its reintegration into the system of waterways from which it emerged. Social participation is the tool used to build up this set of guidelines, involving experts and ordinary citizens working together to use the river to reinvent the city. The focus of the studies, in terms of theme and geographical location, has shifted with the progression of research. At first, the initiative concentrated on the riverside itself, but the project has progressively broadened its scale and scope to cover a whole range of guidelines for the restructuring of the city on a larger scale, later including Beberibe and Tejipió river basins and the city as a whole.

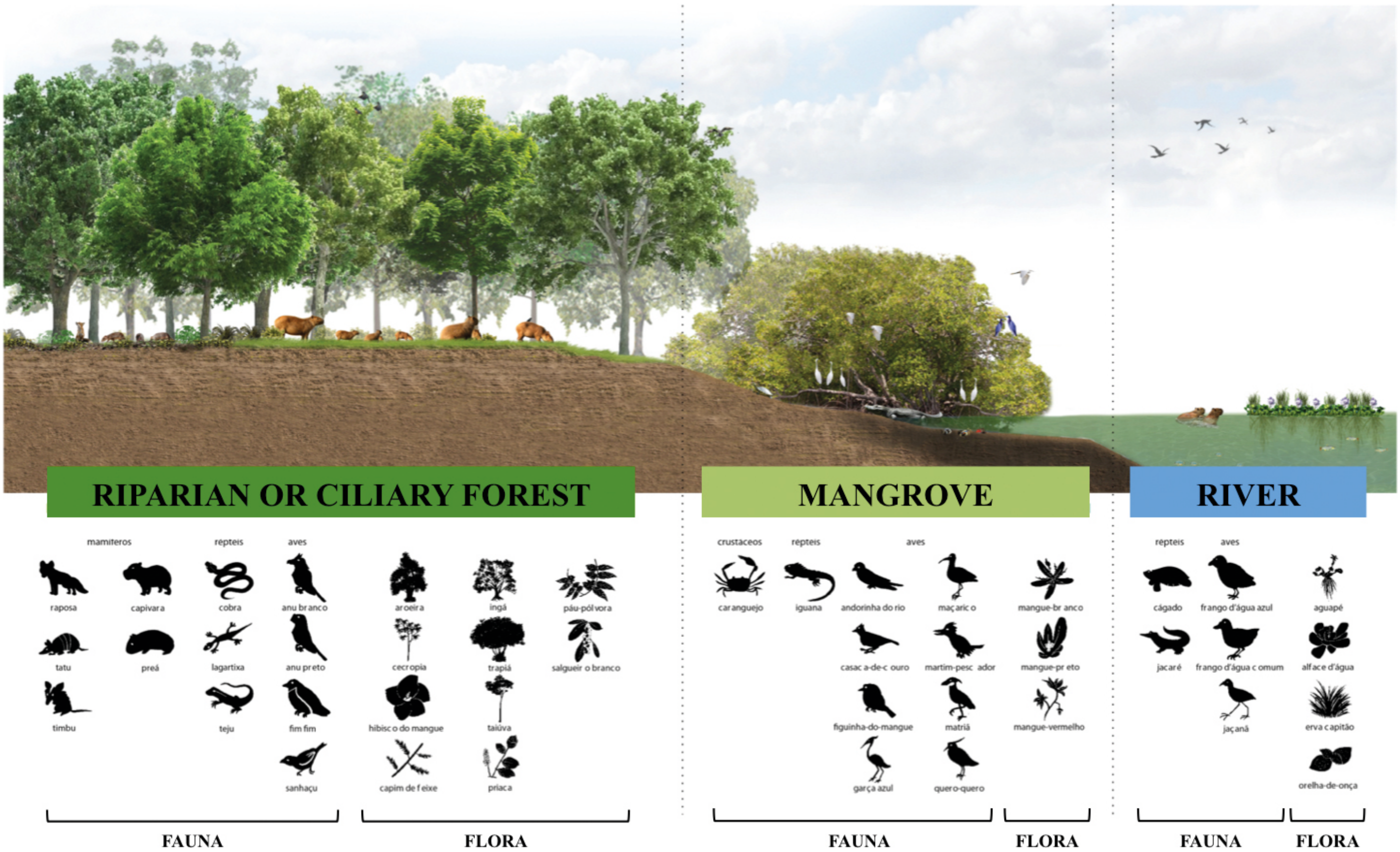
During this experiment, another kind of technical change was envisaged, which subsequently became a specific objective. Interventions were formerly restricted to the physical control of water, conducted primarily by engineers, involving artificialization and pollution of watercourses. However, the increasing intensity and frequency of extreme weather events, such as floods, disasters and the resulting damage, led to the adoption of a new paradigm of sensitive design, regarding urban water resources as part of the overall ideal of sustainability. This has involved experts from fields other than Hydrology, including architects and urban planners.

Therefore, we describe herein the process underlying the development of Capibaribe Park Project, its content and the results achieved so far, and show how they are linked to the latest progressive principles that help hydrologists, urban planners and landscape architects to work together for conceiving and constructing sustainable cities of the future and improving the quality of our lives.

THE MAIN ISSUE: RECIFE, LAND-USE PLANNING, AND MANAGEMENT OF URBAN WATER RESOURCES

The river Capibaribe is an essential part of Recife's territory and identity, having guided its urban development over time. However, its potential to create a landscape that brings the city together is being neglected for decades. Urban sprawl, fueled by a focus on roadways between the 1950s and 1980s, and the absence of an overall city project distanced the city (built by humans) from its natural environment and citizens alike.

The road system ignores pedestrians and cyclists, squeezing them out onto narrow pavements and cycle paths, with inadequate tree covering, public spaces commandeered for parking, both air and noise pollution, and poor security. In this amphibious city, streams were turned into canals, straightened, clad in concrete, and confined between roads. The banks and beds of rivers were occupied by informal housing, impeding natural drainage, and destroying ecosystems associated to riverside vegetation. River banks were affected by unfettered urbanization and used for roads. One project aimed to install four-lane expressways along the full length of Capibaribe on either side. Riverside vegetation was destroyed or altered, and is now mostly composed of non-native species. Despite that, vegetation is still abundant and provides a habitat for a surprisingly diverse fauna, including capybaras, alligators and otters in the river and on its banks; and marmosets and various species of bird in the boughs of trees (Figure 3).



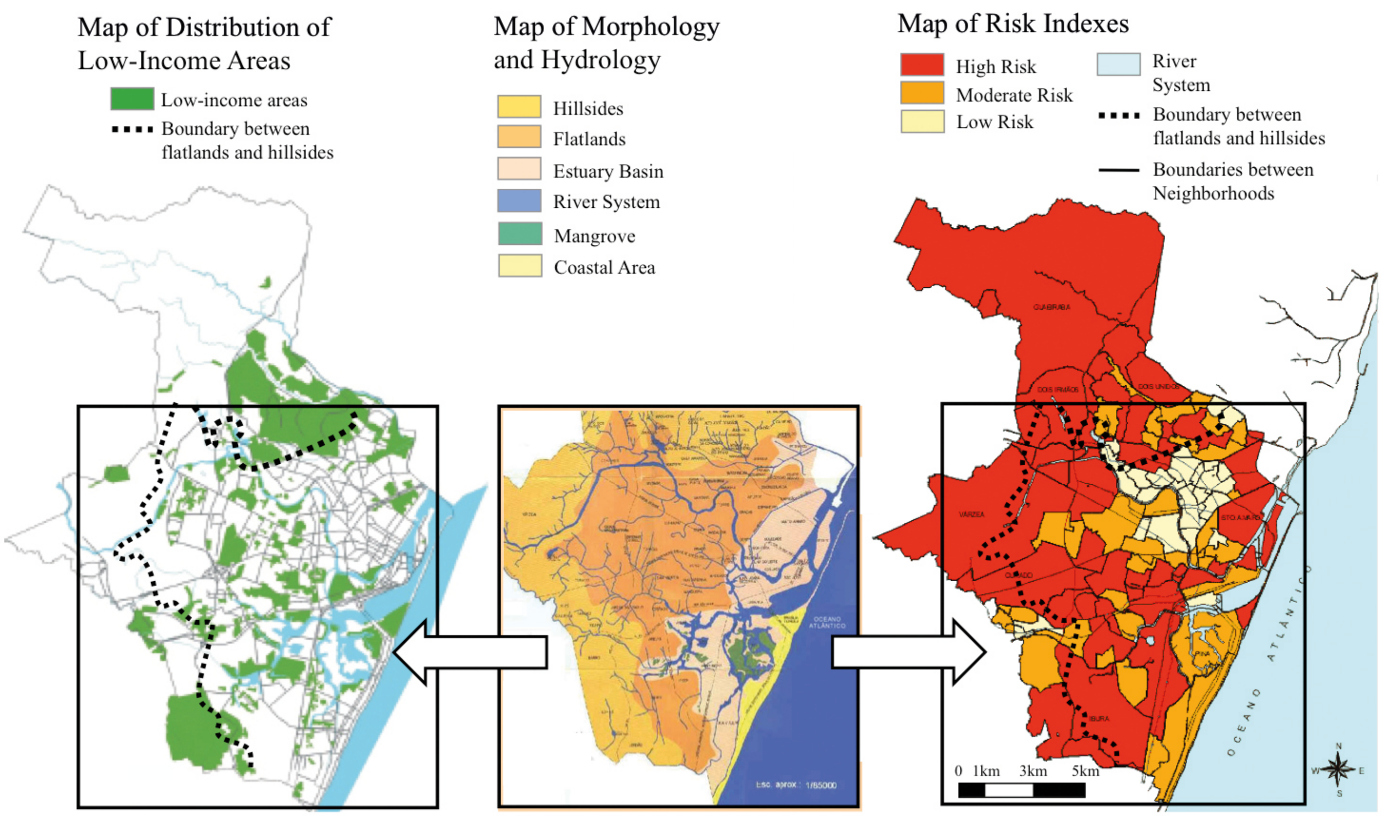
Source: INCITI-UFPE (2019).

Figure 3 – Survey of Ecosystem Fauna.

Recife became a city where land is mostly occupied in an irregular or informal manner, with no planning, and flagrant disregard for urban planning laws, physical and environmental constraints, and the lay of the land. In 2014, the Municipal Sanitation Authority (*Autarquia de Saneamento do Recife* — SANEAR) calculated that over 33% of land in the city is occupied by low-income settlements, with 53% of the population living in such areas (RECIFE, 2016). According to the 2010 Census by the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística* — IBGE), such individuals totaled over 825,000 (IBGE, 2010). The Atlas of Human Development of the RMR (PNUD; IPEA; FJP, 2014) shows that the poorest and most vulnerable people live in the most at-risk areas (Figure 4).

It is no coincidence that these areas are also places where the city conflicts with its waters, with flooding of low-lying areas, landslides, water shortages, and sewage pollution on all sides. However, the conflict between the water dynamics and a pattern of land occupation that is not sensitive to this, with the attendant risks and impacts, is not restricted to underprivileged neighborhoods. Areas inhabited by higher income strata also follow the model of separation of residents, river, and nature. The automobile culture, that chokes the river and its streams, now all channeled into canals, constantly makes its presence felt.

In recent years, the relation between the city and nature has once again attracted the attention of scholars and urban managers. The constraints and opportunities presented by natural features for restructuration, organization and oversight of cities became an essential guide for urban planning. Bourdeau-Lepage (2016) spurs reflection on new approaches to urban planning, suggesting new parameters for work in this field. Resolution of the conflicts between the city and nature require that we abandon the ideal of mastering nature and, instead, seek to reveal its hidden face,



Source: Diniz (2010).

Figure 4 – Land use, relations between urban water resources, poverty, substandard housing, and at-risk areas.

insofar as this accords with the needs and desires of citizens.

Water management is related to land-use planning, both because water resources influence and determine the spatial configuration of human occupation, and because of the influence the latter have in turn on watercourses and flooding. On the one hand, water shapes space, with winding rivers that guide the course of roadways and other urban structures (thoroughfares, leisure areas, and open spaces, in particular). On the other hand, these aspects, in turn, shape the distinct patterns of land use, determining its density, according to the availability of drinkable water or restrictions on the occupation of land prone to flooding or landslides.

There is another kind of relationship between water/nature and city/artifact: the potential to generate or suppress the conditions essential for a good quality of urban life, like expounded by Lima and Garcez (2017). This may be objective, as in the supply of water in sufficient quantities and of sufficient quality for human settlements; or subjective, as in the case of the pleasure that aquatic landscapes furnish, as perceived and experienced by citizens. Either way, these relationships play a fundamental role in creating sustainability: the key notion of the emerging paradigm regarding urban waters.

Brodach and Goffi (2005) argue that sustainable development of cities depends on their capacity to create a balance between the urban system and the human and natural environments. In a rapidly changing urban environment, resilience requires physical elements (site conditions; unpredictable climate events) to be related to social ones (socioeconomic dynamics, at-risk populations, distribution of infrastructure and urban services, planning and management systems). Pincetl (2005) notes that improved quality of life of citizens is the ideal that guides the principles that determine the shape and density of urban environments. The growth of cities, their populations, and consumer's demands resulted in changes that affect "the health of ecosystems" which form part of the physical structure of cities (PINCETL, 2005, p. 209). We need good knowledge of a city to build and oversee it in such a way to gradually improve its formal and operational aspects, preserving the quality of life of its residents.

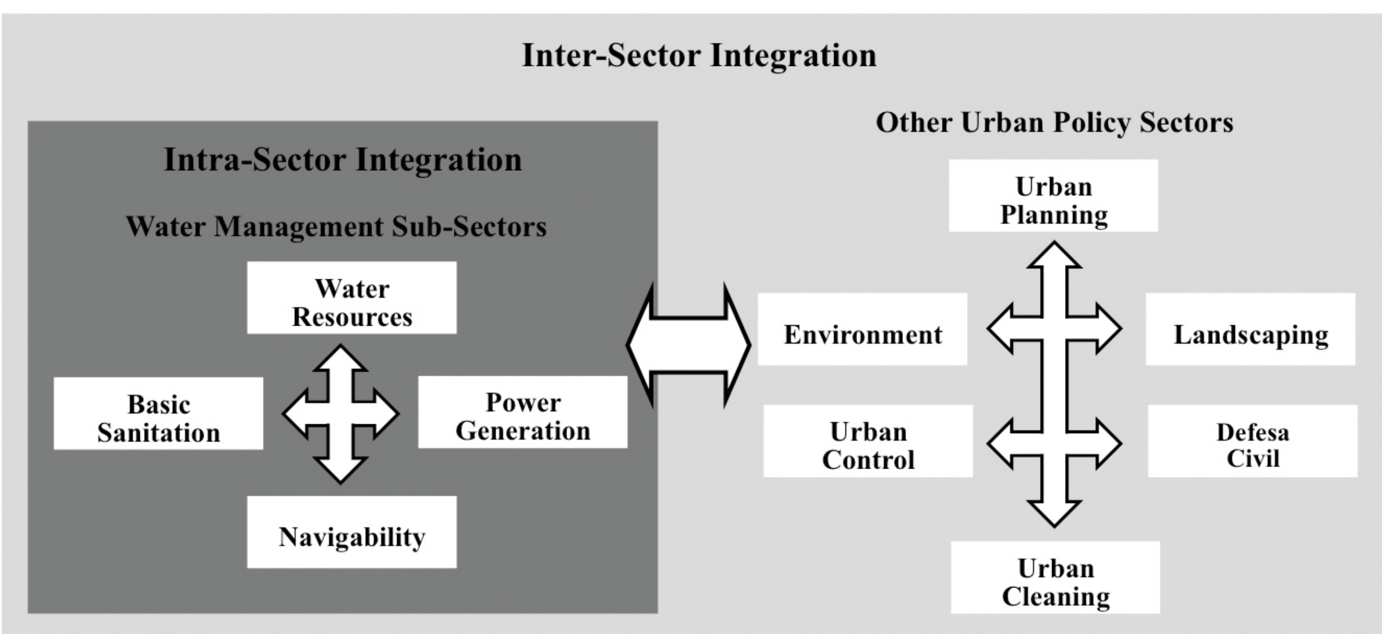
A sustainable city has a balanced ecosystem, whose structural features (the physical elements and relationships between them) respond to the level of evolution of functional needs (activities, flows, and decision-making), its crises and transformations. In the context of climate change, with more frequent accidents and disasters, a resilient city is one in which these elements combine in such a way as to allow it (in order of priority) to resist, react to and recover from the material and human impacts and the damage they cause.

Sustainable urban development requires sustainable management of city water resources that considers the need to focus on the specificities of the processes of land-use planning and their natural, physical, social and political determinants. Places where natural factors dictated by water resources and the action of social organizations occupying space overlap, we can adopt the view posited by Brun (2006), according to which urban water management requires a land-use planning approach. It should be seen in the context of policies regarding land use, coordinated at the sectoral level of zoning and urban planning.

In the clash between urbanization and water resource dynamics, the basic issues that lead to systemic disequilibrium stem from the complex process of producing the urban space. They involve the social and environmental factors that drive or restrain it, the specific interests and status of individuals and institutions involved in conducting the process, and the human experiences and relationships created by it. In other words, we need to address issues of susceptibility and vulnerability and build urban resilience based on coexistence with water resources. These are land-use issues susceptible to planning.

However, to achieve this, we need the effective involvement of various fields of knowledge associated with water resources and cities. In water management, there is a need for dialogue on two levels:

- between distinct sectors, involving cross-sector work on urban policies (environment, urban planning, landscaping, urban control, civil defense, urban cleaning, as well as water management);



Source: Diniz (2010).

Figure 5 – Overview of Inter- and Intra-Sector Integration.

- between water management sub-sectors (basic and environmental sanitation, water resources, power generation, navigability) (Figure 5).

This integrated approach to land-use planning is complex, but water is the cross-cutting issue. It contains the oft-neglected factor of the landscape as a key component of environmental, health and land-use planning policies. A multifaceted issue, which addresses human, social and natural sciences, landscape can either be viewed as a set of (physical, palpable) material and (cultural, subjective) immaterial elements, or as the result of the impact of human activities on the natural environment, filtered by the human eye when in contact with the landscape in everyday existence. Created by human activities in space (DOLLFUS, 1990), landscape only exists when it is perceived by all senses—smell, touch, hearing, sight—with the latter being essential for perceiving the physical spatial aspects of this landscape.

Despite the constraints on such integration, bringing together multidisciplinary fields and distinct public policy sectors opens a new range of possibilities. Urban land-use planning does not usually consider landscape issues to be important, because of a technical culture that pays little regard to the subtler aspects of relationships between society and the built spaces in which people live. Landscape architecture, as a project intervention that aims to order (natural and artificial spatial elements), aims to promote or facilitate sensitive human experiences of the environment, as a supplement to the improvement of urban habitats. In the case of Recife and its main river, this field of work is not only desirable but necessary.

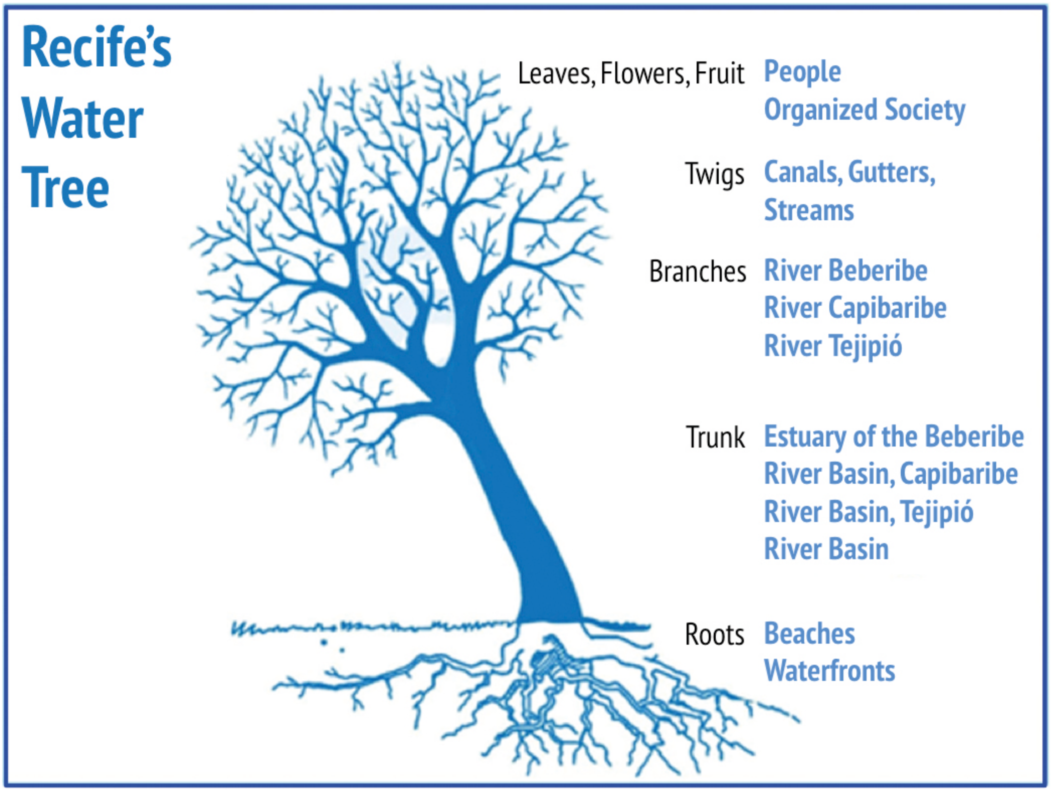
In order to confront the challenges outlined above, there is a need for bold cultural change, broadening the range of fields and techniques available to planners and city managers, supported by the theoretical and methodological inputs that founded the project. A mixture of disciplines is one of the innovations presented for urban interventions that aim to fulfill the complex task of building sustainability and resilience, in a manner that balances the city's growth with conservation of ecosystems. The ecosystems created by rivers enhance the quality of urban *habitats*, enhancing our enjoyment of it and mitigating risks. Although Capibaribe Park Project does not aim to achieve the level of re-naturalization entertained by Brun, Coursière and Casetou (2014), its methodology, presented below, helps to create such a culture, and to aid understanding and practical application of it.

METHODOLOGICAL AND EMPIRICAL CONSIDERATIONS: CAPIBARIBE PARK PROJECT AS AN EXERCISE IN RESOLVING CONFLICTS BETWEEN THE CITY AND ITS WATERS

Seeking to change an already deep-rooted culture, old customs and practices that have often been traditionally accepted as the most appropriate must be broken. This is what researchers from Universidade Federal de Pernambuco and the members of the Research and Innovation for Cities Group (INCITI-UFPE) have done to some extent. In 2011 (in Amsterdam) and 2012 (in Recife), these professionals staged an international workshop, the Recife Exchange Amsterdam (RxA), as part of a partnership between UFPE and ARCAM (Amsterdam Center for Architecture), in which they developed the metaphor of Recife as a water tree (Figure 6), in which the water system structures land use.

The approach adopted considers a broad range of questions to shed light on the dynamics of watercourses and their effect on space in Recife City, as a result of the social and spatial practices that constitute that urban space. Elements of a physical and social nature, and subjective (sensible) and objective (measurable) features were studied, bearing in mind the distinct kinds of information on issues relating to natural and artificial environments. This task involved the mobilization and cooperation of professionals and researchers from a diversity of fields: architects, urbanists, engineers, historians, geographers, social scientists, communicators and designers. The water tree sums up this dynamic system and its components, the roots being the (predominantly conflictual) relationships between water and human beings in the urban environment.

The method used and the results achieved , albeit at a preliminary proposal stage, attracted the attention of the local authorities and, in 2013, INCITI-UFPE was in-



Source: INCITI-UFPE (2019).

Figure 6 – The Water Tree.

vited by Recife City Hall to support a return to a more positive relationship between the river and the people of Recife, promoting vitality and quality of urban life. This request was further developed into a partnership between INCITI-UFPE and the Municipal Department of the Environment and Sustainability (*Secretaria de Meio Ambiente e Sustentabilidade de Pernambuco* — SEMAS-PCR) to develop the project for a park alongside the banks of the river Capibaribe. The project adopted an interdisciplinary approach, mobilizing 40 researchers and professionals divided up into 12 study groups in various higher education institutions. Individuals from various fields of expertise collaborated, and fieldwork was conducted on issues such as Sustainable development, Urban design, Mobility and Accessibility, Botany, Biology, Morphology, Ergonomics, Housing, Engineering, Landscape architecture, Sociology, Law, Economics, History, and Water resources. Eight empirical studies were carried out in collaboration with international teaching institutions, following the workshops, such as Recife Exchange Holland (RXH), held in 2019 as a continuation of Brazilian-Dutch co-operation, now including French partners.

Since the early days of the PCR-UFPE partnership, studies of land-use planning have pointed to the urgent need to adopt a novel approach, expanding not only the geographical scope of project surveys and analyses, but also the dynamics associated to the promotion of quality of the spaces covered by the interventions. In the end, the work undertaken resulted in the proposal of an urban landscape intervention covering 42 neighborhoods and a surface area of 7,744 hectares, and affected the everyday life of roughly 445,000 citizens. A large amount of information regarding the fluvial and riverine environments was accumulated. The data gathered guided the macro-guidelines for land-use planning and a variety of actions that aim to use the river Capibaribe to transform the city. These guidelines start out from the premise that the river forms an axis that brings together various systems: the environment, non-motorized transportation, shared streets, canals, parks, and squares. This park's landscape, covering 30 km of river bank, whose fauna and flora form an ecological corridor, already exists. The challenge is to consolidate and expand it, with gradual regeneration and installation of new green areas and urban equipment, as the needs of riverside communities and the population of the city in general dictate.

Heedful of the concepts and principles of urban ecology, Capibaribe Park Project also adopted approaches from emerging urban planning theory, with citizen participation being a key plank in the development of proposals. Although actively promoted, this participation involves bottom-up management processes, thereby strengthening the spontaneous character of subsequent experiences and the practice of negotiation. The concept of tactile urbanism was also adopted, enabling citizens to participate both in the development of innovative ideas and solutions, and in the construction and experimental implementation of tangible physical models (prototypes) prior to full-scale installation. These conceptual and methodological benchmarks form the basis of the principles outlined by Capibaribe Project in its Urban Development and Environmental Recovery Plan (*Plano Urbanístico de Recuperação Ambiental do Parque Capibaribe* — PURA).

The guiding threads of the methodological schema presented in Figure 7 are interdisciplinarity, participation and experimentation. The studies and urban structures developed examine factors relating to the natural world, social forces, infrastructure, and services. To ensure that project implementation abides by the arrangement agreed by public authorities, society, and the university, the PURA and specific legislation

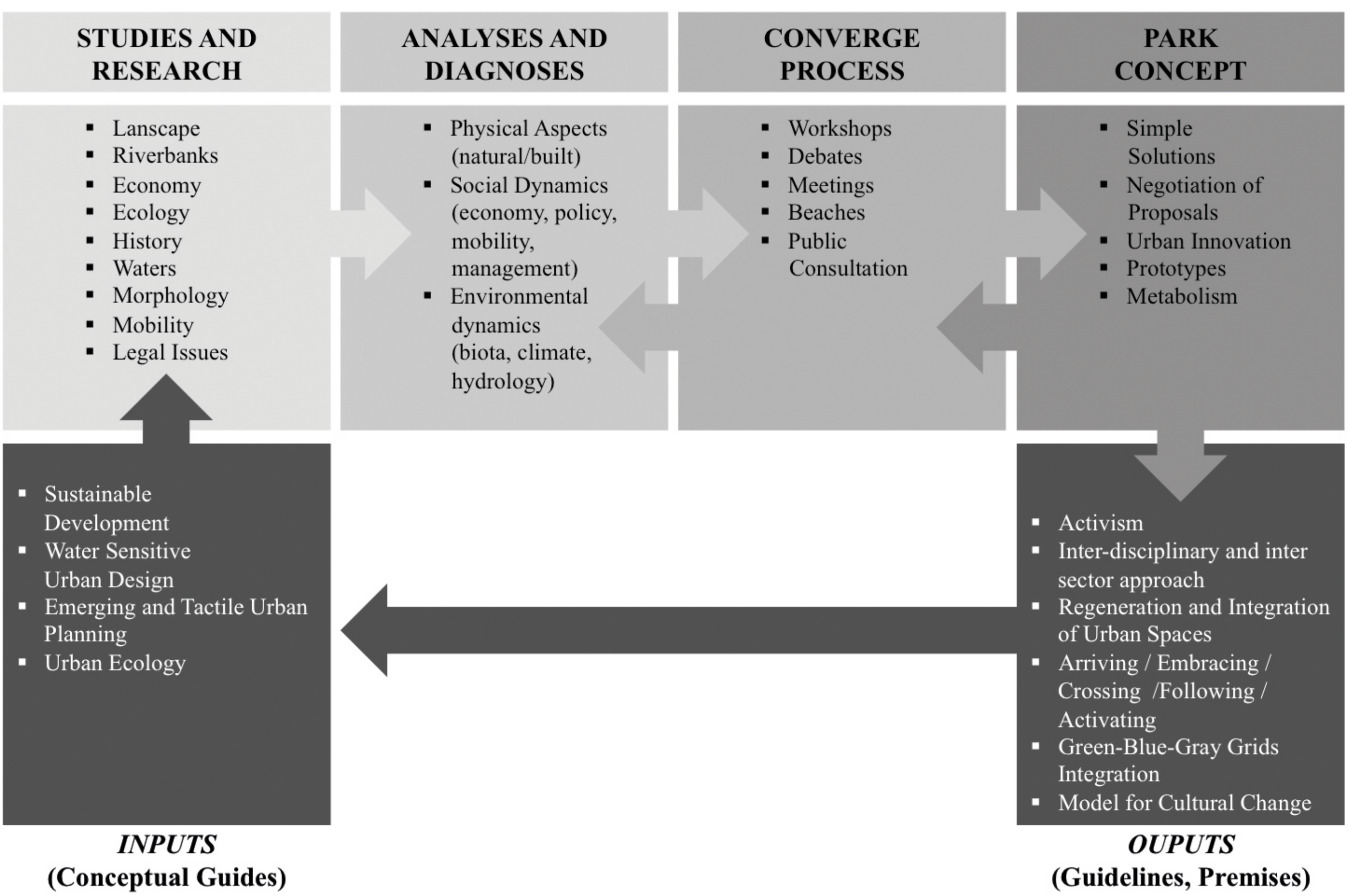


Figure 7 – Capibaribe Park Project Methodology (schema).

relating to the park established medium- to long-term urban intervention guidelines and assurances that the basic precepts of the project will be safeguarded despite changes of government at the local level.

With Capibaribe promoting social and spatial integration, and environmental recuperation and encouraging non-motorized transportation, the PURA consolidated its guiding principles:

- adopting simple solutions: promoting low-complexity, low-cost urban and environmental transformation with high potential for social transformation;
- negotiating proposals: mobilizing various stakeholders to develop joint action;
- promoting innovation in urban planning: developing and implementing urban planning solutions appropriate to the context of each setting, to the needs of each culture and to the requirements of future generations;
- building prototypes: developing solutions that can be implemented experimentally and evaluated, and promoting a feeling of belonging in relation to public places on the river banks;
- metabolizing: expanding the urban planning concerns proposed for the area specifically covered by the PURA in an integrated fashion to other river basins in Recife and neighboring cities.

Therefore, the concept of Capibaribe Park goes beyond a linear park zone of approximately 1 km in width along the whole river, from Várzea neighborhood to Recife's city center in order to encompass a whole park system and a park city.

Empirical features of the planning exercise include the various presentations, discussions, negotiations, and proposal agreements involved in the PURA Capibaribe Park Project interventions. The convergent process that these components combine to create incorporates various social and political segments of society: private citizens, social movements, professional organizations, universities and other educational institutions, stakeholders from the real estate and construction industries, and residents' associations, in addition to the local and state authorities.

Source: INCITI-UFPE (2019).
Figure 8 – Convergence.

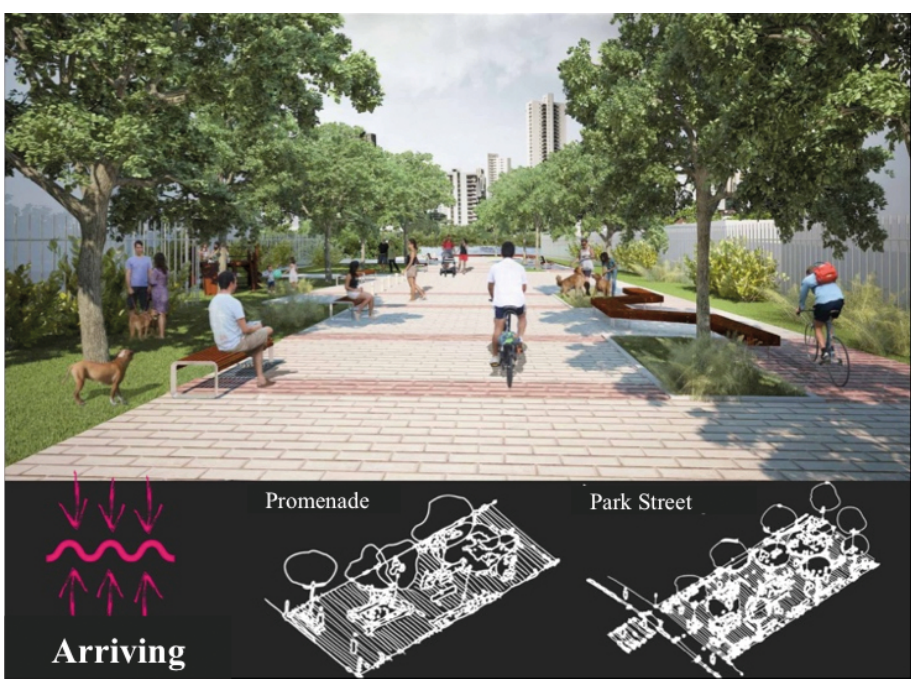
Activities included workshops, regional and themed conferences, debates, and public consultations (Figure 8). The project also organized events to promote its innovative approach. These include so-called 'beaches' — temporary riverside installations used for social events, celebrations and entertainment — that attract large crowds and encourage large numbers of people to play a more active role in promoting the proposals under negotiation.

Examination of local circumstances revealed the potential to integrate various streams and canals, forest reserves and open spaces in urban settings (parks, squares, streets lined with trees), with the so-called 'seepage' into the park zone. This seepage, like the branches of the river itself and its banks, extends into the countryside, reaches neighborhoods and communities further afield and can be installed both along Capibaribe's tributaries and on roads that connect these with the river bank. The integration of various urban landscape systems, combining natural environment, infrastructure, and various complex social needs, is achieved by the creation of shared living spaces. These systems are connected to one another systems by passages that encourage passers-by to share the space. Shared spaces tend to attract greater circulation and promote spontaneous security surveillance.

In view of this potential, the park is structured around five key premises relating to regeneration, renovation and installation of thoroughfares and public spaces to encourage use. They are:

- arriving;
- embracing;
- crossing;
- following;
- activating.

Arriving at the river via parks should be a pleasant experience, encouraging people to walk more (Figure 9). This is related to the urban seepage that expands the sphere of influence of Capibaribe Park, even reaching the busiest city streets and bringing life and movement to the periphery, installing structures that promote movement near the riverbanks or further afield:



Source: INCITI-UFPE (2019).
Figure 9 – Arriving.

- parks, squares, and markets;
- urban integration routes receiving an intense flow of non-motorized and motorized transportation;
- historical routes and routes with tourist potential.

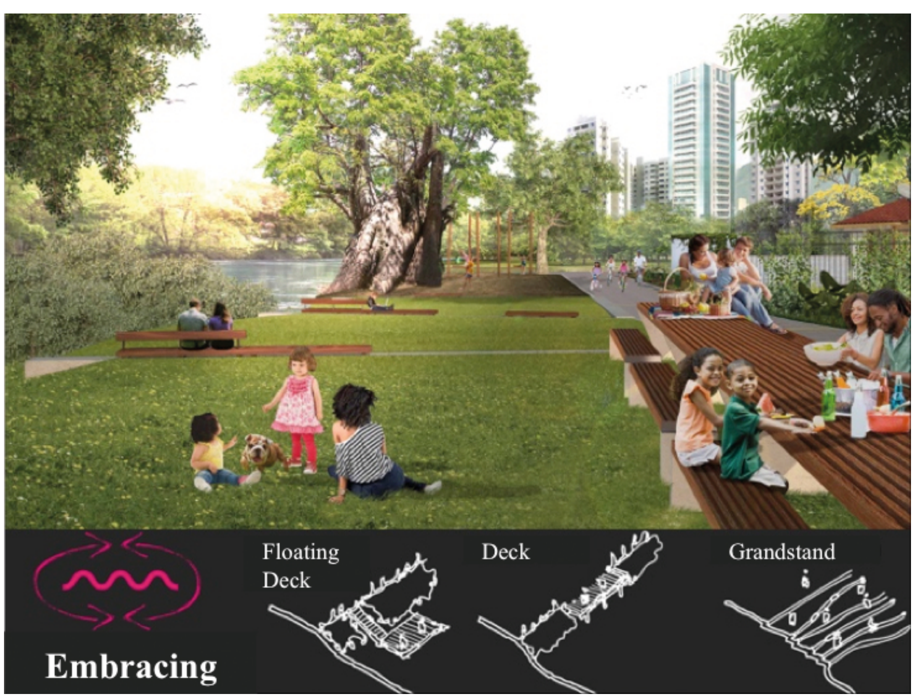
Embracing (Figure 10) creates stopping points, providing leisure activities, and places for residents to meet and spend time together. This develops two concepts of space:

- 'beaches', which are broad linear spaces duly equipped to bolster the occupation and use of strategic points on the riverbanks as leisure areas;
- windows, with spaces in locations that are highly suitable for the contemplation of the river landscape.

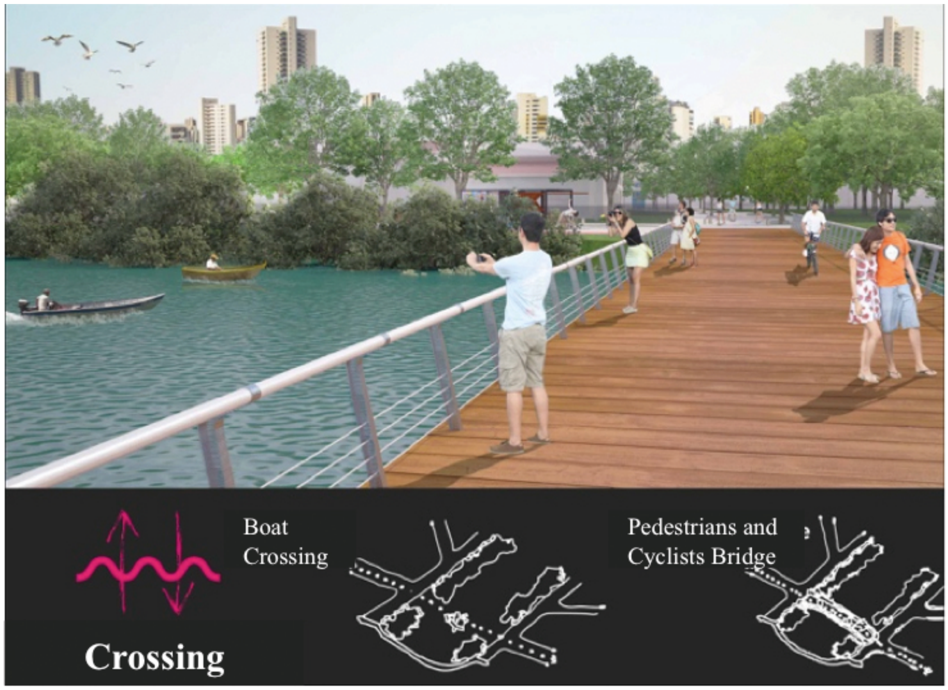
Continuous vegetation cover on both banks structuring the ecological corridor of the river Capibaribe, paradoxically creates a visual barrier that blocks the water view. The challenge with window spaces is to find stratagems for reconciling two needs: the need to remove vegetation to enable residents to see the river; and, simultaneously, the need to preserve and establish the continuity of the ecological corridor.

Crossing (Figure 11) reduces the distance between locations on opposite sides of the city, improving the connectivity of the transport network. This can be achieved with sculpture-like bridges for pedestrians and cyclists, ferry crossings, or another solution that allows individuals to safely cross from one bank to the other. Considering that the river Capibaribe also acts as a barrier, connecting both river banks at strategic points, will have an effect not only at the local level, but also on the overall structure of the city. Furthermore, for over half of its course in the city, there are few bridges. Crossings would thus reduce the distance between locations within Recife City.

Following (Figure 12) entails the creation of a structural element that englobes the totality of the spaces that line the river banks and gives the park the feeling of a single body. It envisages solutions for moving up and down the river, along its banks, across walkways, but also by boat and by using the public river transport system. The stripped down, less complex transport axis



Source: INCITI-UFPE (2019).
Figure 10 – Embracing.



Source: INCITI-UFPE (2019).
Figure 11 – Crossing.

