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GROUNDWATER GOVERNANCE:

CHALLENGES AND PATHS

ANA
NATIONAL WATER AND SANITATION AGENCY - BRAZIL

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MINISTRY OF REGIONAL DEVELOPMENT

GROUNDWATER GOVERNANCE:

CHALLENGES AND PATHS

Brasília – DF
ANA
2022

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Cover Picture
Cover Page: Emergence of fractured aquifer in the Rural Area of Guaribas – Piauí (PI)
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Also available at: https://www.gov.br/ana/pt-br

Cataloging at the source: CEDOC/LIBRARY

N277g National Water and Sanitation Agency (Brazil).

Groundwater governance : challenges and paths / National Water and Sanitation Agency ; Pilar Carolina Villar ; Ricardo Hirata ; José Luiz Albuquerque ; Ana Maciel de Carvalho. – Brasília : ANA, 2022.

201 p. : il.

ISBN: 978-65-88101-38-4

1. Groundwater - management. 2. Groundwater - quality. 3. Transboundary aquifers. 4. Right to use. 5. Governance in aquifer management. I. Title. II. UNESCO.

CDU 556.388(81)

Drafted by Fernanda Medeiros – CRB-1/1864

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AAC – Alter do Chão Aquifer
ABAS – Brazilian Groundwater Association
ABNT – Brazilian Technical Standards Association
ADI – Direct Unconstitutionality Action
ALADYR – Latin-American Desalinization Association
ANA – National Water and Sanitation Agency – Brazil
ANM – National Mining Agency
ANP – National Petroleum, Natural Gas and Biofuels Agency
ANVISA – National Health Surveillance Agency
APA – Aquifer Protection Areas
APP – Permanent Preservation Areas
ARC – Restriction and Control Areas
AUPIT – Association of Users of the Tourão Irrigated Perimeter
BDNAC – National Database on Contaminated Areas
BHRSF – Hydrographic Basin of the São Francisco River
BNCC – National Common Curricular Base
CAF – Latin America Development Bank
CAS – Groundwater Community
CBH – Hydrographic Basin Committee
CBH-AT – Committee for the Hydrographic Basin of Alto Tietê
CBH-SF – Committee for the Hydrographic Basin of the São Francisco River
CDC – Consumer Defense Code
CeReGAS – Regional Center for the Management of Groundwater of Latin America and of the Caribbean
CETESB – Environmental Company of the State of São Paulo
CF/88 – 1988 Constitution of the Federative Republic of Brazil
CNARH – National Registry of Users of Water Resources
CNRH – National Water Resources Council
CONAGUA – National Commission for Waters
CONAMA – National Environment Council
CONERH – State Water Resources Council
CREA – Regional Boards of Engineering and Agronomy
CRH – Water Resources Council
CS – Sustainability Coefficient
DAA – Right to Use Water
DAEE – Department of Water and Electric Power
DGA – General Board of Waters
DNPM – National Department of Mineral Production
EMBRAPA – Brazilian Agriculture and Livestock Research Company
ETA – Water Treatment Station
ETE – Sewage Treatment Station
FEHIDRO – State Water Resources Fund
GAC – Contaminated Area Management
GCM – General Circulation Model
GEF – Global Environment Fund
GIRH – Integrated Water Resources Management
GW – Groundwater
IAH – International Association of Hydrogeologists
IDA – International Desalinization Association
IHP – Inter-Governmental Hydrological Program
IPCC – Inter-Government Panel on Climate Change
ITRC – *Interstate Technology Regulatory Council*
JGB – Jacarta Hydrogeological Basin
JV – Surveillance Boards
LC – Complementary Law
LQP – Practical Quantification Limit
MAPA – Ministry of Agriculture, Cattle-raising and Supply
MAR – *Managed Aquifer Recharge*
MCG – Global Climate Change
MDR – Ministry of Regional Development
MEA – Millennium Ecosystem Assessment
MMA – Ministry of the Environment
MME – Ministry of Mines and Energy
MPSP – São Paulo State Prosecutor General's Office
OAB – Brazilian Bar Association
ODM - **Millennium Development Goals**
SDG – Sustainable Development Goals
OEA – Organization of American States
UN – United Nations
OUA – Organization of Users of Waters
PBMC – Brazilian Panel on Climate Change
PDGAS – Programs for the Development and Management of Groundwater
PEI – State Irrigation Plan
PERH – State Policy (Plan) of Water Resources
PIRH – Integrated Water Resources Plans
PNAS – National Groundwater Program
PNDR – Regional Development National Policy

PNDU – National Urban Development Policy
PNI – National Irrigation Policy
PNLD – National Program of Books and Teaching Material
PNMA – National Environmental Policy
PNOT – National Territorial System Policy
PNPDEC – National Civil Protection and Defense Policy
PNRH – National Water Resources Policy (Plan)
PNS – National Sanitation Policy
PNSH – National Water Safety Policy
PNUD – United Nations Development Program
PNUMA – United Nations Environment Program
PPA – Multi-annual Plan
PPP – Well Protection Perimeter
PRA – State Environmental Regularization Program
PSA – Payment for Environmental Services
PSAG – Guarani Aquifer System Project
PUB – Basic Unit Price
RHN – National Hydrometeorological Network
RIMAS – Integrated Groundwater Monitoring Network
RMR – Metropolitan Region of Recife
RMSP – Metropolitan Region of São Paulo
RNQA – National Water Quality Monitoring Network
RPD – Direct Potential Recharge
RPE – Exploitable Potential Reserve
SAG – Guarani Aquifer System
SAPR – Recife Plains Aquifer System
SAU – Urucuia Aquifer System
SE – Ecosystem Services
SEWRPC – Southeastern Wisconsin Regional Planning Commission
SGB-CPRM – Geological Service of Brazil
SHAC – Common Use Hydrological Sector
SIAGAS – Groundwater Information System
SIG – Geographic Information System
SIGRH – Integrated Water Resources Management System
SINGREH – National Water Resources Management System
SINIMA – National Environmental Information System
SINIR – National Information System on the Management of Solid Waste
SISNAMA – National Environmental System
SNIRH – National Water Resources Information System
SNIS – National Sanitation Information System
SNRH – National Water Resources System
SNSH – National Water Security Department
SQL – *Structured Query Language*
SRH – Water Resources Department
SRHU – Urban Water Resources Department
SSD – Decision-Making Support Systems
STD – Total Dissolved Solids
STF – Brazilian Supreme Court
STJ – Superior Court of Justice
TVA – Tennessee Valley Authority
UC – Conservation Unit
UGRHI – Water Resources Management Unit
UNSDSN – United Nation Sustainable Development Solutions Network
VET – Total Economic Value
VI – Investigative Value
VMP – Maximum Allowed Value
VO – Guiding Value
VP – Preventinon Value
VRQ – Quality Reference Value
ZA – Agroecological Zoning
ZC – Contribution Zone
ZEE – Ecological Economic Zoning

PRESENTATION

The integrated management of surface and groundwater is set by the National Water Resources Policy, established by Law No. 9,433/1997, and it is a fundamental element to ensure water security in Brazil. Despite their natural and social invisibility, these waters are essential for maintaining the flow of rivers and various ecosystems, in addition to guaranteeing the supply of water for various uses, such as supplying vulnerable populations with no access to tap water. In this context, the members of the National Water Resources Management System (SINGREH) have been working to overcome these challenges in terms of the integrated management of water resources.

Given the importance of the topic, the United Nations (UN) has defined the theme *Groundwater – Making the Invisible Visible* for the 2022 World Water Day. The purpose of this choice was to explain the vital role of groundwater in water and sanitation systems, agriculture, manufacturing, ecosystems and adaptation to climate change.

Aware of the relevance of the groundwater issue and in line with national and international debates on water resources, the National Water and Sanitation Agency – Brazil (ANA) has conducted studies and projects to disseminate better knowledge and monitoring of Brazilian aquifers.

ANA has also been meeting a growing demand for training on this subject and, for that purpose, it has been producing teaching materials, such as the Training Volume *Groundwater in the National Water Resources Policy*. This publication is yet another effort by the Agency to promote reflection on the management of aquifers both domestically and internationally.

With this book, the institution seeks to contribute so the various social actors can understand the importance of groundwater and how water resources management instruments can be used to promote an integrated management of surface and groundwater.

Due to its technical quality and the current nature of the topics covered, this material will serve as the basis for four remote-learning courses (EaD) on the subject of groundwater, which will be launched by ANA in 2022. The publication also has editions in both Portuguese and Spanish to reach an increasingly wider audience.

Have a good Read!

ANA Board of Directors

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INTRODUCTION

Life happens over aquifers. They provide sustenance and water for societies and ecosystems. Despite this fact, a large portion of the population does not know them and some persons neither know about their importance, nor can establish a connection between their territory and the aquifers that exist there. If human survival depended on each person's ability to identify the aquifers that provide water to their city, or knowing how they contribute to maintaining major regional rivers, how many would pass the test? This reality impacts the management and governance of groundwater, which requires actions to overcome its natural and social invisibility, as well as a culture of private appropriation in violation of law, which is supported by a tolerance by the Government and society relative to the irregular use of these waters (VILLAR, 2016).

When considering the deepening water scarcity and degradation scenarios, it appears that the survival of humanity depends on building a new pact with water, which certainly includes aquifers. If society does not know about them, there will be no political pressure to implement the necessary action to manage them or to expose the conflicts relative to the appropriation of their water. The expression "*I lost the well*" or "*the spring dried up*" said with resignation, reflects, in most cases, the inappropriate use of these waters, which is not even noticed, being solved, depending on the financial standing of the user, by the drilling a deeper well, or by other alternatives (tanker truck, construction of cisterns etc.) or, in the worst case, by abandoning the land.

Thus, this book promotes knowledge about the different perspectives of aquifers and their importance for society and ecosystems, and it also highlights ways to overcome the challenges. In chapter 1 – **"The construction of groundwater governance and management**" – the groundwater governance structure is contextualized, identifying the concepts of governance, administration and management, as well as presenting the main actors involved in the national water policy and the role of each in promoting groundwater governance. Chapter 2 – "**Groundwater in the hydrosocial cycle**" – details the dynamics of aquifers in the hydrological cycle, their importance as providers of ecosystem services and the main impacts that threaten this water reserve. Chapter 3 – "**Groundwater management: from theory to practice**" – presents the main water management tools and the way each of them have been applied to groundwater. Chapter 4 – "**Governance of groundwater and strengthening the integrated management of water resources**" – presents the strategies and challenges that need to be faced in the search for governance and integrated management of groundwater. At the end of this chapter, there is a gallery of cases composed of four aquifer management experiences that seek to promote solutions to their degradation. Namely: *a)* the remediation process of the Jurubatuba aquifer (in the metropolitan region of São Paulo); *b)* fighting the overexploitation of the Santo Domingo aquifer (Mexico); *c)* the Groundwater Communities in Chile; and *d)* the transboundary management of the Geneva Aquifer, shared between France and Switzerland.

The methodology used is the documentary analysis of legislation, specialized literature and technical documents, as well presentation of case studies that serve to illustrate the functioning of aquifers, that demonstrate the risks of lack of management or the potential of these waters to promote development. To broaden the views on groundwater, the "boxes" and "case gallery" resources were used, for the purpose of deepening the concepts and ideas addressed in the chapters, based on the reports of contributing experts. The boxes are used throughout the text, while the case gallery is configured as a section of Chapter 4, illustrating practical cases that use governance strategies for aquifers despite all the challenges involved in this process.

Therefore, the work constitutes a collective effort of many professionals dedicated to the governance/management of aquifers. The underground water reserve was built naturally over decades, centuries and millennia, therefore, human beings must use this heritage consciously and sustainably, maximizing long-term benefits. Box 1 details the need for a governance process aiming to reconcile the time of existence of aquifers and human beings, as well as revealing the complexity of the challenges to be faced.

Box 1 – The time of existence of aquifers and the time of existence of human beings

Veridiana T. de S. Martins

All the water on Earth has been the same since the origin of the planet, i.e., there is no generation of new water, nor loss of water outside the Earth System. Our planet is an open system for (solar) energy, but a closed system when it comes to water. On the Blue Planet, water has been recycled for over 4 billion years. The water cycle – or hydrological cycle – is responsible for this recycling, and it runs on solar energy. Therefore, the water molecule passes from the solid to the liquid and gaseous state, or the other way around, and is then transferred between different terrestrial reservoirs, such as the sea, lakes, rivers, plants, soil, rocks and animals. Groundwater corresponds to only 1% of the planet's water. On the other hand, it represents 30% of fresh water and 97% of fresh water available in liquid state (MARSHAK, 2019; PRESS *et al*., 2006; REYNOLDS *et al*., 2019; TEIXEIRA *et al*., 2009). In Earth's over four billion years, the same water molecule has been in all reservoirs more than once. In some, water is renewed within days, but in others it can take thousands of years to cross, such as in the case of groundwater.


Figure 1 – Water well in the Castle of Vincennes, France (19th Century)
Photo: Veridiana T. S. Martins.

In the oceans, due to the large volume, water permanence time is approximately 3,000 years; in the atmosphere, water vapor lasts on average only 10 days; in the biosphere, approximately only one week; in the rivers, two weeks; and in soils from two weeks to a year (TEIXEIRA *et al*., 2009; MARSHAK, 2019). In ice caps and glaciers, this value varies from tens to thousands of years, provided that there is testimony of ice in Antarctica dating back 2.7 million years (YAN *et al*., 2019). On the lakes, the permanence time of water is dozens of years. Groundwater has a permanence time that ranging from days, weeks to hundreds of thousands of years. From its recharge area to the discharge area, the Guarani Aquifer presents ages ranging from current to 835 thousand years (AGGARWAL *et al*., 2015). This oldest age was identified in a well in the city of Lins (SP). The further away from the recharge area and the deeper the well, the older the water. The average water flow speed in the Guarani Aquifer is 0.7 m/year (AGGARWAL *et al*., 2015). This means that the waters that are extracted from a well that explores the Guarani in the City of Lins (SP) are not waters that entered the aquifer in the present day, but rather, more than 800,000 years ago. During this period, the hominids that roamed the planet were *Homo erectus* and *Homo heidelbergensis*, who were just starting to control fire. In Brazil, the oldest fossil found is that of Luzia, dating from 12,500 to 13,000 years ago, much more recent than the Guarani waters in this well in Lins.

Water has always been an important natural resource, and both the location of these resources and the domain over their exploration were an imperative to the development of mankind. Water and climate crises, population growth, other uses for water, such as mining, irrigation, power generation, manufacturing, among others, are factors that forced the search and development of techniques capable of extracting water from underground levels. The first wells built by humans date back to 3,000 years BC, were dug forming spirals to allow access with a pack animal, and did not exceed 50 m in depth (CUSHMAN; TARTAKOVSKY, 2017).

At the beginning of the Christian Era the planet's population was just over 170 million. Today there are more than seven billion people (ROSER; ORTIZ-OSPINA, 2019). The quantity of water remains the same. In the last 120 years, the volume of water consumed annually has increased by 500%, while the population has increased by 370% (RITCHIE; ROSER, 2018). This indicates that the need for water resources increases faster than the population. Associated with this, there is an increase in environmental problems and, consequently, contamination of water resources.

Environmental awareness and knowledge about the water systems necessary to avoid and face the contamination of surface and underground water resources was first shown in more recently throughout the history of human evolution. Notwithstanding, the perception of environmental impacts on groundwater resources is still far from ideal. The lack of knowledge about its functioning gives rise to almost magical interpretations about its occurrence and quality, often disconnected from the rest of water resources. It is very common to associate underground water with water provided by God and which, because it comes from nature, is clean: "*the soil filters everything*".

The word *aquifer* is not taught in schools and may sound as strange to adults as it does to children. A certain time, in a transfer test for people with college degrees (people who already had a degree), in the question that asked for the definition of an aquifer, a candidate answered that "*an aquifer was the junction of aquatic beings*". The 2018 National Common Curricular Base (BNCC) does not mention, in its text, groundwater or aquifers, with only one reference to the word *sustainability* in a footnote. The BNCC is responsible for determining the content[1] that must be taught to students in schools and, consequently, the content of textbooks, selected by the National Book and Teaching Materials Program (PNLD). Although some textbooks address the topic of groundwater, the inclusion of this subject is not guaranteed by the BNCC, which reveals that the groundwater topic is not given its proper value, and that teachers are not prepared to work on them in the classroom.

The time of existence of groundwater is very different from the time of existence of society and the destination it gives to water and the problems caused generated by its use. In 2100, there will be 10 billion people depending on the same volume of water as their ancestors, with the worsening of climate change and contamination. How can we reverse this scenario? How can we preserve water quality? How can we use water in a sustainable manner? How can we ensure water quality for future generations?

There is no single answer to these questions, and there is no individual solution either. There is no other way to achieve sustainability other than through knowledge, education, preparation, prevention and collective work. Only by doing that is it possible to improve the ability to recognize and solve problems, promote social organization and civil participation, create public policies and laws that ensure the preservation of water resources and reduce vulnerabilities, improving the perception of groundwater resources. In conjunction, these actions can change the future scenario and guarantee water for the next generations, respecting the time of the existence of aquifers through the time of the existence of humans.

1. "The National Common Curricular Base (BNCC) is a normative document that defines the organic and progressive set of essential learning subjects that all students must develop throughout the stages and modalities of K-12" (text extracted from the website of the Ministry of Education and Culture (MEC) on the internet. Available at: http://basenacionalcomum.mec.gov).


Guarani Aquifer System Tubular Well of SAAE
of São Gabriel do Oeste (MS)
Photo: Roberto E. Kirchheim / ANA Image Database

CHAPTER 1

THE BUILDING OF GROUNDWATER GOVERNANCE AND MANAGEMENT

1.1 GOVERNANCE, ADMINISTRATION AND MANAGEMENT OF GROUNDWATER: ALIGNING THE CONCEPTS

The concept of groundwater governance emerged in literature in the late 2000s. One of its earliest and most used definitions was established in a report issued by the *Global Water Partnership*, which defined it in the following terms:

> it is the set of political, social, economic and administrative systems that exist to develop and manage water resources and the provision of water services at different levels of society. (ROGERS; HALL, 2003, p. 7).

Since then, several concepts and approaches to water governance have emerged (RIBEIRO; JOHNSSON, 2018). In this profusion of literature, the idea of groundwater governance emerged as a specific and more restricted aspect, justified by the following factors (JARVIS *et al*., 2005; MADANI; DINAR, 2012; VILLHOLTH; CONTI, 2018):

- ecosystem importance since groundwater maintains the base flow of rivers, springs and wetlands;
- main reservoir of fresh water available to populations of the planet;
- natural resource most extracted from the subsoil in the world and in Brazil;
- extraction rates exceed replacement rates in many aquifers;
- contamination which often render aquifer inviable due to the technical complexity and depollution costs;
- specific characteristics that cause its management to be difficult, especially relative to the following aspects: a) the natural and social invisibility of these waters; b) the low speed of the underground flow; c) the extension of the aquifers; and d) the difficulty of controlling access;
- cultural perception that these waters are linked to land ownership rights;
- public policies that neglect groundwater and its relations to surface water;
- lack of knowledge concerning the status of these waters and aquifers.

In this context it was understood that emphasizing the governance of groundwater would contribute to fostering reflection on the way in which states, users and society generate this resource, and to seek specific strategies in light of the natural and social particularities of aquifers. There is no consensus on the meaning of groundwater governance, therefore, several definitions can be found in literature.

Groundwater governance can be defined as:

[...] the exercise of competent authority and the promotion of responsible collective action to ensure the sustainable and efficient use of groundwater resources for the benefit of humanity and of the dependent ecosystems. (FOSTER *et al*., 2009, p. 3).

[...] the structure that comprises the laws, regulations and customs pertaining to the use of groundwater, as well as process of engagement of the public, private sector and civil society. It may involve coordinating administrative actions and decision-making processes between and among different jurisdictional levels. This structure fundamentally shapes how groundwater is managed and how aquifers are used. (MEGDAL *et al*., 2014, p. 678).

[...] the promotion of responsible collective action aimed at ensuring the control, protection and socially sustainable use of groundwater resources and aquifer systems for the benefit of humanity and dependent ecosys tems. (FAO, 2016, p. 17).

[...] the structure that encompasses the process, interactions and institutions in which various actors (.i.e., government, private sector, civil society, academia etc.) across multiple geographic areas (.i.e., sub-national, cross-border and global) and institutional/industry, as applicable. (VILLHOLTH; CONTI, 2018, p. 14).

Governance is not to be confused with governability, nor with management or administration, although this distinction raises doubts and despite the fact these terms are sometimes confused with one another. The distinction between these concepts is centered around the number of actors involved and the extension of their scope (VILLHOLTH; CONTI, 2018). **Governability** is a part of governance, however, it is restricted to the "state dimension of the exercise of powers" (GONÇALVES, 2005, p. 3), focusing on the attributes of the government's exercise of power and its systemic conditions, such as: "the political regime (whether democratic or authoritarian), the form of government (whether parliamentary or presidential), the relations between the different branches of power (with higher or lower levels of asymmetry, for example), the party systems (whether multi-party or bipartisan)." (DINIZ, 1999, p. 196).

Governance has a scope that is broader and more inclusive than that of governability, as it incorporates the "set of mechanisms and procedures to deal with the participatory and plural dimensions of society," considering the views not only of the government (governability), but also of scientists, users, nongovernmental organizations, civil society and traditional communities (VILLHOLTH; CONTI, 2018). Consequently, it assumes: *a)* "expanding and improving the means of articulation and management of the different interests"; and *b)* giving the state greater flexibility in action, allowing the decentralization of duties, transferring responsibilities, and expanding "the universe of participating actors, without giving up the instruments of control and surveillance." (DINIZ, 1999, p. 196).

In turn, *management* focuses on actors with jurisdiction to carry out routine actions aimed at diagnosing, monitoring and applying management instruments or laws. It focuses on the performance of technicians and water managers dedicated to implementing laws (policies) through specific actions. Therefore, the management of water resources is a typical role of the state, which is guided by a legal framework in which the guidelines for action, management instruments and identification of those responsible for enforcing the plans, programs and actions are aimed at ensuring the quality and quantity of water to serve current generations and, especially, future generations (CAMPOS; FRACALANZA, 2010). According to FAO (2016, p. 17), the term groundwater management "comprises activities carried out by actors who are legitimized for developing, using and sustainably protecting groundwater resources."

The management of water resources corresponds to the execution of structural and non-structural actions focused on controlling water systems (natural or artificial), with the goal of ensuring the benefit to humans and guaranteeing environmental requirements (GRIGG, 1996). Structural measures are those that require building structures, such as: dams, water distribution stations, water treatment plants (ETAs) and Sewage Treatment Plants (ETEs), or construction work to contain soil erosion, recovery of contaminated areas, de-silting of bodies of water, among others. Non-structural measures correspond to programs or activities that do not require construction, such as zoning of land use and occupation, environmental education actions, campaigns for the legalization of water use etc. (GRIGG, 1996).

To the extent the idea of governance becomes stronger, we see a shift in the paradigm relative to water management, ceasing to be an exclusive issue of technical governmental agencies and passing to look for partnerships with other actors, especially by including other approaches, such as: *a)* social learning; *b)* negotiation and conflict-mediation techniques; *c)* traditional knowledge; *d)* environmental education actions; *e)* creation or expansion of opportunities for participation by users and civil society etc.

The need to strengthen governance is justified by the fact that the challenges in implementing water and environmental management will only be overcome with the support and partnership of various actors whose grasp extends beyond the government and legitimate users of the system, including universities, civil society and traditional communities, as well as nongovernmental organizations and even international organizations. Each of these actors can, in different ways, contribute to the protection of aquifers, such as: *a)* promotion and spreading of technical knowledge; *b)* adoption of water-saving technologies; *c)* adoption of conservation practices in the rural sector or maintaining permeability in urban environments; *d)* respect for legislation in force; *e)* investments in improving water supply and sewage networks, among others.

1.1.1 The concept of Integrated Water Resources Management (IWRM) and its role in the governance of groundwater resources

IWRM became the global benchmark in the management of water resources (BORCHARDT; BOGARDI; IBISCH, 2016). International organizations, such as: *Global Water Partnership*, United Nations Environment Program (UNEP), United Nations Development Program (UNDP), international conferences and editions of the World Water Forum argue that this is the most efficient model to ensure sustainability in the use of water. Its supporters maintain that water problems could be solved by IWRM, regardless of the different physical, economic, social and environmental conditions of the countries (BISWAS, 2008). They warn, however, that application thereof requires an adequate governance context so it can effectively promote proper water governance.

A large portion of literature has attributed its foundation to the principles of the 1002 Dublin Declaration and its inclusion in Chapter 18 of Agenda 21, adopted in Rio 1992, however, its origin predates all of these events (BORCHARDT; BOGARDI; IBISCH, 2016). Some authors claim that the idea of integrated water resources management dates back to the first half of the 19th century, when the *Tennessee Valley Authority* (TVA) was created in 1933, or to the discussions proposed at the Mar del Plata Conference in the 1970s (BENSON; GAIN; ROUILLARD, 2015; BORCHARDT; BOGARDI; IBISCH, 2016).

There is no consensus on what IWRM is, however, the most widespread concept was developed by the *Global Water Partnership*, which defines it in the following terms:

> IWRM is a process that promotes the development and coordinated management of water, land and other related resources in order to maximize the resulting economic and social well-being in an equitable manner without compromising the sustainability of vital ecosystems. (GWP, 2000, p. 22).

This concept aims to promote the horizontal integration of multiple uses and the vertical integration between the different institutional levels (local, state or provincial, national and transborder). Despite the optimism about this concept, it is marked by uncertainties (BISWAS, 2008), such as: by whom and how is this process promoted? What are the related natural resources? What parameters must be maximized and how to choose them? What is the scope of this economic and social well-being? What is sustainability and what are its parameters? How to define vital ecosystems and, on the other hand, which ones are not vital? (BISWAS, 2008; VILLAR, 2015).

In practice, the processes for achieving good governance and implementing IWRM are both challenging and complementary. IWRM encourages water legislation and institutions to adopt the following principles: *i)* the hydrographic basin as a managerial unit of space; *ii)* participation of social actors; *iii)* funding mechanisms; *iv)* monitoring; and *v)* development of information systems. Moreover, it encourages the adoption of the following management strategies (VILLAR, 2015):

- definition of the sates's roles relative to other actors and the way in which the ownership and responsibilities of water users and suppliers are operationalized;
- building partnerships between the government, the private sector, the community and voluntary organizations;
- definition set by law of governmental management institutions and their respective powers;
- search for ways to ensure the sustainable use of the resource;
- analysis of the situation of water resources;
- formation of joint efforts ventures of the various actors involved in the decision-making process, with representation of sectors of society and with gender balance;
- organization of water allocation and extraction systems, wastewater disposal authorizations and databases;
- hydrographic basin-based water resources management;

- organizational structures at basin and sub-basin levels to allow decision-making at the lowest possible level;
- preparation of IWRM plans based on a multi-sector approach and on participation of the various actors.

In the specific case of groundwater, IWRM draws attention to the following key points:

- surface and groundwater cannot be managed separately from each other or independently of related ecosystems (KENNEDY *et al.*, 2009);
- groundwater management requires observing the balance between groundwater extraction and recharge, as well as planning for medium and long-term use (KENNEDY *et al.*, 2009);
- groundwater management must monitor the impact of irrigation and subsidized charges for the use of water and power, which, although desirable from a socioeconomic standpoint, can encourage overexploitation of the aquifer (FOSTER; AIT-KADI, 2012);
- groundwater management must be included in urbanization policies due to the impact of land use and occupation and the absence or inadequacy of sanitation services (FOSTER; AIT-KADI, 2012);
- the spatial scale of the hydrographic basin requires adjustments to promote aquifer management (FOSTER; AIT-KADI, 2012).

Since the 1990s, several governments have changed their legal and institutional frameworks focused on implementing IWRM and incorporating its tools on the hydrographic basin scale. And, provided this is a sociopolitical process, each country has incorporated it differently (MIRANDA; REYNARD, 2020). The next sessions will attempt to detail how Brazil has implemented this process in its water policy.

1.2 THE 1988 FEDERAL CONSTITUTION AND GROUNDWATER

The 1988 Federal Constitution represents a milestone in the management of groundwater, as it radically transformed its legal nature (discussed in detail in Box 2). These waters were governed by the Water Code (Decree 24,643/1934) which, in general, classified groundwater as private waters (Article 8), their use being free for the owners of the land where they were located (Article 96):

> Article 8. Springs and all waters situated on private land are also private when they are not classified as common waters for all, public waters or common waters.
>
> Article 96. The owner of any land may appropriate the water through wells, galleries etc. water existing beneath the surface of their building, so long as it does not harm existing uses or derive or deviate from their natural course the waters in the public domain, water that is public for common use or for private use.

Unlike surface water, mostly classified as public water (common or public), groundwater, for the most part, was considered private. There were, however, two exceptions to this legal treatment, restricted to the case of springs, namely: *a)* form the headwater stream of a river (*caput fluminis*) due to the abundance of its flow, as provided in Article 2, paragraph *e* of Decree 24,643/1934; or *b)* if located on public land (TOVAR, 1955). Only in these two cases would groundwater be considered public.

Therefore, groundwater was linked to property rights (set forth at the time in Article 526 of the 1916 Civil Code). Its use was allowed so long as there was no diversion of springs that supplied populations (Article 94) and did not cause damage or decrease of public-domain or public waters for common or private use by third parties (Article 96, sole paragraph) (TOVAR, 1955). Furthermore, construction that polluted or rendered useless water from another's well or spring was prohibited (Article 98), as well as the opening of a well next to the neighboring property (Article 97).

Articles 34, part. I, and 35 of the 1946 Federal Constitution, whose wording was maintained by the 1967 Federal Constitution, which publicized all surface waters, dividing their jurisdiction between the Federal Government and the States, however, remained silent regarding groundwater, which remained private:

> Article 34. The Federal Government's assets include:
>
> I – lakes and any water currents on land in its domain or that supply more than one State, serve as a boundary with other countries or extend into foreign territory, as well as river and lake islands in areas of borders with other countries;
>
> Article 35. Among the State's assets are included lakes and rivers on land under its domain and those that have their source and mouth in the State's territory.

Consequently, groundwater only became public upon the enactment of the 1988 Federal Constitution, which divided the jurisdiction of water between the

Federal Government and the States, as determined by Articles 20 and 26:

> Article 20. The following are assets of the Federal Government:
>
> III - lakes, rivers and any streams of water on land under their jurisdiction, or that reach more than one State, serve as boundaries with other countries, or which extend into foreign territory or come from it, as well as marginal lands and river beaches;
>
> [...]
>
> IX - mineral resources, including those in the subsoil;
>
> Article 26. The assets of the States include:
>
> I - surface or underground water, flowing, emerging and in deposit, except, in this case, as provided by law, for those resulting from construction carried out by the Federal Government.

The waters attributed to the Federal Government, in part III, are restricted to surface waters (lakes, rivers and water streams) that meet the following conditions: "bordering states or another country, or situated in more than one state or country." (MILARÉ, 2020, p. 1154). In turn, Article 26 assigns to states the surface and underground water resources included in their territory. In the case of groundwater, however, there are no territorial constraints (MILARÉ, 2020). Despite this fact, due to specificities set forth by mining legislation, some groundwater is classified as mineral resources, subject to the jurisdiction of the Federal Government. This topic will be discussed in detail hereafter, in the item *Groundwater and mineral waters*.

Groundwater, therefore, is owned by the States (CAMARGO; RIBEIRO, 2009; FERNANDES, 2019; VILLAR; GRANZIERA, 2020). The Federal Constitution repealed municipal and private waters, whose understanding was corroborated by the National Water Resources Policy (PNRH) (Law No. 9,433/1997), which classified water as an asset under public jurisdiction (Article 1, part I). Consequently, Property Rights no longer applied to water resources, the use of which became subject to State regulation. Most provisions of the Water Code became incompatible with the ownership regime established by the Federal Constitution under the water regime set forth by Law No. 9.433/1997.

Jurisprudence of the Superior Court of Justice (STJ) suggested the possibility of federally-owned groundwater (STJ, 2013; 2016a; 2016b). These decisions adopted the line of argument set forth in Article 20, part III of the 1988 Federal Constitution when attributing to the Federal Government jurisdiction over "rivers, lakes and any water currents", not making a distinction as to whether they are superficial or underground, i.e., the only necessary requirement is to observe the location of the resource, in other words, if it is located on federal land, if it serves as a boundary with other countries, or if it extends/originates in a foreign territory.

This interpretation emerged from lawsuits whose objective was to discuss the legality or illegality of acts of the Government which - supported by state decrees or by Article 45 of the National Sanitation Policy (PNS) (Law No. 11,445/2007) - aimed at preventing the use of wells without a formal authorization, as an alternative source of water in areas equipped with a water supply network. This legal theory, consequently, was raised in lawsuits that did not discuss the state or federal jurisdiction, and took place in a proceeding without the participation of the states or of the Federal Government.

Therefore, the content of the ruling below (and others similar) has no legal force to rule out the state jurisdiction over groundwater. This dispute had already been raised in the Executive and Legislative branches in the 2000s through the discussion of the Proposal for Constitutional Amendment (PEC) 43/2000, which sought to transfer to the federal jurisdiction groundwater that exceeded state limits or that was shared with other countries. PEC 43/2000 was largely stimulated by the discussion over the Guarani Aquifer; however, it was shelved on its merits. Thus, the Constitution, Justice and Citizenship Committee issued a statement opposing the bill:

> The measure enshrined in the proposal in examination is contrary to the decentralized model of water resources management developed in recent years, which, in our view, is the one that best adapts to the need to reconcile the use of resources with environmental management, especially considering the view of our federative system and the size of the country. The debate was held in a public hearing held at the CMA on the ownership and management of water and revealed that the transfer of jurisdiction over groundwater to the Federal Government does not contribute to the improvement of the National Policy on Water Resources. (CASAGRANDE; ABREU, 2010, p. 4).

Excerpt from Special Appeal (Appeal to the Superior Court of Justice] 1.306.093 which addresses the existence of federally owned groundwater in a lawsuit that discusses the possibility of coexistence of wells in areas with a public water network

[...] groundwater is not explicitly mentioned in Article 20, item III, of the Federal Constitution, which defines the assets of the Federal Government. As for Article 26, part I, which provides for state water resources, it addresses it directly. The different form of expression in the two constitutional provisions led some to defend the theory that groundwater would be – always and under any circumstances – under the jurisdiction and owned by the States, never by the Federal Government. This is, it is worth repeating, a misinterpretation of the constitutional text. First, on a teleological level, since the same grounds that materially justify, according to the terms of Article 20 of the Federal Constitution, the federal jurisdiction over surface waters (occupation of federal lands, spreading through more than one State, demarcation of international borders, or international origin or destination) would recommend – even more rightfully so – that groundwater should not be left under the exclusive jurisdiction of the states and the Federal District. Second, because what we have, in a comparison of both articles, is not an omission, pure and simple, of groundwater in Article 20, but the use of a writing technique that does not require a specific mention thereof, provided the legislator only addressed lakes, rivers and any water currents on land under its jurisdiction, or that bathe more than one State, serving as boundaries with others countries, or which extend to/originate from foreign territory. Well, the legislator did not make any reference as to whether said rivers, lakes, and streams were located on the surface or underground. Article 26 indeed had to mention groundwater, because, if it failed to do so, there would be a risk of – by interpretation – stating that all groundwater would be the property of the Federal Government, although that it is nearly impossible (a situation that changes, gradually, upon technological advances) to accurately define where an aquifer begins and ends. Consequently, the intention was not to exclude the Federal Government from the jurisdiction, but to ensure that States would not be separated from groundwater, in order to make coincide the same factual situations of recognition of their jurisdiction over surface water. (STJ. *Special Appeal 1.306.093-RJ*. 2nd Panel. Opinion Author: Justice Herman Benjamin, judged on 05/28/2013).