Source: INCITI-UFPE (2019).
Figure 12 – Following.

communicates a desire to create points of tranquility, repose, and visual silence, guiding the eye towards a clearer view of the river landscape. The project thus pays homage to the landscape by providing recreational, educational and ecological walks, and reclaiming the banks of the river Capibaribe for the citizens of the city.

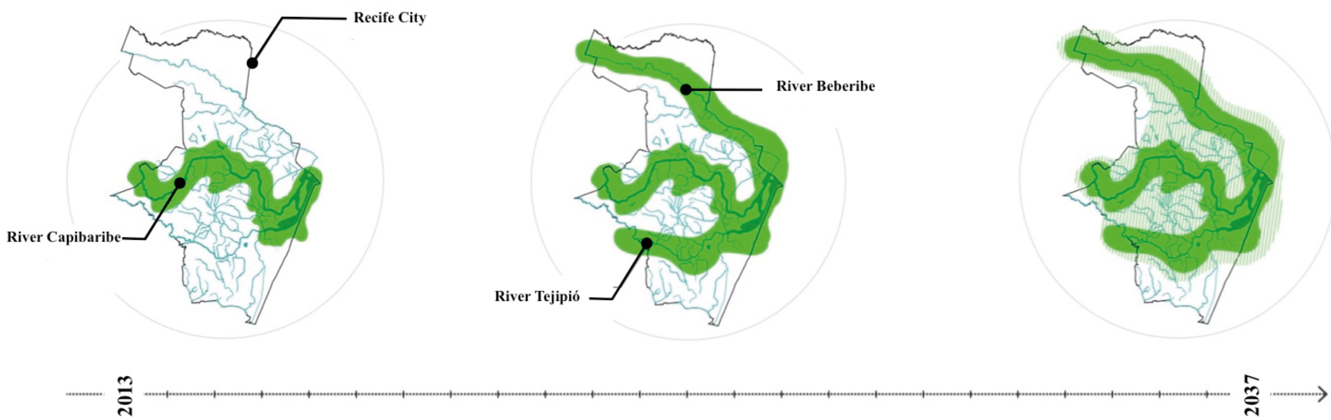
Finally, Activating (Figure 13) aims to bring vitality to urban spaces, arranging them in such a way that they are able to host cultural, social, sporting and business events at various points in Capibaribe Park, and encouraging its use and appropriation by the local population. It also aims to provide community and institutional management in partnership with the private sector, non-profit organizations, and private citizens. This approach may provide the conditions for full-functioning and use of efficient management for safe and well-maintained public spaces.

As a whole, the full array of public works proposed by the project would establish conditions, which, taken together, would provide the kind of connectivity envisaged by May (2006), reconciling access to the riverbanks with protection of riverine ecosystems.

CONCEPTION AND RESULTS: BRINGING ENCHANTMENT, PATHS TOWARDS A PARK CITY

The proposals developed in the course of the project are structured around a gradual implementation, aiming to achieve a transformation that is not only physical and spatial, but also cultural, in relation to the river and the waters of the city. Bringing public sector managers, lawmakers, social movements, businesses, and citizens into this culture will generate the synergy needed to ensure these proposals come to fruition. Capibaribe Park Project is thus envisaged to be the first stage in this transformation. The wider repercussions of the proposals are being approved, in the form of pilot interventions. The long-term potential can already be seen from the results already achieved, to the point that the idea of a single park was insufficiently ambitious has become clear. It is now possible to envisage the broader prospect of creating an entire park city (Figure 14).

Source: INCITI-UFPE (2019).
Figure 13 – Activating.



Source: adapted from INCITI-UFPE (2019).

Figure 14 – Capibaribe Park (Park Zone), System of Parks, Park City.

In the long term, this project faces the greater challenge of appropriation of the urban plan and demands (or pressure) by the population to implement it as discussed and agreed collectively. This also needs to be achieved in a situation in which there is as solution to the issue of continuity across local government administrations, with continuous monitoring and evaluation by academics and an organized civil society. Such continuity is the only way to avoid the project ending up, like many other grand plans for the cities, which are shelved and eventually forgotten, never to see the light of day.

In view of public and private investment restrictions and priorities, implementation needs to be achieved by citizens, making this dream of changing the city something of their own. For these people to have a dream of the future, they need to fall in love with the project now and fight for the park to be made a reality tomorrow.

The need to reach this enchantment stage has resulted in the development of a pilot project along 4 km of the river's left bank, between Parque de Santana Park and Praça do Derby, connecting public spaces that have been regenerated or whose regeneration is under proposal. The area was chosen for various reasons:

- its location on a stretch half way along the course of the river, providing the opportunity for expansion up- or downstream;
- the impossibility of moving around on foot or by bike because of the occupation of the riverbanks by roads and apartment blocks;
- a desire to meet the needs of a variety of economic and social strata of the population in the 500 m sphere of influence of the intervention;
- the visibility of the area, serving as an example for the city residents;
- the presence of a rich historical heritage in the vicinity;
- the existence of two parks and four squares within the area covered.

The project attempted to reveal the landscape of the river so that people could take possession of this heritage by way of one-off interventions that provide places to relax and make it easier to move around. As in the RxA workshop, which sparked debate on the possibility of using the river Capibaribe to transform the city, the project adopted an approach similar to that of the green and blue zones in France. Fascination of water is represented by blue spaces, which are characterized by the presence or influence of or direct contact with water. Vegetation is represented by green spaces, which include the riverside's fauna and flora. And the coexisting surrounding buildings constitute the gray space, which is artificial and made by humans. Together, these three spaces can spark a revival of riverside life.

Sustainability is one of the key premises of the urban planning project, and the proposed solutions thus emphasize:

- the use of highly durable local materials;

- a low energy consumption public streetlighting system, with minimal impact on the local fauna;
- a predominance of native species of plants, which require low maintenance and irrigation;
- promotion of commerce and informal services, such as infrastructure and auxiliary equipment;
- the creation of co-operatives to collect and recycle solid waste, produce compost, set up community vegetable gardens and teach gardening skills;
- prioritization of non-motorized transport.

Pedestrian walkways and cycle routes that line the river should help interconnecting public spaces and facilitate circulation. Places to rest and relax, such as benches, will be provided at intervals of 200 m. These will be of specific benefit to the elderly and people with disabilities. All walkways and public spaces will follow the norms of the overall design. Where there is room, walkways will be provided across the river and along its banks, mounted on pile-driven posts in the river, with low-environmental-impact prefabricated honeycombed slabs. Walkways symbolize the project as a whole, giving people the opportunity to walk over the river, to view the various landscapes produced by this enormous body of water, and to observe the riverside fauna and flora (Figures 15 and 16).

The principle of regeneration of existing public spaces is also applied to Antônio Maria and Vintém Squares, where the proposal is to eliminate the streets that separate them from the river, resulting in direct contact with the riverbank and transforming them into parks. This serves to gradually augment the already existing linear space along the river and help recover irregularly occupied riverbanks. Each square will be treated differently. Antônio Maria Square, next to a school, will be endowed with leisure facilities and a children's playground, enabling children once again to play spontaneously outdoors, and helping to make Recife a child-friendly city. In Vintém Square, near a local urban hub (with local shops, a supermarket, and a mall) and a

Source: INCITI-UFPE (2019).
Figure 15 – Riverside Walkway Proposals for Graças: proposal 1.

Source: INCITI-UFPE (2019).
Figure 16 – Riverside Walkway Proposals for Graças: proposal 2.

low-income community, public spaces will be equipped with food stalls for the street vendors who already work in the area, with beauty spots, and a refuge for riverside fauna.

In Jaqueira Park, alongside one of the most stunning city's riverscapes, where Capibaribe makes an almost 180º turn, there is a plan for an amphitheater that exploits the natural topography of the river bank. This would provide direct contact with the river with a floating pier, beauty spots and various meeting points shaded by trees.

In the immediate vicinity of an old riverside streetcar stop named Ponte D'Uchoa there is an extraordinarily beautiful 200-year-old baobab tree, which was until recently walled off by irregular riverside properties. Recife City Hall recovered an 18 m wide stretch on the edge of a lot and used it for Baobab Garden Project, the first pilot intervention of Capibaribe Park Project. This stage is already complete, and the garden is being used, managed and maintained as agreed by local residents and businesses, with the support of the park activation team (Figure 17).

Baobab Garden realized the potential foreseen by the project and became a tourist attraction. The small floating wharf encourages people to cross the river in ferries at the few points in which this is possible. There is now a considerable number of ferries, underlining the importance of providing urban mobility solutions, using this overlooked form of river transport. This fact inspired the innovative Navegue app, developed by a local startup incubated by Porto Digital, Recife, which aims to provide solutions for expanding river transport by regulating the operation of ferries using water navigation technology.

The project's pilot interventions include the INCITI-UFPE team's response to a request from residents of the neighborhood Graças, which organized a movement called Graças for Us, in reaction to a City

Source: INCITI-UFPE (2019).
Figure 17 – Baobab Garden, pilot Capibaribe Park Project intervention.

Hall project that used already available resources to install a four-lane expressway along the river banks between Torre and Capunga Bridges. Aware of the park concept, the movement argued for the implementation of these principles and became part of a park project collaboration with Recife City Hall with the INCITI activation team. The result was the development of a park way, with walkways, squares, a single-lane main road for cars and bicycles, under the shade of native species of trees. Although it has

Source: INCITI-UFPE (2019).

Figure 18 – Four-lane riverside expressway project.

Source: INCITI-UFPE (2019).

Figure 19 – Walkway project along the left bank of the river Capibaribe.

altered the focus of mobility from cars to cyclists and pedestrians, Caixa Econômica Federal bank agreed to continue with it. In comparison with the original project, centered on the automobile (Figure 18), with the project now implemented, which preserves river banks and values, as a location for riverside walks (Figure 19), it shows the impact an approach that respects the urban environment can have on the quality of riverside spaces.

Likewise, in a project segment between Capunga and Derby Bridges, the expressway was replaced by public spaces with sidewalks and cycle routes, meeting the needs of students, professors and staff of a nearby university, as well as those of local residents. The activation team again supported the reconciliation of activities of street vendors (of food and drink) and other urban needs. The task was to meet a complex demand and develop a multi-purpose location appropriate for these individuals: a town square, a food area (with stalls and food trucks), sidewalks and cycle routes, relaxation areas, large open spaces for recreation, events and exhibitions. All this was funded by resources earmarked for mitigating the impact of the university's installation.

The enchantment phase will eventually be consolidated with the installation of three bridges for cyclists and pedestrians. These architectural interventions should result in the creation of sculpture-like structures within the river Capibaribe landscape and will be contracted in an international competition, thereby fulfilling all the premises of the pilot project: arriving, embracing, crossing, following, and activating.

CONCLUSIONS

The experience of developing Capibaribe Park Project from conception to installation of the first interventions and continuation of the strategic actions envisaged, provides material for evaluation and enriches the debate concerning the paradigms that should guide urban planning policies in general, and land use and water management in particular. The practical results of applying some concepts and premises have already given rise to much valuable reflections.

A digital model of the park zone (Figure 20) envisages regeneration of 51 km of roadways as park roads, the

Source: INCITI-UFPE (2019).

Figure 20 – Conception of the Park Zone (digital model).

installation of 45 km of cycle routes and an increase in the amount of public green areas in the city from 1.2 m^2 per inhabitant (in 2014) to 20 m^2 per inhabitant (in 2037), transforming Recife into a park city in time for its 500th anniversary. The underlying structural principles are closely interconnected: sustainability and regeneration of public spaces are axes that bring about the ideal of equilibrium in the quality of human urban habitat, based on reconciliation of the city and its natural environment. This perspective covers issues such as the forecasting and prevention of risks related to urban resilience, although this is still not the focus of the project. The way forward thus involves teaching a new culture of land-use planning, promoted in everyday life in Recife, concerned with maintaining and valuing the capacity that water has to create pleasing orderly urban spaces and to confer greater cohesion in the city.

Given that Recife is an amphibious city, one challenge posed is that of countering the increasingly continuous and intense effects of rains, by focusing on urban structures and landscapes that move away from the prevailing culture of artificialization and domination of water. This involves investigating new paradigms such as:

- integration of sectors and disciplines;
- water-sensitive design;
- participation as activation (society becoming enchanted by the project and seeing it as its own).

In terms of the first element, the project broadly mobilized disciplines related to the issues at stake, and advanced proposals and solutions that bring together municipal public policy sectors, such as urban planning, environment, mobility, and economy. In terms of water-sensitive design, the project focuses partly on the concept of Water Sensitive Urban Design defined by Australia's National Water Initiative as "the integration of urban planning with management, protection and conservation of the urban water cycle that ensures urban water management is sensitive to natural hydrological and ecological processes" (COAG, 2004, p. 30).

In terms of public participation, the project is in line with the principles of educating society to coexist with urban waters, at various scales of intervention — street, neighborhood, river basin, city — as suggested by authors such as Bernard Chocat (2003). It also prioritizes actions of a non-structural nature — participatory plans, management processes and monitoring — as guides for structural action involving physical infrastructure. This shifts a culture of control and opposition of city and nature, river, and citizen, posing the greatest challenge of all.

In city spaces, where the actions of residents and professionals such as hydrologists, architects and urbanists, landscapers, geographers, and sociologists overlap, some of the changes are covered by urban planning. In principle, this should lead to the promotion of equity in the built environment. This should involve not merely the replication of models, but responses suited to the reality and specific social spatial and physical environmental context of each city. Urbanism is a discipline capable of guiding the organization and control of the development of the city in relation to water. Professionals in this field are thus obliged to promote change by exercising skills such as creativity and innovation with approaches, analyses and solutions guided by the interrelations between social spatial and hydrological dynamics in the urban environment, receptivity, and facilitation of the participation of various other players. In this way, they hope to build hospitable and resilient cities.

Although initially limited to the scope of a collaboration with more restricted objectives, Capibaribe Park Project shows it can incorporate these other features and abilities, broadening both its physical spatial scope and its content. This experience consolidated approaches in which non-structural actions take on greater relative importance and guide those of a structural nature, including planning, participatory management, and collective oversight of convergence with activation, as shown by the outputs in Figure 7. More recently, INCITI has helped the Pelópidas da Silveira City Institute (ICPS) to review Recife's Master Plan, with a proposal for a Landscape Conservation Unit on the banks of the river Capibaribe. Researchers and professionals of UFPE are regularly invited to respond to demands not directly associated to the partnership discussed here. Hence, they have seen an increased recognition of their skills and knowledge and have presented practical solutions that combine urban planning and landscaping to use the river Capibaribe to reinvent Recife City.

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ASSESSING GALLERY FOREST ECOSYSTEMS - CASE STUDY OF THE PAJEÚ GALLERY FOREST

AVALIAÇÃO DE ECOSSISTEMAS FLORESTAIS – ESTUDO DE CASO DA MATA CILIAR DO PAJEÚ

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ABSTRACT

There is a lack of basic information about the Caatinga gallery forests. The aim of the study was to obtain basic information of the Pajeú gallery forest (Pernambuco, Brazil) and offer different ways to restore and conserve it. A characterization of the conservation status and its seed bank was made. The characterization was done using a quality index (QBR index) and an evaluation of land use through satellite images. Research was then conducted on the native plants of the Caatinga riparian forests in order to test active restoration methods in the field. To do so, a multi-criterion analysis was constructed and included all tree and shrub species based on previous local researches and found in literature. After this analysis, some species were grown in a plant nursery to test their germination, survival and growth rates for different soils and irrigation frequencies. Finally, transplantation in the gallery forest was evaluated by observing survival and growth rates of different native species that were directly planted in the forest. Our results show that the global QBR was 43.73 and that 73% of lands had either an insufficient (64%) or bad (9%) quality. However, some areas maintained a high biodiversity. We observed 23,651 seed germinations from the seed bank, where most germinations (53%) came from preserved site. Soils collected during the dry season also offered more seedlings (60%) than their rainy season counterparts (40%). As for active restoration, it was observed that some plants are better suited for tree nurseries and transplantation such as *Sapindus saponaria*, *Vitex gardneriana*, *Celtis iguanaea* and that by selecting the correct plants and techniques, the ecosystem can be restored. There is still a long way to restore Pajeú's gallery forest. But studies like this are essential to increase knowledge of the ecosystem. This study could serve as a reference to design management/restoration strategies, prioritize actions and develop public policies that ensure integrity and long-term conservation of the ecosystem and their functions.

Keywords: tropical dry forest; soil seed banks; restoration; tree nursery; seedlings recruitment; ecosystem integrity; gallery forest quality index.

RESUMO

Faltam informações básicas sobre as florestas de galeria da Caatinga. Os objetivos do estudo foram obter informações básicas da floresta de galeria do Pajeú (Pernambuco, Brasil) e oferecer diferentes maneiras de restaurá-las e conservá-las. Foi realizada a caracterização do estado de conservação e seu banco de sementes. A caracterização foi feita usando um índice de qualidade (índice QBR) e uma avaliação do uso do solo por meio de imagens de satélite. Em seguida, foi realizado um inventário sobre as plantas nativas das matas ciliares da caatinga, a fim de testar métodos ativos de restauração no campo. Para isso, foi construída uma análise multicritério que incluiu todas as espécies de árvores e arbustos, com base em pesquisas prévias locais e citadas na literatura. Após essa análise, algumas espécies foram cultivadas em um viveiro de plantas para testar sua germinação, sobrevivência e taxas de crescimento para diferentes solos e frequências de irrigação. Finalmente, o transplante na floresta de galeria foi avaliado mediante a observação das taxas de sobrevivência e crescimento de diferentes espécies nativas que foram plantadas diretamente na floresta. Nossos resultados mostram que o QBR global foi de 43,73 e que 73% das terras tinham qualidade insuficiente (64%) ou ruim (9%), no entanto algumas áreas mantiveram alta biodiversidade. Foram observadas 23.651 sementes germinadas no banco de sementes, em que a maioria das germinações (53%) veio do local preservado. Os solos recolhidos durante a estação seca também ofereceram mais plântulas (60%) do que os seus homólogos da estação chuvosa (40%). Quanto à restauração ativa, observou-se que algumas plantas são mais adequadas para viveiros e transplantes de árvores como *Sapindus saponaria*, *Vitex gardneriana* e *Celtis iguanaea* e que, selecionando as plantas e técnicas corretas, o ecossistema pode ser restaurado. Há ainda um longo caminho para a restauração da floresta de galeria do Pajeú. Estudos como este são essenciais para aumentar o conhecimento desse ecossistema. Esta pesquisa servirá como referência para orientar estratégias de manejo/restauração, priorizando ações e o desenvolvimento de políticas públicas de conservação a longo termo que garantam a integridade do ecossistema e suas funções.

Palavras-chave: floresta tropical seca; bancos de sementes de solo; restauração; estufa de árvores; recrutamento de mudas; integridade do ecossistema; índice de qualidade da floresta de galeria.

INTRODUCTION

Tropical dry forests are characterized for having a dry season that lasts at least three to four months, an average annual temperature greater than 25°C, and an average annual rainfall of 250–2000 mm (PORTILLO-QUINTERO; SÁNCHEZ-AZOFEIFA, 2010). They represent about 40% of the world's tropical forests, where more than half occur in the Americas (PORTILLO-QUINTERO; SÁNCHEZ-AZOFEIFA, 2010). In Brazil, this ecosystem is known as Caatinga.

The Caatinga is located in the northeast of Brazil and covers more than 735,000 km^2, which represents almost 10% of the country's territory (SANTOS *et al*., 2011; KOCH; Almeida-Cortez; KLEINSCHMIT, 2017). It is recognized as having one of the greatest biological diversity for a semi-arid region in the world (SANTOS *et al.*, 2014), including more than 1,000 plant species (SANTOS *et al*., 2011), of which at least 19.7% are endemic (SOUZA; RODAL, 2010; QUEIROZ *et al*., 2017). This ecosystem has experienced an intense degradation of its habitat (SANTOS *et al.*, 2011), mainly due to human activities (ANTONGIOVANNI; VENTICINQUE; FONSECA, 2018; KOCH; Almeida-Cortez; KLEINSCHMIT, 2017), and projections show that precipitation will be reduced with climate change (HOEGH-GULDBERG *et al*., 2018). It is estimated that around 80% of the vegetation has been modified (RIBEIRO-NETO *et al*., 2016), including gallery forests.

Gallery forests occur adjacent to waterways, comprising both terrestrial and aquatic components as well as the interface between them (NASCIMENTO, 2001; MARUANI; AMIT-COHEN, 2009; MOURA *et al*., 2018). Due to water availability, these ecosystems are different from the rest of Caatinga, being more productive, rich, and diverse (FERRAZ; ALBUQUERQUE; MEUNIER, 2006; DIAS; BOCCHIGLIERI, 2016; LAKE; BOND; REICH, 2017). Their importance lies within the ecosystem services they provide. These services may include the recharge of groundwater through rainwater absorption, prevention of floods, maintenance of water quality, formation of ecological corridors that allow gene flow, prevention of erosion, and siltation of riverbanks. They may also offer shelter and food for animals (PRICE; LOVETT, 2002). Furthermore, they provide benefits to local communities, particularly for the use of medicinal plants, fruits, and wood for construction or cooking (ARAÚJO; CASTRO; ALBURQUERQUE, 2007; ANTONGIOVANNI; VENTICINQUE; FONSECA, 2018).

Despite their importance, these ecosystems are seriously degraded as a result of anthropic activities. Due to their closeness to watercourses and their fertility, the soils of gallery forests are particularly attractive for farmers seeking ground for agricultural practices and livestock activities (PRICE; LOVETT, 2002; FERRAZ; AL-

BUQUERQUE; MEUNIER, 2006). Usually, the land is first deforested for agriculture activities and later is used as grazing sites for livestock (SANTOS *et al*., 2014; SCHULZ *et al.*, 2016). These two activities have a high impact on vegetal communities (RIBEIRO-NETO *et al*., 2016; SCHULZ *et al*., 2018; 2019), resulting in loss and fragmentation of the gallery forests (NASCIMENTO, 2001).

In addition, a high number of exotic species have been introduced to improve productivity of livestock (NASCIMENTO *et al*., 2014; SCHULZ *et al.*, 2016) and agriculture-based activities (DÍAZ-PASCACIO *et al.*, 2018), which threaten native plant populations (NASCIMENTO *et al*., 2014; SCHULZ *et al*., 2019). This situation has resulted in the loss of native biodiversity. Santos *et al*. (2011) have reported that there has been an almost total loss of native biodiversity in the tributaries of São Francisco River. This severely alters the landscape and ecosystem integrity (SOUZA *et al*., 2013). As a result, the soils have eroded, the fauna has lost habitat, and the watercourses have experienced pollution, siltation, and even river death (PRICE; LOVETT, 2002; RAFFERTY; PIMM, 2018; TROVÃO; FREIRE; MELO, 2010). Nevertheless, there is a lack of specific information about the species, composition, and structure of Caatinga gallery forests (SILVA *et al*., 2015; SOUZA *et al*., 2013), as well as its state of conservation (NASCIMENTO, 2001).

These disturbances also have an effect on the soil seed bank (SSB), which is important for the regeneration of the forest and secondary succession. It has been reported that an increase in degradation level results in a decrease of seed density and species richness of the SSB (KASSAHUN; SNYMAN; SMIT, 2009; MENDES *et al*., 2015). When SSB is insufficient for forest regeneration, other measures have to be taken in order to restore gallery forest (BRAGA *et al.*, 2008; REIS; Davide; Ferreira, 2014). This is called active or assisted restoration (HOLL; AIDE, 2011).

To perform an effective restoration, it is indispensable to know and understand the status and characteristics of the site. The first step is to know the ecosystem damage and then identify the system characteristics that are important in determining the ecosystem recovery. Therefore, we can determine realistic and effective goals for restoration (HOBBS, 2007). There are different variables that can be identified directly, like soil characteristics (SOUZA *et al*., 2018a), or indirectly, by GIS tools (DIAS *et al*., 2014). Combining direct and indirect methods, we intend to have a better understanding of the situation in the Pajeú river and so put into place effective restoration actions that are adequate for the ecosystem and population requirements.

The goals of this paper are:

- to characterize the ecosystem integrity of the gallery forest;
- to compare the soil seed bank in areas with different conservation levels;
- to evaluate different plants species and methods of production and transplantation for an active restoration.

METHODOLOGY

Study area

The study was held in the municipality of Floresta, PE, Brazil (8º35’60” S, 38º34’05” W), in the basin of the Pajeú River (Figure 1), an affluent of the São Francisco River, the most important river in the northeast region. The Pajeú is an intermittent river that starts in the municipality of Brejinho and runs for 350 km. The climate in this region is classified as “BSHW”, which means a hot and semi-arid region, with a defined dry season and rains in the summer. The annual mean precipitation is around 500 mm, and the temperature is about 25°C.

Ecosystem Integrity

The quality of the riverbank was evaluated according to its morphological conditions. To do so, there were two protocols applied: the gallery forest quality index—QBR (MUNNÉ *et al.*, 2003) and an evaluation of the quality of the riverbank according to its land use (ACA, 2006). These protocols were applied on the Pajeú river, on a length of 76.17 km, starting from the last dam with high capacity and ending on the influx of the São Francisco River.

Quality index

Based on an analysis of satellite images, 33 sections of homogeneous vegetation were found along the waterway. In each of these sections, the QBR index was applied, as proposed by Munné *et al*. (2003). Both riverbanks were considered to determine the quality of the riparian habitat.

The QBR index assesses four components of the riparian vegetation:

- vegetal coverage (1);
- vegetal structure (2);
- quality of the vegetal coverage (3);
- naturalness of the river channel (4).

Due to the characteristics of the ecosystem, the index was modified according to the suggestions made by ACA (2006) and Sirombra and Mesa (2012). Each component has a value between 0 and 25, and the sum of the four components determine the QBR value (Table 1).

Spearman correlation analyses were made among the components of the QBR index, the QBR value, and the altitude in order to know the influence and relations between them. Once the QBR for each section was obtained, the global QBR value for the entire water body was evaluated, according to the following formula (ACA, 2006):

$$QBR_{WB} = \sum \frac{QBR_i x \left(section\ length\ QBR_i\right)}{total\ length\ WB}$$

In which:
QBR_{WB} = integrated QBR value for the entire water body evaluated;
QBR_i = QBR value obtained for the representative section *I*;
Section length QBR_i = length of the water body represented by QBR_i. Not the length of the section where the index was applied, but the length of the homogeneous area of which QBR_i is representative;
Total length WB = total length of the water body.

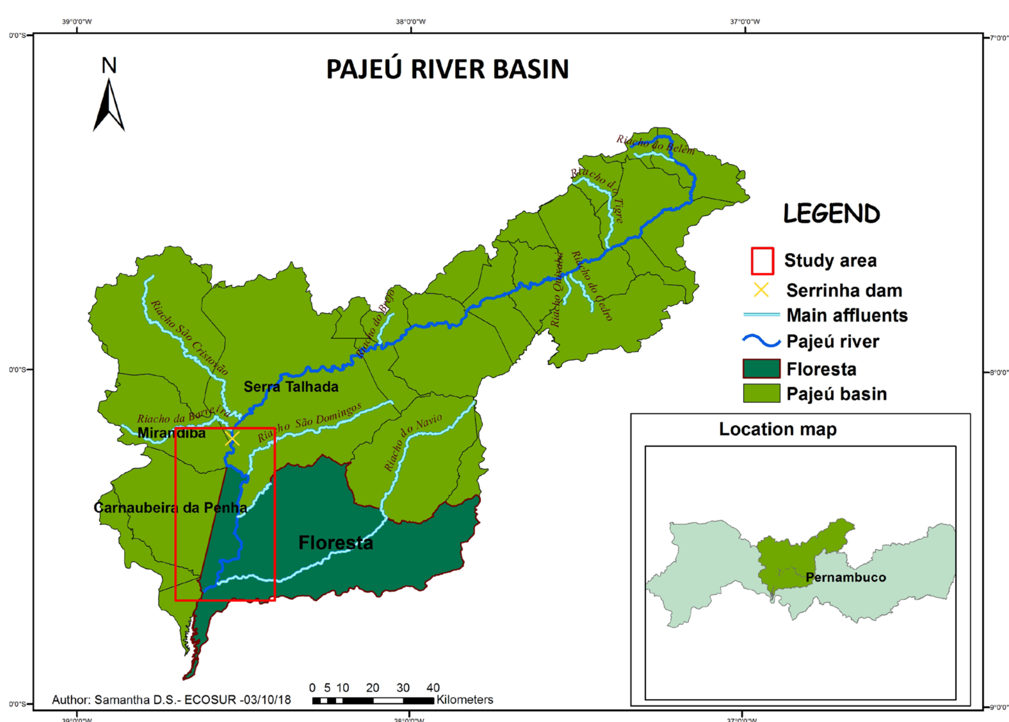

Figure 1 – Study area. Pajeú river basin and Floresta municipality, Pernambuco, Brazil.

Quality of the riverbank according to its land use

The naturalness of the floodplain land use was evaluated according to the protocol established by ACA (2006). The analyzed sites were 187.6 m from the riverbanks on either side. Satellite images were analyzed using Google Earth Pro 7.3.2.5491 (64-bit) and ArcGis 10.5. The land use was classified as agricultural soils/degraded soils, natural areas or urban areas, and the percentage of each land use was calculated. With the percentages obtained, an assessment of the quality of the riverbank was based on the information contained in Table 2.

Combining the results obtained by these protocols, we can obtain the quality of the riverbank based on its morphological conditions according to the Table 3 (ACA, 2006).

Table 1 – Quality of the riparian habitat obtained by the quality (QBR) index.

Quality of riparian habitat	QBR	Quality level
Riparian habitat in natural conditions.	≥ 95	Very good
Slightly disturbed forest	75–90	Good
Forest with major disturbance	55–70	Moderate
Strong alteration, bad quality	30–50	Deficient
Extreme degradation	≤ 25	Bad

Source: modified from Munné *et al*. (2003) and ACA (2006).

Table 2 – Quality of the riverbank according to land uses.

		Quality level		
		Very good	Good	Less than good
% Use	Natural	≥ 85	60	<60
	Agricultural	≤ 15*	40*	>40*
	Urban	0	5	>5

*Agricultural + Urban.
Source: ACA (2006).

Table 3 – Quality of the riverbank according to its morphological conditions.

		QBR index				
		Very good	Good	Moderate	Deficient	Bad
Land use quality	Very good	Very good	Good	Good	Moderate	Deficient
	Good	Good	Good	Moderate	Deficient	Bad
	Less than good	Moderate	Moderate	Moderate	Deficient	Bad

Source: ACA (2006).

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Soil seed bank

Three sites were selected for the characterization of soil seed bank (SSB), all of them in Pajeú riverbanks. The first site was situated in a degraded area, where the native vegetation was removed. Historically, the land was used for conventional agriculture and livestock. The second was a semi-degraded area, used for livestock but at a low intensity, according to Schulz *et al*. (2019). And the third one was a well-conserved area without any historical record of vegetation removal or important disturbances in the past 70 years. The sites were considered as a gradient of perturbation from strongly degraded (site one) to preserved (site three).

Two periods of sample collection were done in 2015: one at the end of the dry season (January) and the other one at the end of the rainy season (July). In each site, 40 samples were collected randomly at least 10 m from the river. The soil was saved in bags and carried to the greenhouse of the Universidade Federal de Pernambuco (UFPE). The analysis of the seed bank was done using the germination method (BROWN, 1992). The soil was laid in polystyrene trays (29 × 29 × 5 cm). The soil was watered every day for three months. All germinated plants were counted and identified. If no germinations happened within a week, the soil was churned.

The seedlings were identified using specialized guides, through comparison with records from the Herbarium Dárdano de Andrade-Lima (IPA — Instituto Agronômico de Pernambuco), and expert consultations. The classification system APG III (2009) was followed.

The habit and dispersion syndrome of each species were recorded (RICHTER; STROMBERG, 2005). Relative frequency, abundance, and density were calculated. As for biodiversity, the species richness (S), Shannon diversity index (H'), Pielou equitability index (J'), and Sorensen similarity index (Ss) were calculated.

Active restoration

Active restoration was divided in three parts: the first was *Plant selection,* the second was *plant production*, and the third was *transplantation*.

Plant selection was based on a multicriteria analysis carried out in 2018. This analysis was based on previous local researches and the information available in literature. One list of all the trees/shrubs present in the gallery forest was elaborated based on Maia (2004) and Souza and Rodal (2010) and non-published data from the authors. Plant selection was also based on seed availability at the time of the experiment, either directly from the trees or shrubs or previously collected by locals.

Only native plants were considered for this forest restoration because it's the most certain way to obtain structure and function recovery in the ecosystem. A grid was elaborated considering four dimensions: adaptation to the environment (endemic from Brazil, drought tolerance, exclusive of gallery forest or occurs also in the caatinga *sensu stricto*). Ecological interest (quick growth, nitrogen fixer, erosion control, shade, fruit or flower visited or used by animals). Anthropogenic interest (used for the local population as food, fodder, wood, medicine, etc.) as described by Josélia and Tatiane Menezes from SOS Caatinga NGO and production feasibility (high germination rate, seed dormancy).

Plant production

The tree nursery was a relatively square structure with a shade canvas that blocked 50% of the light, an essential element for seedling survival where the sun shines about 2,800 hours a year (MOURA; MALHADO; LADLE, 2013; PORTILLO-QUINTERO; SÁNCHEZ-AZOFEIFA, 2010). This canvas was supported by wooden beams. Inside the tree nursery, wood pallets separated the area in four zones. These four zones were used to separate the treatment combinations that were applied to the seedlings. Each combination contained one of two levels of each treatment applied. These treatments were soil type and frequency of irrigation. For the soil type, half the seeds were planted in sand (S) and the other half were planted in a mixture of equal parts sand, goat manure, and clay (A). These plants were initially watered every day, then either every day (1) or every three days (3) when they reached a fourth leaf stage. Five species were used in this experiment; their selection was based on seed availability and nativeness. The species were *Mimosa pigra* (Fabaceae, Calumbi), *Vitex gardneriana* (Lamiaceae, Salgueiro), *Triplaris gardneriana* (Polygonaceae, Pajeuzeiro), *Celtis iguanaea* (Cannabaceae, Jamerim), and *Sapindus saponaria* (Sapindaceae, Saboneteiro). With these different combinations, S3 was used as the reference point because its conditions were most similar to the plants' natural habitat. In the tree nursery experiment, 1,000 seedling bags were used in total, therefore 200 bags were used per treatment combination, meaning every species inside a zone had 50 bags. In each bag, two seeds were planted and watered every day until the seedling had four leaves. If more than one seed germinated per bag, the weaker plant was removed. Four measurements were taken the day of emergence (germination), the survival, the height, and the number of leaves. The first two were taken on a daily basis for approximately 12 weeks whereas the other two were taken weekly for 10 consecutive weeks. This experiment focused on four variables: the percentage of germination at 10 weeks, the percentage of survival at 10 weeks, the maximum height at 10 weeks, and the maximum number of leaves per plant at 10 weeks. Germination is based on the 100 seeds that have been planted for each combination of treatments for each species, so a total of 400 seeds per species and 2,000 seeds in total. However, survival is based on the number of living plants compared to the number of plants saved for the experiment.

A secondary experiment was conducted alongside the first one. In this study, the same five species were submitted to pre-treatments of germination. The pre-treatments were the control, meaning no treatment at all (1), a cold-water submersion for 24 hours (2), a warm water submersion for 15 minutes, immediately followed by 30 minutes in the refrigerator (3), and a mechanical scarification using sandpaper (4). Each pre-treatment was applied to 150 seeds for each species. In total, 3,000 seeds were treated, planted, and watered daily. Germination and day of emergence were recorded. In both experiments, most of the data was modelled according to a generalized linear model (GLM), then ANOVAs were applied to the GLM to determine the effects of the treatments, species, or a combination of those factors on germination, emergence, survival, and growth (height and leaves). All data pertaining to germination and survival are based on a binomial distribution. On the other hand, data applied to growth rates were modelled by a linear model with a Gaussian distribution. ANOVAs were also applied to these linear models.

Transplantation

For an exploratory experiment, 120 plants of five species were transplanted at the end of the 2019 rainy season on Pajeú's riverbanks. The selected species were produced in a tree nursery in 2018: *Schinopsis brasiliensis* Engl., *Tabebuia aurea* (Silva Manso) Benth. & Hook. F. ex S. Moore), *Spondias tuberosa* Arruda, *Albizia inundata* (Mart.) Barneby & J.W. Grimes, and *Lonchocarpus sericeus* (Poir.) Kunth ex DC.

The treatments consisted of a bifactorial model of two and three levels. The *microenvironment* was the first factor, where reforestation taking place in sunny and shaded areas were evaluated. *Mulching* was the second factor, where the control had no mulch and other plants has either straw or coconut fibre at the base.

Transplantation design followed the Food and Agriculture Organization (FAO, 2017) recommendations. The trees were planted in 40 cm^3 holes and each tree was at least 3 m from each other. Irrigation was automatic, using hoses and a water pump. This system delivered 2 L of water a week to each plant. The transplantation was conducted on July 2019.

Height, basal diameter, and leaf number were recorded weekly, as well as survival status. Initial measures were taken after transplantation, and plants were monitored for three months. Survival was evaluated categorically as alive or apparently dead. Relative growth rate (RGR) was estimated as (log [final measure]—log [initial measure])/time in days. When performing the statistical analysis, all distributions were normal. ANOVAs were used to compare the RGR between treatments, and chi-square to compare survival. A GLM Logit was used to relate the initial measure with the probability of survival.

RESULTS

Ecosystem integrity

The global QBR value was 43.73, indicating a conservation status considered as deficient for the gallery forest: 64% of the sites were evaluated as having a deficient quality, 27% a moderate quality, and 9% a bad quality (Figure 2). The QBR index is negatively affected by small dams in 60% of dams the QBR index was worst downstream and 66.66% of sites with the worst quality were close to a dam.

Among the components of the QBR index, the one related to *naturalness* of the river channel was the one with the highest and most constant values in all the sections evaluated, where 42.4% of the sections have a value of 15. This is followed by the component *vegetal structure* with 27.3% of the data having a value of 10. The components of *vegetal coverage* and *quality of the vegetation* were the ones with the lowest values, 32.8% and 61.6% of the data, respectively, had a value of 0.

The Spearman correlation analysis showed that the variables that had a greater influence to determine QBR index were *vegetal coverage* (0.809) and *vegetal structure* (0.674), while the variables *naturalness*

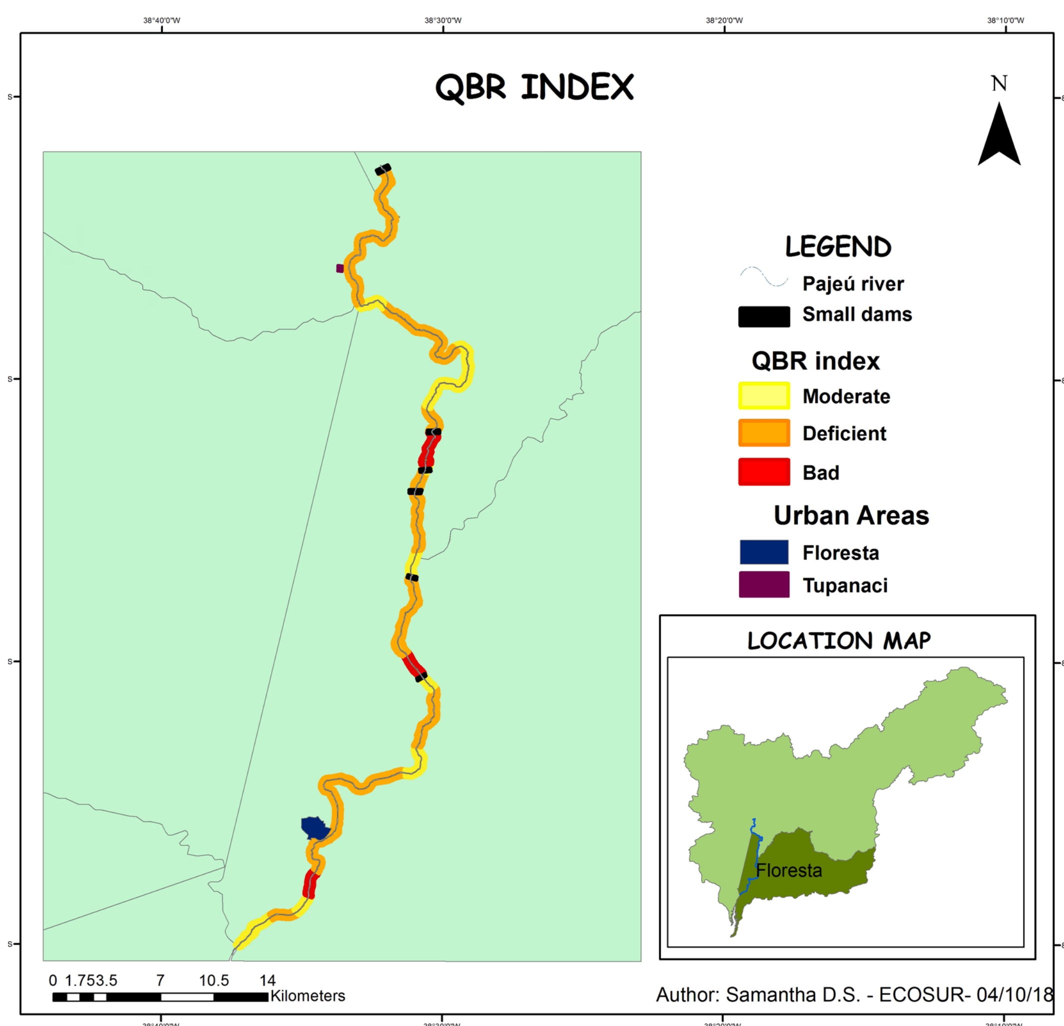


Figure 2 – Quality (QBR) index for Pajeú River, Floresta, Pernambuco, Brazil.

of the river channel (0.404) and *quality of vegetation* (0.273) had a low influence. The *altitude* variable was not correlated with the QBR index but had a positive correlation with *quality of vegetation* (0.403) and a negative correlation with *naturalness of the river channel* (-0.330). Among these variables, there was just one strong correlation (0.517) between *vegetal coverage* and *structure*. Nevertheless, it was interesting to note the negative correlation (-0.156) between *quality of vegetation* and *vegetal structure*.