The inclusion of groundwater in the idea of "rivers, lakes or any streams of water" escapes the technical definition of these terms which, in hydrology literature, are classified as *surface water resources*. Groundwater is not encompassed by these terms, as it moves through pores or fissures in rocks, and therefore – except in very specific situations – the flow does not form water currents, but is slow and heterogeneous, as we will see in more detail in Chapter 2.

The National Water and Sanitation Agency – Brazil (ANA) and several Basin Committees expressed their opposition to PEC [Proposal for Constitutional Amendment] 43/2000 (CASAGRANDE; ABREU, 2010). The arguments for this position refer to the inherent difficulty in specifying the aquifer systems and their limits since aquifers are formed by different geological conditions with different limits. Therefore, creating a system that requires determining which aquifers belong to the Federal Government and which belong to the States would cause great difficulty in management. Moreover, aquifer management must prioritize the local scale due to the characteristics of underground flows.

Therefore, it is incumbent on the States in Brazil to set the policy for managing their groundwater resources, as determined by the guidelines set forth by federal legislation. In addition to defining the jurisdiction over waters, the 1988 Federal Constitution determined in Article 21, part XIX, the duty of the Federal Government "to institute the national water resources management system and define the criteria for granting the right to use it." Article 22, part IV, in turn, gave the Federal Government the exclusive jurisdiction to legislate on water rights (VILLAR; GRANZIERA, 2020). These constitutional commands paved the way for the passing of Law No. 9,433/1997, which lays the foundations for water governance in the country. The state management of groundwater is subject to compliance with the assumptions set by national water legislation. State ownership does not interfere with the Federal Government's ability to establish negotiations involving transboundary aquifers (Article 21, part I, of 1988 Federal Constitution), so much so that Brazil signed, with Argentina, Paraguay and Uruguay, the Agreement on the Guarani Aquifer, whose presuppositions must be respected by the States.

Box 2 - Legal Nature of Groundwater

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Article 3, part V, of Law No. 6,938/1981, when addressing environmental resources, mentions groundwater, interior, surface water and estuaries. These are, consequently, public assets, subject to protection under the National Environmental Policy (PNMA).

This protection also refers to Article 225 of the 1988 Federal Constitution, according to which "Everyone has the right to an ecologically balanced environment, an asset for common use by the people and essential to a healthy quality of life." The expression *asset for common use by the people* is not to be confused with public assets for common use established in Article 99, Part I, of the Civil Code since environmental balance (a macro-asset) is neither public nor private, but refers much more to an interest or a need than to a jurisdiction or ownership (GRANZIERA, 2019). Likewise, Article 1, part I, of Law No. 9,433/1997, classifies water contained in bodies of water (rivers, lakes or aquifers) as an asset in the public domain. The Government, therefore, is not the owner of an ecologically balanced environment, but its manager, whose duty is to manage assets, not as an owner of it, in a reasoned and participatory way (YOSHIDA, 2007; MACHADO, 2010; VILLAR; GRANZIERA, 2020).

Law No. 6.938/1981 defines the environment as "the set of conditions, laws, influences and interactions of a physical, chemical and biological nature, which permits, shelters and governs life in all its forms." In other words, the environmental balance or the ecologically balanced environment that guarantees life in all its forms is the macro-asset, protected by the Constitution, to which asset everyone is entitled. Water is a central component of this immaterial context of the environment. Water is in motion in the hydrological cycle (underground, surface, meteoric) and is connected to the environmental perspective of a macro-asset, classified as an asset with a diffuse nature and of common use by the people (VILLAR; GRANZIERA, 2020; VIEGAS, 2005).

Upon the enacting of the Consumer Defense Code (CDC), the environmental macro-asset, as an asset for common use by the people, passed to be interpreted as a diffuse interest or right "understood as such [...], transindividual goods, indivisible in nature, in the custody of persons both indeterminate and linked by factual circumstances." (Article 81, part I, of the Consumer Defense Code CDC).

Benjamin (1993, p. 75) explains that this "environmental complex is composed of singular entities" which, individually, are also legal assets. In this case, water, including groundwater, as environmental resources (Article 3, part V), consists of micro-assets, subject to specific legal regimes. To that end, specific rules define the custody (federal or state), the use (granting the right to use water resources) and protection (resolutions of the National Environmental Council – Conama).

Groundwater, as a micro-asset, according to Law No. 9,433/1998, is classified as water resources and corresponds to the "portion of water subject to a specific destination for use by an individual or corporate entity." (VILLAR; GRANZIERA, 2020). The private allocation of this water must comply with the criteria set forth in Law No. 9,433/1997, which requires securing the right to use water resources through a substantiated decision issued by the state management agency (VILLAR; GRANZIERA, 2020). Rainwater and those waters derived from bodies of water are no longer characterized as public and become part of the domomion of the person who collected it, as long as the person respects all legal formalities.

On an exceptional basis, the Mineral Water Code defines situations in which groundwater is classified as a mineral resource. For that to be characterized, these waters must have certain physical or physical-chemical characteristics, or even potability, in addition to being suitable for the following types of uses: mineral, thermal, carbonated water, drinking water or intended for bathing purposes. In this case, authorization for research and exploitation is required, as well as obtaining the mining rights from the National Mining Agency. Some states, such as Ceará[1] and São Paulo[2] have determined that the exploitation of groundwater as a mineral resource is also subject to the legislation governing water resources. In this case, these waters are concomitantly characterized as water and a mineral resource.

1. For more information, see Appendix 13 of the Water Resources Management Company – CE (Available at:).
2. In the state of São Paulo, companies destined to the bottling of drinking, mineral or bathing water are subject to registration through the Electronic Grant System for the purpose of managing water resources. In the case of extraction from springs, see Technical Directive DPO 9/2017 and in the case of wells, see the Technical Directive DPO 10/2017.

1.3 THE NATIONAL WATER RESOURCES POLICY (PNRH): A NEW WAY OF MANAGING WATER

The National Water Resources Policy in Brazil was established by Law No. 9,433/1997, and is composed of 57 articles divided into four titles: Title I – National Water Resources Policy; Title II – National Water Resources Management System (SINGREH); Title III – Offenses and Penalties; and Title IV – General and Transitory Provisions. The provisions of the water policy refer to water in general, without differentiating surface and groundwater.

This law transformed the management of water resources thus far regulated by the Water Code (Decree No. 24,643/1934) (POMPEU, 2006). The Water Code, passed by an Interim Administration following the 1930 Revolution, had a centralizing, privatizing and utilitarian vision, focused mainly on the use of hydraulic potential without concern for water conservation (MILARÉ, 2020). Law No. 9,433/1997, in turn, was the result of a long process of debates, and structured a governance model based on decentralized, integrated and participatory management (BARBI; JACOBI, 2007), which incorporated the main guidelines from the IWRM.

Figure 2 demonstrates the foundations, objectives, guidelines, management instruments and institutions set forth in the National Water Resources Policy (PNRH). This law adopted the hydrographic basin as a management unit, allowed the participation of social actors, attributed an economic value to water, determined the organizations responsible for its management, established instruments to guide the use, reuse, protection of water and the relevant information system. Furthermore, it established that water management must comprehend aspects relative to quantity and quality, as well as taking into account the multiple uses of water resources, environmental management, land use, territorial planning and the relationship with estuary systems and coastal regions.

GROUNDS (article 1)
• public asset; • limited natural resource, endowed with economic value; • priority use for human consumption and the watering of animals in situations of scarcity; • multiple use of water; • hydrographic basin as a territorial unit for the implementation of the PNRH and the operating framework of SINGREH; • decentralized and participatory management (Government, users and communities).
OBJECTIVES (Article 2)
• ensuring the current and future generations the necessary water availability, in adequate quality standards for the respective uses; • rational and integrated use of water resources; • prevention and defense against critical hydrological events; • encourage and promote the extraction, preservation and use of rainwater.
GENERAL GUIDELINES FOR ACTION (Article 3)
• systematic management of water resources, without decoupling the aspects of quantity and quality; • adequacy of water resources management to the physical, biotic, demographic, economic, social and cultural diversities of the different regions of the country; • integration of water and environmental management; • articulation of water planning with that of user sectors and with regional, state and national planning; • articulation of water management with land use; • integration of watershed management with that of estuarine systems and coastal zones.
MANAGEMENT INSTRUMENTS (article 5)
• Water Resources plans; • classification of bodies of water into classes, according to the predominant uses of water; • granting rights to use water resources; • charging for the use of water resources; • Water Resources Information System.

SINGREH (article 33)
• National Water Resources Council; • National Water and Basic Sanitation Agency; • State and National District Water Resources Councils; • River Basin Committees; • National, state, DF and municipal public authorities whose powers are related to the management of water resources; • Water Agencies.

Figure 2 - Fundamentals, objectives, guidelines, management instruments and institutional architecture of the National Water Resources Policy

Source: Brazil (Law No. 9.433/1997).

The enforcement of the PNRH is carried out by the National Water Resources Management System (SINGREH), which is materialized as group of bodies and boards assigned implementation of integrated water management. The integration of surface, underground and meteoric water management is necessary due to the inseparable nature of the hydrological cycle. There are, however, a series of challenges that involve the problem of different territory divisions, the jurisdiction of different management bodies and administrative entities, the sector-based division of public policies and the participation of social actors.

Law No. 9, 433/1997 did not provide specific guidelines for groundwater, nor did it define the concept and scope of integrated management or a way of reconciling the territoriality of the hydrographic basin with that of the aquifers, nor did it specify the way to apply the management instruments to the specifics of groundwater, or to build coordination with other policies, such as environmental, sanitation, territorial, coastal, municipal, state and national development. By establishing SINGREH, however, an institutional apparatus was created which is capable of adapting and operationalizing management to the particularities of underground resources. CNRH Resolution 202/2018, in Article 3, determines the main aspects to be considered in the integrated management of surface and groundwater:

I. delimitation of recharge and contribution areas of aquifers for directly connected rivers;

II. estimation of the contribution of aquifers to the base flow of rivers;

III. estimation of recharge and exploitable and renewable reserves;

IV. estimate of integrated underground and surface water availability for different uses, considering the previous items; and

V. the necessary hydrometeorological and hydrogeological monitoring networks.

The passing of Law No. 9,433/1997 represented an advance in water management and, despite its application having prioritized surface resources, gradually, an institutional effort to include groundwater is perceived. However, the lack of technical data, monitoring networks, user adherence to management instruments, government inspection and social awareness of the resource, render its application difficult.

1.4 THE INSTITUTIONAL ARRANGEMENT FOR GROUNDWATER PROTECTION: SINGREH

SINGREH corresponds to the group of bodies and entities that act in the management of water resources in Brazil, with hierarchies and specific attributions according to the scale of their operations. Its objectives were set forth in Article 32 of Law No. 9,433/97:

- to coordinate integrated water management;
- to arbitrate conflicts relative to water resources on an administrative level;
- to implement the National Water Resources Policy;
- to plan, regulate and control the use, preservation and recovery of water resources;
- to promote charging for the use of water resources.

Figure 3 presents the organizational chart and the attributions of the bodies and entities that comprise SINGREH. Due to the division of jurisdiction over water, the system is divided into two levels of jurisdiction: federal and state. This political-administrative architecture is structured by bodies divided into three categories, according to both their nature and scope of operation (GRANZIERA, 2015, p. 125):

- **Boards**: National Water Resources Council (CNRH); State and National District Water Resources Councils; and Hydrographic Basin Committees;
- **Management and control agencies and entities**: National Water and Sanitation Agency (ANA), Water Agencies, agencies and entities of federal, state, Federal District and municipal governments, whose powers are related to the management and control of water resources;
- **Civil water resources organizations**: *a)* inter-municipal hydrographic basins joint ventures and associations; *b)* regional, local or industry-based associations of users of water resources; *c)* technical, teaching and research organizations with interest in the field of water resources; *d)* nongovernmental organizations with objectives pertaining to the defense of diffuse and collective interests of society; *e)* other organizations recognized by the National Council or by the States' Water Resources Councils.

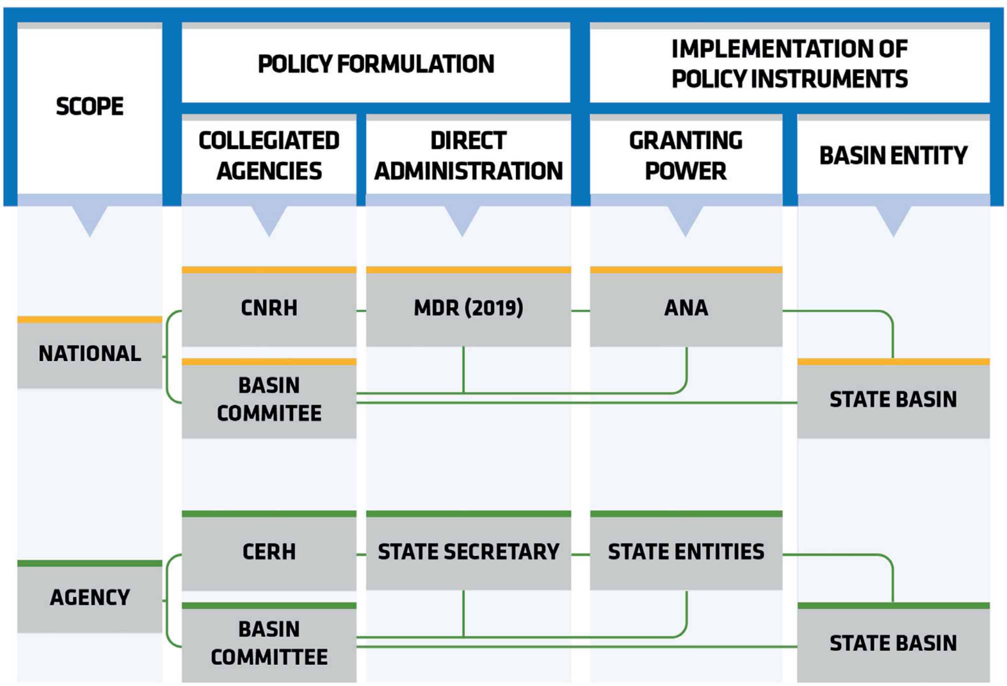

Figure 3 - SINGREH matrix and functioning*

Source: Villar e Granziera (2020, p. 48). (*) The composition, the legal nature and specific attributions of each agency or entity will be detailed in the following items.

SINGREH bodies are responsible for promoting integrated water management and reconciling the territoriality of aquifers and of the basin. Thus, when aquifers exceed the limits of the basin, these bodies must promote "the standardization of guidelines and criteria for data collection and preparation of hydrogeological studies necessary for the identification and characterization of the hydrogeological basin" (Article 4 of CNRH Resolution 15, of January 11, 2001), and the hydrographic basin committees "shall seek the exchange and systematization of the data generated for the perfect characterization of the hydrogeological basin" (Article 4, sole paragraph).

In the case of transboundary or interstate aquifers, SINGREH is responsible for promoting the integration of "agencies of federal, state and Federal District governments with jurisdiction over groundwater management." If any conflicts arise in this process, the Water Resources Councils of the States and the Federal District are responsible for resolving them on a first level, and CNRH will be the appeal and final level (Article 5, § 1, of CNRH Resolution 15/2001). In the case of transboundary aquifers, the agreements executed between the Federal Government and the countries with which the aquifer is shared must be taken into account.

Moreover, the National System and the State and Federal District Water Resources Management Systems must provide guidance to municipalities relative to: a) promoting integrated management of groundwater in order to follow the water resources plans; b) protecting aquifer recharge areas; and c) encouraging the adoption of reuse and artificial recharge practices (CNRH Resolution 15/2001).

Something that cannot be forgotten, however, is that although groundwater is managed by state water resources systems, groundwater systems are part of a national order. Consequently, there is a complete institutional and normative institutional infrastructure that influences this management. States are responsible for organizing the management of groundwater, controlling the use and quality thereof, as well as for monitoring its use, however, its policies must be aligned with the national policy governing water resources. Traditionally, management of use (quantity) is carried out by state water resources agencies, whereas quality aspects are analyzed by state environmental agencies, established by the National Environment System (SISNAMA).

For more information on state water resources and environment agencies, see:
https://www.ana.gov.br/gestao-da-agua/sistema-de-gerenciamento -de-recursos-hidricos/orgaos-gestores/lista-de-orgaos -gestores-estaduais.

The bodies that comprise SINGREH's national structure play an important role in guiding and coordinating this state-level management which will be explained in more detail in the following items.

1.4.1 Ministry of Regional Development: the new coordinator of water management

Originally, the Ministry of the Environment (MMA) was the central body of SINGREH and was also the headquarters of the Water Resources Department (SRH), the National Council of Water Resources (CNRH) and the National Water and Sanitation Agency – Brazil[3] (ANA). At MMA, the Department of Water Resources was responsible for: *a)* monitoring the operation of SINGREH; *b)* promoting the integration of water resources and environmental management; *c)* coordinating the preparation and assisting in the monitoring and implementation of the National Water Resources Plan; *d)* promoting technical and scientific cooperation; *e)* coordinating, within its competency, the preparation of plans, programs and national projects concerning groundwater, and monitoring the development of actions within the principle of integrated management of water resources (Article 11 of Decree 4,755, of June 20, 2003).