Quality of the riverbank according to its land use

We evaluated 2,883 hectares of land to determine the quality of the riverbank according to land uses. It was found that only 40% of the area had natural land use, while 46% of the area had agricultural use, 13% were degraded soils, and 1% were urban areas (Figure 3). According to these percentages, the quality of the riverbank is *less than good*. Based on the results obtained, we found that the quality of the riverbank based on the morphological conditions of this section of the Pajeú river is *deficient*, indicating an important series of alterations which have modified its natural state.

Soil seed bank

Germination and density

A total of 23,651 germinated seeds were found for the three sites for both seasons. In accordance to the level of degradation, 53% were found in the preserved site, 26.2% in the degraded site, and 20.8% in the intermediate site. According to seasons, the dry season presented 14,315 (60%) seedlings, with 10,285 germi-

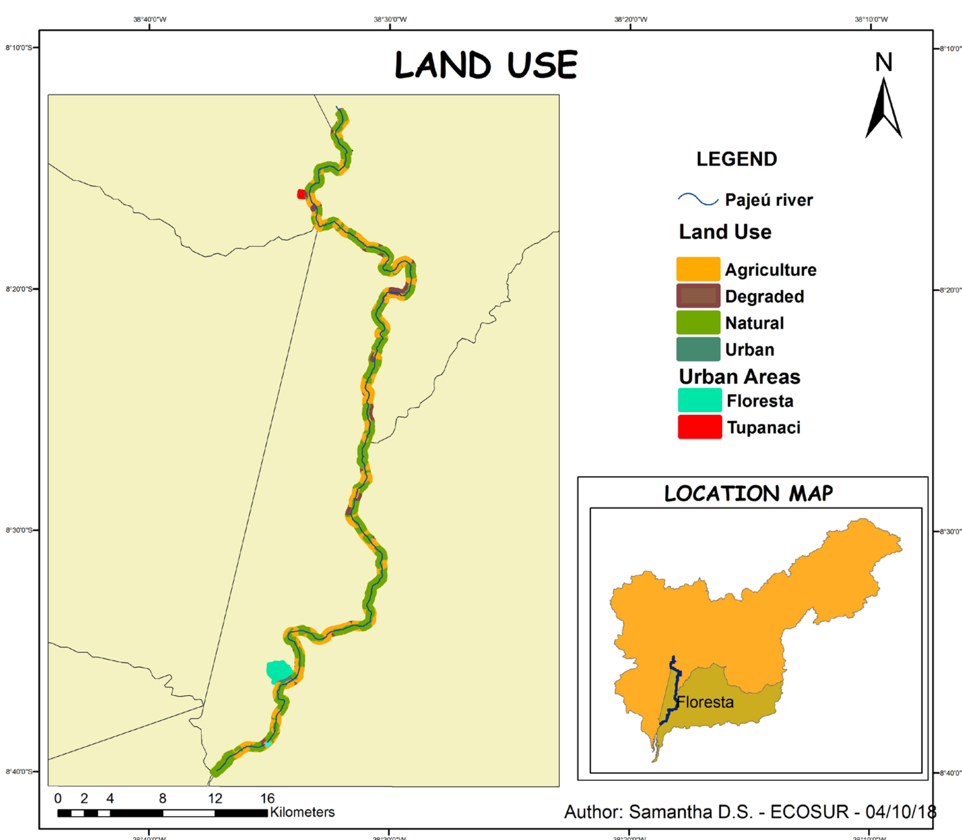


Figure 3 – Land use of the Pajeú basin, Floresta, Pernambuco, Brazil.

nating within the first four weeks and the rainy season presented 9,336 seedlings (40%), with 8,753 germinating in the first four weeks.

Seed density show significant differences between the preserved site and the intermediate as well as the degraded site, but only for the dry season. Comparing between seasons, the dry season presents higher density in preserved and degraded site than during the rainy season (Figure 4). The intermediate site's density did not differ statistically between seasons.

Floristic composition

A total of 89 species of 31 families were found in the SSB, whereof 74.1% were herbs and the rest were trees, shrubs/sub shrubs, or lianas. Adding both season samplings, the richness of the preserved site was 64 species, whereas the intermediate and disturbed site had 53 and 39, respectively.

For the preserved site, the families with the highest numbers, in both seasons, were Poaceae and Cyperaceae (Table 4). More morphospecies were found in the dry season (50) than in the rainy season (39), whereof 25 were common for both seasons.

In the intermediate site, 46 species of 22 families were found for the dry season and 25 species of 11 families for the rainy season, with only 18 species in common. Poaceae was the most represented family in both seasons. For the dry season, the next families with the highest abundance were Cypereceae, then Solanaceae and Rubiaceae. As for the rainy season, it was Portulacaceae and Rubiaceae (Table 4).

In the degraded site, Poaceae was the richest family in both seasons. In the dry season, the following families were Amaranthaceae, Cyperaceae, and Rubiaceae. While in the rainy season, the next family was Amaranthaceae (Table 4). A total of 34 species were found in the dry season and 20 in the rainy season, with 15 species in common.

Floristic diversity and similarity

The Shannon diversity index (H) was calculated for all three sites, preserved site (dry: 1.54, rainy: 1.17), intermediate (dry: 1.30, rainy: 0.85), and degraded (dry: 1.42, rainy: 1). In the dry season, there was no statistical difference between sites. In contrast, in the rainy season, the intermediate site shows statistical difference to the other two sites. Pielou's evenness index (J') did not show any statistical difference between sites nor seasons.

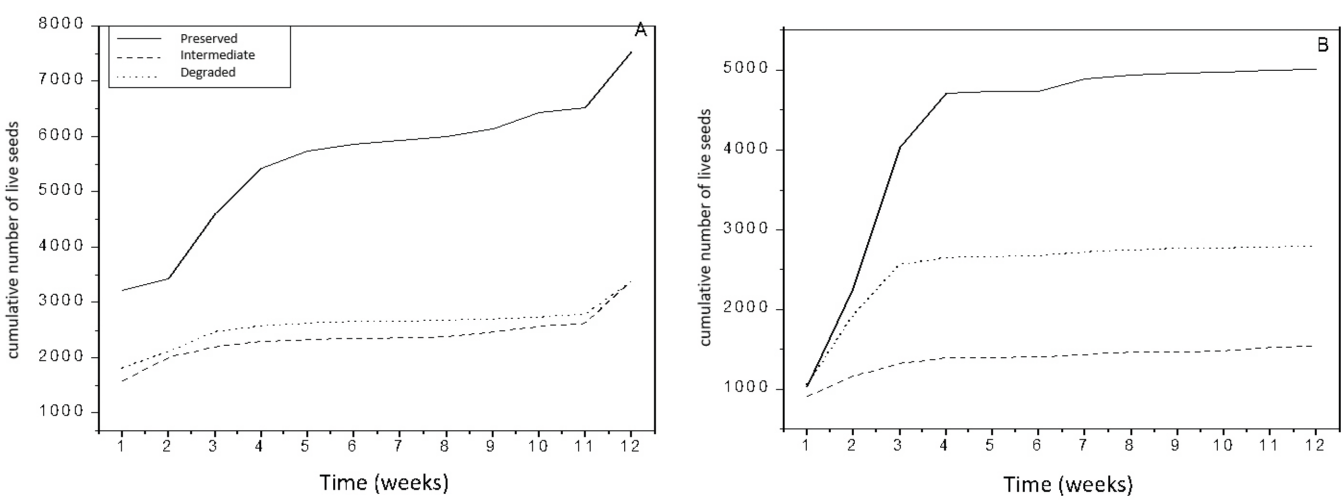


Figure 4 – Cumulative number of viable seeds from the seed bank of three riparian areas of the Pajeú River in a region of the Caatinga in the municipality of Floresta, PE, to (A) end of the dry season and (B) end of the rainy season, in the year 2015.

Species composition similarity between sites was evaluated through Sorensen. In the dry season, the higher similarity (63%) is between intermediate and degraded site; conserved and intermediate sites show 56% similarity, while conserved and degraded 48%. Rainy season keep the same tendency, but with a lower score (53, 44, and 41% respectively). Contrasting between seasons, a conserved area showed a similarity of 57%, intermediate 48%, and degraded 56%.

Plant selection

A total of 68 species (trees and shrubs) were evaluated with the multicriteria grid. Among these, 61 can be found in the gallery forest of Pajeú river and 14 of them are exclusive of this type of ecosystem (they cannot be found in the Caatinga vegetation *sensu stricto*). The other ones can be found both in gallery forest and in caatinga vegetation. Fifteen of the registered plants are endemic of Brazil (REFLORA, 2020), and three of them are in IUCN red list: *Myracrodruon urundeuva* and *Schinopsis brasiliensis* are endangered, and *Amburana cearensis* is considered in danger of extinction.

Each specie was scored by the multicriteria grid. The scores ranged from 2 to 25 (the maximum was 30). Only 22 species got score equal or higher than 15 (Figure 5). Whereof, five were selected, according to seed

Table 4 – Floristic composition by environment and season. Only families with more than one species are shown.

Families	Preserved		Intermediate		Degraded		Total spp.
	Dry	Rainy	Dry	Rainy	Dry	Rainy	
Amaranthaceae	2	2	2	1	3	2	3
Asteraceae	3	2	2	0	1	1	3
Cactaceae	0	2	1	0	0	0	3
Convolvulaceae	2	1	2	0	0	0	4
Cyperaceae	4	3	4	1	3	3	6
Euphorbiaceae	3	1	1	0	2	0	5
Fabaceae	4	0	3	0	2	1	6
Lamiaceae	2	3	2	2	1	0	3
Malvaceae	3	0	0	0	1	0	3
Phytollaccacea	1	1	1	0	1	0	2
Plantaginaceae	2	1	1	0	0	0	2
Poaceae	7	4	7	9	9	6	14
Portulacaceae	2	2	2	2	1	2	2
Rubiaceae	3	3	3	2	3	1	4
Solanaceae	2	1	3	1	0	1	3

availability, for exploring their production in greenhouses. *Albizia inundata, Licania rigida, Spondias tuberosa, Tabebuia aurea and Schinopsis brasiliensis*. *L. rigida*, and *S. tuberosa* are endemic to Brazil. *S. brasiliensis, S. tuberosa*, and *T. aurea* are present exclusively in gallery forest (REFLORA, 2020).

Plant production

The pre-treatment germination experiment/exit of dormancy

This experiment was carried out on four species: *Mimosa pigra*, *Celtis iguanaea*, *Triplaris gardneriana*, and *Sapindus saponaria* (*saboneteiro*). The results of the germination percentage and days of emergence by treatment are shown on Figures 6 and 7, respectively.

The statistical analyses show that, for *Mimosa pigra*, only hot water treatments had a significantly positive effect on the germination rate compared to other treatments. However, pre-treatments did not have an effect on the emerging time of the seedlings. For *Celtis iguanaea*, the best germination rate comes from the control treatment, being significantly better than hot water and sandpaper. In terms of emergence time, all treatments had a similar effect on this species, with an average emergence between 20 days (control and sandpaper) and 21 days (cold and hot water). For *Triplaris gardneriana*, hot water treatment is significantly worse in terms of germination rate than other treatments. This treatment also has the longest emergence time compared to other treatments. Finally, for *Sapindus saponaria* seeds, the sandpaper treatment favoured the germination rate compared to the other treatments. For this species, the sandpaper treatment also significantly reduced the time it takes for seeds to emerge.

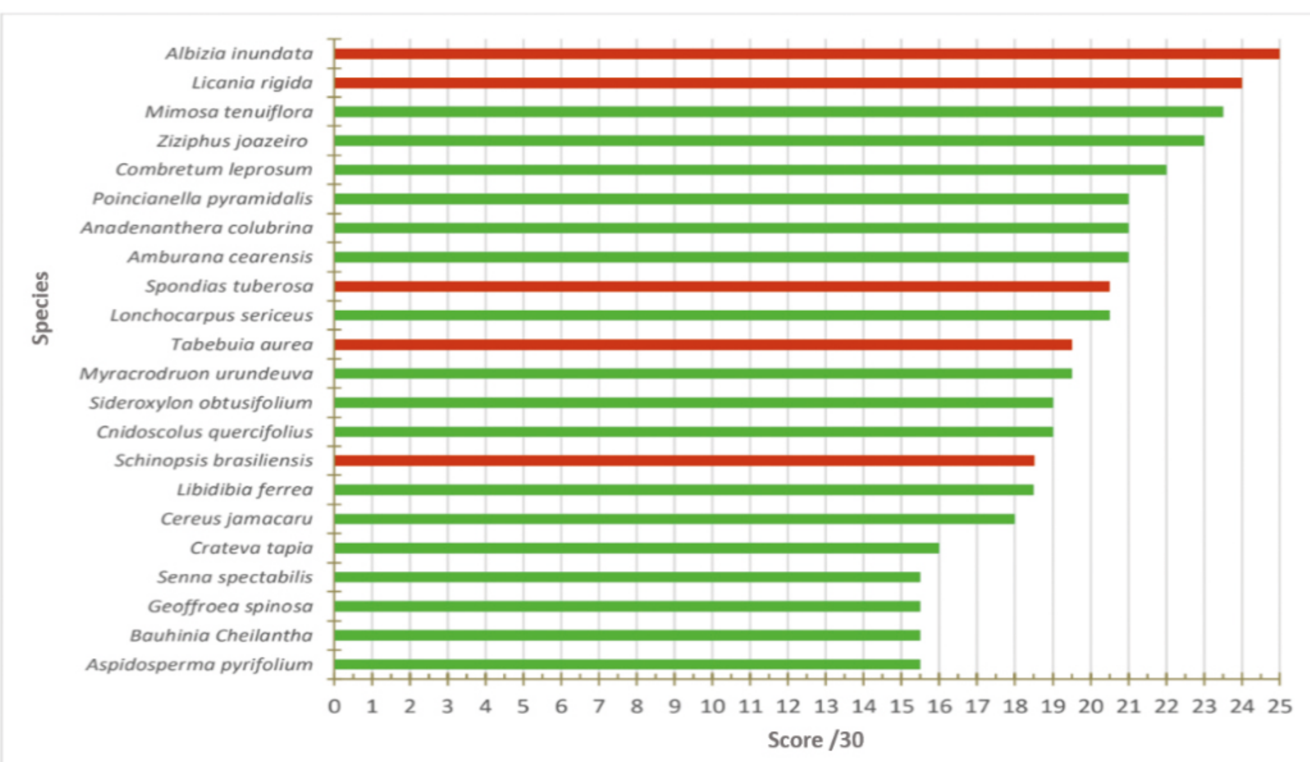
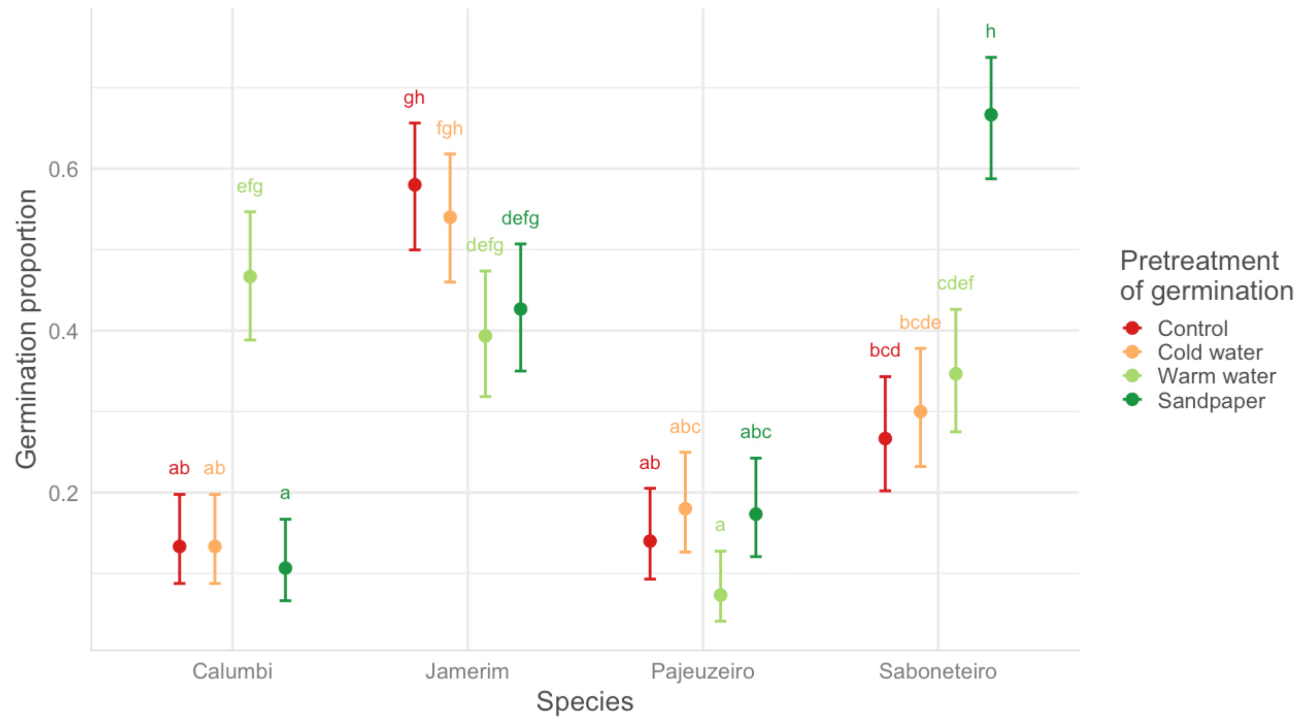
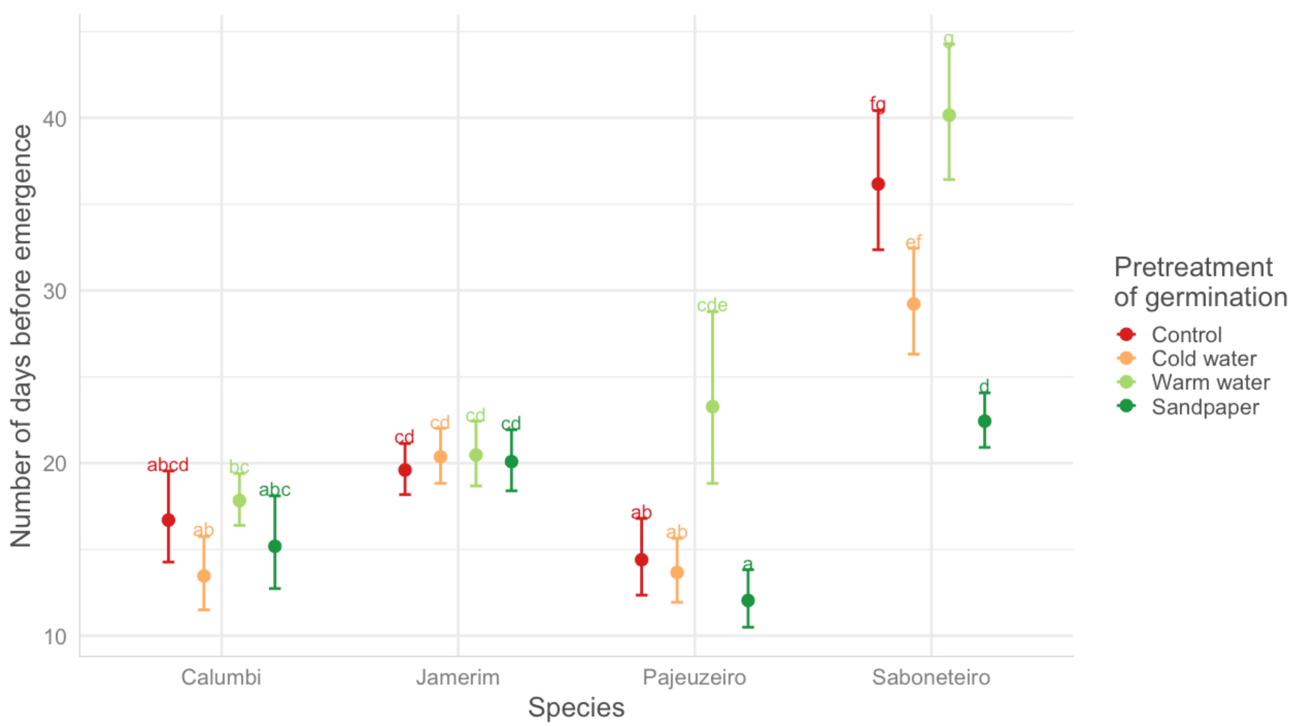


Figure 5 – Total scores obtained for native woody species following multi-criterion analysis; only species with a score above 15/30 are presented. The species in red are those that have been selected for the production of nursery plant.



*Letters represent statistically significate differences between treatments within the same species, as well as among different species.

Figure 6 – Comparison of the germination percentage by treatment and among species: *Mimosa pigra*, *Celtis iguanaea*, *Triplaris gardneriana*, and *Sapindus saponaria*.



*Letters represent statistically significate differences between treatments within the same species, as well as among different species.

Figure 7 – Comparison of the time of emergence of the seeds by treatment and among species: *Mimosa pigra*, *Celtis iguanaea*, *Triplaris gardneriana*, and *Sapindus saponaria.*

Effect of treatments on germination rate, survival rate and plant growth

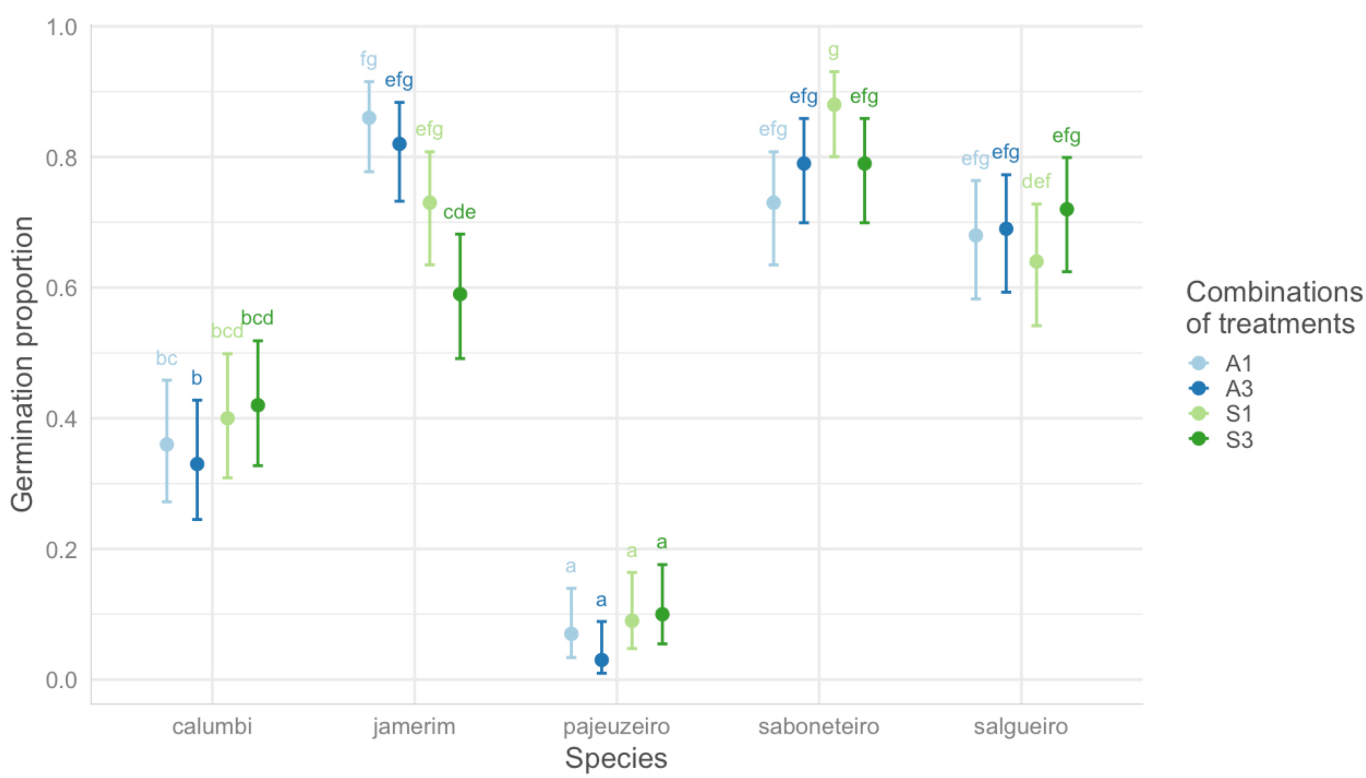
Germination rate and survival rate

Statistical analyses show that none of the treatment combinations have a distinct effect on plant germination for *Mimosa pigra* (33 to 42%), *Triplaris gardneriana* (3 to 10%), and *Vitex gardneriana* (63 to 70%). In the case of the *Celtis iguanaea*, germination is significantly favoured by the amended soils (A1 = 86% and A3 = 82%) compared to the plants in the S3 combination (59%). On the other hand, the combinations in amended soil are not statistically different from the S1 combination (73%). In the case of *Sapindus saponaria*, the proportion of seedlings watered daily is higher in sand (87%) than in the amended soil (72%), but the germination rates of combinations with 3-day watering (S3 = 78% and A3 = 79%) are not statistically different from those of combinations with daily watering (Figure 8). Finally, there is no difference between treatment combinations for plant survival rates for all species tested.

Growth rate

In general, combinations of amended soil treatments significantly improved the height growth of all species (Figure 9). A similar case arises for the growth rate of leaves per plant (Figure 10).

In general, combinations of amended soil treatments appear to significantly improve height growth of all species. The same is true for growth by the number of leaves per plant (Table 5). However, these differences



*Letters represent statistically significate differences between treatments within the same species, as well as among different species.

Figure 8. Comparison of germination proportions by combination of treatments (A1, A3, S1, and S3 in which S = sand and A = mixture of equal parts sand, goat manure, and clay; the numbers 1 and 3 mean watered frequencies: 1 = watered every day; 3 = every three days) and among species: *Mimosa pigra*, *Celtis iguanaea*, *Vitex gardneriana*, *Triplaris gardneriana*, and *Sapindus saponaria*.

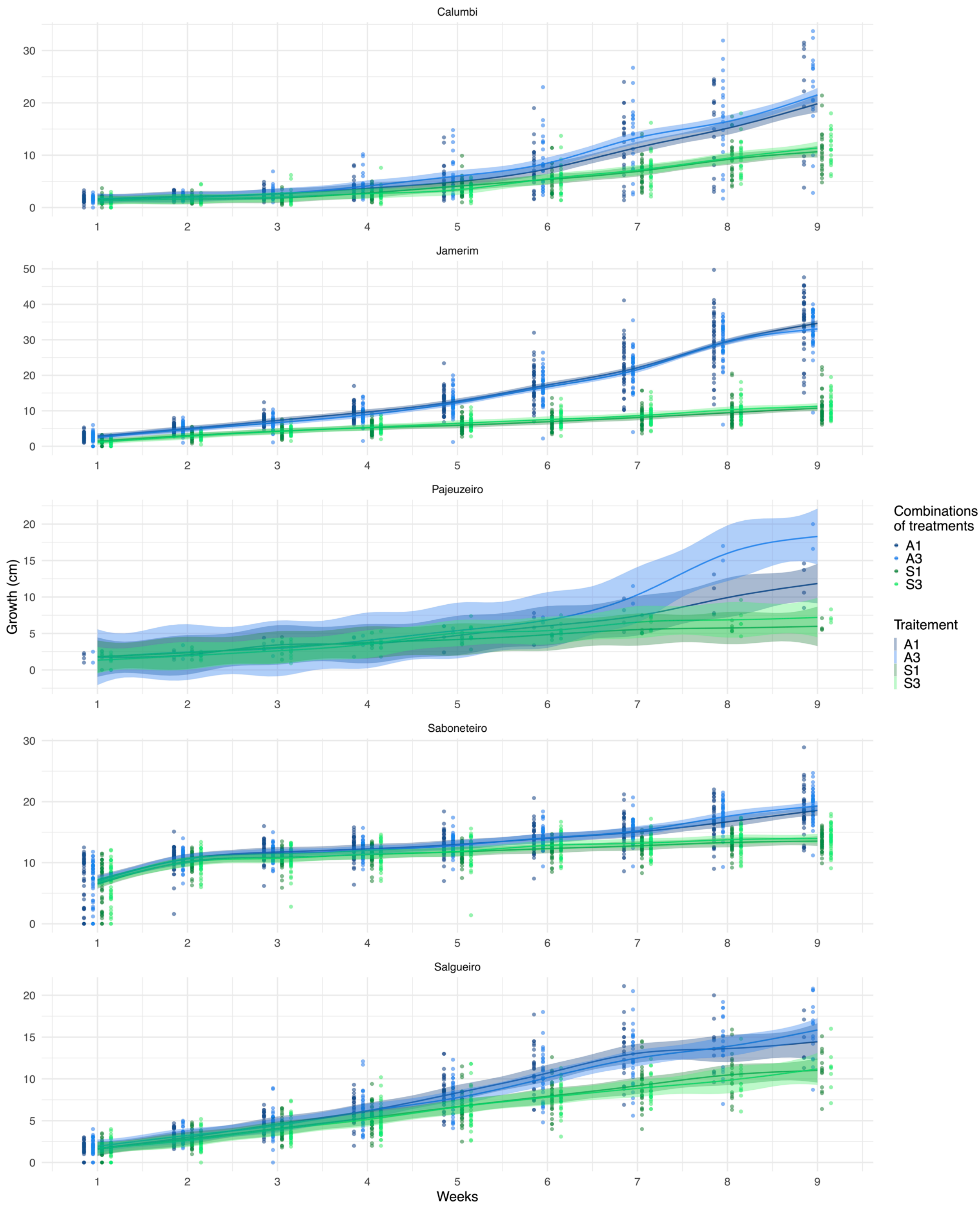


Figure 9 – Growth rates (height in centimetres) for nine weeks with a comparison of different combination of treatments (Soil types: S = sand and A = mixture of equal parts sand, goat manure, and clay; watered frequencies: 1 = watered every day; 3 = every three days) in and between the species: *Mimosa pigra*, *Celtis iguanaea*, *Vitex gardneriana*, *Triplaris gardneriana*, and *Sapindus Saponaria*.

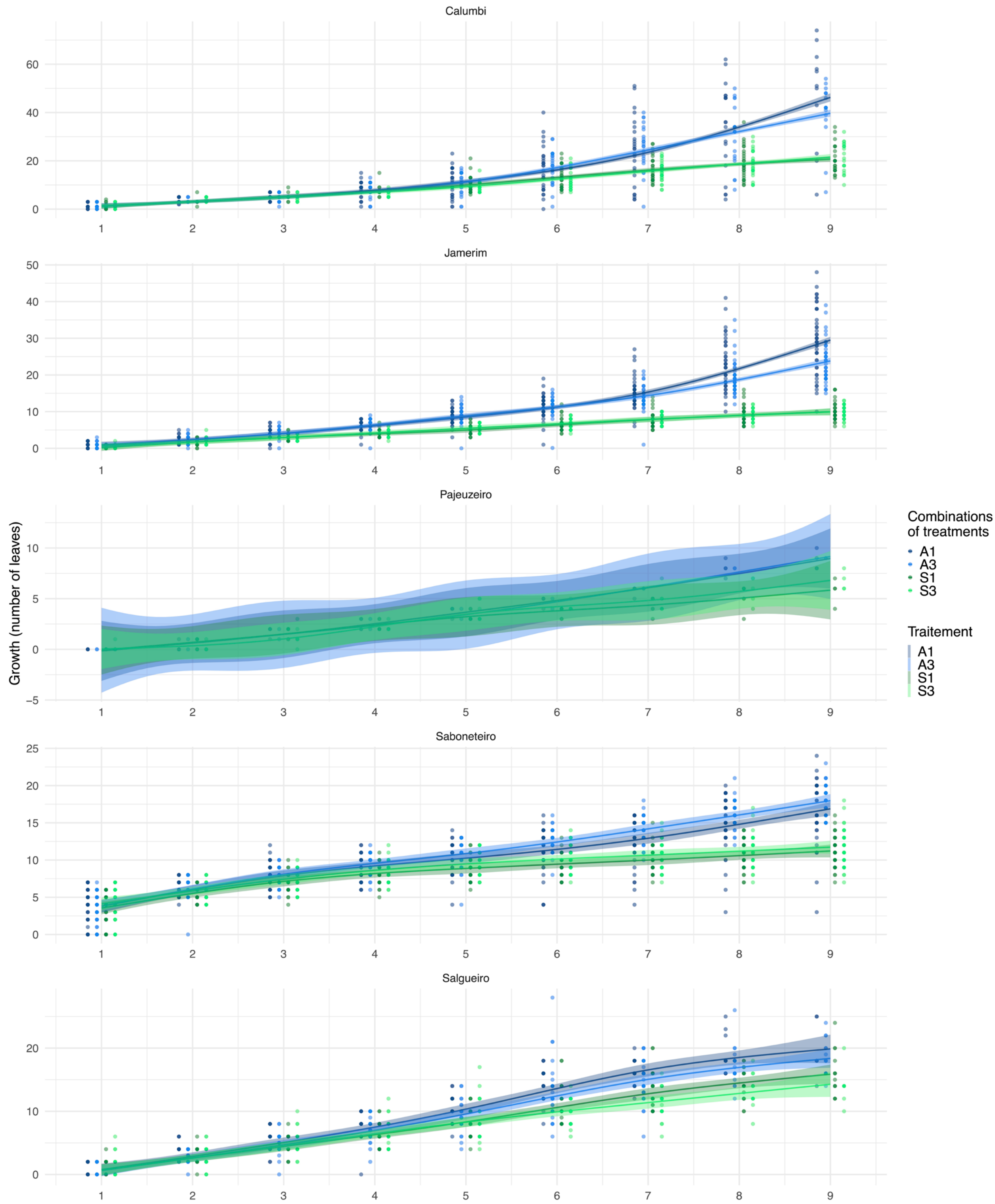


Figure 10 – Growth rates (number of leaves) for nine weeks with a comparison of different combination of treatments (Soil types: S = sand and A = mixture of equal parts sand, goat manure, and clay; Watered frequencies: 1 = watered every day; 3 = every three days) in and between the species: Mimosa pigra, Celtis iguanaea, Vitex gardneriana, Triplaris gardneriana, and Sapindus Saponaria.

are not always significant, such as *Triplaris gardneriana*, who shows no difference between treatment combinations for growth analysis. For *Mimosa pigra* (2.19 cm/wk) and *Sapindus saponaria* (1.32 cm/wk) species, the A3 treatment combination obtained the highest height growth rates while *Celtis iguanaea* (4.02 cm/wk) and *Vitex gardneriana* (1.94 cm/wk) obtained better growth under A1. On the other hand, the differences between the A1 and A3 combinations are not significant. The species follow the same trend with leaf count, where *Mimosa pigra* (4.23 leaves/wk), *Celtis iguanaea* (3.30 leaves/wk), and *Vitex gardneriana* (2.72 leaves/wk) have a faster increase in leaf count under the combination of A1 and *Sapindus saponaria* (1.69 leaves/wk) treatments under A3.

In the case of height growth, the combination of A3 treatments improves growth up to 1.9 times for *Mimosa pigra* and *Sapindus Saponaria*, while the combination of A1 treatments improves growth 3.8 times for *Celtis iguanaea* and 1.5 times for *Vitex gardneriana*. For growth with the number of leaves, an increase of 1.7 times can be observed in *Mimosa pigra*, 2.7 times in *Celtis iguanaea*, and 1.4 times in *Vitex gardneriana* under the combination of treatments A1. Finally, *Sapindus saponaria* sees an increase in leaf count up to 1.9 times higher with the A3 combination.

Transplantation

From the five selected species to transplantation produced in a tree nursery in 2018: *Schinopsis brasiliensis* Engl., *Tabebuia aurea* (Silva Manso) Benth. & Hook. F. ex S. Moore), *Spondias tuberosa* Arruda, *Albizia inundata* (Mart.) Barneby & J.W. Grimes, and *Lonchocarpus sericeus* (Poir.) Kunth ex DC; only *Lochocarpus sericeus* showed statistical difference for the microenvironmental factor, but just for the RGR-Height, being the shade environment where the plants grew more (p-value < 0.01). For basal diameter and leaf number, there were no statistical differences between treatments.

Mulching did not have any effect on growth (height, diameter, nor number of leaves) for any species. However, the interaction between microenvironment and mulching for *L. sericeus* showed effect for the RGR-Height, being sunny-straw lower than all the three shade treatments (shade-coconut, shade-straw, and shade-uncovered); sunny-coconut and sunny-uncovered (control) reported a growth between the other treatments with no statistical difference.

Final apparent survival was 95.8%, but there were any statistical differences between species nor microenvironment nor mulching. For *L. sericeus,* the final apparent survival was 96%, but with some regrowth plants. Initial measures did not have any effect on survival or on growth.

Table 5 – Growth rates by height and number of leaves for all five species by their combination of treatments.

	Height (cm/wk)				Number of leaves (#leaves/wk)			
	S3*	S1	A3	A1	S3	S1	A3	A1
Triplaris gardneriana	0.88	0.56	2.07	1.24	0.92	0.74	1.52	1.14
Mimosa pigra	1.31	1.16	2.19	1.81	2.44	2.50	3.89	4.23
Vitex gardneriana	1.28	1.39	1.90	1.94	1.99	2.05	2.46	2.72
Sapindus saponaria	0.77	0.71	1.32	1.20	0.91	0.88	1.69	1.52
Celtis iguanaea	1.21	1.07	3.82	4.02	1.22	1.21	2.72	3.30

*Soil types: S = sand and A = mixture of equal parts sand, goat manure, and clay; watered frequencies: 1 = watered every day; 3 = every three days.

DISCUSSION

Ecosystem integrity

The quality of the Pajeú riverbank, as measured by the QBR index and the land use, indicates a strong alteration of the habitat. Alterations in the Caatinga have occurred for a long time (SANTOS *et al*., 2014). Specifically, in the riverbanks, land use change is common due to their favourable characteristics for agriculture and livestock (VALERO; PICOS; ÁLVAREZ, 2014), resulting in habitat loss and affecting the species composition of a community (VALERO; PICOS; ÁLVAREZ, 2014).

In the Pajeú River, these are the two main anthropic activities, and so, they have caused a decrease in native vegetation and the invasion of exotic plants, particularly the algaroba (*Prosopis juliflora*) (NASCIMENTO *et al*., 2014), which was introduced to Brazil in 1942, with the intention of providing a supplement for livestock feed (BURNETT, 2017; CUNHA; SILVA, 2012; GOMES; BARBOSA, 2008; SANTOS; DIODATO, 2016, 2017; SCHULZ *et al*., 2016). This invasive plant has resulted in a change in the composition and abundance of species (ARAÚJO *et al*., 2018; RIBEIRO-NETO *et al*., 2016). Allelopathic effects have been reported for this species (CABI, 2020), as well as an increase in soil acidity (SOUZA *et al*., 2018b). Areas with a good arboreal component dominated by this exotic species, and so, the areas with a greater proportion of native species are those with fewer trees. This explains the negative correlation found between vegetation structure and quality of vegetation.

As reported by Souza *et al*. (2013), vegetal coverture was the main variable that determines the quality of the gallery forest. In this case, the fact that the variables naturalness of the river channel and quality of vegetation had almost no influence over the QBR index is due to their low variability among the different sites studied. On the other hand, altitude did not have influence on QBR index, probably because the altitude difference is relatively small (100 metres). Nevertheless, it had a positive influence on the quality of vegetation. This may be due to the difficult access conditions found in the upstream parts of the river that makes difficult to modify native vegetation. This coincides with other studies, where it has been reported that inaccessibility positively influences the conservation of the sites (REIS; DAVIDE; FERREIRA, 2014; VALERO *et al*., 2014; LAKE; BOND; REICH, 2017).