As of Provisional Executive Order 870, of January 1, 2019, converted into Law No. 13,844/2019, the National Water Resources Policy became part of the Ministry of Regional Development (MDR) – a portfolio that emerged from the merger of the Ministries of Cities and National Integration. In addition to the PNRH, the MDR is responsible for the following policies relative to water management: National Regional Development Policy (PNDR); National Urban Development Policy (PNDU); National Civil Defense and Protection Policy (PNPDEC); National Water Security Policy (PNSH); National Irrigation Policy (PNI), observing the competency of the Ministry of Agriculture, Cattle-raising and Supply (MAPA); National Sanitation Policy (PNS), and formulation and management of the National Territorial Planning Policy (PNOT). Furthermore, it began to be responsible for the plans, programs, projects and actions in the management of water resources, infrastructure and guarantee of water security, irrigation, protection & civil defense, management of risk and disasters, housing, sanitation, mobility and urban services (Article 29).

The National Water Resources Department (SNRH) was dissolved and replaced by the National Water Security Department (SNSH), made up of the Department of Water Infrastructure and Support for Water Security Studies, the Department of Strategic Projects, and the Department of Water Resources and Revitalization of Hydrographic Basins (Article 2, part II, b, of Decree No. 10.773/2021). The competency of the SNSH include: a) coordinate the formulation, review, implementation, monitoring and evaluation of the National Water Security Policy, the National Water Resources Policy and their instruments; b) formulate policies, plans and standards and define strategies on integrated management of water resources, including border and transboundary waters; c) coordinate the preparation and review of national plans, programs and projects relative to groundwater, and monitor the development of their actions, in accordance with the principle of integrated management of water resources; and d) perform the duties of the Executive Department

3. Currently, National Water and Sanitation Agency (ANA).

of the National Water Resources Council (Article 19 of Decree No. 10.773/2021).

The powers of the Department of Water Infrastructure and Support for Studies on Water Security, the Department of Strategic Projects and the Department of Water Resources and Revitalization of Hydrographic Basins are found, respectively, in Articles 20, 21 and 22 of Decree 10,773/2021. The Department of Water Infrastructure and Support for Water Safety Studies is responsible for supporting the execution of well drilling and monitoring implementation of project actions focused on expanding the water supply. The Strategic Projects Department, in turn, has a leading role in the preparation of studies and proposals for the National Water Security Policy and its instruments, and in the monitoring, supervision and inspection of actions focused on the strategic use of water and soil resources. The Department of Water Resources and Revitalization of Hydrographic Basins is responsible for: *a)* coordinating, supporting and monitoring the enforcement of Law No. 9,433/1997 and the National Water Resources Plan; *b)* supporting the States and Federal District in the implementation of state management policies and systems; *c)* providing technical support the constitution and operation of hydrographic basin committees; *d)* proposing guidelines for the management of border and transboundary-located aquifers; *e)* prepare plans, programs and projects relative to water resources, including groundwater; *f)* exercising the duties of the Executive Department of the CNRH; and *g)* articulating the management of water resources with use of soil management.

1.4.2 The National Water Resources Council (CNRH) and its role in establishing groundwater guidelines

The CNRH, on a national level, is the advisory and deliberative body of SINGREH, which, since 2019, became part of the Regional Development Ministry's Regulatory Structure. Its line of operation was established by Articles 33, part. I, and 34 to 36 of Law No. 9,433/1997, and in Article 2 of Law No. 9,984/2000, and it was regulated by Decree 10,000/2019. Article 2 of Law No. 9,984/2000 assigns the following duties to CNRH:

Article 2. Is incumbent on the National Water Resources Council promote the articulation of national, regional, state and user sector planning by entities that make up the National Water Resources Management System and formulating the National Water Resources Policy, pursuant to Law No. 9.433, of January 8, 1997.

CNRH's powers are listed in Article 1 of Decree 10,000/2019 and in its Internal Regulations, approved by CNRH Resolution 215, of June 30, 2020. This board-format entity is responsible for establishing complementary guidelines for the implementation of Law No. 9,433/1997. CNRH issued several resolutions in order to guide the management and application of instruments to manage groundwater (Table 1).

These national regulatory acts provide guidance to states and basin committees in the process of applying water instruments to manage groundwater and set management and action guidelines, such as implementation of the integrated monitoring network or the general guidelines for artificial recharge and data exchange between state water resources agencies and the mineral water system.

Until the signing of Decree No. 10,000/2019, CNRH had a Technical Groundwater Panel (CTAS), whose main objectives were: *a)* to discuss and propose insertion of underground water management in the PNRH; *b)* to render legislation relative to the exploitation and compatible use thereof; *c)* to propose institutional mechanisms for integration of water management; *d)* to propose protection and management mechanisms and mitigation and compensatory action; e*)* to analyze and propose actions for either minimizing or resolving conflict (Article 2 of CNRH Resolution 9, of June 21, 2000). The attributions of CTAS were incorporated by the Technical Panel of Integration with Environmental and Territorial Management (CTIGAT) (Article 9, part IV, of Decree No. 10,000/2019).

The CNRH also has jurisdiction act in the resolution of conflicts between states over surface and groundwater. This mediation role can be very important in the case of interstate and transboundary aquifers, or in the case of conflicts involving the contribution of aquifers to federal rivers.

NATIONAL RESOLUTIONS ISSUED BY CNRH	
Resolution CNRH 15/2001	Sets the general guidelines for groundwater management
Resolution CNRH 16/2001	Regulates the granting of the right to use water resources
Resolution CNRH 22/2002	Sets the guidelines for the inclusion of groundwater in the Water Resources Plans
Resolution CNRH 29/2002	Sets the guidelines for granting the use of water resources and use of mineral resources
Resolution CNRH 48/2005	Sets the general criteria for charging for the use of water resources
Resolution CNRH 76/2007	Sets the general guidelines for integration between the management of water resources and the management of mineral, thermal, aerated, drinking water or water intended for bathing purposes
Resolution CNRH 91/2008	Sets the general procedures for the classification of surface and underground water bodies
Resolution CNRH 92/2008	Sets the general criteria and procedures for the protection and conservation of groundwater in the Brazilian territory
Resolution CNRH 107/2010	Sets the guidelines and criteria to be adopted in the planning, implementation and operation of the National Network for Qualitative and Quantitative Integrated Monitoring of Groundwater
Resolution CNRH 126/2011	Approves guidelines for registration of users of water resources and for the integration of databases referring to the use of surface and underground water resources
Resolution CNRH 153/2013	Sets the criteria and guidelines for implementation of Artificial Aquifer Recharge in the Brazilian territory
Resolution CNRH 184/2016	Sets the general guidelines and criteria for defining derivations and abstractions of surface and underground water resources, and releases of effluents into bodies of water and accumulations of small volumes of water, considered insignificant, which do not depend on the granting of the right to use resources water resources, and also provides for other measures
Resolution CNRH 202/2018	Sets the guidelines for integrated management of surface and underground water resources that contemplate the articulation between the Federal Government, the states and Distrito Federal for the purpose of strengthening said management.

Table 1 - Main National Resolutions issued by CNRH relative to groundwater
Source: Villar and Granziera (2020).

1.4.3 ANA's performance in groundwater and the integrated management of water resources

The National Water and Sanitation Agency (ANA), originally the National Water Agency, was created by Law No. 14,026, of July 15, 2020, changed its original name and expanded its list of powers. Article 1 of Law No. 9,984/2000 defines ANA in the following terms:

> a federal entity whose purpose is to implement the National Water Resources Policy, part of the National Water Resources Management System (SINGREH) and which is responsible for setting reference standards for the regulation of public sanitation services, and sets rules for its performance, its administrative structure and its sources of resources.

It is a federal agency operating under a special regime, with administrative and financial autonomy, a member of SINGREH which, in 2019, stopped operating under MMA and began to report to MDR (Decree No. 9,666/2019). Within the scope of its jurisdiction, it has the following functions: to implement the National Water Resources Policy and set reference standards for regulating public sanitation services, as well as to promote the management of waters in the competency of the Federal Government. Its powers are conferred by Articles 4 and 4A of Law No. 9,984/2000.

As for groundwater, ANA seeks to support state management and strengthen the integrated management of surface and groundwater resources, always emphasizing the river-aquifer relationship. Its actions in the field of groundwater are mainly carried out through the implementation of the Action Agenda for the Integrated Management of Surface and Groundwater Resources, hereafter referred to as the Groundwater Agenda, which includes the attributions set forth in the National Groundwater Program (PNAS), included in the National Water Resources Plan. The purpose of this agenda is "to propose and execute a set of actions that will strengthen the implementation of the integrated management of surface and groundwater resources in Brazil", and is structured into five main actions that are divided into several activities (Figure 4):

GROUNDWATER AGENDA

ACTIONS	ACTIVITIES
Promotion of integrated management of aquifers connected with federal rivers	Diagnosis of aquifers connected to federal rivers Elaboration of evaluations for integrated management Proposition of regulatory frameworks and allocations
Preparation of hydrogeologica l evaluations	Identify and carry out studies on aquifers in urban areas supplied by GW Identify and prepare hydrogeological evaluations in interstate and transboundary aquifers Elaborate portfolio for supply solutions with GW in areas with water vulnerability due to critical events
- Data systematization and GW monitoring	Operate and maintain the SAS/SHRH Groundwater System Plan and coordinate the National Integrated Monitoring Network Qualitative and Quantitative Groundwater (RENAMAS)
-Support and elaboration of water resources plans in the GW matter	Elaborate the diagnosis of groundwater in water resource plans Implement actions foreseen in the water resource plans for GW
Training	Specific training planning in integrated management Implementation of specific training in integrated management

Figure 4 - Groundwater Agenda
Source: ANA (2015, p. 12).

ANA seeks to expand hydrogeological knowledge, whose action is carried out through the mapping of aquifers, such as, for example, the preparation of the Map of Aquifer-Derived Areas and Aquifer Systems in Brazil (scale 1:1,000,000) (ANA, 2013). Or, moreover, by carrying out technical studies on interstate or transboundary aquifers and the river-aquifer relationship, as in the case of the Chapada do Apodi Aquifers; Urucuia Aquifer System (UAS) (ANA, 2017); Guarani Aquifer System (SAG); Aquifers of the Amazon Hydrogeological Province (ANA, 2015a); karst environments in the São Francisco Basin (2018) or the pilot project for integrated river/aquifer management in the basins of the Verde Grande and Carinhanha rivers (project in progress, in a partnership with SGB-CPRM). Furthermore, studies are conducted on strategic aquifers for the supply of metropolitan regions, such as Maceió, Natal, Belém, Ilha de São Luís and Manaus.

In light of its role in the preparation of water resources plans in hydrographic basins under the jurisdiction of the Federal Government, ANA included, in a pioneering fashion, the integrated river/aquifer water approach in basin plans, as in the case of the Hydrographic Basin Plans for the rivers Rio Doce, Rio Grande, Rio Paranapanema and Rio Paraguai." The Agency works closely with state water resource management bodies, basin committees and basin agencies for the purpose of preparing hydrographic basin plans.

ANA also has powers to organize, implement and manage the National Water Resources Information System (SNIRH) (Article 4, part XIV, of Law No. 9,984/2000), which stores various data relative to water resources. Moreover, the Agency works in the coordination and planning of the National Network for Monitoring Groundwater, according to CNRH Resolution 107/2010. In 2019, in partnership with the Geological Service of Brazil – (SGB-CPRM), ANA started a pilot project in aquifers with high base flow for jointly operating monitoring points of the Integrated Groundwater Monitoring Network (RIMAS) in a manner integrated with the National Hydrometeorological Network (RHN). The first pilot project included the Urucuia Aquifer System, with around 75 points, operating in conjunction. Currently, RIMAS has approximately 400 monitoring points, distributed through 24 aquifers and 20 states (GENARO; PEIXINHO; MOURÃO, 2019). It is worth noting the pioneering methodology, with a regional scope, developed by ANA for planning underground water monitoring networks, with the base flow among the analyzed variables.

Another contribution of ANA's activities to groundwater pertains to the Water Producer Program. In partnership with several institutions, local projects are executed for adopting soil conservation practices and the recovery and maintenance of vegetation cover for increasing soil permeability and recovering or increasing the water flow from springs, in addition to reducing erosion processes. The Program also encourages the adoption of arrangements for Payment for Environmental Services (PSA), thus contributing to the engagement of rural producers in the adoption and maintenance of good practices implemented. ANA, incidentally, developed a methodology (OLIVEIRA et al. 2021) for identifying the most favorable areas in hydrographic basins for the adoption of conservation practices for the purpose of maximizing recharge

For more information about the program, see the Water Producer website:

https://www.gov.br/ana/pt-br/acesso-a-informacao/acoes-e-programas/programa-produtor-de-agua.

In the discharge of its legal attributions and competencies, ANA relies on partnership and collaboration with other public agencies and institutions and this is the case of the Geological Service of Brazil (SGB-CPRM).

SGB-CPRM is a public company under the Ministry of Mines and Energy, with attributions as the Geological Service of Brazil[4]. Although it is not a member of SINGREH, SGB-CPRM is an important partner of ANA in the survey of geological data on groundwater. The institution has the largest collection of geological, hydrological and hydrogeological data in the country. Moreover, it operates part of the National Hydrometeorological Network (RHN), as well as the Integrated Groundwater Monitoring Network (RIMAS). It is also responsible for the Groundwater Information System (SIAGAS), which has an extensive database of wells in Brazil. The records are composed of information cataloged through files of wells provided by public and private institutions, managers and users of groundwater, whose registration is not valid for verifying water use regularity.

1.4.4 Hydrographic Basin Committees (CBHs) and the inclusion of aquifers in management

The Hydrographic Basin Committees (CBHs) are panels with regulatory, deliberative and consulting attributions, operating under the Government and reporting to the respective Water Resources Councils (Res. 5/2000). They form part of national and state water resources management systems. If their area of operation is a federal river, they are linked to the National Water Resources Council; in the case of state rivers, they are connected to the respective State Water Resources Council.

These operate on a political level and are materialized by building a discussion forum between the Government, users and civil society, and consequently, they are not a legally and formally organized entity. These panel-based entities are characterized as the most important instance of local participation and integration of water planning and management (VILLAR; GRANZIERA, 2020). Law No. 9.433/1997, in Article 38, and CNRG Resolution 5/2000, define their main duties and attributions:

4. See Law No. 8.970, of December 28, 1994.

- to promote debate on issues related to water resources and articulate the action of the intervening entities;
- to arbitrate conflicts pertaining to water resources on a first administrative level;
- to approve the Basin's Water Resources Plan;
- to monitor the execution of the Basin's Water Resources Plan and suggest the necessary measures to achieve its goals;
- to propose to the National Council and to the State Councils of Water Resources the accumulations, derivations, extractions and releases of little expression for the purpose of exemption from the obligation to grant rights to use water resources, according to the relevant jurisdictions;
- to establish charging mechanisms for the use of water resources and suggest the amounts to be charged;
- to make hydrographic basin plans for tributary watercourses compatible with the Water Resources Plan of the Hydrographic Basin of their jurisdiction;
- to approve the Water Agency's proposals submitted to it;
- to submit necessarily water resources plans of the hydrographic basin to public hearing;
- to develop and support initiatives in environmental education;
- to approve its bylaws.

These panel-based entities play a central role in the management and application of management instruments. Law No. 9,433/1997, in Article 37, sets forth that CBHs may have as their field of action: a) the "entirety of a hydographic basin" (part I); b) the "hydrographic sub-basin of a tributary of the main watercourse of the basin, or of a tributary of that tributary" (part II); or c) the "group of contiguous river basins or sub-basins" (part III).

The area of operation of CBHs considers the territoriality of surface water resources, which is easier to define. The hydrographic basin refers precisely to the "geographic space delimited by the respective watershed, whose outflow surface converges to its interior, captured by its relevant drainage network which pertains to it." (ANA, 2015b, p. 7). Although this territorial unit focuses on surface water, it does not rule out managing aquifers found in this space, especially due to the idea of integrated management of water resources.

Since the profile of the hydrographic basin does not always converge with the limits of the aquifers, CBHs must build inter-institutional cooperation arrangements for the purpose of integrated management of surface and groundwater. Proof of that is that CNRH Resolution 15/2001, in Article 4, sole paragraph, determined that in the case of aquifers underlying two or more hydrographic basins, it is incumbent on CBHs to seek the exchange and systematization of the data generated for the perfect characterization of the hydrogeological basin.

The CBH is empowered to approve and monitor the execution of hydrographic basin plans. The board, consequently, must verify if this planning instrument incorporated groundwater, complying with CNRH guidelines, focused on CNRH Resolution 22/2002, 92/2008 and 202/2008. Moreover, CBH is responsible for proposing exemption situations from the mandatory granting of the right of use, and setting the amounts for charging for the use of underground water resources.

Overall, CBHs face difficulties in including groundwater in their discussions. In large part, that is due to the prioritization of surface water resources, the lack of knowledge about groundwater and specialized personnel, or the lack of organization of well users or society relative to aquifers. Environmental education and technical training programs and initiatives focused on groundwater would contribute to promoting knowledge and transforming this reality.

1.5 STATES AND GROUNDWATER MANAGEMENT

The states and Federal District are responsible for defining state policy for their water resources, including groundwater, and for establishing the institutional infrastructure of the State Water Resources Management Systems, implementing the water management instruments provided for in Law No. 9,433 /1997, and promote studies on aquifers (FERNANDES, 2019).

State water management must comply with national rules relative to Water Law, which is under the exclusive jurisdiction of the federal government (Article 22, part IV, of the 1988 Federal Constitution) (FERNANDES, 2019; VILLAR; GRANZIERA, 2020). Law No. 9,433/1997 and the CNRH and CONAMA Resolutions established or regulated management instruments applicable to groundwater; these instruments must be incorporated into state policies, and recommend the conducting of various technical studies within the scope of hydrographic basins (VILLAR; HIRATA, 2022).

Water management instruments can be divided into two categories: those dedicated to water in general and those specific to groundwater. Figure 5 details these management instruments, which are the responsibility of the entities that make up the State Water Resources Management Systems. In addition to water management instruments, there are instruments for other state public policies that can contribute to the management of aquifers, such as: environmental licensing, economic-ecological zoning, agri-ecological zoning, irrigation plans, state sanitation plans, state solid waste plans, management of contaminated areas etc. Moreover, the states and Federal District must encourage municipalities to consider aquifers in municipal territorial planning processes.