The bad conservation status found in our days on the Pajeú River is the result of several factors that have caused strong alterations to the riverbank components. Agricultural land use leads to deforestation (VALERO; PICOS; ÁLVAREZ, 2014), less species diversity (DÍAZ-PASCACIO *et al*., 2018), and decrease connectivity between the riverbank and adjacent natural vegetation (RODRÍGUEZ-TÉLLEZ *et al*., 2016). This provides ideal conditions for the establishment of *P. juliflora* (SANTOS; DIODATO, 2016), which is then disseminated by goats and bovine, facilitating the process of invasion (SCHULZ *et al*., 2016). Once established, the *P. juliflora* prevents the establishment of native species, affecting the function of the ecosystem (NASCIMENTO *et al*., 2014).

Soil seed bank

Germination and density

After the first month in the greenhouse, 71.8% (dry season) and 93.7% (rainy season) of seeds germinated. This high percentage of germination may indicate a quick response of seeds to water. The herb predominance can explain this response, since they need to germinate as soon as possible after the rain season starts to ensure a new seed generation because of their short life cycle (COSTA; ARAÚJO, 2003). By doing that, the herbs are advantaged in environments like the Caatinga, where the annual precipitation is low and irregular (SANTOS *et al.*, 2011). This pattern of germination has been reported by Costa and Araújo (2003), Mamede and Araújo (2008). The observed density values (except for conserved site at end the of the dry season) are consistent with the reported by Garwood (1989) for tropical forest, lower than 500 seeds/m^2. However, they are higher than the values reported by Santos *et al*. (2010) and Mamede and Araújo (2008), but lower than the published in others works for arid or semi-arid ecosystems (COSTA; ARAÚJO, 2003; KASSAHUN; SNYMAN; SMIT, 2009; SILVA *et al.*, 2015).

While dry season, the effect of anthropocentric disturb reducing the SSB was evident, and it may be related not only with the kind of impact, but its intensity (KASSAHUN; SNYMAN; SMIT, 2009). At the end of the rainy season, lower values were recorded perhaps because the seeds were recruited as a seedling while the rainy season (SILVA *et al*., 2013). Santos *et al*. (2011) suggest that seed diminution may be related to the irregular rain pattern, which affects the flowering and fructification, and by consequence, the seed production, concluding that the number of seeds is directly proportional to the amount of rain. Silva *et al*. (2013) also support that total precipitation determine the seed production but suggest that years of high precipitation are required to keep the seed stock on soil.

Floristic composition

Found richness is higher than reported by other works on dry forests (COSTA; ARAÚJO, 2003; MAMEDE; ARAÚJO, 2008; KASSAHUN; SNYMAN; SMIT, 2009), and in others works on caatinga's gallery forest (SANTOS *et al*., 2011; SANTOS *et al*., 2013).

The most abundant families, both in sites and seasons, are herbs. Poaceae was the most represented family, with a total of 14 species. This family is known by dominate some ecosystems and adapt to them. Moreover, it has a good development in sunny places.

Fabaceae was the only family with tree seeds in this study, *P. juliflora* and *L. leucocephala*, both exotic and invasive. Even though *P. juliflora* was reported as invasive of degraded areas, it has an important abundance in the SSB of the conserved area, maybe because the conserved site is surrounded by disturbed areas and also because the site is visited by caprine livestock, which is raised free on the caatinga vegetation. *L. leucocephala* was the third most abundant species of the degraded site and be considered one of the 100 worst invasive species of the world, to which the loss of biodiversity is attributed (NASCIMENTO *et al*., 2014).

Herbs predominance may be related to a life cycle, the high seed production, and their capacity to bear adverse conditions such as high temperatures and droughts. Another factor that contributes to the high number of herbs is that all the sites are surrounded by crop and grazing fields, and not by areas with trees that could be a propagules source. According to Braga *et al*. (2008), a seed bank dominated by herbs proof the bank is ready to start a successional process in a disturbed area.

Santos *et al.* (2013) suggest that the high number of herbs is due to a continuous herb seed production that contrasts with the lower seed production of trees or shrubs. Furthermore, because of the lower viability, bigger seeds vulnerable to an intense depredation and fungi attacks. Shannon values are lower than the ones reported in other works about caatinga seed bank (MAMEDE; ARAÚJO, 2008).

Plant selection

The Multicriteria grid developed for the project allows us to compare and classify tree and shrub species in a pondered scale easy to interpret. Ecological and social criteria were established in order to maintain biodiversity and maximize ecosystem services. Nevertheless, the score of one species may be determined by the availability of information; therefore, species poorly known or studied have lower scores. It was a challenge to find trustable and complete information for planting and cultivating the plants. Some of the species are barely mentioned in literature, and some of the data (such as germination rate or methods to break dormancy) are contradictory. Even if there is focus on the plantation and culture of native species of Caatinga and gallery forest (MAIA, 2004; CARRIÓN *et al.*, 2017), it is still necessary to continue to develop knowledge about the plants and its culture.

Pre-treatment germination

In preliminary research on germination pre-treatments, which aim to bring seeds out of their dormancy, the most recurrent treatments were hot or boiling water and sulphuric acid (NASR; SAVADKOOHI; AHMADI, 2013;

RASEBEKA; MATHOWA; MOJEREMANE, 2014). Since the current experiment wanted to make the manipulations accessible to everyone, sulphuric acid was not used. However, it was anticipated that hot water treatment would be the most effective way to bring the seeds out of their dormancy. In fact, only *M. pigra* germination was improved by hot water. For its part, mechanical scarification had a positive effect on germination and emergence of *S. saponaria*, information already available in the literature (SAUTU *et al*., 2006). Finally, *T. gardneriana* and *C. iguanaea* did not see any difference between treatments. It is difficult to determine why these two species did not respond to the dormancy release methods, since there is no information in the literature. However, in the case of *T. gardneriana*, it is possible that the seed does not have exogenous dormancy, but rather endogenous dormancy (GENEVE, 2003). Indeed, this rather delicate seed, found inside a samara, does not have the hard exterior of the other species tested. Consequently, the treatments applied did not have the desired effect. It is even possible that the hot water damaged the seeds, since the germination rate for this treatment is significantly lower than for the other treatments. A review of the scientific literature indicates that endogenous dormancy can be lifted by constant temperature, alternating hot and cold temperatures, potassium nitrate or gibberellic acid treatments (GENEVE, 2003). These treatments could therefore be tested at a later stage. In the case of *C. iguanaea*, the seeds are covered with a harder outer layer. However, the control treatment showed a better germination rate than hot water and scarification. Therefore, the hypothesis put forward here is that the treatments selected for the experiment were ineffective in bringing the seeds out of their dormancy and that no treatment is needed for the germination rates were high.

Growth and sustainability

After a thorough analysis of the results, I recommend growing *Sapindus saponaria*, *Celtis iguanaea* and potentially *Vitex gardneriana* in amended soils, and watering every two days.

As a first step, we suggest growing *V. gardneriana*, since it has very good growth rates in amended soils (4.02 and 3.82 cm/week) as well as good germination rates (86 and 82%) and excellent survival rates (98 and 94%). Among the species studied, it was the easiest to grow. It has a simple dormancy, or even no dormancy at all, and its maintenance requires daily or bi-daily watering. Irrigation frequencies should be closer together, since the amended soils seem to dry out more quickly. Indeed, this soil has allowed for superior plant growth and therefore requires more water. During the nursery experiment, *V. gardneriana* was the first species to show symptoms of water deficit; wilted leaves, lack of turgidity, dry and cracked soil. More frequent watering is therefore recommended. This species is also a good choice for self-cultivation and forest restoration since it has a good regeneration capacity. In fact, several plants had been injured or cut by an animal, but they all reformed apical buds and restarted their growth.

Secondly, we believe that *S. saponaria* would be a good candidate for nursery culture and gallery forest reforestation. Although it has low growth rates compared to the other species tested (0.71 to 1.32 cm/week), it is a species with good germination rates (73 to 88%) and excellent survival rates (98 to 100%). This secondary succession species (ROMÁN-DAÑOBEYTIA *et al*., 2012) is very easy to grow under any conditions tested and regenerates after injury. Despite lower growth rates, this species has a rapid initial growth rate, reaching 10 cm in height after only 2 weeks. This height is not reached until 5 weeks for *C. iguanaea* and 6 weeks for *V. gardneriana*. In addition, *S. saponaria* had the lowest emergence time in the nursery experiment, with an average of 16 days before germination compared to 17 days for *C. iguanaea* and 31 days for *V. gardneriana*. Ultimately, the pre-treatments applied to the latter two species were not ideal, but this reinforces the idea of simplicity in the cultivation of *S. saponaria*. This species has an easier and more feasible dormancy exit than the other two. In addition, it has many uses and economic benefits for the local population. Indeed, *S. saponaria* already has a recognized role in the recovery of degraded areas, in addition to its medicinal role against ulcers, inflammation, and skin lesions (PELEGRINI *et al.*, 2008; NEVES *et al*., 2018). Furthermore, the fruit is used for the extraction of saponin, used in soap (RIBEIRO *et al.*, 1999 *apud* NEVES *et al.*, 2018), and for its insecticidal properties (PREVIERO *et al*., 2010 *apud* NEVES *et al.*, 2018). Lastly, its heavy, hard, and compact wood is used for construction and the manufacture of tools and toys (LORENZI, 1998).

Finally, the last species recommended for home cultivation and reforestation of the Caatinga is *V. gardneriana*. This specie has germination rates of 64 to 72% and survival rates of 84 to 95%. In addition, it has some of the highest growth rates in the nursery experiment, 1.90 and 1.94 cm/wk. This species is recommended primarily for cultivation and forest restoration for two reasons. The first is the particularity of *V. gardneriana* seeds, which contain several embryos that have the possibility to germinate. This is a particularly interesting feature for reforestation efforts. It is also an interesting feature for other types of reforestation than transplantation, including direct sowing. Possibly, the seeds will improve the germination rate in direct sowing and intraspecific competition may force natural selection of the most suitable individuals to survive. Furthermore, according to Josélia Menezes (SOS Caatinga NGO), *V. gardneriana* is a shrub specie found on the banks of the gallery forests of the Caatinga. Menezes argues that *V. gardneriana* is a very important species for gallery forests, particularly for its role in maintaining the banks and thereby limiting erosion (Josélia Menezes, pers. comm., September 2019). However, this could not be verified in the literature, which does not address the ecological services played by this species. Finally, the species also has an economic role. Its leaves contain compounds used for pharmaceutical and insecticidal purposes (RANI; SHARMA, 2013; SENA FILHO *et al.*, 2017) and its wood is used in the manufacture of poles and tools (TPD, 2019).

Transplantation

Difference in growth in shaded areas may be explained by the nurse effect. The nursing plants benefit the growth of seedlings because of the reduction of stressful factors, both biotic (as herbivory) and abiotic (as high temperature, reducing evapotranspiration, and increasing nutrients in soil) (MOURA; MALHADO; LADLE, 2013; CARRIÓN *et al.*, 2017). Literature reported that seedlings from some species are only founded under the canopy of nursing plants (PATERNO; SIQUEIRA-FILHO; GANADE, 2016; CARRIÓN *et al*., 2017). Competition for water in seasonal dry forest may affect growth, but relation benefits-competition depends on species and their ontogeny (TROVÃO; FREIRE; MELO, 2010).

Mulching did not show either any statistical difference between treatments neither for species nor growth measure. However, in other seasonal dry forest had been reported that mulching increase 65% survival and the plants grow nine times faster (BARAJAS-GUZMÁN; CAMPO; BARRADAS, 2006). The final apparent survival was more than 95%, which is high compared with others seasonally dry forest and other gallery forests (HOLANDA *et al*., 2010; REIS; DAVIDE; FERREIRA, 2014; TORRES; RENISON, 2015). All the apparent dead plants were in the sunny treatment, however there was any statistical difference on microenvironment, nor mulching nor factor-interaction for any species.

Contrasting with another species in dry forests (VEGA-RAMOS, 2016), initial measures had no effect on survival or growth for any neither treatment nor species. That may be explained because it has been documented that the root development is more important than aerial part (DAMASCENO, 2016), but it was not evaluated on this project because it is a destructive measure.

A long-term monitoring to evaluate the ecosystem attributes (such as diversity, management, and functionality) and comparison with attributes of the reference ecosystem to assess the effectiveness of the restoration is essential (FERNANDES; FREITAS; PIÑA-RODRIGUES, 2017; GALETTI *et al*., 2018).

CONCLUSION

Gallery forest of Pajeú river showed high degradation and a low ecosystem integrity, only the areas of more difficult access were little more conserved. This degradation has affected the soil seed bank, and now, even in conserved sites, the proportion of seeds of native trees and shrubs is low. Those conditions had facilitated the establishment of invasive alien species, which makes even more difficult the secondary succession. For that reason, active restoration is necessary. Selecting the species and developing a plan for seedlings production are some of the first steps. Local people have shown they have much knowledge about native species, their uses and management. Seedlings production using native and local seed is possible, with a high rate of growth and germination. And the transplantation to a natural area seems to be effective in the short term.

There is still a long way to restore Pajeú's gallery forest, but studies like this are essential to increase knowledge of the ecosystem. This study could serve as a reference to design management/restoration strategies, prioritize actions, and develop public policies that ensure integrity and long-term conservation of the ecosystem and their functions.

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SERVIÇOS ECOSSISTÊMICOS NO PLANEJAMENTO INTEGRADO DO TERRITÓRIO METROPOLITANO: OFERTA, DEMANDA E PRESSÕES SOBRE A PROVISÃO DE ÁGUA NA REGIÃO METROPOLITANA DE CURITIBA

ECOSYSTEM SERVICES IN INTEGRATED PLANNING OF THE METROPOLITAN TERRITORY: SUPPLY, DEMAND AND PRESSURE ON WATER PROVISION IN THE METROPOLITAN REGION OF CURITIBA

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RESUMO

A sustentabilidade dos assentamentos humanos, principalmente áreas urbanas, e dos ecossistemas como um todo envolve a adoção de estratégias territoriais integradoras, que levem em conta os aspectos ambientais, econômicos, sociais e culturais. O enfoque dos serviços ecossistêmicos pode ser aliado no fortalecimento da visão integrada do território metropolitano e da água como elemento-chave integrador. Nesse contexto, este estudo teve como objetivo a proposição de um conjunto de indicadores de avaliação de capital natural e da oferta e demanda do serviço ecossistêmico de provisão de água para regiões metropolitanas, tendo como recorte a Região Metropolitana de Curitiba (RMC) (PR). O conjunto de indicadores foi selecionado de uma base teórica pautada em levantamento bibliográfico e posteriormente validado por especialistas pelo método Delphi, com envio de questionários eletrônicos em duas rodadas de validação. Os indicadores validados foram utilizados posteriormente para análise da provisão de água na RMC. Embora a mancha urbana concentre as maiores demandas por recursos hídricos, os municípios do seu entorno são os maiores provedores reais ou potenciais de serviços ecossistêmicos. Alguns municípios, principalmente os localizados no extremo norte da RMC, destacam-se pela significativa disponibilidade hídrica. No entanto, a análise demonstra tendência de degradação do capital natural e consequente comprometimento na provisão de água na RMC. Há a necessidade de se ampliar, em grande parte da região, a implementação das políticas de proteção da biodiversidade, de se estimular a criação de novas unidades de conservação e de fortalecer o monitoramento do uso do solo e a busca por soluções inovadoras para melhorar a gestão da água na metrópole.

Palavras-chave: provisão de água; indicadores; planejamento territorial; bacia hidrográfica; sustentabilidade.

ABSTRACT

The search for the sustainability of human settlements, mainly urban areas, and of ecosystems as a whole, involves the adoption of integrating territorial strategies that take into account environmental, economic, social, and cultural aspects. The focus on ecosystem services can be an ally in strengthening the integrated vision of metropolitan territory and water as a key integrating element. In this context, this study aimed to propose a set of indicators for the assessment of natural capital and the supply and demand of the ecosystem water supply service for metropolitan regions, with the Metropolitan Region of Curitiba (MRC), Paraná, as the main focus. The set of indicators was selected from a theoretical basis based on literature review and subsequently validated by specialists using the Delphi method, with electronic questionnaires sent in two rounds of validation. The validated indicators were later used to analyze the water supply in the MRC. Although the urban area concentrates the greatest demands for water resources, the surrounding municipalities are the largest real or potential providers of ecosystem services. Some municipalities, especially those located at the northern end of the MRC, stand out for their significant water availability. However, the analysis shows a trend of degradation of natural capital and consequent impairment of water supply in MCR. There is a need to broaden, in a large part of the region, the implementation of biodiversity protection policies, encourage the creation of new conservation units and strengthen the monitoring of land use and the search for innovative solutions to improve water management in the metropolis.

Keywords: water supply; indicators; territorial planning; river basin; sustainability.

INTRODUÇÃO

A expansão urbana nas grandes metrópoles tem ocorrido de forma crescente e desordenada, gerando diversos problemas ambientais e sociais. As mudanças no uso do solo e a pressão sobre as áreas de mananciais que abastecem os centros urbanos, causadas por essa expansão, impactam a disponibilidade hídrica da qual dependem os diversos setores da sociedade e alteram a oferta e a demanda de serviços ecossistêmicos (GONZÁLEZ-GARCÍA *et al*., 2020).

A Região Metropolitana de Curitiba (RMC) é uma das metrópoles que sofre com a crescente degradação dos recursos hídricos, tanto superficiais quanto subterrâneos, com o agravamento da vulnerabilidade socioambiental em áreas de mananciais e com a falta de planejamento e gestão integrados (GARCIAS; SANCHES, 2009).

A governança urbana voltada à construção de cidades resilientes e sustentáveis passa por fatores como o planejamento do uso do solo, com a adoção de estratégias territoriais e espaciais em todos os setores (UN-HABITAT, 2017).

Uma estratégia territorial de integração e coesão é a perspectiva das bacias hidrográficas, que busca integrar os diversos aspectos que interferem no uso e conservação dos recursos hídricos, como os meios físico, biótico, social, econômico e cultural (AQUINO; MOTA, 2019; YASSUDA, 1993). O Brasil organizou seu sistema de gestão integrada de recursos hídricos em bacias hidrográficas desde a promulgação da Política Nacional de Recursos Hídricos (Lei Federal nº 9.433, de 1997), considerada atual e avançada no tema.

Em regiões metropolitanas, como a RMC, a oferta e a demanda de água em diferentes graus entre os municípios e os diversos usos demandam uma gestão mais integrada dos recursos hídricos, com articulação compartilhada entre entes municipais, sociedade civil, Estado e Comitês de Bacia Hidrográfica, em torno de objetivos comuns. Há, assim, um potencial integrador do território metropolitano com base nos recursos hídricos.

Apesar desse potencial e de sua ampla aceitação, a gestão integrada de recursos hídricos focada na bacia hidrográfica ainda enfrenta dificuldades diversas em sua implantação, como a efetiva descentralização para o nível local da bacia, a dificuldade de articulação entre diferentes níveis de governo e a integração da gestão (PORTO; PORTO, 2008).

Se, por um lado, os recursos e problemas ambientais não se limitam a unidades administrativas, o que fortalece o argumento de que são necessários estudos em escalas mais adequadas à realidade, como a das bacias hidrográficas, por outro lado são fatos que grande parte dos dados está disponível em nível municipal e que os municípios são unidades administrativas que geram recursos e ações que impactam a qualidade ambiental, positiva ou negativamente. Assim, é estratégica a promoção de pesquisas em nível municipal, no entanto, não de forma isolada, mas como parte de um conjunto mais amplo, que é a região metropolitana.

O enfoque dos serviços ecossistêmicos e, especificamente, da análise da oferta e da demanda de água dos diversos municípios que compõem uma região metropolitana e das pressões sobre sua provisão, pode ser aliado no fortalecimento da visão integrada do território metropolitano e da água como elemento-chave integrador. Isso porque todos os entes municipais demandam, em maior ou menor grau, oferta de água, mas apenas alguns possuem o recurso disponível em seu território, e porque a integridade dos ecossistemas influencia na disponibilidade hídrica.

Os serviços ecossistêmicos correspondem aos inúmeros bens e serviços que a natureza gera ao bem-estar humano, derivados direta ou indiretamente das funções dos ecossistemas. Consistem em fluxos de materiais (água e alimentos, por exemplo), energia e informação provenientes dos estoques de capital natural (COSTANZA *et al*., 1997), que englobam todos os elementos abióticos e bióticos dos ecossistemas (assim como os ecossistemas em si), incluindo os recursos naturais (ex. água, solo, vegetação, espécies, ar) (MACE; BATEMAN, 2011; MASEYK *et al*., 2017). O desenvolvimento socioeconômico depende e continuará a depender, em longo prazo, da manutenção dos sistemas ecológicos que o sustentam e lhe dão base (MEADOWS, 1998; GÓMEZ-BAGGETHUN; GROOT, 2007).

A gestão do capital natural pode alterar a provisão de serviços ecossistêmicos, portanto, é importante operacionalizar e relacionar de forma prática os dois conceitos (MASEYK *et al*., 2017), mesmo que alguns modelos emblemáticos no tema (MEA, 2005; TEEB, 2010) falhem em apresentar conexões e interdependências explícitas entre serviços ecossistêmicos e os estoques de capital natural.

As florestas, por exemplo, influenciam substancialmente a quantidade de água que circula em uma bacia hidrográfica pela sua capacidade de evapotranspiração, com consequente aumento da umidade atmosférica e das probabilidades de formação de nuvens e geração de chuva (TEEB, 2010).

Nesse sentido, Layke (2009) afirma que indicadores tanto de estoque de capital natural quanto de fluxo de serviços ecossistêmicos são necessários para embasar as decisões políticas, sendo prioridade desenvolver e implantar ambos os tipos, como é feito por alguns estudos (ex. WEI *et al*., 2017; SHEPHERD *et al*., 2016). A aplicação de indicadores é a forma mais direta de se obterem informações com relevância política sobre a complexa relação entre serviços ecossistêmicos e sociedade (CZÚCZ; ARANY, 2016).

Além disso, há forças motrizes e pressões antropogênicas, como a urbanização e os arranjos institucionais, que têm acelerado a extinção de espécies e alterado as propriedades dos ecossistemas em grande escala (IPBES, 2016), influenciando na provisão de serviços ecossistêmicos, como de água, (TURNER; DONATO; ROMME, 2013) e cuja aplicação em termos de indicadores tem sido realizada por meio de modelos diversos (SINGH *et al*., 2012) e inúmeros estudos, como o de Paula Jr. e Pompermayer (2007).

A provisão de água é considerada um dos serviços ecossistêmicos essenciais para se atingir os Objetivos do Desenvolvimento Sustentável (ODS) (WOOD *et al*., 2018). Diversos trabalhos analisam indicadores de provisão de água como serviço ecossistêmico, como já apontaram, por exemplo, Egoh *et al*. (2012) e Czúcz *et al*. (2018), no entanto são poucos os que tratam de analisar indicadores de serviços ecossistêmicos relacionados à provisão de água e do capital natural que dá base para sua provisão no contexto de regiões metropolitanas (DANIELAINI; MAHESHWARI; HAGARE, 2018; FAVARO, 2017; OLEWILER, 2006).

Além disso, geralmente as pesquisas sobre oferta e demanda de serviços ecossistêmicos não são conduzidas em escalas adequadas à tomada de decisão relacionada ao planejamento, o que dificulta a aplicação da abordagem nas políticas de uso do solo (SAARIKOSKI *et al*., 2018).

Com base nesses pressupostos, esta investigação teve como objetivo propor um conjunto de indicadores de avaliação de capital natural e da oferta e demanda do serviço ecossistêmico de provisão de água para regiões metropolitanas, tendo como recorte a RMC (PR).

Buscou-se fortalecer uma visão mais integrada do território e evidenciar os recursos hídricos como elementos-chave dessa integração, um serviço ecossistêmico do qual todos dependem e cuja conservação, como recurso natural, passa pelo reconhecimento da importância de se manter a integridade dos ecossistemas. Os indicadores elaborados visam subsidiar a tomada de decisão e o processo de governança, permitindo analisar tendências positivas ou negativas e o perfil dos municípios da região metropolitana, somando-se a outras pesquisas, como as de Gutierrez, Fernandes e Rauen (2017) e de Silva *et al*. (2020a; 2020b).

METODOLOGIA

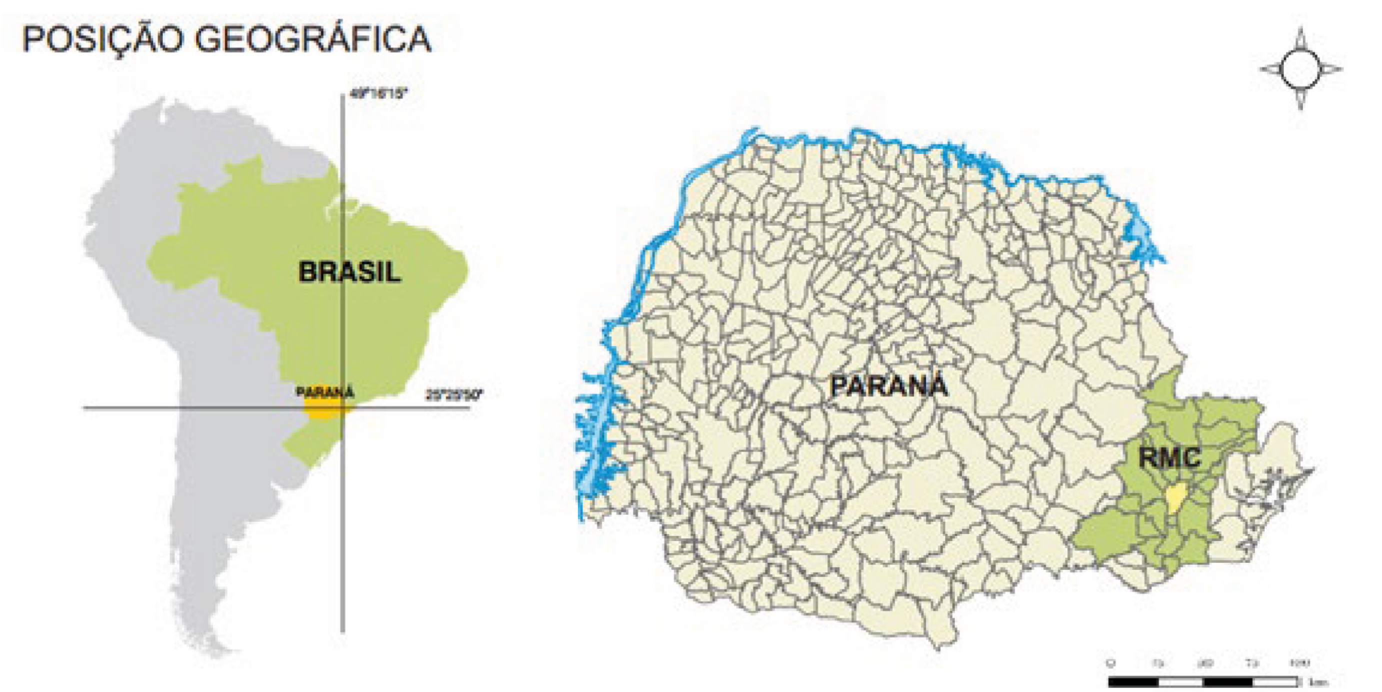
A RMC está localizada no Sul do país, no estado do Paraná (Figura 1). É a oitava região metropolitana mais populosa do Brasil, com 3.615.027 habitantes (IBGE, 2018), e concentra cerca de 30% da população do estado. Também é a segunda maior região metropolitana do país em extensão, com 16.581,21 km^2. A região, por sua localização geográfica estratégica, ocupa posição de relevância nos contextos estadual e nacional, pois está próxima dos principais mercados produtores e consumidores brasileiros e dos países do Mercado Comum do Sul (Mercosul), atraindo, assim, novas indústrias em vários municípios (COMEC, 2017).

A RMC é composta de 29 municípios: Adrianópolis, Agudos do Sul, Almirante Tamandaré, Araucária, Balsa Nova, Bocaiúva do Sul, Campina Grande do Sul, Campo do Tenente, Campo Largo, Campo Magro, Cerro Azul, Colombo, Contenda, Curitiba, Doutor Ulysses, Fazenda Rio Grande, Itaperuçu, Lapa, Mandirituba, Piên, Pinhais, Piraquara, Quatro Barras, Quitandinha, Rio Branco do Sul, Rio Negro, São José dos Pinhais, Tijucas do Sul e Tunas do Paraná.

A pesquisa foi conduzida em quatro etapas:

1. revisão de literatura;
2. seleção dos indicadores;
3. validação dos indicadores;
4. análise do capital natural e dos serviços ecossistêmicos na RMC.

A primeira etapa constituiu-se de levantamento bibliográfico para a construção de marco conceitual referente ao tema. A segunda envolveu a seleção dos indicadores para a análise do capital natural e do serviço ecossistêmico de provisão de água na RMC, por meio de revisão de literatura e com base nos seguintes critérios (OLEWILER, 2006): adequação ao contexto da RMC; relevância em relação ao tema estudado; disponibilidade de dados/custos de coleta e desenvolvimento realistas; qualidade, consistência e confiabilidade e amplitude geográfica adequada (escalas espacial e temporal apropriadas, municipal).



Fonte: COMEC (2012).

Figura 1 – Posição geográfica da Região Metropolitana de Curitiba.

A validação do conjunto de indicadores propostos, terceira etapa da pesquisa, foi realizada com a aplicação do método Delphi. Este se caracteriza como método de estruturação de processo de comunicação em grupo, de forma que esse processo seja efetivo em permitir que se lide com um problema complexo, entre eles a estruturação de modelos (VEIGA; COUTINHO; TAKAYANAGUI, 2013; WRIGHT; GIOVINAZZO, 2000; LINSTONE; TUROFF, 1975).

Delphi foi a técnica considerada mais apropriada para a validação do conjunto de indicadores do estudo por ser útil para estruturar o aperfeiçoamento de instrumentos de pesquisa. Outros trabalhos já aplicaram a técnica no contexto de indicadores e de serviços ecossistêmicos e demonstraram sua eficiência em integrar conhecimentos e criar consenso (ex. BENITEZ-CAPISTROS; HUGÉ; KOEDAM, 2014; BARRON; SHEPPARD; CONDON, 2016). Por meio desse método, são realizadas rodadas de aplicação do questionário de pesquisa, até que se alcancem a integração e o consenso entre as respostas dos especialistas consultados.

Para esta pesquisa, o questionário com os indicadores selecionados foi enviado a especialistas escolhidos entre profissionais com experiência em temas ligados ao capital natural e serviços ecossistêmicos (KRUEGER *et al*., 2012).

A aplicação dos questionários, realizada entre julho e setembro de 2018, foi feita em duas rodadas de validação, por meio eletrônico. Os especialistas assinam um Termo de Consentimento Livre e Esclarecido no qual constam informações sobre a pesquisa e o processo de participação, incluindo a garantia da preservação da identidade, possibilidade de recusa a qualquer momento e ciência sobre benefícios e riscos da pesquisa. Na primeira rodada, os especialistas foram convidados a atribuir um grau de relevância a cada indicador. Após a compilação dos resultados do grupo, a segunda rodada consistiu no envio do conjunto reformulado de indicadores, que permitiu a revisão das opiniões individuais e a estruturação final do conjunto de indicadores.

O retorno foi de 12 questionários, de 20 enviados a especialistas do poder público, do terceiro setor e da academia. Com isso, houve retorno de 60% do total de especialistas convidados a participar da pesquisa. Normalmente, há taxa de abstenção entre 30 e 50% na primeira rodada e entre 20 e 30% na segunda (WRIGHT; GIOVINAZZO, 2000).

Foram validados seis indicadores de provisão de água, sendo dois relacionados à oferta de água, três à demanda de água e um que aponta a relação entre oferta e demanda para abastecimento urbano, seis indicadores de capital natural e oito de forças motrizes e pressões (Quadro 1).

Quadro 1. Indicadores utilizados na análise de oferta e demanda de provisão de água na Região Metropolitana de Curitiba (RMC).

Tema	Indicador	Fonte
Provisão de água	Disponibilidade hídrica dos mananciais de abastecimento da RMC (oferta em litros por segundo ($L.s^{-1}$) por bacia hidrográfica)	Plano Estadual de Recursos Hídricos do Paraná (2009c)
	Demanda hídrica municipal total e por tipo de uso (demanda) (vazão captada em litros por município)	Plano Estadual de Recursos Hídricos do Paraná (2009a; 2009b)
	Disponibilidade hídrica subterrânea (potencial) da RMC (oferta em $L.s^{-1}$ por aquífero por bacia hidrográfica)	Plano Estadual de Recursos Hídricos do Paraná (2009d)
	Demanda hídrica das águas subterrâneas (vazão captada em $L.s^{-1}$ por município)	Plano Estadual de Recursos Hídricos do Paraná (2009a; 2009b)
	Consumo de água per capita (L/hab./dia)	Plano Estadual de Recursos Hídricos do Paraná (2009a; 2009b) com dados do Sistema Nacional de Informações de Saneamento (SNIS) de 2004.
	Avaliação da oferta-demanda do abastecimento urbano de água	Agência Nacional de Águas (2015)

Continua...

Quadro 1. Continuação.

Tema	Indicador	Fonte
Capital natural	Área de proteção aos mananciais (% do município)	Coordenação da Região Metropolitana de Curitiba (COMEC) (2016)
	Área de vegetação nativa (hectares e % do município)	Cálculo feito com dados do Mapbiomas de 1985 a 2017
	Áreas Estratégicas para Conservação da Biodiversidade (% do município)	Dados do Instituto Ambiental do Paraná (IAP) (2009) e cálculo realizado com uso de *software* livre para geoprocessamento QGIS.
	Porcentagem de Unidades de Conservação de Proteção Integral em relação ao total de floresta nativa no município	Instituto Ambiental do Paraná (IAP, 2018) e dados não publicados da Sociedade de Pesquisa em Vida Selvagem e Educação Ambiental.
	Porcentagem de Unidades de Conservação de Uso Sustentável em relação à área total do município	Instituto Ambiental do Paraná (IAP, 2018) e dados não publicados da Sociedade de Pesquisa em Vida Selvagem e Educação Ambiental.
	Área com agropecuária (hectares e % do município)	Cálculo feito com dados do Mapbiomas de 1985 a 2017 (PROJETO MAPBIOMAS, 2018)
Força motriz e pressão	População total (por município)	Instituto Brasileiro de Geografia e Estatística (IBGE) (2017b)
	Densidade demográfica (hab./km²)	Instituto Paranaense de Desenvolvimento Econômico e Social (IPARDES) (2018)
	Grau de urbanização (%)	IBGE (2010)
	ICMS Ecológico – recurso do ICMS repassado ao município	Secretaria de Estado da Fazenda (SEFA) (IPARDES, 2018)
	Área de mineração como proporção da área total do município (%)	Dados de 1985, 2000 e 2017 do Projeto Mapbiomas (PROJETO MAPBIOMAS, 2018)
	Estimativa de domicílios em assentamentos precários em áreas urbanas (%)	Marques *et al*. (2007) – dados Centro de Estudos da Metrópole (CEM-CEBRAP)
	Índice de esgoto tratado referente à água consumida	Sistema Nacional de Informações sobre Saneamento (SNIS) (2016)
	Taxa de cobertura do serviço de coleta de resíduos sólidos domiciliares em relação à população total do município	Sistema Nacional de Informações sobre Saneamento (SNIS) (2016)
	Porcentagem de estabelecimentos agropecuários com uso de agrotóxicos (%)	Censo Agropecuário (IBGE, 2017a)

ICMS: Imposto sobre Circulação de Mercadorias e Serviços.

O indicador de demanda hídrica dos mananciais de abastecimento da RMC (oferta) (L.s^{-1} por bacia hidrográfica) leva em conta os diversos tipos de uso da água. Há outros setores, além do abastecimento público, que possuem demandas hídricas diferentes: setores agrícola, industrial e de mineração, cujos comportamentos de consumo, combinados ou individualmente, podem afetar a cadeia como um todo, seja no abastecimento público, seja em outras categorias.

Os indicadores de disponibilidade hídrica subterrânea (potencial) da RMC (L.s^{-1} por aquífero por bacia hidrográfica) e de demanda hídrica das águas subterrâneas (vazão captada em L.s^{-1} por município) foram incluídos pela relevância das unidades aquíferas na RMC.

A avaliação da oferta-demanda do abastecimento urbano de água é um indicador para o qual já se produzem dados no âmbito do acompanhamento do alcance dos ODS.

Na intenção de se retratar o capital natural que dá base para a geração do serviço de provisão de água, foram inseridos indicadores que pudessem apresentar o estoque, calculado em área.

Para essa análise, empregou-se um indicador de proporção do município com Áreas de Proteção aos Mananciais (referenciado pela Lei Estadual nº 12.248, de 31 de julho de 1998 — PARANÁ, 1998), áreas que têm como finalidade controlar o uso e ocupação do solo de forma a garantir condições de qualidade da água compatíveis com o abastecimento público. O termo usado atualmente é Áreas de Interesse de Mananciais de Abastecimento Público da RMC, referenciado pelo Decreto nº 4.435, de 29 de junho de 2016 (PARANÁ, 2016). Por ser relativo ao capital natural, o indicador tem como objetivo apontar, de forma aproximada, em que medida e de que forma os recursos hídricos que são responsáveis pela provisão de água estão distribuídos na metrópole.

Além deste, o indicador de área de vegetação nativa como proporção da área total do território (% do município) foi considerado chave por ser amplamente aceito e utilizado. Também se aplicou o indicador de área prioritária para conservação como proporção da área total do território (% do município), inspirado diretamente em estudos realizados pelo Ministério do Meio Ambiente e na Resolução nº 05/2009 da Secretaria do Meio Ambiente e Recursos Hídricos do Instituto Ambiental do Paraná (SEMA/IAP), que estabelece o mapeamento de Áreas Estratégicas para a Conservação e a Recuperação da Biodiversidade no Estado do Paraná (IAP, 2009). Também foram analisados outros dois indicadores de capital natural relacionados à conservação da biodiversidade: porcentagem da vegetação nativa do município em unidades de conservação (UC) de proteção integral e porcentagem do município com UC de uso sustentável.

Adicionalmente, examinaram-se indicadores relacionados às forças motrizes e pressões que impactam positiva ou negativamente a provisão de serviços ecossistêmicos, cuja escolha teve como base teórica o relatório metodológico sobre avaliação de serviços ecossistêmicos elaborado pela Plataforma Intergovernamental sobre Biodiversidade e Serviços Ecossistêmicos (IPBES) (2016). Assim, foram selecionados neste escopo indicadores demográficos relacionados à poluição ambiental, além de um indicador de governança.

A análise dos indicadores de capital natural e de serviços ecossistêmicos na RMC, a etapa 4, incluiu a coleta de dados e a análise dos resultados, realizadas tanto temporal quanto espacialmente, para avaliação da heterogeneidade da metrópole em relação ao capital natural e ao fornecimento do serviço ecossistêmico de provisão de água.

Além da tabulação e da análise de dados secundários (conforme fontes relacionadas no Quadro 1), realizadas com auxílio do *software* Excel versão 2017, foram elaborados mapas com o *software* livre QGIS Desktop, versão 2.18. Adotaram-se como bases cartográficas o Instituto Brasileiro de Geografia e Estatística (IBGE) para obtenção das malhas municipais, o mapa das Áreas Estratégicas para Conservação da Biodiversidade do Paraná, do Instituto Ambiental do Paraná (IAP, 2017), e os mapas da Coordenação da RMC (COMEC) para cálculo do indicador de porcentagem do município com área de proteção aos mananciais.

RESULTADOS E DISCUSSÃO

Oferta e demanda de água na RMC

As principais bacias hidrográficas que ocorrem na RMC são a do Alto Iguaçu e a do Ribeira (a bacia Litorânea também está nos limites da região, abrangendo parcialmente Tijucas do Sul e São José dos Pinhais).