Figure 5 - Water management instruments in public policy

Source: Villar and Hirata (2022, p. 5).

CNRH resolutions highlight the importance of conducting technical studies on groundwater, mainly within the scope of basin plans, to contemplate their integration with surface waters (see CNRH Resolution 92/2008 and Resolution 202/2018). These regulatory standards determine, for example, the conducting of hydrogeological studies to outline areas of recharge and vulnerability to aquifer pollution; groundwater availability and demand diagnoses; integrated hydrological assessments that outline the contribution of aquifers to directly connected rivers; and estimation of the contribution of the aquifer to the base flow of rivers. They also highlight the importance of installing state networks to monitor the quality and quantity of groundwater (Article 10 of CNRH Resolution CNRH 92/2008) and hydrometeorological and hydrogeological monitoring networks (Article 3, part V of CNRH Resolution 202/2018), as well as the issuance of quality reports (Article 13, § 2, and Article 33 of Conama Resolution 396/2008).

The states and Distrito Federal are responsible for the management of groundwater, even in the case of interstate and transboundary aquifers. Most aquifers cross state borders and, in some cases, even national ones. Data shows the importance of state water resources policies and systems and their joint action to manage aquifers, mainly by establishing joint monitoring actions, information exchange and management actions that protect recharge areas and groundwater flow when shared. There is also a need for greater coordination between the federal and state systems, something that is already happening in the case of surface waters through the National Water Quality Monitoring Network (RNQA) and the Program to Encourage Disclosure of Water Quality Data – Qualiágua Program (Resolution ANA 643/2016). Box 3 shows that there is still a long way to go in consolidating state management.

Box 3 – States and groundwater management

Luciana Cordeiro de Souza-Fernandes

Groundwater is considered a state asset, i.e., their management must be carried out by the states and the Federal District, which are responsible for legislating the management and protection thereof. However, there is a lack of studies on how this state management is done. Souza-Fernandes and Oliveira (2018a,b,c,d) carried out a work in collecting state water legislation from the five Brazilian regions (Midwest, North, Northeast, Southeast and South) and concluded that only 12 States have specific groundwater legislation: São Paulo, Minas Gerais, Santa Catarina, Rio Grande do Sul, Distrito Federal, Goiás, Mato Grosso, Mato Grosso do Sul, Alagoas, Pernambuco, Maranhão and Pará.

The 26 States and Distrito Federal, therefore, have already established their State Water Resources Policies (PERH), and in some states groundwater has been governed throughout their PERHs. This means, as we may see in the Collection of Brazilian Groundwater Legislation – in its five volumes – that in these states there is no individualized legal regulation of the management and use of groundwater in the way that it is in force, for example, in São Paulo.

Regarding the analysis of existing legislation, the authors reached the following conclusions: a) there is repetition of concepts and determinations from the São Paulo law (Law No. 6,134, of June 2, 1988), a precursor to the legislation on groundwater; b) not all states established the creation of protection and conservation areas for groundwater; and c) the laws of the States that did legislate on the matter failed to observe the peculiarities of the local hydrogeology.

The protection of groundwater requires a joint effort between states and municipalities due to the interconnection between these waters and the soil. This is especially important in areas of aquifer recharge and outcrop because, given their vulnerability, they require specific tools and/or legal instruments (urban planning) to protect the soil and, consequently, the quality of groundwater.

Link to the collection: https://materiais.aguasustentavel.org.br/coletanea.

1.6 MUNICIPALITIES AND THEIR ROLE IN AQUIFER MANAGEMENT

The 1988 Federal Constitution elevated municipalities to the category of federative entities, which is not usual in other federative systems (MIRANDA; REYNARD, 2020). Despite extinguishing the concept of municipal water, the Constitution considerably increased the political, legal, administrative and financial autonomy of municipalities, assigning them various powers that made them protagonists in the management of water resources (MIRANDA; REYNARD, 2020; VILLAR; GRANZIERA, 2020).

Municipalities acquired exclusive administrative jurisdiction to provide public services of local interest (Article 30, part V, of 1988 Federal Constitution), among which the organization and provision of sanitation, either directly or under a concession or authorization regime. The relationship between sanitation and aquifers is direct. These waters are an important water source for public supply or for alternative supply solutions when there is no public network, or even to relieve the demand for water from the concession holder provider of water for non-residential use (HIRATA *et al.*, 2019). Moreover, the absence of a sewage collection network, as well as poor management of solid waste are the main sources of contamination of aquifers (HIRATA *et al.*, 2019).

Municipal sanitation management must pay attention to the following aspects:

- to verify and supervise the way in which the provision of the water services interferes with the water levels of the aquifer;
- to control, through sanitary surveillance, the quality of water distributed to the population;
- to monitor compliance with legal obligations relative to the use of groundwater;
- to include provisions governing protection of the aquifer in services contracts, such as: payment for environmental services generated by the maintenance of recharge areas; water level monitoring programs; expansion and renovation of sewage collection networks; mechanisms to encourage soil permeability in recharge areas; and environmental education campaigns;
- to promote awareness campaigns on the rational use of groundwater and regional aquifers;
- to ensure proper disposal of solid waste.

The municipality also has exclusive jurisdiction to promote territorial planning through planning and control of the use, subdivision and occupation of urban land (Article 30, part VIII, of the 1988 Federal Constitution) and exclusive legislative jurisdiction in matters of local interest (Article 30, part I, of the 1988 Federal Constitution). Consequently, this entity becomes primarily responsible for setting limitations to the use and occupation of urban territory to protect aquifers, using the instruments provided by Article 4 of the City Statute (Law No. 10,257/2001), with special focus on the master plan, municipal zoning and the creation of protected territorial spaces. Municipal territorial planning must comply with the guidelines set forth in the hydrographic basin plans in order to contribute to integrated management of water and soil (CNRH Resolution CNRH 15/2001, Article 6).

Therefore, the municipality may impose administrative restrictions on the use of the soil, such as: *a)* adopting stricter environmental parameters for the occupation of recharge areas; *b)* prohibition of installation of activities or enterprises that are potentially polluting in recharge areas; *c)* imposing higher percentages of green areas or technologies that contribute to ensuring soil permeability; *d)* encouraging the adoption of reuse areas; or *e)* establishing conservation units in recharge areas. In that sense, CNRH Resolution 15/2001 determines that SINGREH bodies must propose mechanisms to encourage municipalities to protect aquifers and adopt practices of artificial water reuse and recharge (article 6, sole paragraph).

Article 23 of the Federal Constitution grants common administrative jurisdiction in environmental matters, which allows municipalities to take actions aimed at protecting the environment and combating pollution in any of its forms; preserving forests, fauna and flora; promoting the improvement of basic sanitation conditions; registering, monitoring and inspecting the concessions of rights to research and exploit water and mineral resources in their territories (see article 23 of the 1988 Federal Constitution). Moreover, Complementary Law (LC) 140/2011, in Article 9, part XIV, *a* and *b*, regulated the municipal competence for the environmental licensing of activities that cause or may cause environmental impact on a local level. Box 4 summarizes the main municipal powers relative to water.

Box 4 – Municipal competency relative to water

Pilar Carolina Villar
Didier Gastmans
Hermam Vargas

Municipalities have the following legal responsibilities related to water resources and related topics:

1. to provide sanitation services (1988 Federal Constitution, Article 30, part V, and Law No. 11,445/2007);
2. to promote territorial planning, through planning and control of the use, subdivision and occupation of urban land (Article 30, part VIII);
3. to include measures that encourage natural or artificial reuse and recharge in territorial planning instruments or in public service contracts (article 6, sole paragraph, of CNRH Resolution 15/2001);
4. to protect the environment and combat pollution (1988 Federal Constitution, Article 23, part VI and Complementary Law No. 140/2011);
5. to execute and enforce in the municipality the national, state and municipal policies pertaining to protection of the environment and manage the environmental resources in its competency (Complementary Law No. 140/2011, Article 9, parts I, II and III);
6. to promote the integration of programs and actions of federal, state and municipal government bodies and entities pertaining to environmental protection and management in the municipality (Complementary Law No. 140/2011, Article 9, part IV);
7. to promote the development of studies and research aimed at environmental protection and management, disseminating the results obtained (Complementary Law No. 140/2011, Article 9, part VI);
8. to organize and maintain the Municipal Environmental Information System and provide information to other entities (Complementary Law No. 140/2011, Article 9, parts VII and VIII);
9. to promote and guide environmental education and awareness (Complementary Law No. 140/2011, Article 9, part XI);
10. to promote the environmental licensing of activities or undertakings with a local environmental impact (Complementary Law No. 140/2011, Article 9, part XIV);
11. to monitor compliance with environmental standards (1988 Federal Constitution, Article 23, part VI and Complementary Law No. 140/2011, art. 17, § 3);
12. to participate in the composition of the Basin Committees (Article 39 of Law No. f9,433/1997);
13. to promote integration of local policies for basic sanitation, use, occupation and conservation of the soil and environment with national and state policies on water resources (Article 31 of Law No. 9,433/1997);
14. to formulate public policy on basic sanitation and provide sanitation services directly or by delegation, defining the entity responsible for regulation and inspection, as well as its procedures (Article 9 of Law No. 11,445/2007);
15. to prepare basic sanitation plans in a manner compatible with the basin plans (articles 9 and 19 of Law No. 11,445/2007);
16. to carry out the integrated management of solid waste generated (Article 10 of Law No. 12,305/2010);
17. to contribute jointly with the Federal Government and the states to the maintenance and organization of the National Information System on Solid Waste Management (Sinir), providing information on the waste generated (Article 12 of Law No. 12,305/2010);

18. to prepare municipal plans for the integrated management of solid waste (Article 18 of Law No. 12,305/2010);
19. to provide the information requested by the coordination of the National Health Surveillance System (Article 2 of Law No. 9,782/1999);
20. to exercise water quality surveillance in conjunction with the Health Surveillance in order to inspect the water quality in the system or collective alternative supply solution (MS Ordinance 5/2017);
21. to ensure information to the population concerning the quality of water for human consumption and health risks (MS Consolidation Ordinance 5/2017, amended by MS Ordinance 888/2021, Article 12, parts V and VI);
22. to implement the guidelines for monitoring the quality of water for human consumption defined at the national and state levels (MS Consolidation Ordinance 5/2017, amended by Ordinance 888/2021).

1.7 USER RESPONSIBILITY IN GROUNDWATER MANAGEMENT

The use of groundwater is done through wells in springs or other abstraction structures. The main users of groundwater (larger amounts) employ driven wells[5] and benefit exclusively from these waters, whose use is in their control. Groundwater users, therefore, are fundamental actors in order to achieve the objectives set forth in Law No. 9,433/1997.

Each State has its own specific requirements relative to the use of groundwater, however, in general, it is under the responsibility of users of the groundwater: a) obtaining the necessary permits to drill the well and to use the groundwater (e.g., a well drilling permit, granting the right of use or other documents that attest to an exempt or insignificant use); b) contract reputable drilling companies that follow the technical standards; c) register with the wells registry; d) operate and maintain the well in accordance with technical standards to protect it from contaminants; e) monitor the quality and quantity of water, keep pumping within the recommended technical parameters and the terms of the grant; f) store the necessary information about the well profile and operation; g) provide groundwater extraction using devices that allow water collection, level measurements, flow and volume withdrawn to carry out quantitative and qualitative monitoring; h) collect the amounts owed for the use of water in cases where the charge is implemented in the basin; and i) plug abandoned or unproductive wells as instructed by the state management agency. Moreover, users can adopt technological solutions that allow savings or optimization of the use of water resources, as well as contribute to the inspection process, by reporting or advising non-regularized landowners (VILLAR; GRANZIERA, 2020).

In the case of groundwater classified as mineral, thermal, gaseous, drinking or intended for bathing purposes, the following obligations are highlighted: a) obtain research authorization and a mining permit from the National Mining Agency (ANM); b) comply with the terms set forth in the research authorization and in the mining permit issued by ANM; c) protect, conserve and use these sources in accordance with technical requirements; d) establish mineral water protection perimeters; e) observe the requirements of the state water resources management agency for this type of enterprise relative to the need for granting, registration or drilling authorizations (Villar; Granziera, 2020, p. 129).

In addition to following state and federal regulations, users must ensure that their wells are designed, built and operated in accordance with technical regulations. The Brazilian Association of Technical Standards (ABNT) issued a series of standards relative to the design, construction and operation of wells, which must be complied with. They are: NBR 12212:1992 – Design of a deep driven well to extract groundwater; NBR 12244:2006 – Construction of a deep driven well to extract groundwater; NBR 13604:1996 – Filters and PVC casing tubes for deep driven wells – Specifications; NBR 13605:1996 – Filters and PVC casing tubes for deep driven wells – Dimensional

5. Wells are divided into two main categories: i) driven wells; and ii) excavated wells, which have different names, depending on the region of Brazil. The driven (tubular) well is a cylindrical and vertical drilling carried out by machines, coated with material in PVC with additives or in steel in the form of tubes and filters, popularly referred to as an *artesian* or *semi-artesian well*. The artesian well, however, is that driven well in which the water rises naturally, without the aid of pumps, spouting above the surface of the ground. The excavated well ("cacimba" or "amazonas") is a shallow well with a large diameter.

Determination – Test Method; NBR 13606:1996 – PVC casing tubes for deep driven wells – Determination of the flexural modulus of elasticity – Test method; NBR 13607:1996 – PVC casing tubes for deep driven wells – Verification of bending under impact; NBR 13608:1996 – PVC casing tubes for deep driven wells – Verification of the performance of the threaded joint – Test method; NBR 15495-1:2007, corrected version 2:2009 – Groundwater monitoring wells in granulated aquifers – Part 1: Design and construction.

Based on water efficiency, users can adopt technological solutions that provide savings or enhancements in the use of water resources, as well as contribute to the inspection process, by reporting or advising clandestine owners since irregular use can harm the water availability of legalized users. It is worth pointing out, moreover, the responsibility for abandoned or unproductive wells, which must be plugged, as determined by the procedure set by the state management agency, since these wells represent a potential source of contamination of the aquifer and a risk to the safety of both people and animals.

In Brazil, unfortunately, most groundwater users are irregular, therefore, they fail to comply with legal and technical obligations relative to drilling, construction and operation of wells, configuring a "private appropriation without regulation of groundwater, which corresponds to a form of usurpation of water." (VILLAR, 2016, p. 92). Therefore, owners of wells that are not part of the government license system use a good for common use by the people as if it were a private asset, without providing any contribution to society, generating socio-environmental impacts that harm society, users and the ecosystems. The use of these waters without the authorization of the state government can be classified as an administrative infraction and a criminal offense, as specified in Tables 10 and 11 of Chapter 3, regardless of the obligation to recover and/or indemnify the damage caused to the environment or to third parties.

1.8 GROUNDWATER AND MINERAL WATERS IN BRAZIL

Mineral and drinking waters are extracted from natural sources or by extracting groundwater (ASSIRATI, 2018), and are characterized by being "special groundwater" and "distinct from common water by different stages of mineralization." (QUEIROZ; PONTES, 2015, p. 15). All mineral water exists underground, however, not all groundwater is mineral water (HIRATA *et al*., 2019).

The extraction of these waters is intense, classified as the most exploited mineral resource in the Brazilian subsoil (HIRATA *et al*., 2019). In 2017, extraction for beverage composition was 21.9 billion liters, while bathing uses consumed 82.2 billion liters in the 83 existing concessions distributed across the "states of Goiás (with 92.7% of the volume used). declared), Santa Catarina (2.5%), São Paulo (2.0%), Mato Grosso do Sul (1.4%), Paraná (1.3%), Rio Grande do Sul and Pernambuco (with less than 1% each)." (ASSIRATI, 2018, p. 2).

Brazil is the 5th largest global market for bottled water (ASSIRATI, 2018) and has more than one thousand areas of mineral and drinking water mining, with 48% located in the Southeast region (QUEIROZ; PONTES, 2015). Figure 6 details the concessions for mineral or drinking water mining relative to hydrogeological domains. Some of these concessions are located in areas that have problems related to water scarcity.

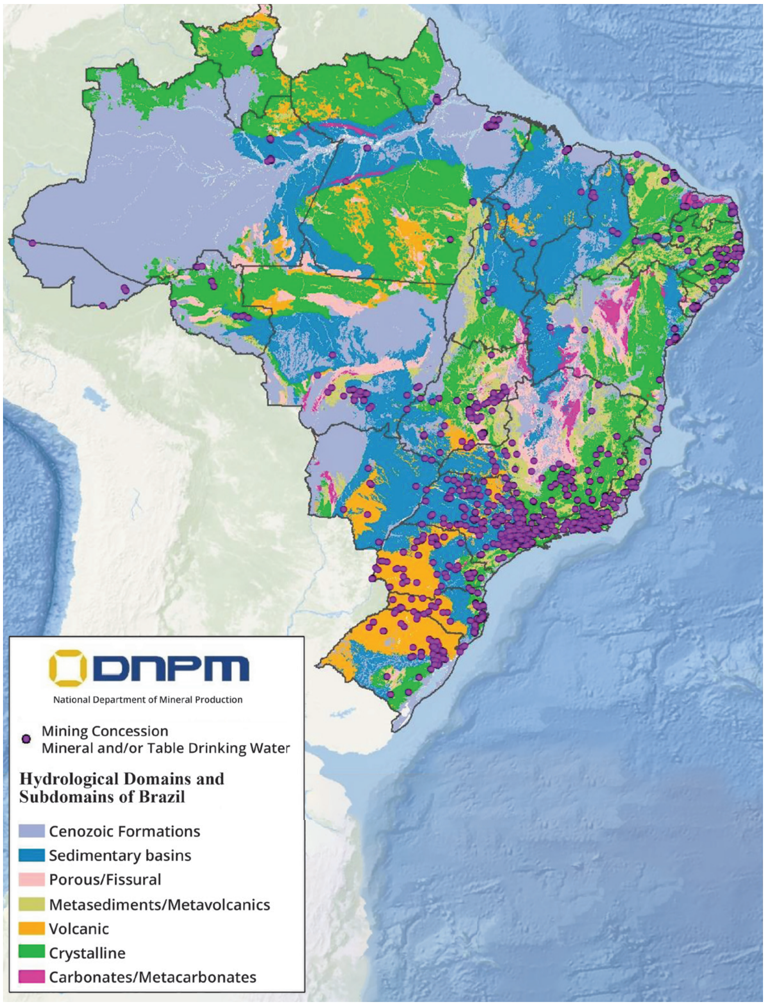

Figure 6 - Map of mineral and drinking water mining concessions in Brazil
Source: Queiroz and Pontes (2015, p. 27).

These waters are also closely linked to tourism, whether for medicinal purposes or resorts. Although there are no studies on its economic role, important tourist complexes were built based on its exploration, such as: Araxá (MG), Poços de Caldas (MG), Rio Quente (GO), Caldas Novas (GO), Olímpia (SP), Águas de Lindoia (SP), Santo Amaro da Imperatriz (SC), Gramado (RS), among other locations.

Mineral waters are defined in Article 1 of the Mineral Waters Code (Law Decree 7,841, of August 8, 1945) in the following terms:

> Mineral waters are those from natural sources or artificially abstracted sources that have chemical composition or physical or physical-chemical properties different from ordinary water, with characteristics that give them medicinal properties.

The definition of "drinking water" can be found in Article 3 of the Mineral Waters Code (Law Decree 7,841, of August 8, 1945), which describes it in the following terms:

> the water with normal composition originated from natural sources or artificially abstracted sources that only meet potability conditions for the region.

Mineral water has medicinal properties, while drinking water only meets potability requirements. Its marketing requires that the label inform the type of water, i.e., whether mineral or drinking water. Law Decree 7,841/1945 classifies mineral waters into 12 groups, according to their chemical composition (Table 2); the sources are classified according to the gases present and their temperature (Table 3).

Classification	Characterization according to chemical composition
Radifers	dissolved radioactive substances, which gives them permanent radioactivity
alkaline-bicarbonated	alkaline components equivalent to a minimum 0.200 g sodium bicarbonate ($NaHCO_3$)/ liter
Alkaline-earthy	alkaline-earthy compounds equivalent to at least 0.120 g of calcium carbonate (CaCO3)/ liter
a) alkaline-earth calcium	at least 0.048 g of Ca cation, in the form of calcium bicarbonate ($Ca(HCO_3)_2$)/liter
b) magnesium alkaline-earth	at least 0.30 g of Mg cation in the form of magnesium bicarbonate ($MgCO_3$)/liter
Sulfated	at least 0.100 g/liter of sulfate anion ($SO42^-$) combined with sodium ($Na1^+$), potassium ($K1^+$) and magnesium ($Mg2^+$) cations
Sulphurous	at least 0.001 g of the sulfur anion (S)/liter
Nitrated	a minimum 0.100 g/liter of nitrate anion ($NO31^-$) of mineral origin
Chlorinated	a minimum 0.500 g of sodium chloride (NaCl)/liter
Ferruginous	at least 0.005 g iron cation (Fe)/liter
Radioactive	radon (Rn) dissolved
a) weakly radioactive	radon content (Rn) between 5-10 units. Mache/liter, at 20º C and pressure of 760 mm Hg
b) radioactive	radon content (Rn) between 10-50 units. Mache/1 liter, at 20º C and pressure of 760 mm Hg
c) strongly radioactive	radon (Rn) content > 50 units. Mache/liter, at 20º C and pressure of 760 mm Hg
Toriatives	content of thoron (Tn) (an isotope of radon) in dissolution, equivalent in electrostatic units to at least two Mache units/liter
Carbogaseous	200 ml of dissolved free CO2, at 20°C and 760 mm Hg pressure/liter
Oligominerals	Do not reach the limits set by legislation, but they have proven medicinal properties attested by studies subject to supervision and approval of the Permanent Crenology Commission

Table 2 - Classification of mineral waters according to their chemical characteristics
Source: Brazil (Law Decree 7.841/1945).

Classification of sources regarding gases	Description
radioactive sources	
a) weakly radioactive	at least a gas flow of one liter/minute (l.p.m.) with a radon content between 5-10 units. Mache/liter of spontaneous gas, at 20º C and pressure of 760 mm Hg
b) radioactive	at least a gas flow of 1 l.p.m., with a content between 10-50 un. Mache/liter of spontaneous gas, at 20º C and pressure of 760 mm Hg
c) strongly radioactive	at least a gas flow of 1 l.p.m., with a radon content greater than 50 units. Mache/liter of spontaneous gas, at 20º C and pressure of 760 mm Hg
Thorium sources	a minimum least a gaseous flow rate of 1 1.p.m., with a thorium content at emergence equivalent in electrostatic units to two Mache units/liter.
Sulfur sources	those that have a defined release of hydrogen sulphide in the emergency.

Classification of sources according to temperature	Description
Cold springs	temperature below 25° C
Hypothermal sources	temperature between 25 and 33° C
Mesothermal sources	temperature between 33 and 36° C
Isothermal sources	temperature between 36 and 38° C
Hyperthermal sources	temperature above 38° C

Table 3 - Classification of mineral sources in terms of gases and temperature
Source: Brazil (Decree-Law No. 7.841/1945).

Although mineral and drinking waters are located underground, they have been classified as mineral resources under the Mineral Water Code. According to Article 4 of the code, the commercial use of these resources requires a regime of successive authorizations for exploitation and mining concessions, established by the Mining Code (Decree-Law No. 227, of 28 of February 1967), which reworded the Decree-Law No. 1985, of January 29, 1940.

By classifying these waters as mineral resources, their legal domain was assigned to the Federal Government, based on Article 20, Part IX, of the 1988 Federal Constitution[6]. Thus, Decree No. 9,406, of June 12, 2018, determines that it is incumbent on the Federal Government "organizing the management of mineral resources, the mineral production industry and the distribution, trade and consumption of mineral products", as well as formulating the "public policies for research, mining, processing, commercialization and use of mineral resources" (Article 3).

The authorization for research and mining, inspection and regulation of the trade in these waters is an attribution of the federal government, which is discharged through the National Mining Agency (ANM), set forth by Law No. 13,575/2017, and linked to the Ministry of Mines and Energy (MME). The ANM assumed all the attributions of the extinct National Department of Mineral Production (DNPM) (see article 32 of Law No. 13,575/2017).

The Mineral Water Code allows any groundwater to be classified as a mineral product, so long as the rules imposed by ANM and the potability requirements of the National Health Surveillance Agency (Anvisa) are met. Therefore, groundwater intended for bottling and bathing would be under the jurisdiction of the Federal Government and would be classified as *mineral resources*.

The Mining Code, on the other hand, indicated not only the possibility of deposits of mineral water existing, but also of groundwater. These two types of deposits were addressed by Article 5, repealed by Law No. 9,314, of November 14, 1996, and in Article 10, still in force, which sets the need for special regulation for both. We must bear in mind that at the time of enactment of these laws, water resources were governed by the 1934 Water Code, which classified groundwater, mostly as private, while the Federal Constitutions of the time did not even mention it. Upon the enactment of the 1988 Federal Constitution, which expressly included groundwater as a state asset, a constitutional obstacle was created for the creation of federal groundwater deposits since these were placed under the jurisdiction of the states and regulated by the legislation of water resources.

Groundwater, according to its use, may be subject to different legal treatments, even if extracted from the same aquifer and with equivalent physical-chemical characteristics. If intended for general uses, it is classified as water resources; if intended for bathing uses or for bottling mineral and drinking water, it is considered mineral resources (VILLAR; GRANZIERA, 2020).

The deposits are, however, classified as mineral water if they meet the following requirements: *a)* they are used for the special purposes of the mineral water legislation; *b)* fulfill the necessary quality requirements; and *c)* carry out the administrative procedure with ANM, requesting authorization for a research and mining concession, which are mandatory for those wishing to exploit this bathing and bottling potential (BOSON, 2002; CAUBET, 2009; QUEIROZ; PONTES, 2015). The research authorization is the moment when the applicant and ANM make the first contact, defined

6. Article 20. The following are assets of the Federal Government: IX – mineral resources, including those underground.

as "the execution of the work necessary for the defining the deposit, its evaluation and the determination of the feasibility of its economic use." (Article 2, part V, of Resolution 76/2007). On the other hand, the concession of a mining permit for mineral, thermal, aerated, drinking water or intended for bathing purposes is defined as "an administrative act through which the interested party is granted the right to industrial use of deposits of mineral, thermal, aerated, drinking water or water intended for bathing purposes." (Article 2, part V, of Resolution 76/2007).

On the other hand, if the exploration of groundwater takes place for general purposes, such as supply, irrigation or industrial use, thee waters are subject to the legal regime of state water resources, whose main formalities are: *a)* obtaining the right to use the water resources or proof of their waiver (e.g., declaration of insignificant use); *b)* registration in the user registry; and *c)* charging for the use of water, if implemented at the basin. The granting of rights to use groundwater must comply with the priorities of the water resources plans and this extraction is accounted for in the water balance of the basin.

The exploration of mineral water deposits can impact the management of water resources, interfering with the availability of groundwater and surface water, however, this type of use is not usually accounted for in the water balance of the basin. For circumventing this issue, CNRH Resolution 76/2007 established "general guidelines for the integration between the management of water resources and the management of mineral, thermal, aerated, drinking water or water intended for bathing purposes." This Resolution recognized "the need for integration and coordinated action between bodies and entities whose jurisdiction refers to water resources, mining and the environment." To facilitate this procedure, Article 3 of CNRH Resolution 76/2007 recommends that water and mineral management bodies share information and jointly define the content and technical studies of the administrative procedures involved. In Article 3, sole paragraph it is determined that the information to be shared refers, at a minimum, to:

> I. to titles of mining rights for research or mining of mineral, thermal, gaseous, drinking water or water intended for bathing purposes for inclusion in the Water Resources Information System and consideration by water resources management bodies;
>
> II. administrative acts related to the use of water resources, such as: granting the right of use, prior permits and authorizations for the construction of wells, for their inclusion in the mineral resources information system and consideration by the mineral resources management body;
>
> III. to the area object of research request for mineral, thermal, aerated water, table water or water intended for bathing purposes;
>
> IV. the area or source protection perimeter set by the mineral resources management body in order to be considered by the water resources management bodies;
>
> V. restriction and control areas established by the competent water resources management body or provided for in the water resources plans, to be considered by the mineral resources management body;
>
> VI. the quantitative and qualitative monitoring available in management bodies;
>
> VIII. those necessary for the formulation of water resources plans and the performance of hydrographic basin committees.

The mineral resources management organ must observe the authorization acts and uses registered with the water resources management organ at the time of analysis of the "application for authorization to research mineral, thermal, aerated, drinking water or water intended for bathing purposes." (Article 6). The water resources management agency, in turn, when analyzing the application for granting the right to use water resources must observe "the information produced by research requirements, research permits and mining ordinances for mineral, thermal, gaseous, drinking water or water intended for bathing purposes." (Article 7).

Despite representing a positive step, its operationalization faces limitations in promoting the coordination of the federal management of mineral waters with the state management of groundwater (SERRA, 2009; SCALON, 2011; VILLAR; GRANZIERA, 2020). CNRH Resolution 76/2007 determines that the information provided by water resources management organs be observed; however, the information is not binding relative to ANM's decision, which represents a problem, as explained by Villar and Granziera (2020, p. 115):

> Mineral, thermal, aerated, drinking water and water intended for bathing purposes are mineral resources, however, they are also water resources that integrate the water balance of the basin and constitute one of the multiple uses of water. In fact, these waters have a special legal nature, since they are part of the field of operation of two legal systems, mineral and water resources.

A management model that could improve this integration process would condition users of mineral, thermal, aerated, drinking waters and water intended for bathing purposes, both in terms of mining and water resources standards since they have complementary natures (FERREIRA JÚNIOR , 2007). Based on the state jurisdiction over groundwater and concurrent and common competency, states can establish rules that required the need to grant the right to use groundwater classified as mineral, thermal, gaseous, drinking water and water intended for bathing purposes. (FERREIRA JUNIOR, 2007). Furthermore, they can subject their extraction to a charge, something that is made, for example, in the state of Ceará. These requirements could be justified pursuant to Article 12, Part II of Law No. 9,433/1997, which conditions all "extraction of water from underground aquifers" 0to the granting of the right of use. The law uses the generic term aquifer water and not groundwater resources.

CNRH Resolution 29/2002, in Article 2, Part I, determines that granting of the right to use groundwater is a requirement for mining activities. Article 9, however, considers that what is contained in the aforementioned resolution does not apply to mining governed by the Mineral Waters Code. The granting of the right of use serves a dual purpose: a) guarantee access to the resource; and b) control the use of water to guarantee the water balance of the basin. Consequently, the mining permit guarantees the exploiter of the deposit the right of access to the mineral resource (mineral, thermal, aerated water, drinking water or water destined for bathing purposes), while the granting of the right to use the water resources guarantees that this exploitation is subject to socio-environmental control (FERREIRA JÚNIOR, 2007). Therefore, the inclusion of mineral waters in the water resources system would contribute to subjecting these waters to the principles of water rights, such as their multiple use, helping to avoid conflicts, such as those that occurred between private companies and the municipalities of the "Water Circuit", in Minas Gerais.

As for the possibility provided by CNRH Resolution 76/2007 having sought to build a basis for integration between the legal regime for mineral water and water resources, moving even further is necessary. The Mineral Water Code must be interpreted in light of the 1988 Constitutional Regime and harmonized with Law No. 9,433/97. And, although the waters covered by the Mineral Water Code are classified as a mineral resource, they are water extracted from aquifers and, therefore, must be submitted to the concession-granting process.

In Brazil, although the topic has only been superficially explored, there are conflicts concerning the uses of groundwater and mineral waters, as is the case of Caldas Novas and Rio Quente in the state of Goiás (ANDRADA; ALMEIDA, 2012) or even in the hydromineral resorts in the Water Circuit (Circuito das Águas), in Minas Gerais (Caxambu, São Lourenço, Cambuquira and Lambari) (BORGES *et al.*, 2006). The requirement for a state grant of the right to use water resources for being issued a mining permit would contribute to a more efficient management of water (VILLAR; GRANZIERA, 2020).

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The surging of the karst aquifer in the Pacuí Basin
in the Montes Claros and Coração de Jesus border (MG)
Photo: Eduardo Gomes de Assis / ANA Database

CHAPTER 2

GROUNDWATER IN THE HYDRO-SOCIAL CYCLE

2.1 THE HYDROLOGICAL CYCLE AND GROUNDWATER

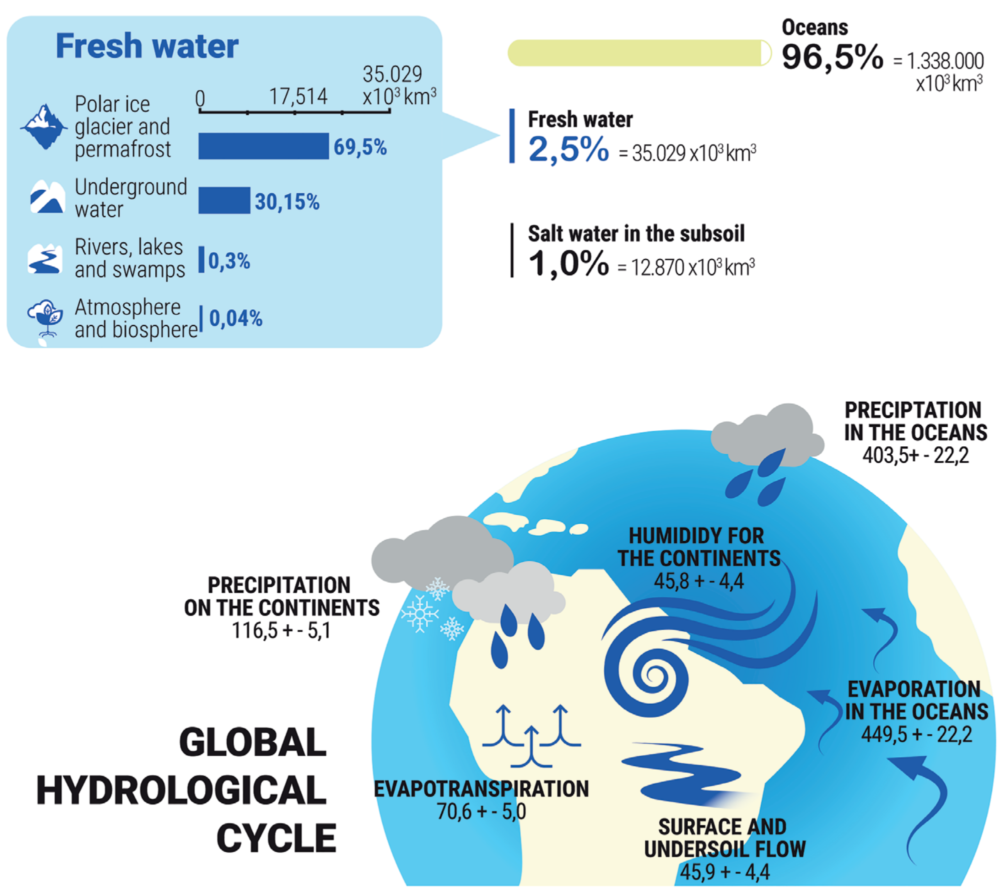
The water cycle, scientifically known as the *hydrological cycle*, is a simplified way of describing the movements and transformations undergone by water on planet Earth. Water is always in motion, circulating on surfaces (glaciers, icebergs, rivers, lakes, seas etc.); through the atmosphere (clouds); or underground (aquifers, aquitards), as shown in Video 1. This cyclical movement is related to changes in energy between the atmosphere, the ocean and continents, sustaining the climate and much of its natural variability (OKI; ENTEKHABI; HARROLD, 2004; COCKELL *et al.*, 2011). Sunlight (solar radiation) and the heat from the Earth's interior (emitted by radioactive nuclear reactions) are the energy sources that promote the transformation of water states (liquid, solid and gaseous) and, consequently, its continuous movement through the Planet.