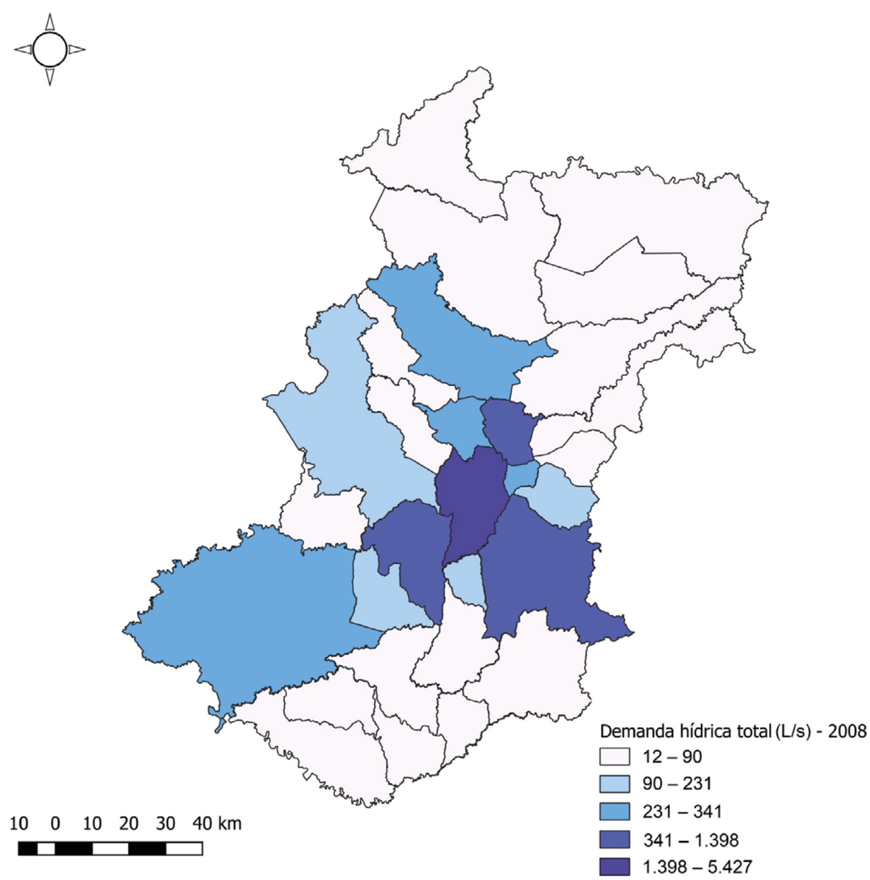
A bacia do Ribeira, que atende os municípios ao norte da RMC, possui disponibilidade hídrica superficial de 66.136,18 $L.s^{-1}$ e demanda hídrica de 788,8 $L.s^{-1}$. A bacia do Alto Iguaçu, que atende a porção ao sul da RMC, apresenta disponibilidade hídrica 27% menor do que a do Ribeira, de 48.190,69 $L.s^{-1}$, e demanda 12 vezes maior.

Assim, a oferta do serviço ecossistêmico de provisão de água é bem maior na bacia do Ribeira do que na bacia do Alto Iguaçu e, no entanto, a demanda pelo serviço é muito superior nesta última, na qual se encontra a grande mancha urbana da metrópole.

O sistema integrado de abastecimento na RMC, que em 2010 atendia 12 municípios dos 29 da região, é operado pela Companhia de Saneamento do Paraná (Sanepar) e composto de quatro sistemas produtores: Sistema Iraí (Barragem do Rio Iraí), Sistema Iguaçu (Canal de Água Limpa), Sistema Miringuava (Rio Miringuava) e Sistema Passaúna (Barragem do Passaúna) (ANA, 2015). As captações desses sistemas se localizam em Curitiba e seu entorno, abrangendo os municípios de Pinhais, Quatro Barras, Piraquara, São José dos Pinhais, Campo Largo e Araucária.

A demanda hídrica total calculada neste estudo, considerando-se os diversos usos (abastecimento, agricultura, pecuária, indústrias e mineração), é nitidamente maior nos municípios de Curitiba, Colombo, Araucária e São José dos Pinhais (Figura 2). Cada tipo de uso interfere na demanda por recursos hídricos (tanto na quantidade quanto na qualidade), refletindo-se nas disponibilidades presentes e futuras e podendo comprometer as metas de sustentabilidade no uso dos recursos hídricos.

Quando se analisa a demanda hídrica por tipo de atividade, o abastecimento público é o que prepondera, com 8.375,8 $L.s^{-1}$, somando todos os municípios.



Fonte: com base em dados do Plano Estadual de Recursos Hídricos do Paraná (PARANÁ, 2009a; 2009b).

Figura 2. Demanda hídrica total ($L.s^{-1}$), Região Metropolitana de Curitiba, 2008.

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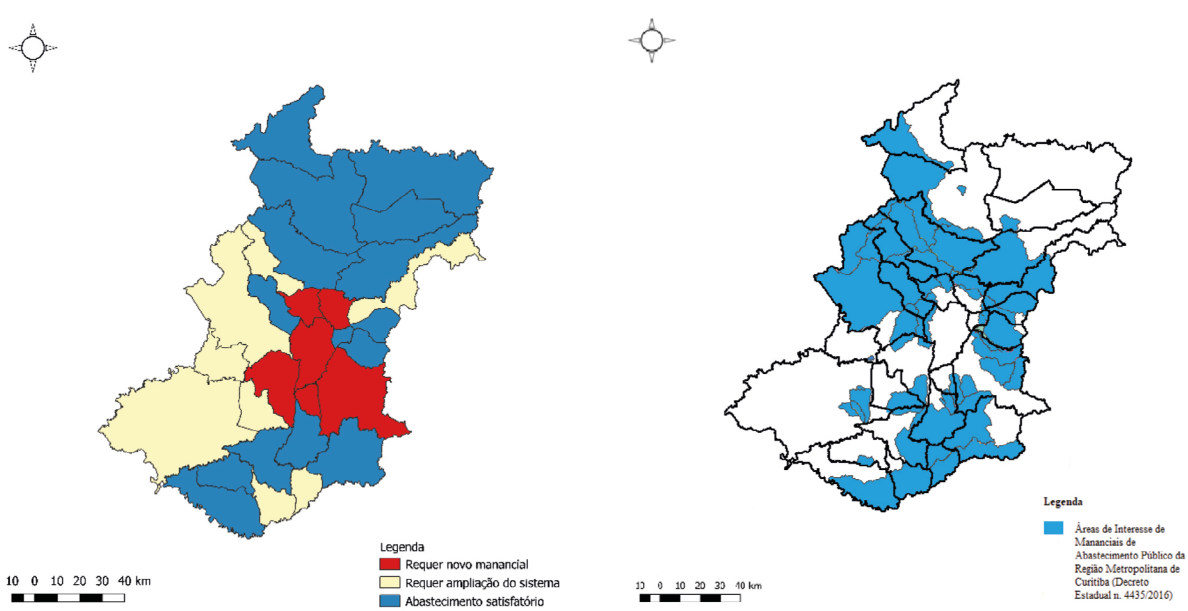
Isso representa 73% de toda a demanda hídrica da RMC, com destaque para o município de Curitiba. O setor industrial é o segundo que mais demanda provisão de água, com 1.774,9 $L.s^{-1}$, no entanto observa-se que essa demanda se concentra majoritariamente no município de Araucária. A agricultura fica em terceiro lugar, com 1.089,73 $L.s^{-1}$, e concentra-se principalmente nos municípios de Colombo (250,8 $L.s^{-1}$), Lapa (228 $L.s^{-1}$) e São José dos Pinhais (219,5 $L.s^{-1}$).

Fica evidente a situação do município de Curitiba como o maior receptor do serviço de provisão de água, com demanda de 5.427 $L.s^{-1}$, 74% maior do que o segundo maior receptor, o município de Araucária (1.397,5). Destacam-se também outros municípios, como Colombo (920,4 $L.s^{-1}$) e São José dos Pinhais (862 $L.s^{-1}$), pertencentes ao Núcleo Urbano Central (NUC) da RMC.

A densidade populacional é um dos principais fatores de pressão sobre os recursos hídricos. Quanto maior ela é, maiores são também a demanda por abastecimento, o volume de resíduos e efluentes gerados e o impacto sobre áreas naturais (SUDERHSA, 2007). A demanda mais elevada por serviços ecossistêmicos em locais mais urbanizados é algo que também foi observado por Baró, Gómez-Baggethun e Haasee (2017) e Favaro (2017), mostrando que a urbanização é fator diretamente associado ao aumento da demanda por serviços ecossistêmicos.

No município de Araucária, a principal demanda é industrial, ao contrário de Curitiba, cuja maior demanda é por abastecimento público em virtude da alta densidade demográfica, muito superior à dos demais municípios. Colombo possui mais demanda por abastecimento público também, e é o terceiro município em densidade demográfica na RMC, mas utiliza em grande parte fontes subterrâneas, ao contrário de Curitiba. Em São José dos Pinhais, a maior demanda também é por abastecimento público, advindo de fontes superficiais, em sua maioria, mas a demanda oriunda da agricultura também tem bastante relevância.

A avaliação da oferta-demanda do abastecimento urbano de água mostra que são esses mesmos municípios (Curitiba, Colombo, Araucária e São José dos Pinhais), além de Almirante Tamandaré e Fazenda Rio Grande, que requerem novo manancial para suprir sua demanda de abastecimento público até 2025. A comparação entre esse indicador e as áreas de proteção aos mananciais da RMC reforça que a maior demanda pela provisão de água não está nos municípios que abrigam a maior oferta potencial desse serviço ecossistêmico (Figura 3).



Fonte: com base em Agência Nacional de Águas (2015) e Coordenação da RMC (2016), respectivamente.

Figura 3. Avaliação da oferta-demanda de água na Região Metropolitana de Curitiba (RMC), em 2015, e áreas de proteção aos mananciais da RMC, em 2016.

Diagnóstico do projeto Águas do Amanhã, desenvolvido pelo Grupo Paranaense de Comunicação (GRPCOM) e finalista do prêmio ANA, reuniu dados e demonstrou que a bacia do Alto Iguaçu sofre com as pressões antrópicas. Possui qualidade da água que varia de medianamente a extremamente poluída, em decorrência de fatores como ocupações irregulares e deficiência na cobertura de coleta de esgoto. Além desses fatores, na bacia existem áreas de risco de inundação, pressão pelo uso de mananciais e ausência de mata ciliar em diversos locais (GRPCOM, 2011).

Essa pressão crescente sobre os mananciais torna cada vez mais complicada a utilização dos recursos hídricos mais próximos à mancha urbana de Curitiba. A região leste da RMC, que abriga as nascentes do Rio Iguaçu era, em 2003, o principal manancial de abastecimento da região, responsável pelo atendimento de 70% da demanda (ANDREOLI *et al*., 2003). Há expansão desordenada da malha urbana, que vem pressionando os mananciais. Locais favoráveis a essa expansão, por estarem distantes das áreas de mananciais, possuem limitações como distância da capital e geografia dos terrenos (GARCIAS; SANCHES, 2009).

Portanto, fica evidente que a urbanização, por um lado, gera o aumento da demanda por provisão de água e outros serviços e, por outro, leva à degradação de recursos naturais e perda de serviços ecossistêmicos, com efeitos irreversíveis e, em longo prazo, demandando planejamento do território em nível regional (OLIVEIRA-ANDREOLI *et al*., 2019; GREN; ANDERSSON, 2018; XIE *et al*., 2018).

No entanto, quando se pensa no planejamento territorial em nível metropolitano, tendo em conta os mananciais, há instrumentos importantes sendo aplicados na RMC, com envolvimento decisivo da COMEC, órgão coordenador metropolitano, as áreas de proteção ambiental (APA) e unidades territoriais de planejamento (UTP), que fazem parte do o Sistema Integrado de Gestão e Proteção aos Mananciais da RMC (SIGPROM), criado por meio de legislação específica para as áreas de mananciais, a Lei Estadual nº 12.248/1998. Entre os objetivos do SIGPROM, destaca-se o de assegurar as condições necessárias essenciais à recuperação e preservação dos mananciais para o abastecimento público e a compatibilização de ações de proteção ambiental e dos mananciais com a política de uso e ocupação do solo. As APA são um instrumento da política ambiental metropolitana, voltada à regulamentação do uso e da ocupação do solo nas áreas de drenagem das bacias hidrográficas de mananciais de abastecimento público atual e futuro. Apesar dessa vinculação positiva, nenhuma das cinco APA que se situam nesse contexto, as do Iraí, do Piraquara, do Pequeno, do Passaúna e do Verde, possui plano de manejo, instrumento fundamental para que elas cumpram sua função de aliar as atividades humanas à proteção aos recursos naturais. Todas elas, com exceção da APA do Rio Pequeno, possuem apenas zoneamento.

As UTP são unidades territoriais que sofrem pressão por ocupação e estão localizadas em áreas urbanas de municípios que integram as áreas de interesse de proteção de mananciais. Fazem a transição entre áreas já consolidadas e áreas rurais e/ou de proteção ambiental. As UTP da RMC se localizam em locais com loteamentos de alta densidade implantados (com aprovação em décadas anteriores). Nas UTP existe a possibilidade de troca do potencial construtivo por áreas de interesse público de preservação. Na RMC existem cinco UTP: de Campo Magro, Pinhais, Guarituba, Itaqui e Quatro Barras.

Mas a atuação em nível metropolitano na implementação desses importantes instrumentos de proteção dos mananciais de abastecimento não garante o suprimento da demanda hídrica futura na bacia do Alto Iguaçu, cujo cenário é de intensa pressão antrópica.

A degradação dos mananciais de abastecimento limita o desenvolvimento e impõe uma demanda antecipada de se buscar água em locais cada vez mais distantes e com maior custo de implantação e operações dos sistemas (ANDREOLI *et al*., 1999).

Para proteger as áreas de mananciais que garantem o abastecimento atual na Grande Curitiba, onde se concentra a maior parte da população da metrópole, é preciso, além de monitoramento do uso do solo para evitar maior pressão sobre esses mananciais, assegurar a proteção de fontes futuras de abastecimento.

A bacia do Ribeira é uma das alternativas futuras de abastecimento hídrico na RMC. Municípios como Campo Largo, Campo Magro, Itaperuçu e Rio Branco do Sul se situam total ou majoritariamente nessa bacia e apresentam mais de 90% de seu território abrangido por áreas de proteção aos mananciais.

O uso dos recursos existentes na bacia do Ribeira para abastecimento urbano da metrópole já tem sido discutido há décadas. Na década de 1990 foi proposta a elaboração de estudos visando ao uso múltiplo do Reservatório de Tijuco Alto — Bacia do Alto Ribeira — em Adrianópolis para essa finalidade, chamado Projeto Alto Ribeira (COMEC, 1997), aliás, com o risco de graves impactos ambientais (URBAN, 2003).

O Plano das Bacias do Alto Iguaçu e Afluentes do Alto Ribeira apontou, em 2007 (SUDERHSA, 2007), a relevância futura de rios localizados na bacia do Ribeira para abastecimento urbano, como a bacia do Açungui, na região de Campo Largo. No entanto, é relevante ressaltar que as dimensões dos reservatórios terão grandes impactos ambientais e sociais, além de envolverem dificuldades técnicas e altos custos operacionais em decorrência de fatores como a distância da região polo e relevo altamente acidentado, com vales profundos e muita vegetação.

Além do potencial hídrico existente na bacia do Ribeira para abastecimento público da Grande Curitiba, as fontes subterrâneas de água na RMC possuem bastante relevância. A unidade aquífera Pré-Cambriana, por exemplo, é fundamental como complemento ao abastecimento público e corresponde a 20% de toda a demanda de água da RMC, sendo utilizada principalmente por condomínios e postos de serviço (PARANÁ, 2009d).

O aquífero Carste, ou Karst, é considerado uma área de interesse para abastecimento público e, segundo o Plano Estadual de Recursos Hídricos do Estado do Paraná (2009d), representa uma alternativa para o abastecimento de parte da RMC, sendo dotado de ótima qualidade para consumo humano e alta produtividade na irrigação. Os municípios que estão sobre o Carste são abastecidos com águas subterrâneas. No entanto, sua exploração exige cautela, perante a vulnerabilidade do aquífero, em relação ao uso de defensivos agrícolas na região (PARANÁ, 2009d). Esse aquífero é considerado uma área de interesse de mananciais.

No entanto, este estudo identificou que muitos municípios localizados na região do Carste e/ou que fazem parte da bacia do Ribeira estão em situação preocupante quanto ao seu capital natural, com necessidade de adoção de medidas como a criação de novas UC, como será exposto na seção a seguir.

Forças motrizes e pressões sobre o capital natural e a provisão de água na Região Metropolitana de Curitiba

Na RMC, o aumento populacional e a expansão da mancha urbana têm aumentado a demanda pelo uso e ocupação do solo e, consequentemente, gerado pressão sobre os recursos naturais.

Houve perda de vegetação nativa em praticamente toda a RMC, e os municípios que mais perderam florestas estão localizados na bacia do Ribeira, na porção noroeste da RMC: Cerro Azul, Doutor Ulysses e Rio Branco do Sul. Assim, para além das áreas mais centrais da metrópole, verifica-se que foram municípios mais distantes do núcleo central os que perderam maior área de vegetação nativa entre 2000 e 2017 (Figura 4). Esse cenário ressalta a necessidade de garantir a proteção dos fragmentos florestais que ainda restam e dos remanescentes de mata atlântica, principalmente os que estão desprotegidos, especialmente nos municípios inseridos em áreas de proteção aos mananciais.

A RMC possui cerca de 20% do território composto de áreas estratégicas para a conservação, apresentando relevante extensão nas porções leste e oeste. No entanto, apenas uma pequena porção do território metropolitano é composto de UC, seja de uso sustentável, seja de proteção integral. E, entre as 73 UC de proteção integral e áreas correlatas na RMC, apenas 11 possuem plano de manejo, um instrumento importante para a conservação ambiental, pois estabelece as normas para o trato dos recursos naturais.

A análise da proporção de UC de proteção integral em relação à área total (ha) de floresta nativa nos municípios da RMC revela uma situação preocupante em relação à conservação da biodiversidade na metrópole. Dos 29 municípios da RMC, 11 não possuem UC de proteção integral e nove têm entre 0 e 1% desse tipo de UC em relação à floresta nativa do município.

Já quanto às UC de uso sustentável, nota-se sua existência no entorno do município de Curitiba, o que reflete, em grande parte, a vinculação das áreas de proteção ambiental (APA) com as bacias contribuintes das

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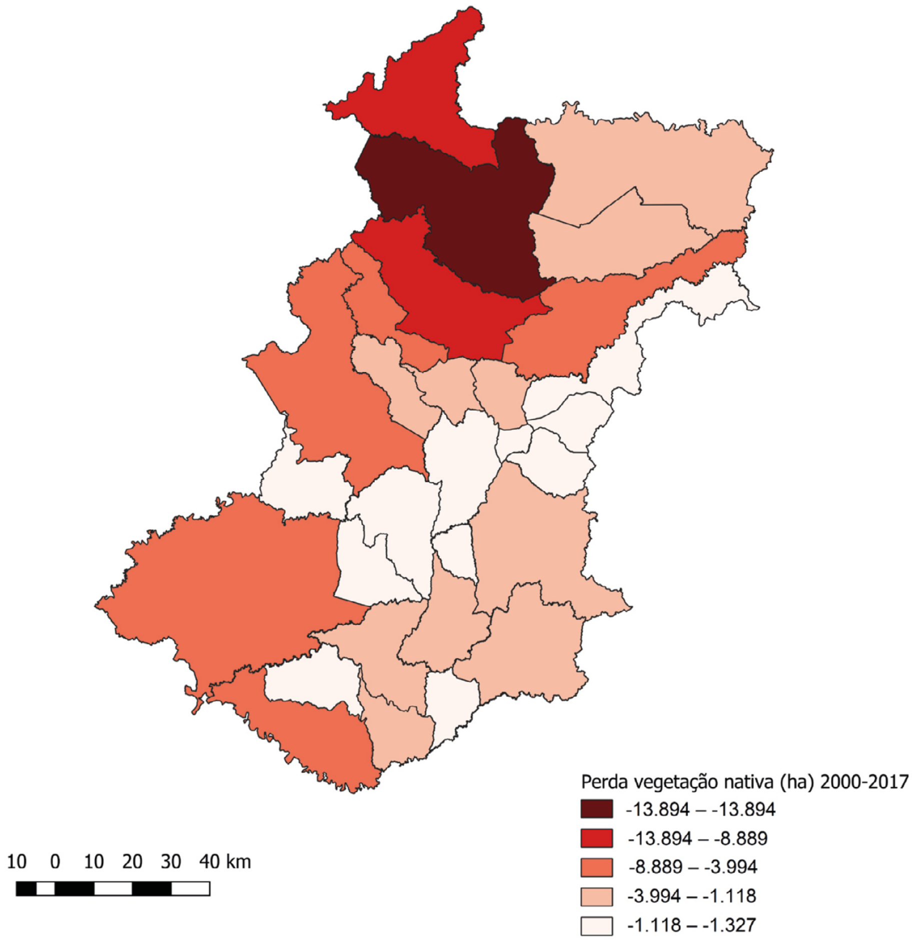

Fonte: com base em dados do Mapbiomas de 2000 a 2017 (PROJETO MAPBIOMAS, 2018).

Figura 4. Perda de vegetação nativa na Região Metropolitana de Curitiba entre 2000 e 2017.

represas de abastecimento público atual e futuro: as APA do Iraí, do Piraquara, do Pequeno, do Passaúna e do Verde.

De forma geral, toda a porção norte da região necessita de atenção prioritária pela tendência à diminuição significativa de vegetação associada a outros fatores, como extensa área de mananciais e de áreas estratégicas para conservação, ausência ou insuficiência na proteção de remanescentes em UC e/ou aumento da área com agropecuária.

Muitos municípios em estado de atenção prioritária em relação ao capital natural possuem baixa densidade demográfica e baixo grau de urbanização e se configuram como provedores reais ou potenciais de serviços ecossistêmicos como a provisão de água. A maior densidade demográfica está localizada em apenas alguns municípios, pertencentes ao núcleo central mais urbanizado, onde se concentram as maiores demandas hídricas. É preciso manter a integridade dos ecossistemas nos municípios menos urbanizados, não apenas para garantir a provisão de serviços ecossistêmicos para o centro urbano, mas também para frear a aceleração da degradação ambiental decorrente do aumento populacional e da urbanização crescente, conforme apontam Danielaini, Maheshwari e Hagare (2018). Já se sabe que proteger a biodiversidade e a vegetação natural, especialmente em áreas de interesse para abastecimento urbano, é muito importante, pois os ecossistemas previnem a poluição dos recursos hídricos, reduzem a erosão e evitam inundações. Esses são fatores que ajudam na provisão de água potável (CBD, 2012).

Nesse sentido, a situação na RMC demonstra tendência de degradação do capital natural e consequente comprometimento na provisão de água em longo prazo na RMC, quando se consideram os municípios da bacia do Ribeira de forma geral. Manter a integridade dos ecossistemas na região é fundamental para garantir a provisão de recursos hídricos nessa bacia. Além dessa tendência, existem outras pressões sobre a provisão futura de água ao NUC da RMC, composto de municípios como Curitiba, São José dos Pinhais, Colombo e Araucária. Os assentamentos precários são uma dessas pressões. Sua existência gera impactos como precariedade no saneamento, com consequente poluição dos mananciais, desmatamento e aumento no risco de enchentes. No contexto da bacia do Ribeira e das áreas de proteção aos mananciais, o município de Rio Branco do Sul se destaca por possuir 35% de assentamentos precários em relação ao total de domicílios, embora esteja integralmente em área de mananciais. Outros municípios da bacia inseridos majoritariamente em áreas de mananciais também sofrem essa pressão, como Itaperuçu (19,8%) e Campo Magro (19,6%). Doutor Ulysses, Tunas do Paraná e Cerro Azul também fazem parte da bacia e, embora tenham apenas parte de seus territórios abrangida por áreas de proteção aos mananciais, estão entre os mais preocupantes em proporção de assentamentos precários: 100% nos dois primeiros e 67,2% em Cerro Azul.

Outra pressão é a atividade de mineração, que ocorre em 22 dos 29 municípios da RMC, mas geralmente em pequena escala. O município de Rio Branco do Sul é o que possui a maior área de mineração na RMC: são 113,2 ha, o que corresponde a 58% de toda a área de mineração da região. As áreas com mineração se referem à extração mineral de grande porte, com existência de clara exposição do solo por ação de maquinário pesado. Destacam-se também, na bacia do Ribeira, os municípios de Fazenda Rio Grande e Itaperuçu, por suas atividades de mineração. Sabe-se que a mineração pode ter impacto negativo sobre os recursos hídricos e, considerando-se a importância da região como potencial futuro de utilização do serviço ecossistêmico de provisão de água para a metrópole, são necessários atenção e monitoramento desse tipo de atividade na região.

Para além dos fatores relacionados ao uso do solo que causam pressão sobre os mananciais e, consequentemente, à provisão de água para a metrópole, o uso de agrotóxicos, o esgoto não tratado e a disposição inadequada de resíduos sólidos podem comprometer a qualidade dos recursos hídricos. Na bacia do Ribeira, chama atenção a elevada proporção de estabelecimentos que utilizam agrotóxicos no município de Campo Magro (49,2%), embora este tenha 100% de sua extensão compreendida em áreas de proteção aos mananciais, sendo grande parte da bacia do Ribeira. Doutor Ulysses e Cerro Azul também possuem áreas de proteção aos mananciais e lideram no uso de agrotóxicos por estabelecimento na bacia: 71,1 e 50%, respectivamente.

A bacia do Alto Iguaçu, já altamente impactada por diversos fatores, alguns já mencionados, também chama atenção em relação ao uso de agrotóxicos. A porção sudeste da RMC, além dos mananciais da bacia do Ribeira, configura-se como região de potencial hídrico para o abastecimento da metrópole. Tijucas do Sul possui significativa proporção de áreas de mananciais e tem 44,4% dos estabelecimentos com uso de agrotóxicos. Piên (87,2%), Rio Negro (86,6%) e Quitandinha (85,2%) também têm porções significativas de áreas de proteção aos mananciais e lideram no uso de agrotóxicos em termos de proporção de estabelecimentos que fazem uso desse tipo de substância.

O plano de recursos hídricos da bacia do Alto Iguaçu (SUDERHSA, 2007) apontou a significativa produção agropecuária na região como fator que dificultaria a captação na bacia do Rio da Várzea, considerada fonte importante para abastecimento futuro da RMC.

Quanto ao tratamento de esgoto, na RMC, dos 22 municípios para os quais há dados disponíveis, apenas Curitiba (93%), Piraquara (80,5%) e Pinhais (80,1%) estavam em situação adequada de tratamento de esgoto em 2016.

O município em pior situação é Cerro Azul, que apresenta tratamento de esgoto referido à água consumida de apenas 1,4%. Em seguida vem Itaperuçu, com 15,8% de tratamento de esgoto, cuja atenção para o problema de saneamento deve ser uma prioridade, dada a sua relevância hídrica. Quitandinha (22,5%) e Mandirituba (25,3%) também estão em situação precária nesse sentido.

Já com relação à coleta de resíduos sólidos, nota-se na RMC maior cobertura nos municípios com características mais urbanas, como Colombo, Curitiba e Pinhais,

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nos quais 100% da população tem acesso ao serviço. Os mais mal colocados na RMC são os municípios de Cerro Azul, com 39,2% de coleta, Mandirituba, com 43,5%, e Agudos do Sul, com 49,6%, todos com relevância potencial para a provisão de água.

As pressões antrópicas geradas sobre os recursos hídricos da RMC demandam atenção e monitoramento, além de ação fiscalizatória e a adoção de medidas que garantam a proteção desses recursos e a provisão de água para a metrópole, como soluções baseadas na natureza e na infraestrutura verde. É preciso intensificar também a implementação de iniciativas de pagamento por serviços ambientais na região, visando à proteção dos recursos hídricos. A RMC já apresenta diversas ações nesse sentido, que podem ser incentivadas e potencializadas.

O Imposto sobre Circulação de Mercadorias e Serviços (ICMS) Ecológico, instrumento de política pública criado pioneiramente no Paraná, embora não seja denominado formalmente de pagamento por serviços ambientais, se configura como tal, pois trata do repasse de recursos financeiros aos municípios que abrigam em seus territórios UC ou áreas protegidas, ou ainda mananciais para abastecimento de municípios vizinhos. Metade dos recursos repassados pelo ICMS Ecológico é destinado a municípios que tenham em seu território manancial de abastecimento de água que se destine ao suprimento da população do município vizinho.

Os municípios da RMC que mais receberam recursos oriundos do ICMS Ecológico em razão dos mananciais foram Piraquara, Campo Magro e São José dos Pinhais. Obtiveram em 2017, respectivamente, R$ 23.607.257,81, R$ 10.766.454,76 e R$ 9.160.783. Os três municípios são relevantes no abastecimento da área urbanizada da RMC.

Em tese, os recursos devem ser utilizados em ações de conservação da biodiversidade e de preservação dos mananciais, mas a aplicação efetiva desses repasses em ações dessa natureza não é certa. A Sociedade de Pesquisa em Vida Selvagem e Educação Ambiental (SPVS, 2018, p. 15) afirma que “pouco do valor recebido pelas prefeituras é investido nas áreas naturais que representam a fonte dos recursos”.

O indicador de pagamento por serviços ambientais (PSA), por fim, mostrou que 10 municípios da RMC possuíam, em 2018, algum mecanismo que utilizava o PSA, seja em arcabouço legal e/ou programas e/ou projetos de iniciativa privada ou pública. Embora importantes, são iniciativas ainda pontuais.

Em termos de PSA voltados aos recursos hídricos na RMC, destacam-se os projetos piloto desenvolvidos pela SEMA do Paraná para conservação dos recursos hídricos na Bacia do Rio Piraquara, no município de Piraquara e na bacia do Rio Miringuava, em São José dos Pinhais. As ações da SEMA são respaldadas na Lei Estadual nº 17.134/2012 (PARANÁ, 2012), que institui o PSA, regulamentada pelo Decreto Estadual nº 1.591/2015 (PARANÁ, 2015), que estabelece como uma das modalidades de PSA a conservação dos recursos hídricos.

CONCLUSÕES

Na RMC, a mancha urbana, onde estão municípios como Curitiba, Pinhais, Almirante Tamandaré e Colombo, concentra as maiores demandas por recursos hídricos. Esses municípios se caracterizam muito mais como receptores do que como provedores do serviço de provisão de água.

Ao redor de Curitiba se concentram APA e UTP que possuem papel importante na preservação dos principais mananciais que atualmente abastecem a metrópole e que são um fator positivo quando se considera seu planejamento territorial. Ainda assim, é inevitável a busca por novos mananciais ao longo do tempo, diante da alta degradação na bacia do Alto Iguaçu e do aumento crescente na demanda pela provisão de água.

Se, por um lado, parece evidente que a dinâmica urbana da metrópole se concentre nos municípios que fazem parte do chamado NUC, onde estão as principais movimentações pendulares de população e mesmo os mananciais que abastecem a mancha urbana, é imprescindível notar que são os municípios do entorno os maiores provedores reais ou potenciais de serviços. Alguns, principalmente os localizados no extremo norte da RMC, destacam-se pela significativa disponibilidade hídrica, com potencial futuro de abastecimento.

No entanto, a RMC como um todo demonstra tendência de degradação do capital natural e consequente comprometimento na provisão de água em longo prazo, com destaque para a bacia do Ribeira, que apresenta potencial para abastecimento futuro da Grande Curitiba.

O estudo demonstra que a perspectiva dos serviços ecossistêmicos favorece a busca por coesão entre os municípios da RMC, quando se observa que as dinâmicas que ali ocorrem vão além daquelas mais evidentes na mancha urbana, extrapolando os municípios mais urbanizados.

Nesse contexto, o planejamento territorial na RMC deve ser pensado tendo em vista esses fluxos de serviços. E, dessa forma, a conservação da biodiversidade deve ser encarada não como elemento desconectado da realidade urbana, mas relevante para a proteção de áreas fundamentais para a provisão de serviços ecossistêmicos como a água.

Embora a legislação e os instrumentos de recursos hídricos sejam bem formulados, indicando as necessárias integrações com as diversas políticas e a gestão descentralizada como princípios básicos desse sistema, na prática ainda há dificuldades. Não obstante permaneça o desafio histórico de se criarem arranjos institucionais e territoriais no espaço metropolitano que favoreçam o desenvolvimento socioeconômico e ambiental de forma harmônica e integrada, adotar a perspectiva da oferta e demanda de serviços ecossistêmicos do qual dependem os municípios da metrópole pode ser um caminho para fortalecer essa integração territorial.

Além dos desafios de governança e das demandas de planejamento já conhecidas, como monitoramento do uso do solo, fiscalização e criação de áreas protegidas, os tempos atuais demandam a busca por soluções inovadoras para melhorar a gestão da água na metrópole, por meio de seu uso racional e método cíclico, e retardar a necessidade de se buscar captação em mananciais cada vez mais distantes e com maior custo operacional.

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ASSESSING FUTURE SCENARIOS OF WATER AVAILABILITY USING CMPI5 HIGH RESOLUTION CLIMATE MODELS – CASE STUDY OF THE ALTO TIETÊ BASIN

AVALIANDO CENÁRIOS FUTUROS DA DISPONIBILIDADE HÍDRICA UTILIZANDO MODELOS CLIMÁTICOS DE ALTA RESOLUÇÃO CMIP5 – ESTUDO DE CASO DA BACIA DO ALTO TIETÊ

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ABSTRACT

Global climate change and extreme climate variability directly affect the hydrological cycle and rainfall variability, which highlights the importance of studying climatic conditions as a support for water resource management in regions with low water availability, such as the Upper Tietê River Basin (Bacia Hidrográfica do Alto Tietê – BHAT). This study aims to present a diagnosis for BHAT water availability conditions in future climate scenarios, based on the high-resolution models CMCC-CM, MIROC4h, ETA-MIROC5, and ETA-HADGEM2-ES, for the time slices 2020-2040, 2041-2070, and 2071-2099, in order to provide climate information for BHAT's management. The main results showed a clear upward trend in the average annual temperatures. For the RCP8.5 scenario, the average annual increase was 0.5°C from 2006 to 2099. Precipitation showed high interannual variability without a specific defined trend. The average annual flow showed a slight positive trend in the period 2006–2099. However, it also presented a decrease in the monthly average flow in the wet period (13%) and an increase in the dry period (9.7%), compared to the historical data simulated for the time slice 2020–2040 of the RCP8.5 scenario. However, the annual increase in BHAT water availability at future scenarios should not be sufficient to meet the growing demand for water in the region. Therefore, it is necessary to evaluate water availability based on other high-resolution climate models, in order to evaluate uncertainties, and in other regions with different supply systems that provide water to the São Paulo Metropolitan Region, identifying alternative water supply sources.

Keywords: climate projections; CMIP5; water availability; water resources management; Upper Tietê River Basin.

RESUMO

As mudanças climáticas globais e a variabilidade climática extrema impactam diretamente o ciclo hidrológico e a variabilidade de precipitação, tornando importante o estudo de condições climáticas como subsídio ao gerenciamento de recursos hídricos em regiões com baixa disponibilidade hídrica, como a Bacia Hidrográfica do Alto Tietê (BHAT). O estudo teve por objetivo apresentar um diagnóstico das condições de disponibilidade hídrica na BHAT, utilizando cenários climáticos futuros dos modelos de alta resolução CMCC-CM, MIROC4h, ETA-MIROC5 e ETA-HADGEM2-ES, nos *time slices* 2020-2040, 2041-2070 e 2071-2099, de forma a fornecer informações climáticas para gestão da BHAT. Os principais resultados mostraram uma clara tendência de aumento das temperaturas médias anuais, sendo que para o cenário RCP8.5, verificou-se um incremento médio anual de 0,5°C de 2006 até 2099. Já a precipitação apresentou alta variabilidade interanual, sem tendência específica definida. A vazão média anual mostrou leve tendência de aumento no período 2006–2099, porém com diminuição das vazões médias mensais no período úmido (13%) e aumento destas no período seco (9,7%), em comparação com os dados históricos simulados no *time slice* 2020-2040 do cenário RCP8.5. No entanto, o acréscimo anual na disponibilidade hídrica da BHAT nos cenários futuros não deve ser suficiente para acompanhar a crescente demanda por água na região. Mostra-se, assim, necessária a avaliação da disponibilidade hídrica com base em outros modelos climáticos de alta resolução, a fim de avaliar as incertezas, e nas regiões dos demais sistemas de abastecimento da Região Metropolitana de São Paulo, identificando fontes alternativas de abastecimento de água.

Palavras-chave: projeções climáticas; CMIP5; disponibilidade hídrica; gestão de recursos hídricos; Bacia Hidrográfica do Alto Tietê.

INTRODUCTION

Climate changes are characterized based on weather variations in multiple time scales and directly affect the planet's hydrological cycle and precipitation variability, thus being able to impact availability and scarcity of water in several regions of the globe, from local to regional scales (GESUALDO *et al*., 2019). Water scarcity, in its turn, can impact other departments, such as public water supply and hydroelectric sectors (SILVEIRA *et al*., 2018).

In recent decades, both frequency and intensity of drought occurrences around the world have significantly raised, most likely due to the increase in the global mean temperature. Climate conditions characterized by the occurrence of extreme events implied major impacts in South America, for example, the drought in Brazil's northeast region from 2010 to 2016. In addition, there was a second major drought event in Brazil's southeast region in 2014 and 2015 (MARENGO; BERNASCONI, 2015; MARENGO *et al*., 2018; CALADO; VALVERDE; BAIGORRIA, 2019).

Thus, the study and dissemination of climate conditions can help to drive adaptation and impact mitigation plans and water management policies (BORK *et al*., 2017), if they are objective enough to be considered by the authorities involved in decision-making processes. This information can be used, for example, for watersheds management, in order to provide benefits for the preservation of these natural resources, reducing the risks of natural disasters (CABRERA *et al*., 2009).

The drought of 2014–2015 in Brazil's southeast region adversely affected the water availability of the Cantareira System, the largest water supply system in the São Paulo Metropolitan Region (SPMR). It reflected over the current management of water resources from Upper Tietê River Basin (*Bacia Hidrográfica do Alto Tietê* — BHAT) and the need for risk reduction (FISCH; SANTOS; SILVA, 2017; OTTO *et al*., 2015; NOBRE *et al*., 2016; CALADO; VALVERDE; BAIGORRIA, 2019).

The BHAT covers most of SPMR's portion, which is composed by 39 cities, and 35 of which are inserted into Alto Tietê's region (FABHAT, 2014). Given the importance of this river basin and the regional water availability, several researches have already been produced so far in order to provide climatic information diagnosis and projection of future scenarios, subsidizing the management of water resources. In the study by Lira and Cardoso (2018) on the trend of river flows in the main Brazilian hydrographic basins, for the period 1931–2014, an increase in the quarterly flow in winter and spring at Tietê river basin was observed, with statistical significance, in addition to a smaller increase in annual flow, when compared to other sub-basins of Paraná River.

Pereira's *et al*. research (2008) evaluated results from the Hydrometeorological Forecast System (HFS) regarding the BHAT, including short- and immediate-term forecast obtained through numerical modeling on a local scale. Moreover, in Calado, Valverde and Baigorria's research (2019), teleconnection indicators were evaluated, such as the El Niño phenomenon, the Pacific Decadal Oscillation (PDO) and extreme events in the variability of the seasonal precipitation and flow in the Cantareira System region.

Silva and Valverde (2017) developed another study on the use of future climatic scenarios information for the management of BHAT, which evaluated the regional water availability for future scenarios based on a global climatic model from the Meteorological Research Institute — Japanese Meteorological Agency (MRI-JMA) for A2 emission scenario and an empirical hydrological model. It has been verified that, for the future period comprehended between 2017 and 2039, the variability in both precipitation and temperature in BHAT will lead to an increase in the variability of the seasonal flow, which indicates the susceptibility to floods and inundations in the summer and water scarcity events in the fall and winter (SILVA; VALVERDE, 2017).

A recent study published by Gesualdo *et al*. (2019) investigated the influence of climate changes on water availability in Jaguari River Basin (JRB), part of the Cantareira System, which is the main source of freshwater to nine million people in SPMR. Making use of a conceptual hydrological model and a conjunction of future projections generated by seventeen General Circulation Models (GCM) for two Intergovernmental Panel on Climate Changes (IPCC) (RCP4.5 and RCP8.5), it was found that a greater interannual variability for the flow is expected, from January to March, as well as an extension of the drought season until November (currently from June to September), with a decrease of over 50% in October, indicating October and November as the most vulnerable months to water scarcity.

The use of climate models for the study of water availability is an important tool for the integrated and preventive management of water resources, in order to evaluate the resilience of a specific region to the impacts of climate changes and to increase the management potentialities aiming water security, despite the existence of uncertainties related to this sort of model to forecasting future climate scenarios (SILVA; VALVERDE, 2017). Therefore, the importance of producing studies that generate complementary results for the use of climate models to evaluate water availability in the BHAT is highlighted, such as the application of other climate models to assess the climate variability through several future scenarios.

Thus, the objective of this study was to present a diagnosis of the water availability conditions in BHAT for future climate scenarios based on high-resolution models, for the time slices 2020–2040, 2041–2070, 2071–2099. Therefore, it is believed that this type of study might serve as subsidy for the management of water resources in one of the most populated river basins in SPMR, where the water demand for the population's subsistence might be affected by the extreme climate variability, in a context of global climate changes.

STUDY AREA, DATA AND METHODOLOGY

The study area covers the totality of BHAT, which is located upstream from the Pirapora dam, comprehending a total draining area of 5,868 km^2, until the source of Tietê River in Paraitinga River, in Salesópolis, as illustrated in Figure 1. It counts with a total mean precipitation of 1,400 mm/year, presenting a wet period from November to March and a drought period from June to August, with contribution of important affluent rivers, such as Pinheiros River. It consists of 34 highly urbanized cities, with a total population of around 20 million inhabitants and, therefore, a mean demographic density of 3,000 inhabitants/km^2, considering the total river basin draining area. The elevated population contingent and the expressive economic potential of industries and services make the demand for water resources in the river basin approximately twice as big as its availability. The water demand in the region raises due to the increasing population growth, despite the low rate growth due to the high consolidation degree of the basin's urbanization and the higher levels of consumption of the local population, classifying the basin as one of most critical in the state of São Paulo. Eight water supply systems are responsible for supplying the basin's population: the Cantareira System; Alto do Tietê and Rio Claro Systems; Guarapiranga-Billings, Grande and Cotia Systems (FUSP, 2009; FAHBAT, 2014).

In order to achieve this study's goal, which is the analysis of the basin's future scenarios of water availability, in terms of tributary flow, temperature and precipitation data were analyzed in monthly scale from two global models of high spatial resolution from the Coupled Model Intercomparison Project – Phase 5 (CMIP5).

The CMIP5 is a project of the Working Group on Coupled Modeling (WGCM), from the World Climate Research Programme (WCRP), with the contribution of the Analysis, Integration and Modeling of the Earth System Project (AIMES) from the International Geosphere Biosphere Programme (IGBP). The project's objective is to produce a high-quality set of multimodal data, available for free, in order to promote the progress in the knowledge concerning climate changes and variability. The CMIP5 high-resolution models selected for this study were the Italian CMCC-CM and the Japanese MIROC (TAYLOR; STOUFFER; MEEHL, 2012). The application of high-resolution models is recommended for researches that need to evaluate climate conditions and to identify extreme events in small regional areas (TAYLOR; STOUFFER; MEEHL, 2009), such as the BHAT covered area.

For that reason, this study also used data from two regional climate models, both developed by the *Centro de Previsão de Tempo e Estudos Climáticos do Instituto Nacional de Pesquisas Espaciais* (CPTEC/INPE): The Eta-MIROC5 and Eta-HadGEM2-ES, which respectively use the global models MIROC5 and HadGEM2-ES from CMIP5 as boundary conditions (CHOU *et al*., 2014b).

The CPTEC/INPE regional models were developed within the scope of the research group PROJETA (Projections of climate change for South America which were regionalized by the ETA Model), based on the automation of the extraction process and availability of data generated by CPTEC/INPE of regionalized climate projections for Brazil. The temperature and precipitation simulations of the Eta-MIROC5 and Eta-HadGEM2-ES models, available through PROJETA, were considered in this study for RCP4.5 and RCP8.5 emission scenarios (CHOU *et al*., 2014b; CHOU *et al*., 2014a; LYRA *et al*., 2018).

Greenhouse gas emission scenarios are used in climate studies to provide plausible future projections of global climate change, considering numerous variables, including socioeconomic and technological changes, energy and soil use, as well as quantifications of greenhouse gas emissions and air pollutants. They are used as input data in the configuration of climate models and as a basis for assessing possible climate impacts, mitigation options, and cost management.

The IPCC's fifth report used the Representative Concentration Pathways (RCP), which are a set of scenarios capable of calculating different levels of greenhouse gas emissions, considered as the radiative forces associated with climate models, including also projections of emissions and concentrations of pollutants and land use, also forcing climate change. These concentrations

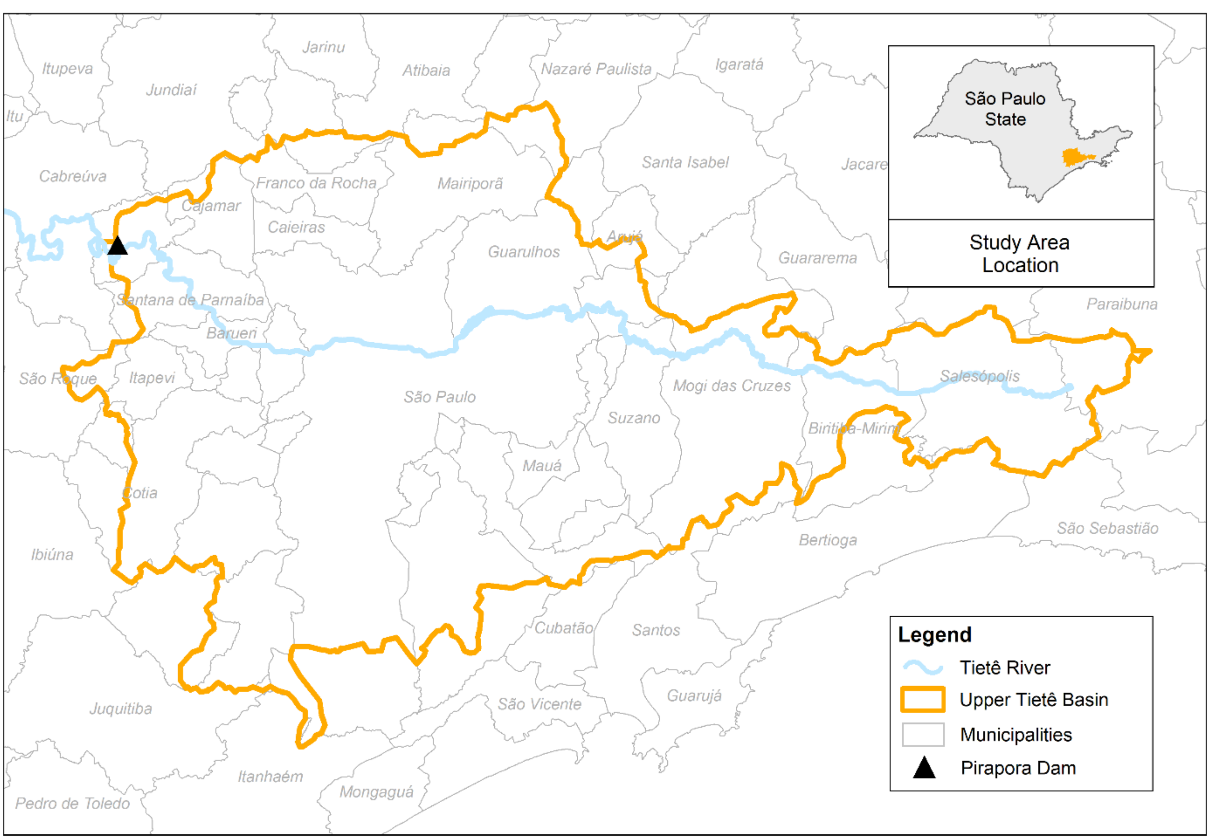


Figure 1 – Study area: Upper Tietê River Basin.

are used as the primary product for setting up RCP scenarios, serving as input information for climate model simulations. RCP consider different levels of radioactive forces, being 8.5, 6, 4.5, and 2.6 W/m^2, covering the period from 1850 to 2100 (VAN VUUREN *et al.*, 2011). Two known scenarios in this set are RCP8.5, which considers high concentrations of pollutant emission with radiative force of 8.5 W/m^2, and RCP4.5, which considers radioactive force of 4.5 W/m^2 and mitigation actions to control emissions (TAYLOR; STOUFFER; MEEHL, 2012). The emission scenarios considered in this study for each model are RCP4.5 and RCP8.5 in the 2006-2100 period. Table 1 summarizes the main characteristics of the four models considered in this study. It is worth mentioning that, for the MIROC4h model, there is no data available for the future scenario RCP8.5 and, from the year 2036, for the RCP4.5 scenario. Therefore, when the mean data of all models for precipitation and temperature are calculated, only the missing data of this model are not considered.

The methodology used in this study to obtain data in terms of affluent flow, enabling historical analyses and future scenarios of water availability in BHAT, based on data from the models described in Table 1, is summarized in the diagram in Figure 2.

Table 1 – Main characteristics of the models considered for analysis in this study.

Model	Developer	Coverage	Spatial Resolution (km)	Parameters	Available Period
CMCC-CM	Euro-Mediterranean Center on Climate Change (CMCC), Italia	Global	82.3 × 82.5	Temperature and Precipitation	Historical: 1961–2005 Future Scenarios RCPs: 2006–2100
MIROC4h	Model for Interdisciplinary Research on Climate. Version 4, High Resolution, Japan	Global	61.7 × 61.8	Temperature and Precipitation	Historical: 1961–2005 Future Scenarios RCP4.5: 2006–2039
ETA-MIROC5	CPTEC – SP, Brazil	Regional	20 × 20	Temperature and Precipitation	Historical: 1961–2005 Future Scenarios RCPs: 2006–2100
ETA-HADGEM2-ES	CPTEC – SP, Brazil	Regional	20 × 20	Temperature and Precipitation	Historical: 1961-2005 Future Scenarios RCPs: 2006–2100

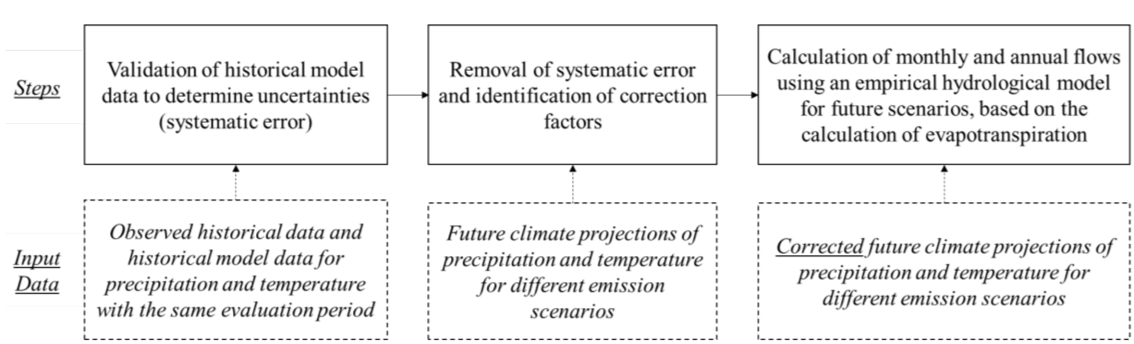


Figure 2 – Methodology applied to obtain monthly and annual affluent flow data for future scenarios of climatological modeling.

Firstly, historical data on precipitation and temperature of each of the models were validated to evaluate their performance in representing the seasonal cycle of precipitation and temperature in BHAT in relation to the historical data. For the validation of the models, data from the Climatic Research Unit (CRU) were used, which were considered as historical data in the analysis (CRU, 2019). The CRU is an institution widely recognized for its studies on natural and anthropogenic climate change, focusing on the development and updating of various data sets from weather stations around the world, widely used in climate research, including the global recording of parameters such as temperature and precipitation. The CRU database is composed of global terrestrial data in a high-resolution grid of 0.5 × 0.5º or thinner (HARRIS *et al.*, 2014). The period of CRU data used in this study comprises the years 1961 to 2005, the same corresponding to the historical simulations of the models, with the spatial resolution of 50 km. The evaluation metrics for the analysis of errors related to the models were BIAS (Equation 1), which represents the systematic error of the model, the Root Mean Square Error (RMSE) (Equation 2) and the Anomaly Correlation Coefficient (AC) (Equation 3). The definition of anomaly for the AC metric is the difference between the simulated and the observed values.

$$BIAS = \frac{1}{n}\sum(F-O) \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum(F-O)^2} \quad (2)$$

$$AC = \frac{\sum\{[(F-C)-(\overline{F-C})][(O-C)-(\overline{O-C})]\}}{\sqrt{\sum[(F-C)-(\overline{F-C})]^2\sum[(O-C)-(\overline{O-C})]^2}} \quad (3)$$

In which:

F = the value simulated by the model;

O = the observed value;

C = the climatological value.

After determining the uncertainties of the precipitation and temperature simulations of the models, the systematic error was removed using the Direct Approach technique, widely used to correct the outputs of climatic projections on a monthly scale (LENDERINK *et al.*, 2007; OLIVEIRA *et al.*, 2015; SILVA; VALVERDE, 2017). This technique is expressed by the formulation presented in Equation 4.

$$K^{FC}_{(1961-2005)} = K^{F}_{(1961-2005)} \times \left(\frac{K^{O}_{(1961-1991)}}{K^{C}_{(1961-1991)}}\right) \quad (4)$$

In which:

KFC = the corrected value of the climate variable in the evaluation period;

KF = the value without correction of the climatic variable in the evaluation period;

KC = the mean monthly climatic variable of the model in the control period;

KO = the mean monthly climatic variable observed for the control period.

With the application of the Direct Approach technique, the correction factor was found, which was used in the scenarios of RCP4.5 and RCP8.5 emissions to obtain the corrected monthly and annual data precipitation and temperature of each of the climatic models used.

Regarding the methods of application, the objective of the study is the evaluation of water availability for future climatic scenarios based on the behavior of the monthly flow in the basin, and climatic models do not generate flow in their simulations. Thus, this study used a statistical hydrological model that relates precipitation, flow, and evapotranspiration built by Silva (2016) for BHAT. This empirical model was developed based on observed data of precipitation and flow, using the fundamental equation of water balance, which includes the sum of the processes of water inputs and outputs in a basin in the form of a mathematical relationship (SILVA, 2016).

According to Vilela and Mattos (1975), the application of the general equation of water balance is conditioned to the complexity of the study of a basin and some simple mathematical models are important tools for hydrological studies, once they allow establishing a relation between the variables of water balance: evapotranspiration, precipitation, and flow. Thus, Silva (2016) constructed an empirical regression model, determining a dependent variable, in this case, flow, which changes due to independent variables, such as precipitation and evapotranspiration.

The empirical model developed for flow calculation was determined from coefficients derived from the simplified global hydrological equation of a river basin. For this, monthly data of precipitation and potential evapotranspiration (PET) of the sub-basin area and affluent flow of the exutory of the sub-basin were used on the monthly scale. The empirical relation, a fourth-order polynomial equation, is presented in Equation 5. Further details on the development of the empirical model can be found in the study by Silva (2016) and Silva and Valverde (2017).

$$Q = \left(\frac{0{,}0103P^4}{PET^4} - \frac{0{,}0859P^3}{PET^3} + \frac{0{,}289P^2}{PET^2} - \frac{0{,}1406P}{PET} + 0{,}4994\right) \times PET \quad (5)$$

In which:

P = precipitation;

PET = the potential evapotranspiration.

For the calculation of PET, this study used the corrected temperature series and the formulation of Thornthwaite (1948) in Equation 6 (*apud* SILVA, 2016).

$$PET = Fc.16.\left(\frac{10T}{I}\right)^a \quad (6)$$

In which: $I = \sum_{i=1}^{12}\left(\frac{T}{5}\right)^{1,514}$ and $a = 6{,}75.10^{-7}.I^3 - 7{,}71.10^{-5}.I^2 + 1{,}7292.10^{-2}I + 0{,}49239$

In which:

T = the mean monthly temperature of a given month;

Fc = the correlation factor as a function of latitude and month (Table 2);

I = the annual heat index;

a = the function exponent of the annual index.

Thus, based on the calculation of the PET and with the corrected precipitation for future scenarios, Equation 5 was applied for the derivation of the monthly and annual flow data for the historical period and future scenarios of each model.

In the evaluation and analysis of projections in the future period for different time slices (2020-2040, 2041-2070, and 2071-2099), the anomalies metric (Equation 7) was used to assess the increase (excess) or decrease (deficit) of variables (precipitation, temperature, and flow) in relation to the climate simulated by a model in the present (SILVA, 2016).

$$Anomaly = \frac{1}{M_{total}}\sum_{i=1}^{M_{total}}(K_F - K_{Mc}) \quad (7)$$

In which:

KF = the monthly value projected by the model in the future period (times slices);

K_{Mc} = the monthly value estimated by the model for the simulated climate (1961–2005);

M_{total} = the total number of observations.

Table 2 – Thornthwaite monthly evapotranspiration correlation factor (Fc) as a function of the study area (BHAT) — Latitude 23ºS.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fc	1.15	1.00	1.05	0.97	0.95	0.89	0.94	0.98	1.00	1.09	1.10	1.17

Source: Tucci and Beltrame (2001) and Silva and Valverde (2017).

RESULTS

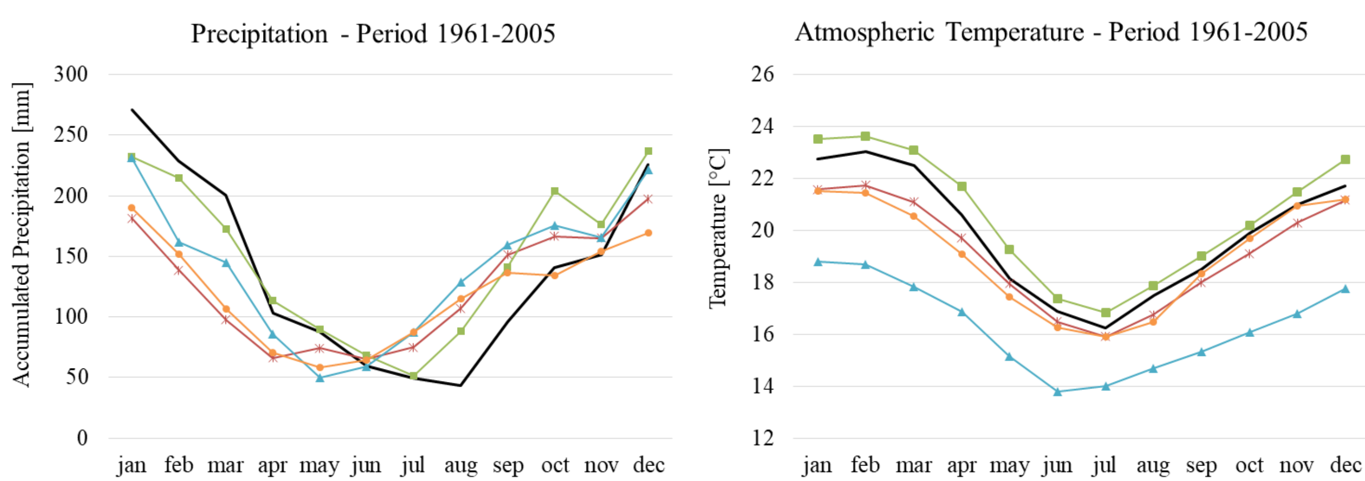
At first, the validation of historical data (1961–2005) of climate models (Table 1) was performed, and it was possible to evaluate their performance in representing the seasonal climatic pattern of precipitation and temperature in BHAT, compared to the historical data derived from CRU. Figure 3 presents the results obtained from the validation, illustrating the mean seasonal cycle in the period between 1961 and 2005 for temperature and precipitation, including the metrics of errors related to each of the models.

From the errors obtained related to the models, it is possible to highlight which models presented the best performance among them in Figure 3, for each parameter and for each of the metrics used in the validation. In green, the best results are highlighted between each metric, and in red, the worst results (high BIAS and RMSE, and low AC).

Figure 3 shows that the dry period in all models is displaced approximately 2 months in relation to the observed data (CRU). CRU data show the wet period between November and March and the dry period between June and March, as already characterized by the literature as the normal behavior of seasonality in BHAT (FUSP, 2009; SILVA; VALVERDE, 2017). Climate models show approximately the dry period between April and June and the wet period from November to January.

As a result, most models underestimated precipitation in summer and autumn, and overestimated it in winter and spring. The MIROC4h model is the closest to that observed in summer, autumn and winter, which is reflected in performance metrics. For temperature, it is observed that climate models follow the same seasonality as observed data (CRU), demonstrating hot and cold periods that coincide seasonally. However, the MIROC4h model overestimates the mean monthly temperature by almost 0.5°C compared to the observed data, while the other models underestimate the same data, presenting mean monthly temperatures of almost 1°C below, reaching a variation of more than 2.5°C for ETA-MIROC5.

Regarding the metrics for both the RMSE and AC, the model that presented the best performance



Legend: Observed, CMCC-CM, MIROC4h, ETA-MIROC5, ETA-HADGEM2-ES

Model	CMCC-CM			MIROC4h			ETA-MIROC5			ETA-HADGEM2-ES		
Metric	BIAS	RMSE	AC	BIAS	RMSE	AC	BIAS	RMSE	AC	BIAS	RMSE	AC
Temp.	-0.746	1.651	0.814	**0.663**	**1.494**	**0.860**	**-3.583**	**3.875**	0.806	-0.832	1.930	**0.749**
Prec.	-14.220	**104.098**	**0.333**	10.805	**91.136**	**0.524**	**1.145**	97.984	0.418	**-18.308**	102.150	0.366

Figure 3 – Results from the validation of seasonal cycles of precipitation and temperature.

for the two parameters (precipitation and temperature) was MIROC4h, since it presented values close to those observed, as described above. Being that, only for temperature, BIAS was the one that presented the lowest value also for the MIROC4h model. For BIAS, the ETA-MIROC5 model presented the lowest value for precipitation. The ETA-HADGEM2-ES model presented the worst AC results for temperature and BIAS for precipitation.

Thus, it was necessary to remove systematic errors related to the models. Therefore, the direct approach formulation was applied and the correction factor for the monthly values of each model was found. This factor was applied month by month for the entire historical period. The results of the corrected seasonal precipitation and temperature cycles confirm the removal of the mean monthly errors for the seasonal cycle for the 1961–2005 period, since the mean monthly values of the series coincide with the mean monthly values of the observed CRU data, both for precipitation and temperature.

The correction factors found for the historical data were applied to the data of the future scenarios of all the models evaluated, for the scenarios of RCP4.5 and RCP8.5 emissions in the 2006–2100 period, thus minimizing the uncertainties related to the systematic error generated in the historical simulation and propagated to the projections of the climate models.

Figure 4 shows the annual variability of historical precipitation and temperature for the results of simulations with each model after correction, in the 1961–2005 period, and in future scenarios. The greatest discrepancy in data variability in the future scenario is noted for the ETA-HADGEM2-ES model, which deviates from the results simulated by the other models, generally presenting lower precipitations (Figures 4A and 4B) and higher temperature (Figures 4C and 4D). From the corrected data of precipitation and temperature for future emission scenarios, it was possible to obtain the historical values and flow projections for BHAT, according to the methodology of this study (Figure 2). Figures 4E and 4F show the annual flow variability calculated for each simulated model in the 1961–2005 period, as well as in future scenarios. It is observed that, for both RCP4.5 and RCP8.5 emission scenarios, all models present annual flow variability and most values are in the approximate range of 40 to 80 m^3/s. The CMCC-CM model stands out when presenting some mean annual flow peaks over the studied period, indicating that the occurrence of extreme flow values will be more frequent for this model. These anomalies can be better evaluated based on the analysis of annual seasonality and identification of anomalies in the monthly flow means, presented in Figures 4E and 4F.

Table 3 presents the monthly flow anomalies expressed as a percentage for future RCP4.5 and RCP8.5 scenarios. By separating the analysis period by time slices (2020–2040, 2041–2070, and 2071–2100), anomalies in relation to the historical period simulated by each model are more clearly observed. It is noted that for the wet period, in the months of January, February and March, anomalies with decreased flow rates are evidenced for all models in the future scenarios of RCP4.5 and RCP8.5, with the exception of the CMMC-CM model, which presents only positive anomalies in almost every month throughout the period studied. This behavior is mainly verified for the 2020–2040 time slice, which characterizes a short-term anomaly prediction.

For long-term time slices, both negative and positive anomalies are presented in the wet period of the study area for simulated models, however, with less marked variations than in the short term. In the period characterized by little precipitation in the study area (also called dry period), between June, July, and August, it is inferred, based on Table 3, that there will be an increase in the mean monthly flows in all time slices of the simulated models, except for the ETA-HADGEM2-ES model, which presents small negative anomalies in the dry period, only in the short term.

The results of the CMCC-CM model stand out, which presented the greatest positive anomalies in the dry period for all the time slices, reaching an increase of 61% in relation to the historical period for the mean monthly flow in June, in the 2071–2100 slice of the RCP8.5 scenario. The results of the ETA-HADGEM2-ES model are also noteworthy, showing the greatest negative anomalies in the wet period for all the time slices. The anomalies for this model reached a decrease of 28% in relation to the historical period of the mean monthly flow in January, in the 2020–2040 time slice of the RCP4.5 scenario, which also considers the adoption of mitigation measures to control environmental impacts.

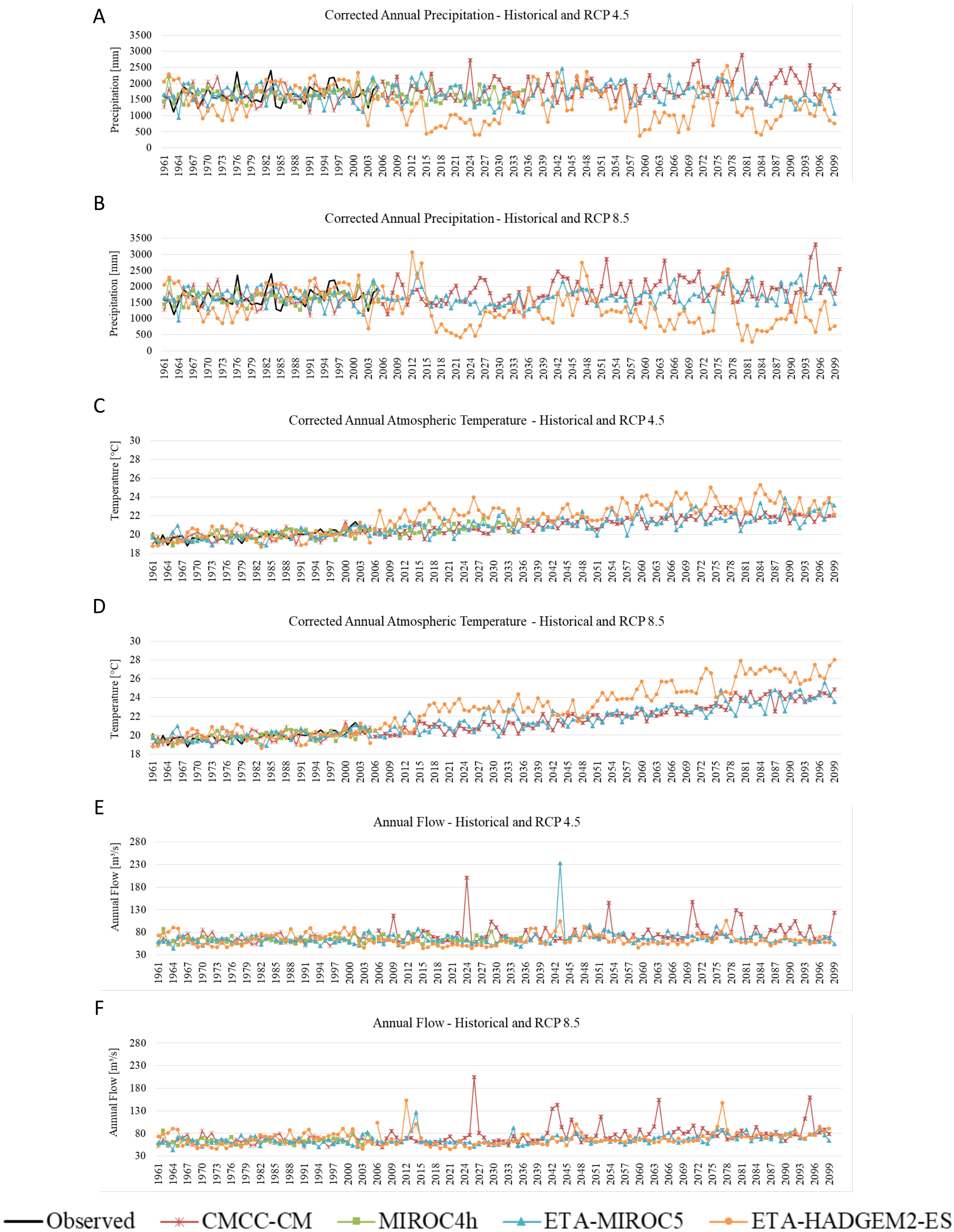


Figure 4 – (A, B) Annual variability of precipitation, (C, D) temperature, (E, F) and flow rate in the historical period (1961–2005) and future scenarios (2006–2100) for each corrected model.

The results presented for anomalies, in general, show an increase in the mean monthly flows during the dry period (Jun-Jul-Aug) in the BHAT region for the seasonal cycle of the future projections simulated by the models, as well as a decrease in the mean monthly flows in the wet period (Nov-Dec-Jan). This behavior shows a different pattern from the anomalies found in the study on the future scenario of water availability at BHAT carried out by Silva and Valverde (2017), who analyzed the simulations of the Japanese MRI-JMA model for the A2 emissions scenario. The study results presented an increase in the mean monthly flows during the wet period and a decrease in the dry one.

Since the flow is strongly influenced by precipitation and indirectly by temperature, Figure 5 presents the annual climatic projections of precipitation and temperature in the BHAT for the emission scenarios RCP4.5 and RCP8.5, which were estimated by calculating the mean of the annual values of all analyzed models (CMCC-CM, MIROC4h, ETA-MIROC5, and ETA-HADGEM2-ES) from 2006 to 2100. The trend lines by emission scenario are also presented, divided by time slice.

For precipitation (Figure 5A), it is not possible to observe a clear and unique trend along the whole period, either of increase or decrease in the future scenarios evaluated in RCP4.5 and RCP8.5. Analyzing by periods,

Table 3 – Monthly flow anomalies for the emission scenarios RCP4.5 and RCP8.5, in relation to the historical period simulated by each model (in %)

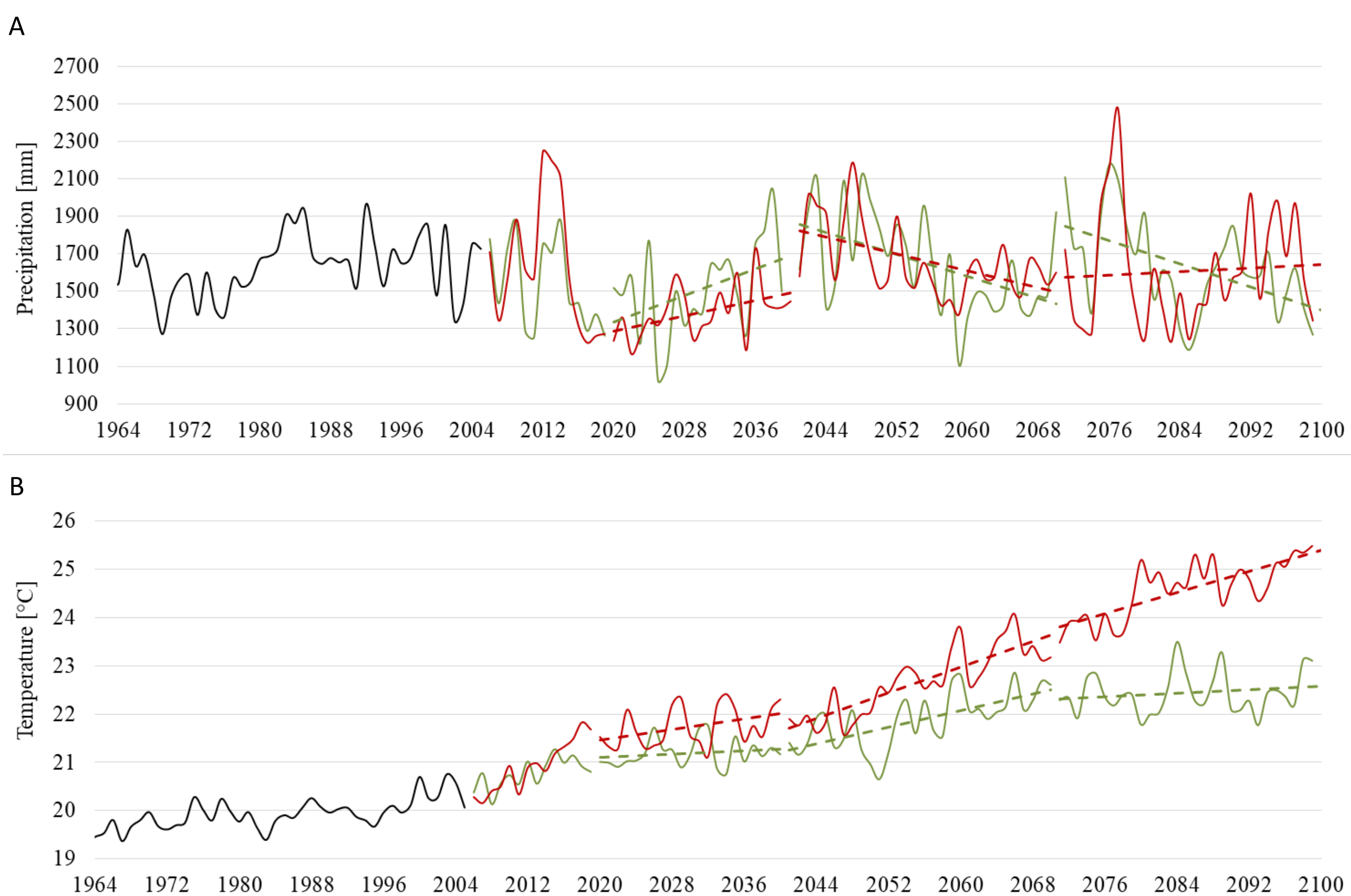
Scenario	Model	*Time Slices*	Monthly Anomaly [%]											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP4.5	CMCC-CM	2020-2040	4	5	16	-5	26	23	22	10	10	16	6	-1
		2041-2070	5	15	0	8	21	38	12	8	7	14	14	1
		2071-2100	12	20	26	19	26	60	37	24	15	21	18	-2
	ETA-MIROC5	2020-2040	-18	-8	-17	-12	2	12	3	3	12	29	12	0
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	-7	8	-10	-7	13	12	7	6	20	18	21	-1
	ETA-HADGEM2-ES	2020-2040	-28	-18	-20	0	-12	-8	-5	8	-9	9	-14	-29
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	-25	-17	-5	3	11	25	14	20	5	18	-2	-19
	MIROC4h	2020-2035	-4	-4	10	12	-5	2	3	1	-3	-2	3	0
RCP8.5	CMCC-CM	2020-2040	1	-13	15	10	3	42	18	7	3	-6	5	-1
		2041-2070	5	15	0	8	21	38	12	8	7	14	14	1
		2071-2100	23	28	15	44	26	61	17	32	17	35	34	-3
	ETA-MIROC5	2020-2040	-14	-5	-15	-12	-9	-9	-2	3	2	21	0	-5
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	9	1	4	10	31	38	12	21	36	48	42	15
	ETA-HADGEM2-ES	2020-2040	-27	-21	-17	5	-3	4	18	7	-6	-10	-17	-28
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	-10	-4	1	33	23	44	47	50	20	31	14	-1

in the short term (time slice of the 2020–2040 period), there is a slight tendency to increase the accumulated precipitation in both emission scenarios, being this more accentuated for the RCP4.5 scenario, which considers mitigation measures to control environmental impacts. However, in the long term (time slices in periods 2041–2070 and 2071–2100), the RCP8.5 scenario presents an inter-annual variability with the occurrence of more intense events in some periods in relation to the RCP4.5 scenario.

As for the temperature (Figure 5B), it is possible to observe a clear tendency of annual mean increase in the two future scenarios presented. For the RCP8.5 scenario, the growth is more accentuated in all the time slices presented, with an mean annual increase of 0.5°C between the years 2006 and 2099, being the total annual mean temperature variation of 5.2°C between these two years. In addition, the RCP8.5 scenario even showed a difference in the annual mean temperature of 3.4°C compared to the RCP4.5 scenario in the year 2080.

Figure 6 presents the annual flow climate projections for the BHAT, calculated based on the mean of the annual values obtained from each model evaluated, for the RCP4.5 and RCP8.5 scenarios. There is a slight trend of flow growth in the study area for the two scenarios, of significance proven by the p-value statistical test, considering the mean annual flows in the study area, with greater variability and intensification of anomalies in the future scenario (period from 2006 to 2099).

In Figure 7, it is possible to evaluate in more detail the differences between the mean and the variance of the results for the two simulated emission scenarios, by presenting the curve of the normal distribution of the annual mean flow values in the two simulations.



*The projections for the future scenarios in this table were estimated by averaging the annual values of all analyzed models (CMCC-CM, MIROC4h, ETA-MIROC5, and ETA-HADGEM2-ES).

Figure 5 – Annual climate projections of precipitation and temperature for BHAT obtained through the mean of the analyzed models*.

This evaluation considered a sample space with a minimum flow value equivalent to the mean minus 4 standard deviations of the flow series of the future scenario, and a maximum flow value equivalent to the mean plus 4 standard deviations of the flow series. It can be observed that there is an increase in the mean and variance of the projected annual mean flow of the emission scenario RCP8.5 in relation to RCP4.5.

Figure 8 shows the mean monthly pattern in the historical period (1964–2005) and in the future scenario (2006–2100) for CPR4.5 and CPR8.5, illustrating the mean annual seasonality in the study area for these periods.

Table 4 presents the mean monthly flow anomalies for the RCP4.5 and RCP8.4 emission scenarios, in relation to the mean historical period simulated by the four models.

Regarding seasonality conditions, as shown in Figure 8 and Table 4, once more there is an increase of mean monthly flows during the dry period (Jun-Jul-Aug) in the BHAT region. In addition, it is possible to observe a downward trend in mean monthly flows in the wet period (Nov-Dec-Jan), and for the RCP8.5 emission scenario the decrease in flow is more accentuated in the 2020–2040 time slice, reaching a value 13% lower than the mean monthly flow in the month of January, in comparison with the simulated historical mean. In the drought period, the increase in mean monthly flows is more pronounced both in the RCP4.5 emission scenario, reaching an increase of 48% in the mean monthly flow for June for the 2041–2070 time slice, and in the RCP8.5 emission scenario, which also shows an increase of 48% in the mean monthly flow for June, but for the 2071–2100 time slice.

Table 4 shows that for the average situation, as well as the anomalies presented for each of the models in Table 3, there are more intense negative anomalies in the short-term forecast time slices (2020–2040), while for long-term scenarios, there are less pronounced positive anomalies.

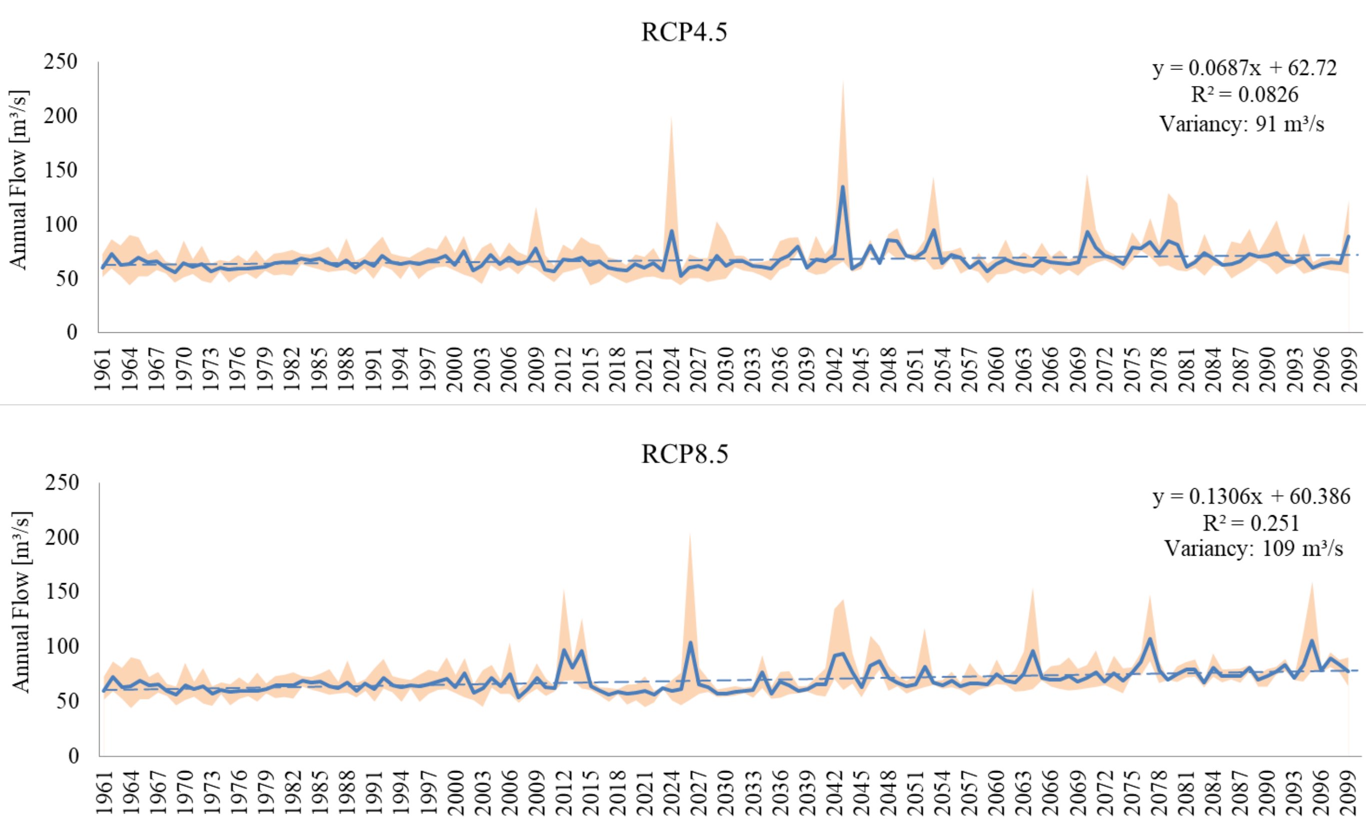
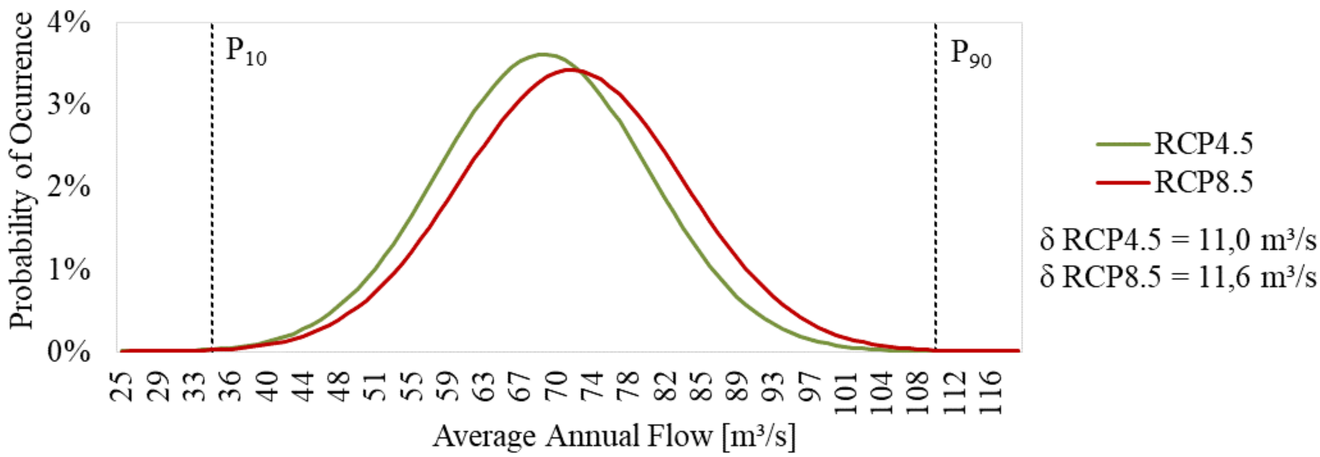


Figure 6 – Mean annual flow projections for BHAT in the RCP4.5 and RCP8.5 emission scenarios.