Video 1 – Water Cycle (hydrological cycle)

Production: ANA

Available at: https://www.youtube.com/watch?v=vW5-xrV3Bq4.

The quantity of water on the planet is constant, however, its distribution in nature occurs unevenly and cyclically, undergoing physical and chemical changes over space and time, and it can be found in liquid states (seas, rivers, lakes, etc.) and aquifers), solid (snow, hail and glaciers) and gas (atmosphere, fumaroles and volcanic clouds) (COCKELL *et al.*, 2011). The oceans are the largest reservoirs of water on the planet, however, the largest volumes of fresh water are found in glaciers and aquifers. Figure 7 shows the distribution of these volumes and the annual average of flows in the global hydrological cycle.



Annual average of flows in the global hydrological cycle and associated uncertainties, in years 2000 to 2010 Source: Rodell et.al. (2015)

Figure 7 – Water volume and annual average of flows in the hydrological cycle

Source: Shiklomanov and Rodda (2003); Rodell *et al.* (2015), adapted by Dora Atman.

The movement of water on the planet was recorded in antiquity, however, it was only in the 17th and 18th centuries that the importance of seawater evaporation as a source of moisture on the continents and supply of freshwater reservoirs was identified (MANOEL FILHO, 2008). This moisture is distributed in the form of rainfall and snow, contributing to the flow of rivers and volumes stored in lakes and aquifers.

The functioning of the hydrological cycle is influenced by several natural factors, such as: *a)* variations in the incidence of solar radiation, controlled by the internal dynamics of the Sun and by variations in the position and trajectory of the earth in the solar system; *b)* changes in the composition of the atmosphere and ocean water; *c)* winds and ocean currents; *d)* volcanism; *e)* the type, pattern and density of vegetation cover; *f)* variations in the spatial distribution and number of living beings; and *g)* soil and subsoil types (COCKELL *et al*., 2011; GROTZINGER; JORDAN, 2013). Figure 8 presents the main natural phenomena that regulate the water transfer processes in the hydrological cycle.

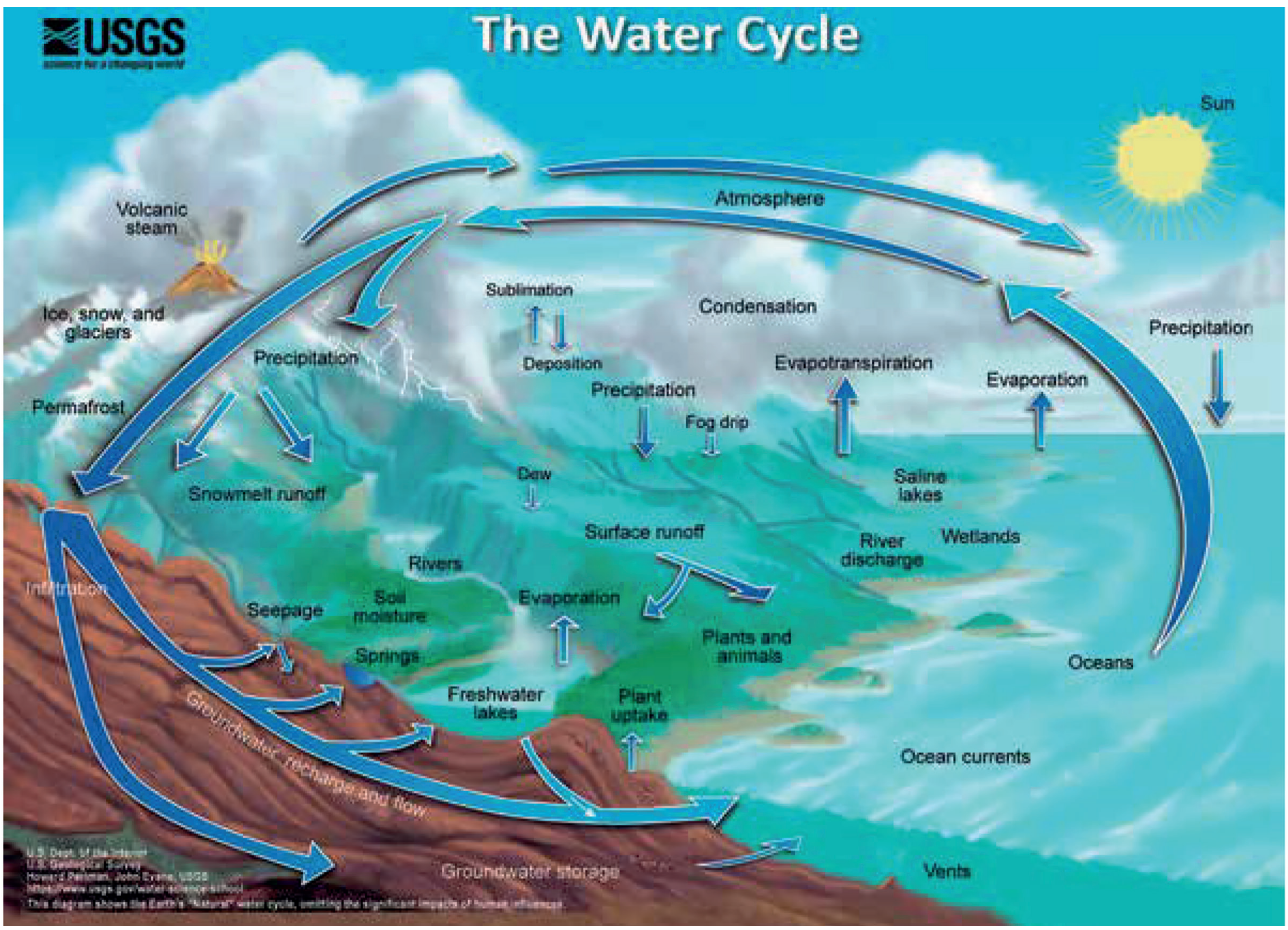


Figure 8 – Water cycle
Source: USGS (2017).

Among the processes that regulate water availability, the following stand out: *i)* evaporation; *ii)* evapotranspiration; *iii)* precipitation; *iv)* surface outflow; *v)* base flow; and *vi)* infiltration. These processes form the drainages and provide recharge, discharge and percolation. The definitions of each term are described below:

i. **Evaporation**: Evaporation is a type of vaporization that occurs on the surface of a liquid as it passes into the gaseous (vapor) state. On Earth, evaporation is the physical phenomenon of water and energy transfer induced through the flow of latent heat from water surfaces to the atmosphere. The evaporation rate depends on the availability of energy, the mass/energy transfer mechanism, the dimensions of the water surfaces and the volumes of reservoirs and lakes. The main meteorological factors involved in this process are: solar radiation, air and water temperature, wind speed, air humidity, atmospheric pressure, and the characteristics of the surrounding environment (OKI; ENTEKHABI; HARROLD, 2004).

ii. **Evapotranspiration:** evapotranspiration is the removal of water from the surface to the atmosphere by the combination of two processes: evaporation plus plant transpiration. Plant transpiration is responsible for the exit of water from the interior of the plant through openings in the plant epidermis, ensuring gas exchange between the plant and the atmosphere. Naturally, plants lose water mainly through the stomata, which are small openings in the leaves, responsible for regulating the output of substances (gases and water vapor) produced in the leaves. Almost all the water absorbed from the soil by plants is lost through transpiration, and only a small part is converted to plant tissues.

Atmospheric Rivers and the Amazon Rainforest

In Brazil's case, the evapotranspiration of the Amazon Forest impacts the water availability of other basins and Brazilian regions. The Amazon Forest releases "20 billion tons of water per day", exceeding the flow that the Amazon River dumps into the sea (17 billion tons), directly influencing the climate (NOBRE, 2014, p. 13). The influence of the forest on climate can be explained by the biotic pump theory (Video 2). According to this theory, the "transpiration and condensation processes mediated and manipulated by trees" modify "atmospheric pressure and dynamics", generating "greater moisture supply from the ocean to the interior of forested continents" (NOBRE, 2014, p. 13). As the Amazon rainforest evaporates as much or more water than the contiguous ocean surface, it is able to suck "from the sea to the land the currents of air loaded with moisture [...], which will bring rains to the forest-covered area." Deforestatinon reduces evapotranspiration and, consequently, condensation, which reverses the flows of moisture that will go from land to sea, creating a desert (NOBRE, 2014, p. 13).

The humidity generated by the forest forms air masses loaded with water vapor, which are carried by the winds from the Amazon Basin to the Central-West, Southeast and South of Brazil, contributing to the formation of rainfall in these regions. These moist air masses are called flying rivers, as they can be equated with *true atmospheric waterways* (Video 3).

Vídeo 2 – Illustrative scheme of the Biotic Pump
https://www.youtube.com/watch?v=0CS9y8JIH2Y
Produced by: Rios Voadores

Video 3 – Atmospheric Rivers Documentary
https://www.youtube.com/watch?v=0Mwo5PVB0ro
Produced by: Bettina Ehrhardt in collaboration with Thomas Hagenbrock and Michael Schucht

iii. **Precipitation**: is the process of condensation of atmospheric water vapor that agglutinates and precipitates or falls on the earth's surface. Precipitation occurs due to the joint action of two processes: cooling and addition of moisture, causing part of the atmosphere to be saturated with water vapor (reaching 100% humidity). Water added to the Earth's surface from the atmosphere occurs in liquid (rain) or solid (snow or ice) form. Precipitation varies greatly across geographic space and time. Rain tends to run off or seep into the ground. Snow can accumulate on glaciers and ice caps, where it can be frozen for thousands of years or melt and outflow in the form of streams and rivers, or infiltrating the ground. The melting of the polar ice caps increases the water level of the oceans, while the accelerated melting of glaciers can compromise the flow of water courses, important for the supply to populations.

iv. **Surface outflow**: it is defined by the flow of water that occurs on the surface of the soil when it is saturated with moisture or when it is impermeable. These waters, usually originated from precipitation can form successive floods, drainages (streams, creeks, rivers), lakes, etc. Its outflow occurs in a diffuse or concentrated way, and it can form ephemeral flows along the valleys, depending on the intensity of the rains and the characteristics of the surfaces (such as slope, topography and type of vegetation cover).

    Surface drainage: represents the courses and flows of surface water that form streams, streams, creeks and rivers. They may be *intermittent* (when the water flows in their courses during the rainy season and dries up with the drought), or *perennial* (when the water flow remains throughout the hydrological year and does not dry up). *Intermittent* watercourses are formed by surface and subsurface outflow of rainwater; *perennial* courses also receive groundwater flows from aquifers. Perennial underground flows keep springs and their water courses constant, in addition to contributing directly to the increase in flow downstream of the springs through surges along the course itself.

v. **Infiltration**: is the passage of water from the surface into the soil. The infiltration capacity of the soil depends on its topography, vegetation cover, degree of moisture, physical-chemical properties and the intensity and duration of rainfall. Infiltration occurs due to several factors, including: gravity, capillary forces, adsorption and osmosis. Infiltration decreases as the soil moisture content in the surface layer increases. If the rate of precipitation exceeds the rate of infiltration, surface outflow is favored, so that each soil has a potential infiltration limit.

    Percolation: process by which water moves vertically and downwards along the unsaturated zone (vadose or aeration zone) after infiltrating soils and rocks. The *unsaturated zone* is the portion of the subsurface where the spaces between soil and rock particles are filled with water and air (soil moisture). During percolation, the process of natural filtration of water through the soil and its enrichment with mineral elements also occurs. The percolation of water in the soil occurs when its infiltrated volume is sufficient to force the downward displacement of the water.

    Recharge: when the water enters the subsurface, it is distributed in the voids in two main zones: the non-saturated zone and the saturated zone. Recharge occurs when water that percolates into the unsaturated zone descends and reaches the aquifer surface or phreatic surface (water saturated zone). The water can come from the infiltration of rainwater, melting water or even from rivers and lakes. The areas of the hydrographic basin that allow water infiltration constitute recharge areas. In the saturated zone, the voids are completely filled with water. The threshold between these two zones is called the *water table* or *groundwater level*. At the base of the unsaturated zone is a wet region called the *capillary fringe*. This region has variable thickness and represents a transition from the unsaturated zone to the saturated zone, and occurs due to capillary forces that impel water from the aquifer to the upper void spaces of neighboring soils. Recharge, therefore, occurs when water seeping into the unsaturated zone reaches the top of the aquifer (water-saturated zone).

Infiltration, *percolation* and *recharge* are portions of water that are difficult to estimate. Infiltration tends to be greater than the percolated volume, which, in turn, is greater than the recharge volume. The reason for that is that some of the water is trapped or absorbed on soil or rock particles along the way, and some is evaporated in the process. If the saturated zone is very deep and precipitation or infiltration rates are low, infiltration and percolation can occur along the surface layers, but recharge will be zero. Aquifers, therefore, are not supplied homogeneously, with areas that are more favorable for recharge, and changes in land use can alter it. Thus, it is important that the management of water resources takes this characteristic into account.

Discharge: this is the process of leaving water from aquifers, where groundwater emerges and flows on the surface (source locations) and, mainly, along water courses, such as rivers or lakes and oceans. Underground discharge is responsible for the perennialization of rivers. The discharge of discharges related to aquifers that store large volumes of water tends to be high and of a perennial character and little affected by long drought periods. In karst-type aquifers, where groundwater flow occurs concentrated in conduits and caves, springs are often called "water eyes" as the impression is that a river appears on the surface. In shallow aquifers of small dimensions, such as aquifers on slopes of hills and mountains, however, groundwater discharges have low flows and, many of them, can only work during the rainy season (intermittent) or for a few days after the rain events (ephemeral). The Forest Code (Law No. 12.651/2012) classifies two types of aquifer discharges as *permanent protection areas*: springs[1] and *water holes*[2]. It is interesting to note that laws address directly direct and necessary protection to the sources of a river and water points, however, they are silent on the base flow from the aquifers, which is responsible for maintaining the continuity of the rivers, thanks to the discharge of large volumes of water.

vi. **Base flow or groundwater flow**: is the movement of water along the saturated zone. Water in soil and saturated rocks flows into voids such as pores, open fractures, and other voids left by the dissolution of minerals. These spaces need to be interconnected so that water can flow. The force of gravity and the pressure of the water column generate the movement of groundwater. Its flow always occurs in the direction of the highest to the lowest hydraulic head, which is the sum of the altimetric elevation load plus the pressure head of the water column at a given point in the underground reservoir. Hydraulic load is measured through monitoring wells distributed along the underground reservoirs, together with a knowledge of the hydrogeological system, which allows defining the direction of the flow.

Contrary to popular knowledge, in most cases groundwater does not form underground rivers or streams of water[3], but fills pores and fractures in way to the way a sponge absorbs water, flowing slowly. These waters represent the hidden dimension of the hydrological cycle and are underestimated in the hydrosocial cycle. In addition to their role in the hydrological cycle, these waters influence geological aspects, such as slope stability, land subsidence, induction of tremors and earthquakes, migration and accumulation of oil, as well as ecosystem aspects related to the maintenance of wetlands (swamps, mangroves, wetlands) and surface water courses (MANOEL FILHO, 2008).

1. On the occasion of the judgment of ADIN [Direct Unconstitutionality Action] No. 4,903, the Supreme Court (STF) recognized that intermittent springs must also be considered Permanent Protection Areas (APP).
2. *Water Holes ["Water Eye" in Portuguese]:* popular name with no technical-scientific link that in general understanding is synonymous with *spring*. It is believed that its origin comes from the circular and punctual shape of some springs and the consequent visual aspect of the water flow that resembles an eye, a result of the water pressure that appears forming a rising bubble. This type of spring is visually different from others that are dispersed in wetlands and are not punctually visible. In practice, this denomination is not related to the intermittent nature of the flows of the springs, but to the visual aspects that characterize some point springs.
3. Exceptionally, it is possible to find some caves, lava and ice ducts or horizontal springs that resemble water currents.

2.1.1 The hydrosocial cycle

Human beings are active agents in the processes of the hydrological cycle, interfering in order to increase or decrease these natural flows, whether in the territory or outside it (LINTON; BUDDS, 2014). The form of water circulation is also influenced by the institutions, infrastructure and social practices of politicians, citizens, entrepreneurs, users and consumers. This idea has strengthened the concept of the hydrosocial cycle, which politicizes the biophysical conception of the hydrological cycle processes. Water does not just move through rain, rock pores and air masses, but through a complex network of water mains, pipes, wells, treatment plants, cisterns, irrigation pivots, garden hoses, leaks, legal rights, quality standards, transport networks, markets and consumers (BUDDS; LINTON; McDONNELL, 2014).

Water availability is a natural, but also social, fact that requires the following analyses: *a)* who uses water and how?; *b)* who has access or control over the resource?; *c)* how does the use of water influence power relations in the countryside and in the city?; *d)* how does its presence or absence determine the conformation of a society?; *e)* how do financial flows interfere with water availability, regardless of the hydrological cycle?; *f)* how does society interfere with the elements that make up the hydrological cycle?; *g)* which uses and which actors benefit from hydraulic infrastructures? (LINTON; BUDDS, 2014).

Human action and the climate change phenomenon change the natural dynamics of the elements that compose the hydrological cycle, directly interfering in the way water circulates through the territory, changing the patterns of water availability and its distribution through the territory and through time. Areas that had good water availability and regular rainfall may face drought or flood phenomena, the economic, social and environmental consequences of which are unknown. Groundwater is part of this hydrosocial cycle, and it is impacted by extractions, leaks from water and sewage networks, excess irrigation, waterproofing of cities, changes in land use and loss of vegetation cover, as well as the impacts caused by the variability and climate change. If determining the natural trajectories of groundwater is a complex task in and of itself, from the hydrosocial perspective it becomes even more challenging given the limited geological and hydrological studies and the impacts of human activities on the hydrological cycle. Moreover, we are facing a lack of information concerning its use, which, in the Brazilian case, is mostly unknown and underestimated.