*P10 is the 10th percentile, P90 is the 90th percentile, and δ is the standard deviation.

Figure 7 – Normal distribution curves of the annual mean flow for the mean values calculated for the future emission scenarios RCP4.5 and RCP8.5, considering the period 2006 to 2100*.

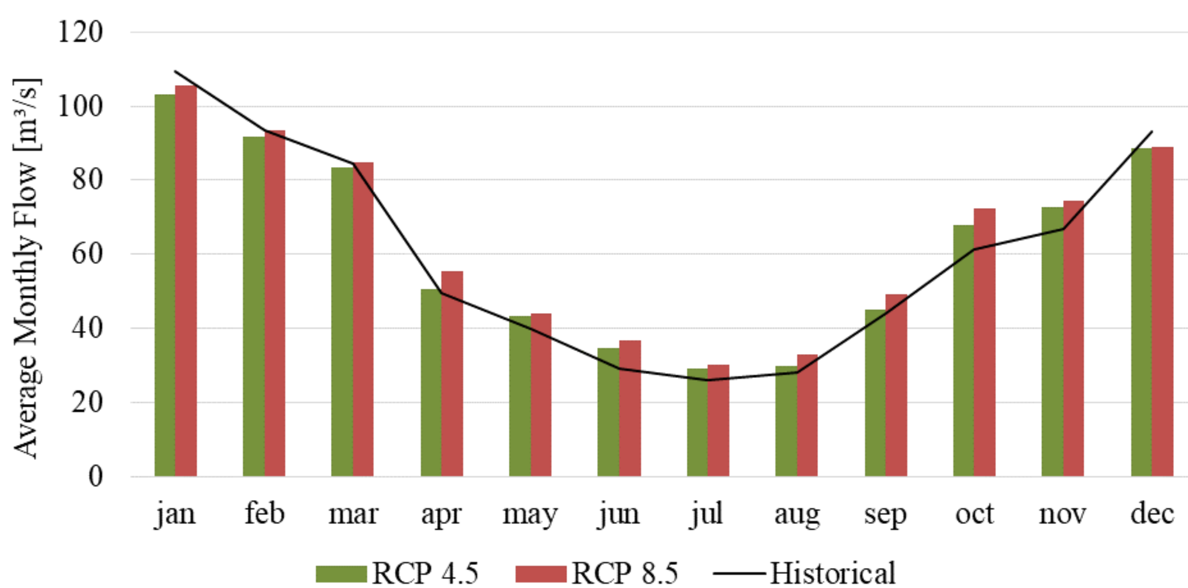


Figure 8 – Mean monthly flow pattern in the historical period (1964–2005) and future scenario (2006–2100) for RCP4.5 and RCP8.5.

Table 4 – Mean monthly flow anomalies for the emission scenarios RCP4.5 and RCP8.4, in relation to the mean historical period simulated by the four models (in %).

Scenarios	*Time Slices*	Monthly Anomaly [%]											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP4.5	2020-2040	-11	-6	-3	-1	3	8	6	5	2	13	2	-7
	2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
	2071-2100	-6	4	4	5	17	32	19	17	13	19	12	-7
RCP8.5	2020-2040	-13	-13	-6	1	-3	12	11	6	-1	2	-4	-11
	2041-2070	-11	1	7	-11	8	8	3	10	23	34	26	10
	2071-2100	7	8	7	29	27	48	25	34	25	38	30	4

The study by Lyra *et al*. (2018) evaluated the influence of climate change on the annual seasonality of temperature and precipitation in SPMR using the ETA-HADGEM2-ES model, which was also evaluated in this study. For spatial resolutions of 5 × 5 and 20 × 20 km, the study by Lyra *et al*. (2018) reinforces that it is difficult to identify patterns in rainfall behavior in southeastern Brazil, since it underestimates the rainfall events associated with the South Atlantic Convergence Zone, and neither model captures the heaviest rainfall (above 150 mm/d). However, the authors found that the ETA-HADGEM2-ES model shows more pronounced warming projections in the SPMR, with maximum temperatures increasing by 9°C by the end of the century in the RCP8.5 scenario. Precipitation volume decreased and the mean annual precipitation reached a reduction of more than 50% in the state of Rio de Janeiro and between 40 and 45% in São Paulo. In the present study, the analysis with the same model also presented reduced precipitation (Figures 4A and 4B) and accentuated temperatures (Figures 4C and 4D) throughout the evaluated future period (2006–2100).

The present study also found a reduction in precipitation volume for the BHAT region more evident in the ETA-HADGEM2-ES model projection, when compared with the other models analyzed (CMCC, ETA-MIROC5, and MIROC4h), which showed an upward trend. For this reason, the models (Figure 4A) showed a lot of variability in their mean until 2099. However, the analysis for smaller periods (time slices) showed a decrease in precipitation from the historical period to the beginning of the year 2020, and that there would still be an increase until 2040, to soon present a new reduction.

Previous works in the SPMR and BHAT region, such as those of Marengo *et al*. (2012), Silva *et al*. (2017), and Silva and Valverde (2017), which used Special Report on Emissions Scenarios (SRES) from IPCC (NAKICENOVIC *et al*., 2000), identified increased precipitation and flow, respectively, mainly in summer. However, with the new RCP4.5 and RCP8.5 scenarios, and specifically for the ETA-HadGEM2-ES model, a reduction in precipitation was identified until the end of the 21st century. This result influenced the calculated mean flow that presented a significant reduction, mainly for the near future 2020–2040, in the summer. Other studies that evaluated water availability for future climate scenarios in river basins that feed producing systems that supply the BHAT were developed by Gesualdo *et al*. (2019) and Pontes *et al*. (2019) for the JRB. The JRB is the main tributary of the Cantareira System, which is responsible for the water supply of 4.5 million inhabitants of the SPMR.

Pontes *et al*. (2019) used the SWAT hydrological model and four climate models (GFDL, HadGEM, IPSL, and MIROC) in three emission scenarios (RCP2.6, RCP6.0, and RCP8.5) to determine the tributary flow of the JRB. The results did not show a consensus among the climate models in the simulation of rainfall until the 21st century. While the GFDL model simulated a substantial decrease in precipitation, especially in the RCP8.5 scenario, similar to the results obtained by this study, the other models showed increasing precipitation. Under these conditions, the calculated flow rate was reduced (maximum, mean, and minimum flow) in the case of the GFDL model, while for the other models the maximum discharges increased.

The study by Gesualdo *et al*. (2019) also worked with the JRB to analyze climate change scenarios that may impact the flow. Using the ensemble of 17 climate models from CMIP5 for the RCP4.5 and RCP8.5 emission scenarios and a hydrological model. The authors found that the flow rate showed greater annual variability, with significant increases between January and March and a 2-month extension of the dry hydrological season (June to September) through November. Also, according to the model simulations, there will be a reduction of more than 35% in the flow from September to November, with a reduction of more than 50% in October. These data portray a condition contrary to the results obtained in this study for BHAT, a region close to JRB, which verified a trend of decreasing mean monthly flows in the wet period for a characteristic that extends from November to March, and an increase in mean monthly flows in the dry period.

Although the above-mentioned studies have not been addressed for the area of BHAT, they are related to the study area of the present work, since JRB is part of the Cantareira System, one of the main water supply systems of the BHAT. If there is a decrease or increase in water availability, as simulated by the hydrological models that used the climate model simulations, it will directly affect the water supply in the SPMR.

FINAL CONSIDERATIONS

For a successful integrated and preventive management of water resources, especially in large metropolitan regions such as the SPMR, it is necessary to prepare studies to assess the region's resilience to the impacts of climate change, ensuring a condition of water security. A potential tool to provide inputs for the elaboration of these studies is the use of climate models as a complement to hydrological ones for the study of water availability. The results of this study complement the results of previous studies already elaborated for the assessment of water availability in BHAT with the use of climate models for the assessment and comparison of climate variability among several future scenarios. It reaffirms that the water demand for the subsistence of the population in the region of the BHAT can be affected by extreme climate variability in the context of global climate change.

The main conclusions of this study show that, when the mean between the four models (ensemble) evaluated is calculated, there is a small tendency to increase the mean annual flow in the future projections analyzed in the period 2006–2100 with statistical significance, for the RCP4.5 and RCP8.5 emission scenarios. The mean and variance of the annual flow in the period analyzed, as well as the positive tendency, are slightly more accentuated for the RCP8.5 scenario, considered as the most extreme.

Another result verified through this study covers the seasonality of the mean monthly flow pattern identified in the BHAT, both calculated based on the monthly means of the future analyzed period (2006–2100) and for each time slice. The results showed there will be a decrease in the mean monthly flows in the wet period for the study region of up to 13% in the 2020–2040 time slice, while in the dry period there is an increase in these means (9.7%) for the RCP8.5 emissions scenario, compared with the simulated historical data.

This seasonal behavior for the future scenarios differs from those already observed in studies already conducted for Tietê River Basin, such as the study by Silva and Valverde (2017), which presents a pattern of increased mean monthly flows during the wet period, and a decrease in the dry one. In the study by Lyra *et al*. (2018), for future projections in the Southeast region of Brazil using the ETA-HADGEM2-ES model, seasonal rainfall patterns similar to those verified for the seasonality of the mean monthly flows presented in this study for BHAT were verified.

It should be noted that the studies mentioned above used only one climate model for analysis, the regional ETA-HADGEM2-ES (RCP emission scenarios) (LYRA *et al*., 2018) and the global high-resolution MRI model (SRES scenario – A2) (SILVA; VALVERDE, 2017). However, in analyses of climate projections of emissions scenarios, the use of more than one model is recommended in order to reflect the range of uncertainties and qualities that each of the climate models may present. Even when working with a set of models, the mean results (ensembles) can offer better performance than any individual model (DHAKAL; KAKANI; LINDE, 2018; GLECKLER; TAYLOR; DOUTRIAUX, 2008). For this reason, in addition to showing the individual simulation of each model, in this work, the mean of the simulations of each analyzed variable was calculated.

Regarding the mean annual temperature, there was a consensus of the models for a progressive increase until 2099, which did not occur for precipitation. Although the temperature increase causes greater evapotranspiration, it is the change in the rainfall regime that is determinant for the water balance, especially in the flow.

Considering the critical situation of BHAT in the state of São Paulo, the importance of analyzing seasonal climatology is emphasized, and the decrease in flow during the rainy season in the near future (2020–2040) is considered as a warning that reaffirms the need for more alternative sources of water supply in the region.

The results of Gesualdo *et al*. (2019), which show an 89% increase in the mean flow in the Jaguari basin in the summer, a result of the ensemble of 17 climate models (RCP4.5) for the near future (2010–2040), may seem optimistic, since this basin supplies water for the BHAT and would partially compensate for the deficit found in the results of this work. However, Gesualdo *et al*. (2019) warn in their study about the problem of the extension of the dry season until November (currently June to September) in the Jaguari basin, which completely alters the hydrological cycle of the basin, with an increased risk of floods and droughts and an extension of its critical period.

Thus, it is recommended that future work be carried out to evaluate the availability of water in the BHAT region based on other high-resolution climatic models, with different resolutions and emission scenarios. This word could reinforce whether there is a recurrent pattern for the Southeast region of Brazil, since some results of the models used by other studies presented here showed results both contrary and similar to those verified in this study.

The recommendation is to use at least two models for analyzing climate projections. It is also important to emphasize that there are divergences between different climate models that simulate climate projections, since they depend on several factors (spatial resolution, parameterization, emission scenarios, whether it is regional or global, etc.). For this reason, it is recommended to evaluate more than one model and to analyze the consensus in addition to uncertainties. The simulation of a model, in the context of climate change, is not considered a forecast, but rather a projection of a potential scenario.

Moreover, it is suggested the development of water availability studies, based on simulations of future projections using global and regional models, also for other regions of the SPMR supply systems besides BHAT, such as the Cantareira System and the São Lourenço System, in order to provide subsidies for the management and operation of these systems. This initiative could verify the need to include alternative water sources to supply the SPMR. It is also recommended that, in future works, conceptual hydrological models be used in the methodology, including variables such as infiltration rate, base flow, recharge flow, and surface humidity in the calculations.

However, the results obtained in this work and in the other studies cited are not yet sufficient to guide public policies aimed at minimizing future risks involving variability and climate change in a context of water security in the SPMR, but they serve as subsidies to guide the development of new studies.

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ANÁLISE DE PROJEÇÕES DAS MUDANÇAS CLIMÁTICAS SOBRE PRECIPITAÇÃO E TEMPERATURA NAS REGIÕES HIDROGRÁFICAS BRASILEIRAS PARA O SÉCULO XXI

ANALYSIS OF CLIMATE CHANGE PROJECTIONS ON PRECIPITATION AND TEMPERATURE IN BRAZILIAN HYDROGRAPHIC REGIONS FOR THE 21ST CENTURY

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RESUMO

A fim de obter informações acerca dos possíveis impactos no regime dos campos de precipitação e no regime de temperatura nas regiões hidrográficas brasileiras em decorrência do aumento das emissões de gases de efeito estufa, este trabalho teve como objetivo analisar as projeções resultantes de nove modelos participantes do Coordinated Regional Climate Downscaling Experiment (CORDEX), considerando os cenários *representative concentration pathways* (RCP) 4.5 e RCP8.5 para o século XXI. Os modelos utilizados foram: *Canadian Centre for Climate Modelling and Analysis – Canadian Earth System Model (The second generation)* (CCCma-CanESM2), *Commonwealth Scientific and Industrial Research Organization* (*version Mk3-6-0*) (CSIRO-Mk3-6-0), *Irish Centre for High End Computing – European Community – EARTH* (ICHEC-EC-EARTH), *Institut Pierre Simon Laplace – 5 Component Models version A – Medium Resolution* (IPSL-CMSA-MR), *Model for Interdisciplinary Research on Climate version 5* (MIROC5), *Hadley Center Global Environment Model version 2 – Earth System* (HadGEM2-ES), *Max Planck Institute – Meteorology – Earth System Model* (MPI-M-ESM), *Norwegian Climate Centre – Norwegian Earth System Model version 1 – Medium resolution* (NCC-NorESM1-M) e *National Oceanic and Atmospheric Administration – Geophysical Fluid Dynamics Laboratory – Earth System Model version 2M* (NOAA-GFDL-ESM2M). Foram analisadas as anomalias e a tendência dos campos de precipitação e temperatura médias anuais no período de 2006 a 2095. Todos os modelos projetaram aumento da temperatura em todas as regiões. Para o cenário RCP8.5, a anomalia da temperatura indicou aumento de até 1,58ºC na região hidrográfica amazônica. A precipitação também pode aumentar em algumas regiões hidrográficas. A mediana das anomalias sugeriu aumentos entre 10 e 30% no Atlântico Leste, Atlântico Nordeste Ocidental, Atlântico Nordeste Oriental, Paraguai, Parnaíba, Tocantins-Araguaia e São Francisco. Anomalias negativas foram identificadas no sudeste e principalmente no sul do Brasil, indicando reduções na precipitação. O teste de Mann-Kendall-Sen sugeriu uma possível intensificação no regime de precipitações anuais em grande parte das regiões hidrográficas, exceto as do Atlântico Sul, Paraná e Uruguai. Em ambos os cenários, o teste apontou ausência de tendência na região do Atlântico Sul pela maioria dos modelos. Todos os modelos apresentaram tendência positiva significativa para a temperatura nos dois cenários e em todas as regiões. A maior e a menor tendência de aquecimento foram observadas no norte e no sul do país, respectivamente.

Palavras-chave: CSIRO-Mk3-6-0; ICHEC-EC-EARTH; HadGEM2-ES; mudanças climáticas.

ABSTRACT

In order to obtain information about the possible impacts on the precipitation and temperature fields regime in the Brazilian hydrographic regions, due to the increase in greenhouse gas emissions, this study aimed to analyze the projections resulting from nine models participating in the Coordinated Regional Climate Downscaling Experiment (CORDEX), considering the scenarios RCP4.5 and RCP8.5 for the 21st century. The models used were CCCma-CanESM2, CSIRO-Mk3-6-0, ICHEC-EC-EARTH, IPSL-CMSA-MR, MIROC5, HadGEM2-ES, MPI-M-ESM, NCC-NorESM1-M, and NOAA-GFDL-ESM2M. The anomalies and trends of the mean annual rainfall and temperature fields in the period from 2006 to 2095 were analyzed. All models projected temperature increases in all regions. For the RCP8.5 scenario, the temperature anomaly indicated an increase of up to 1.58ºC in the Amazonian hydrographic region. Precipitation is also expected to increase in some hydrographic regions. The median of anomalies suggested increases of between 10 and 30% in the Eastern Atlantic, Western Northeast Atlantic, Eastern Northeast Atlantic, Paraguay, Parnaiba, Tocantins-Araguaia, and San Francisco. Negative anomalies were identified in the Southeast and mainly in the South of Brazil, indicating reductions in precipitation. The Man-Kendall-Sen test suggested a possible intensification of the annual rainfall regime in most hydrographic regions, except those in the South Atlantic, Parana, and Uruguay. In both scenarios, the test showed no trend in the South Atlantic region by most models. All models showed a significant positive trend for temperature in both scenarios and in all regions. The highest and lowest warming trends were observed in the North and South of the country, respectively.

Keywords: CSIRO-Mk3-6-0; ICHEC-EC-EARTH; HadGEM2-ES; climate change.

INTRODUÇÃO

A mudança climática vem instituindo-se como um desafio global diante dos impactos que são produzidos em todas as esferas da existência (ANA, 2016). Um dos principais efeitos decorrentes das mudanças do clima recai sobre a esfera hídrica: alterações significativas no ciclo da água (ANA, 2016; SILVEIRA *et al*., 2016). De acordo com a Agência Nacional de Águas (ANA, 2016), essas modificações comprometem a disponibilidade hídrica, aumentando a frequência de eventos hidrológicos críticos. Esses problemas afetam, por exemplo, o abastecimento de água potável, o saneamento e a produção de energia e alimentos, sistemas que se relacionam inextricavelmente, caracterizando uma abordagem denominada de nexo água-alimento-energia.

Na abordagem do nexo, é interessante destacar como a integração entre os sistemas opera em via de mão dupla. No Brasil, o elo entre recursos hídricos e energia sustenta os processos de abastecimento, tratamento e uso da água, ao mesmo passo que fundamenta a geração de hidroeletricidade (ROTHAUSEN; CONWAY, 2011). A interconexão entre os sistemas de energia e de alimentos, por sua vez, norteia a produção de biocombustíveis no país. Além da produção de alimentos, a agricultura brasileira oferta matéria-prima para produzir combustíveis líquidos de diferentes fontes, como a cana-de-açúcar, a soja, o girassol, a mamona, o milho, o sebo bovino, entre outras (ANP, 2017; AZEVEDO; LIMA, 2016). A oferta interna de energia considerando essas fontes caracteriza uma das maiores matrizes de energias renováveis do mundo (AZEVEDO; LIMA, 2016; BRASIL, 2018). A produção de etanol por meio da cana-de-açúcar destaca mundialmente o Brasil como grande produtor de biocombustíveis. Logo, a produção agrícola brasileira desempenha papel fundamental na economia do país, atendendo à demanda de produção dos biocombustíveis e atuando como fonte essencial de renda no cenário econômico nacional (BOULAY *et al*., 2018; ANA, 2017).

De outra forma, a relação entre alimentos e água subsidia a segurança alimentar, sendo a água um recurso indispensável na produção dos alimentos. O Brasil ocupa o quinto lugar (63.994.479 ha) no mundo em área cultivada, tendo como predecessores a Índia, os Estados Unidos, a China e a Rússia. Sua parcela agrícola correspondia a 3,42% da área total cultivada no mundo e 7,6% das terras cultivadas no próprio país no ano de 2016, informações que ressaltam o potencial mundial da agricultura brasileira (MIRANDA, 2018).

Em escala global, o Brasil é uma das regiões mais suscetíveis às mudanças climáticas (VAN VLIET *et al*., 2013; STOCKER *et al*., 2013). ANA (2016) e Silveira *et al*.

(2014; 2018) indicam que a geração de energia hidroelétrica no país é afetada pelas alterações ocorridas nos padrões de escoamento dos rios e influenciadas principalmente pelos efeitos da mudança do clima sobre os padrões de precipitação em conjunto com modificações no uso e na ocupação do solo. Em resposta, os impactos atingem especialmente o sistema elétrico brasileiro, no qual se tem observado o crescimento da demanda energética, que por sua vez exige a expansão da capacidade instalada por meio da construção de usinas, entre elas hidroelétricas, provocando alterações nos ecossistemas (SOITO; FREITAS, 2011; STOCKER *et al*., 2013).

De modo a garantir a segurança energética do país, tem-se buscado adotar outras fontes de geração de eletricidade, a citar o uso de usinas termelétricas, no entanto o incremento energético por essa fonte, além de demandar alto custo operacional, eleva a emissão de gases de efeito estufa (GEEs), acentuando o aquecimento global (MERCURE *et al*., 2019; PRADO JÚNIOR *et al*., 2016). Nesse contexto, o celeiro energético pautado no uso dos biocombustíveis destaca-se por ter emissão cerca de duas vezes menor de GEEs quando comparada à quantidade emitida pela queima de combustíveis fósseis (BERGER *et al*., 2015), entretanto a produção de biocombustíveis requer alto consumo hídrico e provoca mudanças no uso da terra motivadas pela necessidade de expandir a área ocupada para fins de produção, bem como suprir a demanda por culturas para exportação, o que implica a competição com a produção de alimentos e o aumento do desmatamento (GOPALAKRISHNAN *et al*., 2009; MERCURE *et al*., 2019). Em suma, os impactos das mudanças climáticas são sentidos em todos os sistemas integrados pelo nexo água-alimento-energia.

Estudos voltados para identificar e avaliar como as alterações e a variabilidade do clima podem afetar o globo atuam como subsídios fundamentais na elaboração de planos mitigadores aos impactos gerados (SILVEIRA *et al*., 2018). Esses estudos requerem informações de escala regional/local que podem ser obtidas de análises provenientes de modelos climáticos globais (MCGs) com a aplicação de técnicas tais como o *downscaling* dinâmico, que regionaliza a escala desses dados (SALES *et al*., 2015). Nesse sentido, surgiu o Projeto Coordinated Regional Climate Downscaling Experiment (CORDEX), que fornece uma metodologia padronizada dos experimentos de *downscaling* dinâmico sobre alguns domínios, em escala regional, das projeções globais provindas dos modelos que compõem o Coupled Model Intercomparison Project Phase 5 (CMIP5) (GIORGI; JONES; ASRAR, 2009; GUIMARÃES *et al*., 2016).

Alguns estudos recentes vêm sendo realizados com o *downscaling* dinâmico abordando a metodologia do CORDEX sobre domínios que envolvem o Brasil e a América do Sul. Guimarães *et al*. (2016) e Sales *et al*. (2015) investigaram o clima atual e futuros cenários climáticos utilizando diferentes modelos climáticos regionais (MCRs) para o Nordeste do Brasil (NEB) e regiões norte e sul do NEB, respectivamente. Da mesma forma, Reboita *et al*. (2014) determinaram a melhor configuração do MCR *Regional Climate Model version* 4.3 (RegCM4.3) para simular o clima no domínio da América do Sul para uso no CORDEX. Ainda em relação a esse domínio, três MCGs (Max Planck Institute – MPI, Geophysical Fluid Dynamics Laboratory – GFDL e Hadley Center Global Environment Model – HadGEM2) foram usados para o *downscaling* do MCR RegCM4 no trabalho de Da Rocha *et al*. (2014), com o intuito de investigar o sinal de precipitação do fenômeno El Niño Oscilação Sul (ENSO) na América do Sul em três períodos — presente (1975–2005), próximo ao futuro (2020–2050) e futuro distante (2070–2098) —, em dois cenários de GEEs: *representative concentration pathways* (RCP) 4.5 e RCP8.5.

O objetivo deste trabalho foi analisar as projeções de alguns modelos participantes do CORDEX considerando os cenários RCP4.5 e RCP8.5 para o século XXI, a fim de identificar mudanças nos padrões de variabilidade na precipitação e temperatura nas regiões hidrográficas do Brasil.

MATERIAIS E MÉTODOS

Região de estudo

A área de estudo compreende as 12 regiões hidrográficas (RHs) brasileiras: Amazônica, Atlântico Leste, Atlântico Nordeste Ocidental, Atlântico Nordeste Oriental, Atlântico Sudeste, Atlântico Sul, Paraguai, Paraná, Parnaíba, São Francisco, Tocantins-Araguaia e Uruguai, conforme mostra a Figura 1. A seguir, a conjuntura dos recursos hídricos no Brasil elaborada pela ANA (2015) descreve essas regiões.

Inserida na Bacia Amazônica, a RH Amazônica possui uma área que totaliza aproximadamente 45% do território brasileiro e abrange os estados do Acre, do Amazonas, de Rondônia, de Roraima, do Amapá, do Pará e de Mato Grosso. Apresentando grande disponibilidade hídrica superficial (o equivalente a 81% da disponibilidade superficial do Brasil) e compondo uma expressiva rede de drenagem, possui como rios de destaque: Purus, Juruá, Xingu, Solimões, Madeira, Negro e Guaporé. Sua precipitação média anual é de 2.205 mm, valor que representa cerca de 25% a mais do que a média nacional (1.761 mm).

A RH Atlântico Leste, a RH Atlântico Nordeste Oriental, a RH do Parnaíba e a RH do São Francisco compreendem uma área percentual do território brasileiro de pouco mais de 3,9, 3,4, 3,9 e 7,5% respectivamente. Uma grande parte de todas essas regiões hidrográficas situa-se no semiárido nordestino, sendo caracterizada pelos períodos prolongados de estiagem, motivada pela baixa pluviosidade e alta evapotranspiração, o que lhe confere precipitação média anual inferior à média nacional. A RH Atlântico Leste distribui-se pelos estados da Bahia (69%), de Minas Gerais (26%), de Sergipe (4%) e do Espírito Santo (1%), contendo em seu leque de rios principais o Salgado e Gavião, enquanto a Atlântico Nordeste Oriental abrange seis estados: Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco e Alagoas. Nessa região, os principais açudes são banhados pelos rios Jaguaribe e Piranhas-Açu. A RH Parnaíba, por sua vez, abrange porções dos estados do Piauí (77%), do Maranhão (19%) e do Ceará (4%). Atravessando diferentes biomas (cerrado, caatinga e costeiro), entre os seus principais cursos d'água se destacam os rios Parnaíba, Piauí e Poti. De outra forma, a RH do São Francisco compreende sete estados: Bahia, Minas Gerais, Pernambuco, Alagoas, Sergipe, Goiás e Distrito Federal. Fomentando a base de suprimento de energia da Região Nordeste, essa RH possui 10.708 MW de potencial hidroelétrico instalado, o que equivale a 12% do

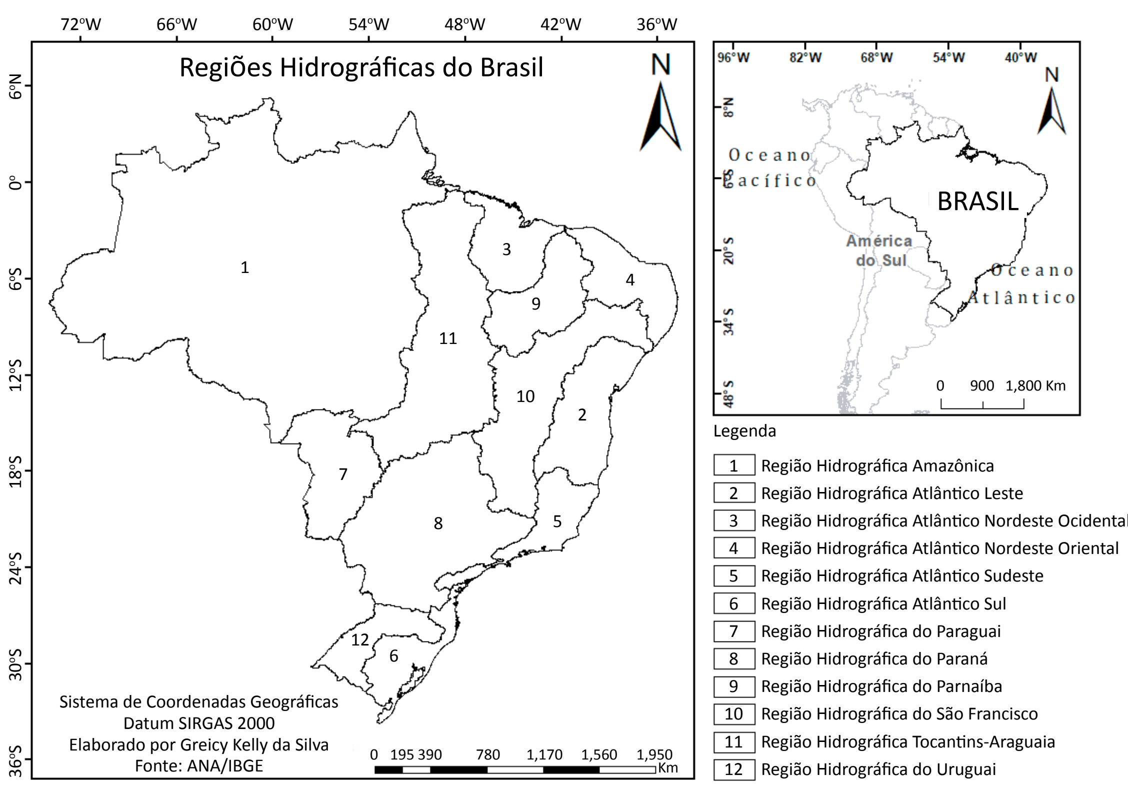


Figura 1 – Regiões hidrográficas do Brasil.

total no país, destacando-se as usinas de Xingó, Paulo Afonso IV, Luiz Gonzaga e Sobradinho.

A RH Atlântico Nordeste Ocidental abrange 3% do território nacional, compreendendo o estado do Maranhão e pequena parcela do Pará. Seus rios principais são o Gurupi, o Mearim, o Itapecuru e o Munim. Sua precipitação média anual é um pouco abaixo da média do país: 1.700 mm. A RH Atlântico Sudeste, a RH Atlântico Sul e a RH do Paraná são consideradas as regiões hidrográficas mais expressivas do território brasileiro em termos de contingente populacional e desenvolvimento econômico. Enquanto a Atlântico Sul possui, em área, um total percentual equivalente a 2,2% do país (envolvendo quatro estados — São Paulo, Paraná, Santa Catarina e Rio Grande do Sul), a Atlântico Sudeste detém 2,5%, alcançando cinco unidades da Federação (Minas Gerais, Espírito Santo, Rio de Janeiro, São Paulo e Paraná), e a do Paraná, com área equivalente a cerca de 10% do território nacional, abrange sete estados: São Paulo, Paraná, Mato Grosso do Sul, Minas Gerais, Goiás, Santa Catarina e Distrito Federal. A RH do Paraná é ainda a responsável pela maior demanda de recursos hídricos do Brasil. Seu potencial hidroelétrico aproveitado corresponde a 47,5% do total instalado no país, e ela apresenta o maior aproveitamento do potencial hidráulico disponível. Itaipu, Ilha Solteira e Furnas destacam-se entre as inúmeras usinas hidroelétricas em operação nessa região.

Também denominada de Bacia do Alto Paraguai, a RH do Paraguai possui área de 363.446 km^2 (4,3% do território brasileiro) e abrange parte dos estados do Mato Grosso e do Mato Grosso do Sul. Essa região situa a maior área úmida contínua do mundo: o pantanal mato-grossense (no qual 90% de sua extensão está localizada no Brasil). Entre seus principais cursos d'água, destacam-se o Rio Paraguai. Com rico potencial hidroelétrico, a região possui 1,4 GW já aproveitado, o que corresponde a 1,3% do total instalado no Brasil. Também com importância significativa para o país, a RH do Uruguai sobressai em função das suas atividades agroindustriais e do potencial hidroelétrico que se distribui ao longo do Rio Uruguai e de seus afluentes, gerando potência instalada de aproximadamente 6.000 MW. Com, em território nacional, área equivalente a 3%, abrange partes dos estados do Rio Grande do Sul (74%) e Santa Catarina (26%). É frequente, no entanto, a ocorrência de eventos críticos nessa região, tais como enchentes, alagamentos, enxurradas e inundações.

À frente da expansão da fronteira agrícola, a RH Tocantins-Araguaia destaca-se pelo cultivo de grãos e pelo potencial hidroenergético. Com uma área que engloba 10,8% do território brasileiro, a região abrange os estados de Goiás (21%), Tocantins (30%), Pará (30%), Maranhão (4%), Mato Grosso (15%) e o Distrito Federal (0,1%). Detém 15% da capacidade da hidroeletricidade total instalada no país, com potencial de 13,14 GW.

Dados observacionais

A base de dados observacionais utilizada para verificar a destreza dos modelos do CORDEX sobre as 12 regiões hidrográficas é proveniente do Global Precipitation Climatology Centre (GPCC) e fornecida pelo Principal Science Advisor National Oceanic and Atmospheric Administration (PSA NOAA), por Oceanic and Atmospheric Research (OAR) e por Earth System Research Laboratory (ESRL) (NEW; HULME; JONES, 1999), conforme o *link* http://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html. O conjunto de dados usado corresponde à climatologia de precipitação de 1901 a 2013, em uma grade regular com resolução espacial de 0,5º. Esse banco de dados foi gerado por pesquisadores do GPCC que reconstruíram dados observacionais de precipitação mensal do globo para a grade de espaçamento de 0,5 × 0,5º, com base em métodos estatísticos diversos (SCHNEIDER *et al*., 2011).

Projeto CORDEX

Este trabalho utilizou dados mensais de campos de precipitação (variável *pr*) e temperatura do ar próximo à superfície (variável *tas* — temperatura média) obtidos de nove modelos climáticos globais (ver Tabela 1) que atuaram como condição de contorno no processo de *downscaling* dinâmico para o modelo regional sueco Rossby Centre regional atmospheric model (RCA4) pelo CORDEX, obtendo simulações mais refinadas e com resolução espacial de 0,44 × 0,44º. As simulações tiveram como domínio a área da América do Sul (SAM-44), e foram calculadas as médias espaciais dos resultados para cada ponto de grade, sendo esta obtida por meio da interpolação bilinear da grade original de SAM-44 sobre cada região hidrográfica do Brasil.

Tabela 1 – Modelos globais do Coordinated Regional Climate Downscaling Experiment (CORDEX) utilizados e suas respectivas instituições/agências e países.

Modelos	Instituição ou Agência; País
CCCma-CanESM2	Canadian Centre for Climate Modelling and Analysis; Canadá
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization em colaboração com Queensland Climate Change Centre of Excellence; Austrália
ICHEC-EC-EARTH	Irish Centre for High-End Computing; Irlanda
IPSL-CM5A-MR	Institut Pierre Simon Laplace; Paris
MIROC5	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies e Japan Agency for Marine-Earth Science and Technology; Japão
HadGEM2-ES	Met Office Hadley Centre; Reino Unido
MPI-M-ESM	Max Planck Institute for Meteorology; Alemanha
NCC-NorESM1-M	Integrated Earth System Approach to Explore Natural Variability and Climate Sensitivity (EarthClim) e Research Council of Norway; Noruega
NOAA-GFDL-ESM2M	National Oceanic and Atmospheric Administration e Geophysical Fluid Dynamics Laboratory; Estados Unidos

A base de dados compreende as séries mensais de 1951 a 2005 (período de referência), e de 2006 a 2100 foi o período considerado para as projeções. Estas abrangeram o cenário intermediário RCP4.5 e o cenário de emissões muito altas de GEEs, o RCP8.5. Vale ressaltar, de acordo com o quinto relatório do Painel Intergovernamental sobre Mudanças Climáticas (IPCC), que as RCPs são utilizadas para elaborar as projeções descrevendo quatro diferentes caminhos do século XXI (RCP2.6: cenário otimista; RCP4.5 e RCP6.0: cenários intermediários; e RCP 8.5: cenário mais pessimista), considerando as emissões de GEEs, as concentrações atmosféricas, as emissões de poluentes do ar e o uso do solo (STOCKER *et al*., 2013). Ainda nesse contexto, as forçantes radiativas, que definem o nome das RCPs, sugerem estabilização ou pico no fim do século em questão, pressupondo, portanto, níveis de 4,5 e 8,5 $W.m^{-2}$ para os cenários abordados neste trabalho.

Análise de tendência e variabilidade das séries temporais observadas e modeladas

Esta seção apresenta as metodologias utilizadas para analisar as projeções dos campos de precipitação e temperatura dos modelos globais do CORDEX, bem como as tendências e os padrões de variação das séries históricas. Quanto à avaliação de tendência/variabilidade, abordou-se o uso de métodos clássicos, como a média e a mediana móvel, o teste de Mann-Kendall e o teste de declividade de Sen.

Análise das projeções

As projeções de precipitação e temperatura dos modelos globais do CORDEX foram analisadas nas 12 regiões hidrográficas para o período de 2006 a 2095 para os cenários RCP4.5 e RCP8.5.

Cálculo das anomalias médias anuais

Neste trabalho, para o cálculo da anomalia média anual (A_{anual}) da precipitação, foi utilizada a Equação 1:

$$A_{anual} = \frac{(P^{a}_{XXI} - P^{a}_{XX})}{P^{a}_{XX}} \cdot 100 \quad (1)$$

Em que:

P^{a}_{XXI} = a média da precipitação anual para o cenário do século XXI;

P^{a}_{XX} = a média da precipitação anual para o cenário histórico.

De outro modo, para o cálculo da anomalia da temperatura, considerou-se a diferença entre a média da temperatura do período no século XXI e a média do período no século XX.

Métodos clássicos

A média (μ) descreve a amostra que compõe a série como um único valor que representa o centro da distribuição dos dados. O grau de dispersão desses dados é determinado pelo cálculo do desvio padrão (σ) (SPIEGEL, 1978). A mediana, por sua vez, atua como uma medida de posição e localiza-se no centro da série, dividindo-a com uma mesma quantidade de elementos antes e depois dessa medida (CORREA, 2003).

Neste estudo, a análise da tendência foi realizada por meio do método de Mann-Kendall. Segundo Moreira e Naghettini (2016), o teste não paramétrico de Mann-Kendall vem sendo amplamente usado para a detecção de tendências em séries de observações hidrológicas, apresentando resultados satisfatórios. Sendo assim, de acordo com Yue, Pilon e Cavadias (2002) e Wagesho, Goel e Jain (2012), para uma série $(x_1, x_2, ..., x_n)$ proveniente de uma amostra de n variáveis aleatórias independentes e identicamente distribuídas, a estatística do teste de Mann-Kendall é dada pela Equação 2:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sinal(x_j - x_i) \quad (2)$$

Em que:
x_i e x_j = valores sequenciais;
i e j = índices de tempo;
n = o número de elementos da série (MOREIRA; NAGHETTINI, 2016).
O termo $Sinal\ (x_j - x_i)$ é resultado da Equação 3:

$$Sinal(x_j - x_i) = \begin{cases} +1 & x_j - x_i > 0 \\ 0 \quad se & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \quad (3)$$

De acordo com Burn e Elnur (2002), na análise de tendência por intermédio do teste de Mann-Kendall, há dois importantes parâmetros a ser considerados: o nível de significância α e a declividade β, sendo este último determinado pela Equação 4:

$$\beta = Mediana\left[\frac{(x - x_i)}{(j - i)}\right], \quad (4)$$

Em que:
$i < j$.

O teste de declividade de Sen, por sua vez, pode ser considerado o complemento do teste de Mann-Kendall, pois fornece a magnitude das tendências detectadas. Segundo Tao *et al*. (2014), a declividade é estimada pela estatística Q, dada pela Equação 5:

$$Q_{ij} = \frac{(x_j - x_i)}{(j - i)}, \quad (5)$$

Nessa situação, x_i e x_j estão relacionados com os valores da variável em estudo nos tempos i e j e $i < j$ (MOREIRA; NAGHETTINI, 2016). O valor positivo ou negativo para Q indica tendência crescente ou decrescente, respectivamente. A declividade de Sen é dada pela mediana dos N valores de Q_{ij}. No caso de haver apenas uma referência em cada período de tempo e sendo n o tamanho da série, tem-se a Equação 6:

$$N = \frac{n(n-1)}{2} \quad (6)$$

Para N ímpar, a declividade de Sen é expressa pela Equação 7:

$$Q_{mediana} = Q_{\frac{N+1}{2}} \quad (7)$$

Em caso de N par, a declividade de Sen é dada pela Equação 8:

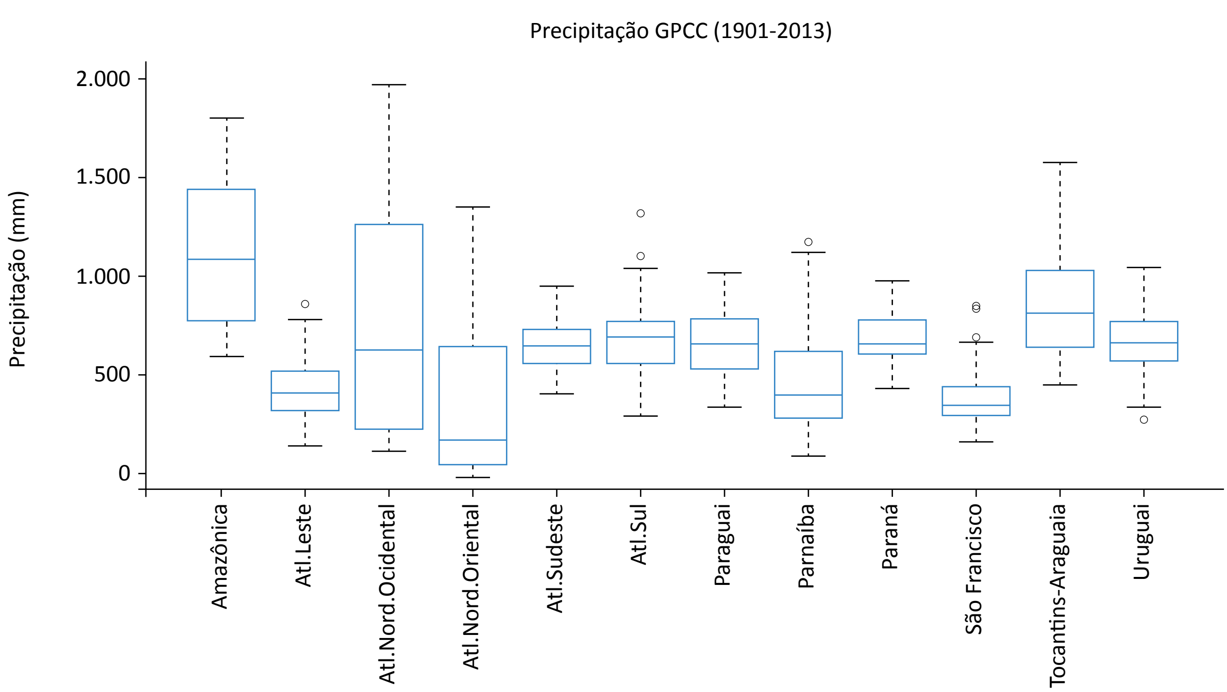
$$Q_{mediana} = \frac{\left[Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right]}{2} \quad (8)$$

RESULTADOS E DISCUSSÃO

Na Figura 2 é possível observar precipitações consideradas como discrepantes (*outliers*), principalmente nas RHs Atlântico Sul e do São Francisco, além do Atlântico Leste e Parnaíba. No Atlântico Sul, o evento mais atípico aproximou-se dos 1.319 mm. O Atlântico Nordeste Oriental apresentou o menor quartil 1 (inferior) e o menor valor de mediana, indicando que 25% dos seus dados de precipitação estavam abaixo dos 44,17 mm e que 50% desses dados foram representados por uma precipitação de 163,03 mm.

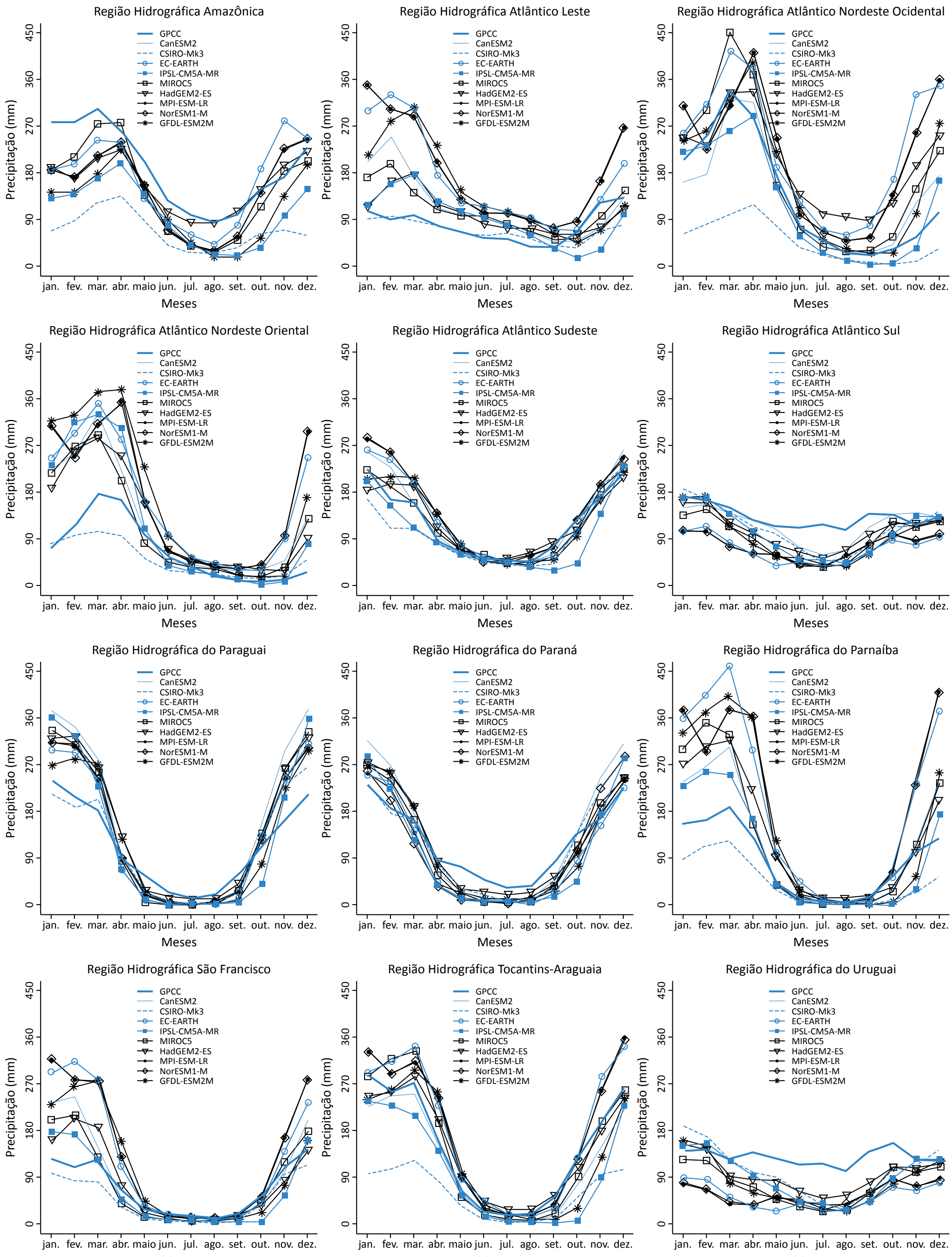
De outra forma, a RH Amazônica deteve o maior quartil 3 (superior) da série, concentrando 25% dos seus dados acima dos 1.432,5 mm, além de denotar a maior mediana, apontando representação da sua precipitação em 1.902,8 mm no percentual de 50% dos seus dados. Em contrapartida, foi o Atlântico Nordeste Ocidental que exibiu, entre as demais regiões, maior precipitação acumulada: 1.966,2 mm. Também se verificou a existência de parte da variabilidade interanual em cada região. As regiões hidrográficas com maior variabilidade são as RHs do Atlântico Nordeste Ocidental e Oriental. Nas demais regiões, especialmente as do sul do país, não foi constatada tanta variação, o que talvez demonstre estabilidade no clima dessas regiões. Nas bacias do nordeste, a variação entre anos muito úmidos (com valores próximos a 2.000 mm no Nordeste Ocidental, por exemplo) e muitos secos impacta consideravelmente na gestão dos recursos hídricos.

De acordo com a Figura 3, a maioria dos modelos do CORDEX divergiu quanto à quantidade de precipitação vista pelo GPCC nas regiões hidrográficas brasileiras. De modo geral, foi na região do Atlântico Sudeste que a maioria dos modelos melhor representou a climatologia observada, superestimando, no entanto, a precipitação nos meses de janeiro, fevereiro, março e abril. As maiores divergências entre os modelos no que tange à quantidade precipitada foram notadas nas regiões Amazônica, Atlântico Leste, Atlântico Nordeste Oriental, Paraguai, Parnaíba, São Francisco e Tocantins-Araguaia, ou seja, em parte do norte e nordeste do Brasil, em que os modelos não conseguiram representar a sazonalidade, principalmente nos meses de novembro a abril, que, em suma, se associam ao período característico da ocorrência de chuvas nessas regiões. De outra forma, uma sazonalidade mais comportada, porém abaixo da climatologia averiguada, foi apontada no sul e sudeste do país, nas RHs Atlântico Sul, Paraná e Uruguai. O modelo CSIRO-Mk3 foi o que mais representou satisfatoriamente a precipitação observada, entretanto subestimou-a na maioria das regiões estudadas.



Atl. Nord. Ocid.: Atlântico Nordeste Ocidental; Atl. Nord. Orie.: Atlântico Nordeste Oriental; Atl.: Atlântico.

Figura 2 – Gráfico boxplot da precipitação média anual considerando a série de dados do Global Precipitation Climatology Centre (GPCC) para o período de 1901 a 2013 em todas as regiões hidrográficas estudadas.



GPCC: *Global Precipitation Climatology Centre*; CanESM2: *Canadian Earth System Model (The second generation)*; CSIRO-Mk3-6-0: *Commonwealth Scientific and Industrial Research Organization (version Mk3-6-0)*; EC-EARTH: *European Community – EARTH*; IPSL-CM5A-MR: *Institut Pierre Simon Laplace – 5 Component Models version A – Medium Resolution*; MIROC5: *Model for Interdisciplinary Research on Climate version 5*; HadGEM2-ES: *Hadley Center Global Environment Model version 2 – Earth System*; MPI-ESM-LR: *Max Planck Institute – Meteorology – Earth System Model Low Resolution*; NorESM1-M: *Norwegian Earth System Model version 1 – Medium resolution*; GFDL-ESM2M: *Geophysical Fluid Dynamics Laboratory – Earth System Model version 2M*; Atl.: Atlântico; Atl. Nord.: Atlântico Nordeste.

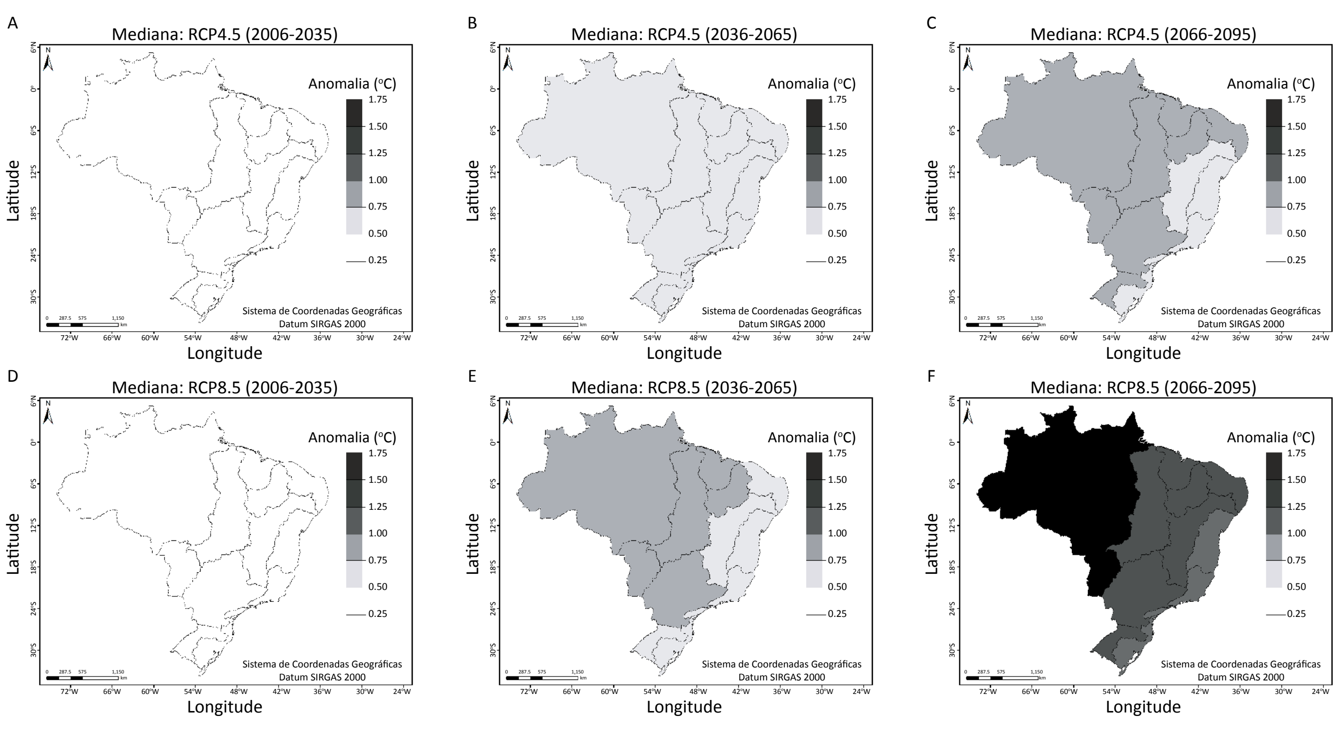
Figura 3 – Precipitação climatológica dos modelos do Coordinated Regional Climate Downscaling Experiment (CORDEX) e Global Precipitation Climatology Centre (GPCC) para as 12 regiões hidrográficas do Brasil.

Cenários de precipitação e temperatura

As Figuras 4A, 4B e 4C mostram a mediana das anomalias de temperatura para o cenário RCP4.5 para os períodos de 2006 a 2035, 2036 a 2065 e de 2066 a 2095, respectivamente. Considerando o cenário RCP8.5, as Figuras 4D, 4E e 4F trazem também para os períodos supracitados, respectivamente, a mediana das anomalias de temperatura. Nas Figuras 4A e 4D é possível observar que, para o primeiro período (2006–2035), a mediana das anomalias de temperatura permaneceu abaixo dos 0,5ºC em ambos os cenários (RCP4.5 e RCP8.5). No segundo período (2036–2065) e para o cenário RCP4.5, a mediana das anomalias de temperatura variou entre 0,51 e 0,69ºC em todas as regiões, de acordo com a Figura 4B. Por outro lado, a Figura 4E ilustra que algumas regiões hidrográficas destacaram no cenário RCP8.5 anomalias superiores, com valores entre 0,8 e 0,89ºC. No terceiro período (2066–2095) e sob o cenário otimista, o sinal da anomalia intensificou-se levemente, apresentando a mediana entre 0,70 e 0,81ºC para a maioria das regiões, excetuando-se as RHs do São Francisco, Atlântico Leste, Atlântico Sudeste e Atlântico Sul, como pode ser visto na Figura 4C.

Para o mesmo período e cenário RCP8.5, observaram-se as maiores anomalias de temperatura. A Figura 4F mostra que as RHs Amazônica e do Paraguai apresentaram valores de medianas de 1,58 e 1,57ºC, respectivamente. Aqui, as regiões Atlântico Leste, Atlântico Sudeste e Atlântico Sul indicaram anomalias também intensas se comparadas a de outros períodos, permanecendo entre 1,13 e 1,18ºC. A mediana das anomalias das demais regiões variou entre 1,28 e 1,49ºC.

As Figuras 5A, 5B e 5C apresentam a mediana das anomalias de precipitação para o cenário RCP4.5 para os períodos de 2006 a 2035, 2036 a 2065 e de 2066 a 2095, respectivamente. Por outro lado, as Figuras 5D, 5E e 5F mostram também para os períodos mencionados acima, respectivamente, a mediana das anomalias de precipitação no cenário RCP8.5. As Figuras 5A e 5D exibem a mediana da anomalia de precipitação para o primeiro período e

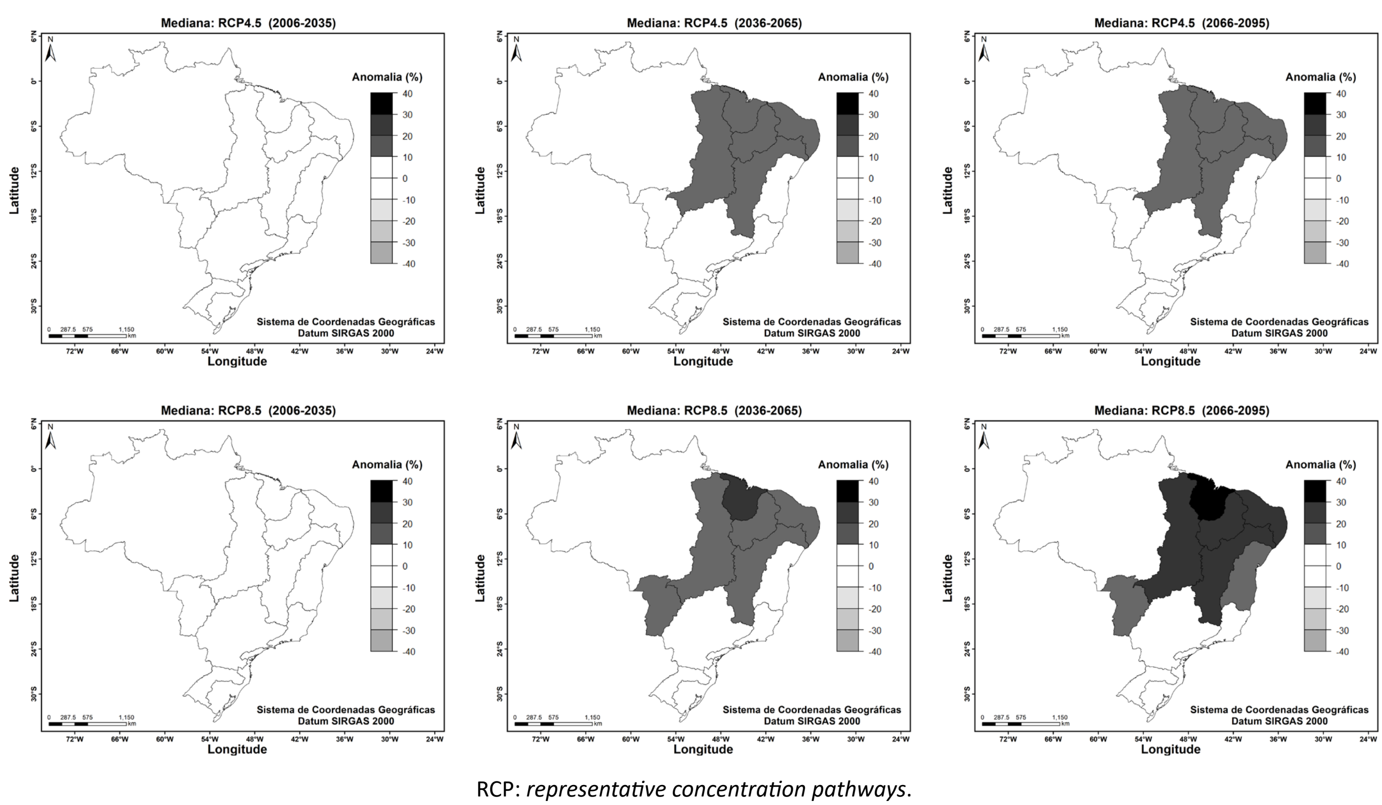


RCP: *representative concentration pathways*.

Figura 4 – Mediana das anomalias de temperaturas anuais dos modelos do Coordinated Regional Climate Downscaling Experiment (CORDEX) para o cenário RCP4.5 no período de (A) 2006 a 2035; (B) 2036 a 2065; (C) 2066 a 2095; e para o cenário RCP8.5 no período de (D) 2006 a 2035; (E) 2036 a 2065; (F) 2066 a 2095.

para os dois cenários como positiva e com módulo inferior a 10% em todas as regiões hidrográficas. No segundo e no terceiro período, para o cenário RCP4.5 (Figuras 5B e 5C), houve leve intensificação dos valores de anomalia, variando sua mediana entre 10 e 20% para as RHs do Tocantins-Araguaia, São Francisco, Parnaíba, Atlântico Nordeste Oriental e Atlântico Nordeste Ocidental. Com exceção desta última e para as demais regiões citadas, sob o cenário RCP8.5 e no segundo período (Figura 5E), destacou-se a mediana da anomalia de precipitação também entre 10 e 20%. De outra forma, ainda sob o cenário pessimista e para o último período projetado, a Figura 5F mostra que as RHs Tocantins-Araguaia, São Francisco, Parnaíba e Atlântico Nordeste Oriental tiveram suas anomalias intensificadas com valores de mediana entre 20 e 30% e entre 10 e 20% para as regiões do Atlântico Leste e Paraguai. A RH Atlântico Nordeste Ocidental apresentou-se com as medianas das anomalias mais intensificadas entre as demais no segundo e no terceiro período — 22,3 e 30,4%, respectivamente —, no entanto também foram apontadas reduções por meio das anomalias negativas identificadas no sudeste e principalmente no sul do Brasil, nas regiões do Atlântico Sudeste (RCP8.5, de 2006 a 2035), Atlântico Sul (RCP4.5, no período de 2066 a 2095) e no Uruguai (RCP4.5, de 2066 a 2095 e RCP8.5 no segundo e no terceiro período).

Para o cenário RCP4.5, a Figura 6 mostra que os modelos CanESM2 e CSIRO-Mk3 foram os mais pessimistas, estimando redução de até 2,76 mm/ano na maioria das regiões hidrográficas. O modelo CSIRO-Mk3 também se revelou pessimista no estudo de Guimarães *et al*. (2016), apontando o possível surgimento de uma extensa área hiperárida em algumas regiões do Ceará, no nordeste do Brasil. Para as regiões localizadas no sul do país — Atlântico Sul, Paraná e Uruguai —, os modelos não identificaram indícios de tendência significativa para a precipitação, com exceção da região hidrográfica do Uruguai, em que o modelo IPSL-CM5A-MR indicou tendência negativa de 1,48 mm/ano. Ainda sob esse cenário, o mesmo modelo sinalizou aumento da precipitação na maioria das regiões, especialmente no Atlântico Nordeste Ocidental, em que a tendência alcançou 7,66 mm/ano.

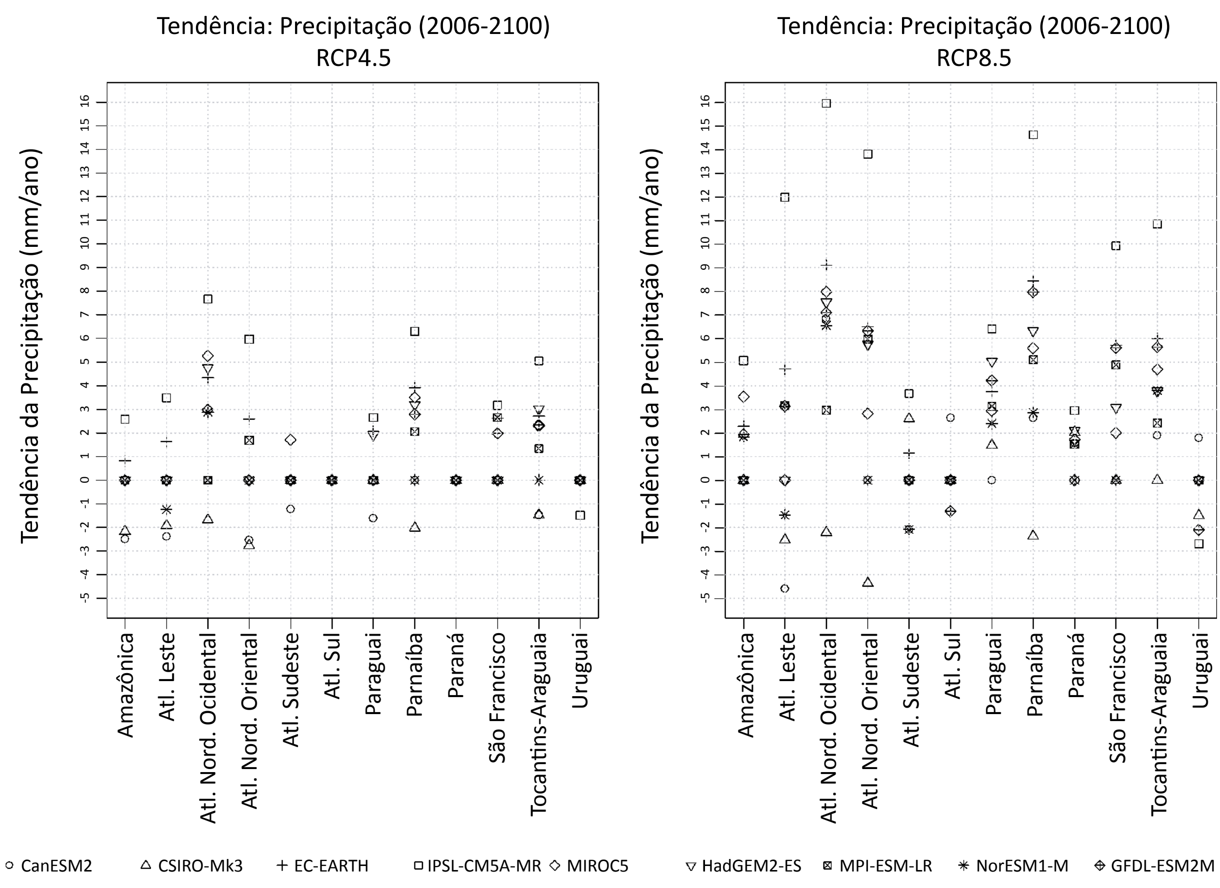


RCP: *representative concentration pathways*.

Figura 5 – Mediana das anomalias de precipitações anuais dos modelos do Coordinated Regional Climate Downscaling Experiment (CORDEX) para o cenário RCP4.5 no período de (A) 2006 a 2035; (B) 2036 a 2065; (C) 2066 a 2095; e para o cenário RCP8.5 no período de (D) 2006 a 2035; (E) 2036 a 2065; (F) 2066 a 2095.

Para o cenário RCP8.5, no geral, identificou-se maior nível de incerteza associado à variável de precipitação, e a maioria dos modelos mostrou tendências significativas para grande parte das regiões hidrográficas e com grande dispersão dos seus módulos de declividade. As incertezas e dispersões encontradas podem estar relacionadas com o fato de as regiões associadas experimentarem variabilidade climática motivada por diversos sistemas atmosféricos e oceânicos, dificultando a representação climática da precipitação e um acordo entre os resultados apresentados pelos modelos (GUIMARÃES *et al.*, 2016). Comparados ao cenário anterior, esses módulos foram bastante pronunciados, revelando uma possível intensificação no regime de precipitações anuais em grande parte das regiões hidrográficas, exceto as supracitadas localizadas no sul do país. Aqui, o Atlântico Sul foi a região com maior indicativo de ausência de tendência entre sete dos nove modelos. O modelo IPSL-CM5A-MR continuou atuando de forma otimista na maioria das regiões, estimando o aumento da precipitação em até 15,95 mm/ano, com destaque para o Atlântico Nordeste Ocidental. A redução mais significativa foi sinalizada para o Atlântico Leste, de 4,36 mm/ano pelo modelo CanESM2.

De acordo com o teste de Mann-Kendall-Sen realizado, todos os modelos do CORDEX apresentaram tendência positiva significativa para a variável temperatura e para

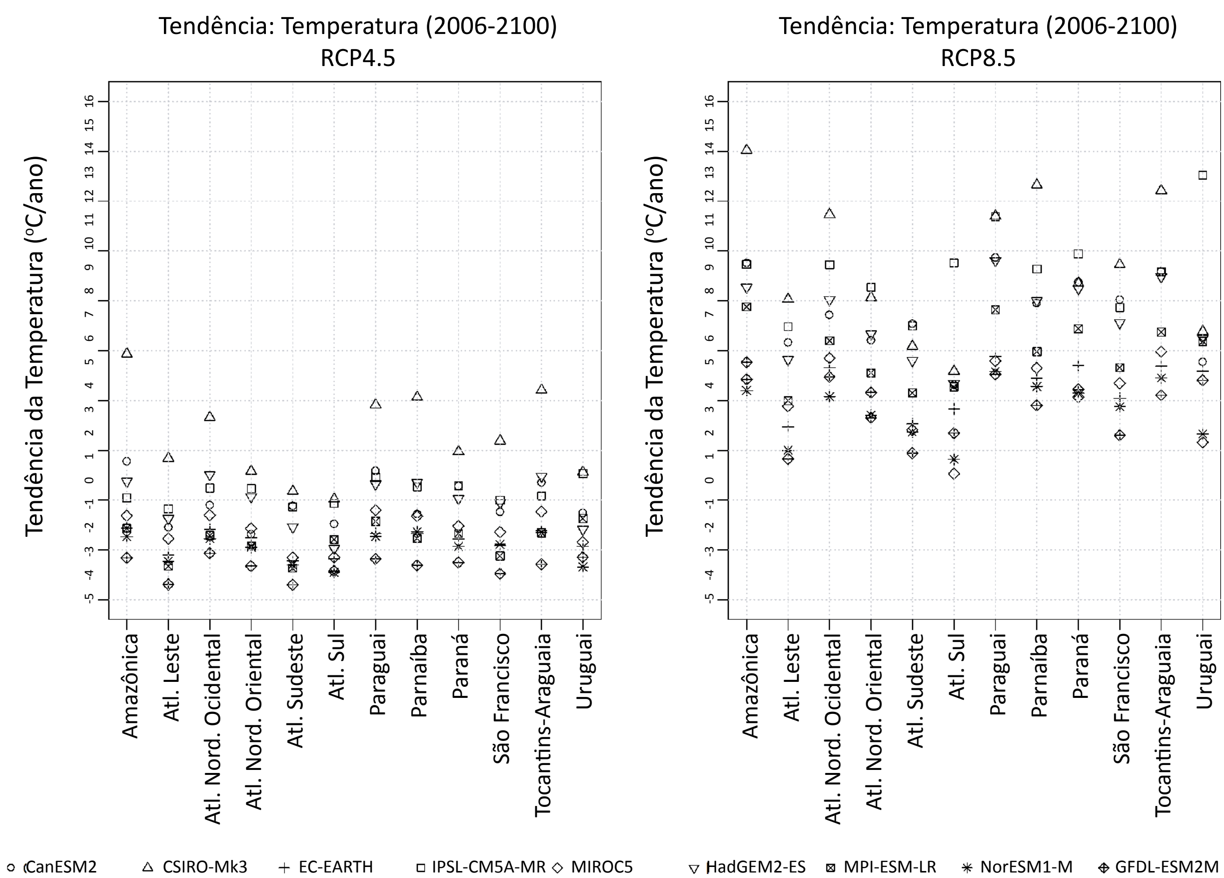


CanESM2: *Canadian Earth System Model (The second generation);* CSIRO-Mk3-6-0: *Commonwealth Scientific and Industrial Research Organization* (*version Mk3-6-0*); EC-EARTH: *European Community – EARTH*; IPSL-CM5A-MR: *Institut Pierre Simon Laplace – 5 Component Models version A – Medium Resolution;* MIROC5: *Model for Interdisciplinary Research on Climate version 5;* HadGEM2-ES: *Hadley Center Global Environment Model version 2 – Earth System;* MPI-ESM-LR: *Max Planck Institute – Meteorology – Earth System Model Low Resolution*; NorESM1-M: *Norwegian Earth System Model version 1 – Medium resolution;* GFDL-ESM2M: *Geophysical Fluid Dynamics Laboratory – Earth System Model version 2M;* Atl.: Atlântico; Atl. Nord.: Atlântico Nordeste.

Figura 6 – Tendência da precipitação, segundo o teste de Mann-Kendall-Sen, para o período de 2006 a 2100 para os cenários representative concentration pathways (RCP) 4.5 e RCP8.5 nas regiões hidrográficas do Brasil.

ambos os cenários em todas as regiões hidrográficas. Avaliando o cenário mais otimista RCP4.5, o conjunto de modelos indicaram aquecimento entre 0,12 e 0,59ºC/ano. O modelo CSIRO-Mk3, seguido de CanESM2 e IPSL-CM5A-MR, projetou as maiores tendências de aquecimento em todas as regiões, alcançando a marca de 0,59ºC/ano na RH Amazônica. O modelo GFDL-ESM2M projetou a menor tendência de temperatura na maioria das regiões, excetuando-se a do Uruguai, em que o modelo NorESM1-M foi responsável pelo menor incremento da variável. A menor tendência de aquecimento foi observada na região do Atlântico Sudeste. Tomando o cenário que destaca o aumento das emissões dos GEEs, RCP8.5, notaram-se tendências superiores ao cenário RCP4.5.

A Figura 7 mostra que os modelos CSIRO-Mk3 e IPSL-CM5A-MR indicaram tendências de aumento na temperatura média de até 1,0 e 0,95ºC/ano, respectivamente. A maior tendência de aquecimento, comparada à do cenário anterior, foi vista também na RH Amazônica: 1ºC/ano. Já o incremento na temperatura se demonstrou menos pronunciado na maioria das regiões hidrográficas pelos modelos NorESM1-M e GFDL-ESM2M, alcançando 0,38ºC/ano para ambos. A menor tendência de aquecimento foi projetada pelo modelo MIROC5 para a RH Atlântico Sul: 0,35ºC/ano.



CanESM2: *Canadian Earth System Model (The second generation);* CSIRO-Mk3-6-0: *Commonwealth Scientific and Industrial Research Organization* (*version Mk3-6-0*); EC-EARTH: *European Community – EARTH*; IPSL-CM5A-MR: *Institut Pierre Simon Laplace – 5 Component Models version A – Medium Resolution;* MIROC5: *Model for Interdisciplinary Research on Climate version 5;* HadGEM2-ES: *Hadley Center Global Environment Model version 2 – Earth System;* MPI- ESM- LR: *Max Planck Institute – Meteorology – Earth System Model Low Resolution*; NorESM1-M: *Norwegian Earth System Model version 1 – Medium resolution;* GFDL-ESM2M: *Geophysical Fluid Dynamics Laboratory – Earth System Model version 2M;* Atl.: Atlântico; Atl. Nord.: Atlântico Nordeste.

Figura 7 – Tendência da temperatura, segundo o teste de Mann-Kendall-Sen, para o período de 2006 a 2100 para os cenários representative concentration pathways (RCP) 4.5 e RCP8.5 nas regiões hidrográficas do Brasil.

CONCLUSÕES

O presente trabalho indica que a maioria dos modelos que compõem o projeto CORDEX divergiu quanto ao total precipitável observado em grande parte das regiões hidrográficas, como, por exemplo, as que abrangem o norte e o nordeste do Brasil, porém a climatologia averiguada foi razoavelmente bem representada no sul e sudeste do país, mesmo tendo sido subestimada. Os meses que se associam ao período chuvoso, em geral de novembro a abril, destacaram as maiores divergências entre as climatologias plotadas. O modelo CSIRO-Mk3 foi o que melhor representou a precipitação constatada, subestimando-a, no entanto.

Os modelos do CORDEX projetam o aumento da temperatura para as regiões estudadas, conforme resultados evidenciados nos trabalhos de Sales *et al*. (2015) e Guimarães *et al*. (2016). No período de 2006 a 2035, os cenários RCP4.5 e RCP8.5 mostraram-se semelhantes, permanecendo abaixo dos 0,5ºC em todas as regiões. Levando em conta o cenário RCP8.5, as anomalias foram consideravelmente superiores nos períodos de 2036 a 2065 e de 2066 a 2095, em que os modelos indicaram valores entre 0,8 e 1,57ºC em grande parte das regiões.

O conjunto de modelos indica que a precipitação também deve, em geral, aumentar para os dois cenários em algumas regiões hidrográficas. O módulo das anomalias apresenta-se superior no cenário mais pessimista: RCP8.5. Nesse cenário, para o período de 2066–2095, a mediana sugeriu aumentos entre 10 e 30% nas RHs do Atlântico Leste, Atlântico Nordeste Ocidental, Atlântico Nordeste Oriental, Paraguai, Parnaíba, Tocantins-Araguaia e São Francisco. Anomalias negativas foram identificadas no sudeste e principalmente no sul do Brasil, como observado também no trabalho de Da Rocha (2014), nas regiões do Atlântico Sudeste (RCP8.5, de 2006 a 2035), Atlântico Sul (RCP4.5, no período de 2066 a 2095) e Uruguai (RCP4.5, de 2066 a 2095 e RCP8.5 no segundo e no terceiro período), sinalizando reduções na precipitação.

Avaliando individualmente os modelos de acordo com o teste de Mann-Kendall-Sen realizado, maior nível de incerteza associado à variável de precipitação foi observado para o cenário RCP8.5 quando comparado ao cenário otimista. A maioria dos modelos mostrou tendências significativas para grande parte das regiões hidrográficas e com grande dispersão dos seus módulos de declividade, que, por sua vez, tiveram valores bastante pronunciados, sugerindo uma possível intensificação no regime de precipitações anuais em quase todas as regiões hidrográficas, exceto as do Atlântico Sul, Paraná e Uruguai. Em ambos os cenários, o teste apontou ausência de tendência na região do Atlântico Sul pela maioria dos modelos. O modelo IPSL-CM5A-MR foi o mais otimista e direcionado ao Atlântico Nordeste Ocidental. O modelo CanESM2, no entanto, apresentou-se como o mais pessimista, projetando a maior redução no Atlântico Leste no cenário RCP8.5.

Considerando a variável temperatura, todos os modelos apresentaram tendência positiva significativa e para ambos os cenários em todas as regiões hidrográficas. No cenário mais otimista, o modelo CSIRO-Mk3, seguido de CanESM2 e IPSL-CM5A-MR, projetou as maiores tendências de aquecimento, resultado que concorda com o trabalho de Guimarães *et al*. (2016). O modelo GFDL-ESM2M projetou a menor tendência de temperatura na maioria das regiões, excetuando-se a do Uruguai, em que o modelo NorESM1-M foi responsável pelo menor incremento da variável. A menor tendência de aquecimento foi observada na região do Atlântico Sudeste. Tendências superiores às do cenário RCP4.5 foram apresentadas pelos modelos CSIRO-Mk3 e IPSL-CM5A-MR (conforme também mostrado por Guimarães *et al*., 2016). A maior tendência de aquecimento foi verificada no norte do país, na RH Amazônica. Já o incremento na temperatura se demonstrou menos pronunciado pelos modelos NorESM1-M e GFDL-ESM2M na maioria das regiões hidrográficas. A menor tendência de aquecimento foi projetada pelo modelo MIROC5 para a RH Atlântico Sul.

Quanto ao nível de incerteza identificado com base em algumas divergências apresentadas nas projeções resultantes dos modelos do CORDEX, puderam-se traçar possíveis mudanças nos padrões de variabilidade dos campos de precipitação e temperatura das regiões hidrográficas do Brasil, o que, de acordo com o que foi sugerido por Silveira *et al*. (2018), permite auxiliar na adoção e no desenvolvimento de práticas de políticas e gestão de mitigação dos impactos provocados pelas mudanças climáticas sobre o nexo água-alimento-energia no país.

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