2.2 WHAT ARE AQUIFERS AND HOW DO THEY WORK

In hydrogeology[4], geological formations can be classified according to their ability to store and transmit water into three categories: *aquifers*, *aquitards* or *aquicludes*:

a) the *aquifer* is a "geological formation capable of accumulating and transmitting water through its pores, fissures or spaces resulting from the dissolution and transport of rocky materials." (CNRH Resolution 202/2018, Article 2, Part I). In practice, only those geological units capable of producing water through wells, under economically viable conditions, are considered to be aquifers;

b) aquicludes are geological formations that contain water in their interior, however, they do not have any transmission capacity;

c) aquitards are semi-permeable formations that may contain water, but their transmission occurs very slowly, rendering economic exploitation unfeasible.

Aquicludes and aquitards can be related to aquifers insofar as they delimit their top and/or base, however, they have little or no ability to transfer water, and are considered impermeable or semi-permeable. The classification of formations in one of these categories is done through the evaluation of the rock or sediment's ability to transmit water, represented by the hydraulic conductivity parameter (or proportionality coefficient of Darcy's Law[5]). The hydraulic conductivity of aquifers, i.e., the speed of their water flow is equal or higher than 10^{-4} cm/s (or 8.64 cm/day).

The distribution of aquifers in the territory depends on geological and geomorphological processes occurring on the continent. Aquifers can be classified according to their rock types and the pressure to which they are subjected. These characteristics influence

4. Hydrogeology: the field of geology that deals with the distribution and movement of groundwater in the soils and rocks of the earth's crust.

5 Darcy's Law is a phenomenological constitutive equation that describes the flow of a fluid through a porous medium (DARCY, 1856). Cabral (2008, p. 77) explains this equation in didactic terms.

water storage capacity, flow velocity, recharge rates and vulnerability to contamination. Understanding the distribution of rock types in the territory and the way in which their characteristics influence the flow of groundwater helps to distinguish the main aquifers in the country, i.e., those with greater water storage and transmission capacities. The relevance of the rock as an aquifer is defined through its physical-chemical properties, among which we can mention porosity, permeability (or hydraulic conductivity), conditions of occurrence (extension, thickness and structure), technical possibility and economic capture.

Classification of aquifers, according to rock types

Brazil has an ancient geological structure that was exposed to erosion agents during a long geological time (MENTE, 2008). Its rocks generally form the impermeable base (basement) that supports all types of aquifers (MENTE, 2008). These rocks underwent several processes of deformation, folding, and fracturing, among others, that induced the formation of free spaces (fractures) and allow the percolation and storage of water, enabling the formation of fissure or fractured aquifers. This basement sometimes suffers erosion, forming low areas, known for their topographically depressed format, such as basins. Over geological time, these rocks were buried by sediment packages, forming sedimentary basins. In sediments, water percolates into the spaces between the grains (intergranular pores) that were formed along with the deposition of the sedimentary package, giving rise to intergranular or sedimentary aquifers. Finally, in marine basins, by chemical precipitation, carbonate rocks (rich in carbonates-CO3) were formed, also called karst rocks. In the latter case, water percolates through the rock through the spaces of fractures, cracks or cavities generated by chemical dissolution caused by the flows of rainwater, giving rise to karst aquifers.

Therefore, according to the origin of the rock or sediment, as well as its degree of consolidation, fracturing or dissolution, aquifers can be classified into three simplified categories:

a) fissure-form or fractured (Box 5);

b) granular or sedimentary (Box 6); and

c) karsts (Box 7).

According to ANA (2013), aquifers and sedimentary aquifer systems outcrop in 53.8% of the national territory, fractured in 44.7% and karst in only 1.5% (Figure 9).

Figure 9 – Distribution of fractured, sedimentary and karst aquifers in Brazil
Source: Diniz *et al*. (2014, p. 25).

Aquifers do not occur homogeneously or uniformly in the Brazilian territory. The composition of rocks or sedimentary packages, as well as exposure to different climates, causes each aquifer to present specific conditions of infiltration, percolation, flows, storage and water discharges, impacting both water production and quality.

Box 5 – Fractured aquifers

Amélia Fernandes

Typical fractured aquifers are made up of intrusive crystalline, metamorphic and igneous rocks, which are geological materials with low primary permeability. In this type of material, groundwater is stored and transmitted through rock fractures, i.e., from its secondary porosity. In many volcanic rocks, such as basalts, the primary porosity can be filled and the groundwater flow occurs predominantly through secondary porosity, i.e., through voids delimited by fracture faces (DOMENICO; SCHWARZ, 1990; FREEZE; CHERRY)., 1979; SINGHAL; GUPTA, 2010). In sedimentary rocks of low primary permeability, such as shales, siltstones, mudstones, some limestones and cemented sandstones, groundwater flow through fractures can also be important.

Overall, rocks have fractures of various orientations, which connect to each other, forming a system or network (Figure 10). Usually, the porosity in these aquifers is low, but the groundwater flow velocity can be high, causing only a small percentage of fractures to be made up of good ducts (Figure 11).

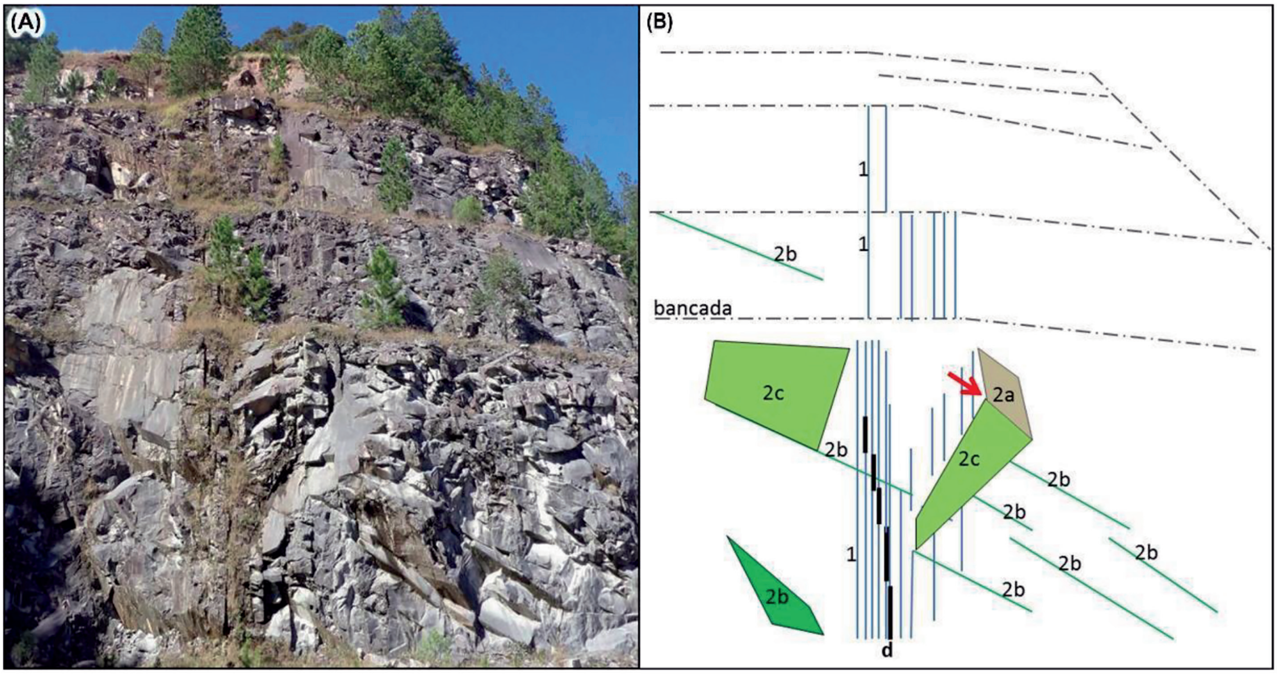


Figure 10 – (A) Granite quarry wall (Itapecerica da Serra, SP), with a total height of approximately 90 m, with several plateaus; (B) Schematic of the wall in (A) with representation of vertical fractures (1, 2a) and inclined fractures (2b, 2c)

Source: Fernandes *et al*. (2016, p. 80).

In the lower half of the rocky wall there are horizontal fractures (shaded lines) along which water flows and vegetation grows, showing that they are permeable and constitute good conduits.

Figure 11 – Basalt quarry wall in Ribeirão Preto (SP), approximately 50 meters-high.

Source: Fernandes *et al*. (2016, p. 80).

Fracture openings are predominantly very small and often vary between 0.01 and 0.05 mm. These openings, in a medium with one fracture/meter provide hydraulic conductivity values (K) between ~ 10^{-8} and ~ 10^{-6} m/s. The K values for igneous and fractured metamorphic rocks vary in five orders of magnitude, i.e., from 10^{-8} to 10^{-4} m/s (Figure 11) (see, for example, ROULEAU *et al*., 1996; SHAPIRO *et al*., 2007; PARKER *et al*., 2018). Unfractured crystalline rocks have extremely low K values and are comparable to shale and clay (FREEZE; CHERRY, 1979).

Fractured aquifers are important for supplying populations in many regions. The sustainable exploration thereof requires studies on production potential, as well as cases of contamination of these aquifers by human activities, which need to be assessed for protecting public health. Understanding the properties of the fracture network is critical to assess and predict the transport of contaminants through the fractured rock aquifer and prevent the loss of water resources.

Another great motivation to study these aquifers is the increase in water demand, mainly for public supply and for industrial and agricultural activities. The São Paulo Metropolitan Region (RMSP) and the Northeast of Brazil are examples of regions whose water demands significantly depend on typical fractured aquifers, consisting of metamorphic and igneous crystalline rocks. Groundwater flow can cause instabilities, so studies of fractured aquifers, among other applications, are necessary for carrying out engineering works and for assessing the risk of natural disasters (for example, landslides).

Box 6 – Sedimentary aquifers

Ingo Wahnfried

Sedimentary aquifers are composed of sediments or sedimentary rocks, whose deposits emerge in 70% of the earth's surface (WILKINSON *et al.*, 2009). The predominant porosity of this class of geological units is primary, generated when sediments are deposited. This causes the porosity to be distributed throughout its volume, facilitating the extraction of stored water. The total porosity of unconsolidated sediments varies between 25 and 40% for gravel; 25 and 50% for sand; and 35 and 50% for silt (FREEZE; CHERRY, 1979), which shows the tendency of porosity to decrease with increasing granulometry (sediment size). In sedimentary rocks, porosity is always lower than that of material with the same unconsolidated granulometry, mainly due to the compaction process. Sandstones have porosity of 5 to 30%; 0 to 20% non-karstified carbonates; and shales from 0 to 10% (KRUSEMAN; RIDDER, 1994). Porosity is also influenced by the degree of grain selection, its sphericity and the occurrence of cementation. Pores in very small dimensions do not allow water to escape by gravity. The specific capacity values, due to this characteristic, are always lower than the total porosity values, with values ranging between 1% for clays and 30% for coarse sands (KRUSEMAN; RIDDER, 1994).

In addition to porosity, parameters such as hydraulic conductivity and storage coefficient, heterogeneity and anisotropy are defined by the characteristics of the sediments or sedimentary rocks that form the aquifer units. Hydraulic conductivity depends on the connectivity between the pores and, therefore, does not have a mandatory correlation with their volume. Therefore, the great diversity of types of deposits and sedimentary rocks causes their hydraulic conductivity to vary by 11 orders of magnitude. Freeze and Cherry (1979) indicate approximate hydraulic conductivity values varying between 10^{-11} m/s for marine clay, and 10^{-1} m/s for gravel, whereas for shale, the minimum conductivity is 10^{-12} m/s and the maximum is 10^{-5} m/s for non-karstified carbonates.

The most common anisotropy in sedimentary aquifers is caused by the granulometric variation between different strata. The horizontal hydraulic conductivity can be two to ten times greater than the vertical in alluvial formations with horizontal stratification, but this factor can reach 100 when there is an intercalation of clay layers (KRUSEMAN; RIDDER, 1994).

The flow distributed throughout the entire volume of the sedimentary aquifer causes the actual water velocity in pores and gorges to be small compared to karst and fractured aquifers. Particulate matter suspended in water is fully retained in this context, even in events of intensive recharge, such as storms.

Generally, the water quality is good. The great diversity in the mineralogy of the grains that compose the sedimentary aquifers influences hydrochemistry. The presence of clay minerals facilitates the exchange of cations and anions, which can either favor the retention of contaminants or slowly release cations from connate water, stagnant in isolated pores, by diffusion (POETER *et al.*, 2020). The most representative exceptions are arsenic and fluoride contamination, whose occurrences are associated with specific locations where there is presence of minerals that have these elements in their composition, and the climatic, geomorphological and hydrochemical contexts necessary for their mobilization (AMINI *et al.*, 2008; RAVENSCROFT; BRAMMER; RICHARDS, 2009).

In the Amazon, despite the abundance of surface water, two-thirds of municipal population centers are supplied totally or partially by groundwater (WAHNFRIED; SOARES, 2012; ANA, 2021), with a predominance in the use of sedimentary aquifers (see Figures 12 and 13). ANA (2015) conducted a study in the region that showed the existence of 14 sedimentary lithostratigraphic units with hydraulic continuity and varied hydrogeological potential. These units form the *Amazonian Aquifer System*, which, in the Brazilian territory, occupies an area of approximate two million km^2 (Video 4).

Video 4 – Amazon Aquifer

https://www.youtube.com/watch?v=ro-5gvwiIhQ

Produced by: ANA

One of these lithostratigraphic units of the Amazon Aquifer System is the Alter do Chão Aquifer (AAC) – an important source of supply for cities such as Manaus and Santarém. The AAC is constituted by intercalations of sandstones, claystones, siltstones and, subordinately, conglomerates. Its average thickness varies between 200 and 400 m, reaching 1,266 m (ANA, 2015), and its outcropping area is of 312,574 km^2 (ANA, 2005). The AAC is predominantly free, with semi-contained to contained portions, sometimes in the same region.

Figure 12 – Groundwater returning to the surface in the Novo Remanso Formation, Manaus (AM). This spring contributes to the base flow of a tributary of the Tarumã-Açu river.

Photo by Ingo Wahnfried.

Figure 13 – Well in a school in the community of Retiro, Municipality of Humaitá (AM), on the left bank of the Madeira river. The marks on the wall indicate the level reached by the river in 2014. The well explores quaternary sedimentary deposits.
Photo by Ingo Wahnfried.

Box 7 – Karst aquifers

Paulo Galvão

Karst aquifers are those composed of carbonate rocks that have been karstified, generating networks of conduits/cavities through which water is transmitted and stored (Figure 14). Its origin is the result of the dissolution process of soluble rocks, such as limestone, dolomite, quartzite, sandstone with carbonate cementation etc., known as *karstification*. This phenomenon requires meeting at least the following conditions: (*1*) rock with chemical ability to dissolve; (*2*) acidic water (solvent), resulting from the contact of rainwater with carbon dioxide (CO2) in the atmosphere or in the soil, capturing CO2 from organic matter; (*3*) hydraulic gradient (differences in hydraulic loads that allow the flow of solvent; and (*4*) discontinuities in the rock (gaps/fracture, bending, bedding plane or stratification) that allow the flow of water.

For example, water (H2O) infiltrates the soil, captures carbon dioxide molecules (CO2), becomes acidic, generating carbonic acid (H2CO3) which, in contact with limestone (CaCO3), reacts to form calcium bicarbonate (HCO-3), the product of dissolution. The whole process can be summarized by the following equation (WHITE, 2003): 2 H2O + CaCO3 + CO2 ↔ H2O + Ca^{2+} + 2 HCO-3. Over time, the discontinuities in the rock widen and, progressively, a hierarchical structure develops, such as a system or network of karst conduits. If it is in a water-saturated zone, this karst structure will be considered a karstic aquifer. The underground flow, therefore, determines the hydrogeological structure of the karst environment which, in turn, creates a feedback effect, modifying the conditions of that flow. These conditions result in aquifers which can take unexpected underground flow paths and drainage points that are often not predicted based on the surface topographic and hydrological scenario (GOLDSCHEIDER; DREW, 2007).

Consequently, the famous karst geomorphological landscapes are generated on the surface, characterized by occurrences of sinkholes (result of subsidence of soils/rocks on or near the surface due to karst zones below), uvalas (when two sinkholes/sinks advance sufficiently and come together), caves or grottos (result of speleogenesis, forming a succession of networks of conduits that evolves over time, with dimensions that allow access to human beings) (Figure 15), *dead* drainages (when the drainage is abruptly diverted to a subsurface conduit system) and karst springs (discharge), where groundwater emerges from the local karst system to feed rivers and streams (PALMER, 2007).

Regarding karst recharge, there are two categories: (1) autogenic recharge, which occurs when the karst area itself recharges, via direct water entry into sinkholes, sinkholes or caves; and (2) allogeneic recharge, which occurs in adjacent non-karst areas and, indirectly, recharges the aquifer, as, for example, when water infiltrates the sandstone layer overlying the karst. These characteristics may reflect the degree of intrinsic vulnerability of the aquifer to surface contamination.

Karstification also results in different conditions of permeability and hydraulic conductivity within the aquifer, depending on the shape, quantity, distribution and interconnectivity of the voids or karst structures. It is in this scenario that the triple permeability model is discussed (WHITE, 2003), which consists of: (*1*) rock matrix permeability (primary porosity, common in Mesozoic reefs and aeolian limestones); (*2*) fracture permeability (secondary porosity, in incipient marble karsts); and (*3*) conduit permeability (tertiary porosity, karst itself). Most karst aquifers, however, present at least double permeability (matrix-fracture, matrix-conduct or fracture-conduct), or triple permeability (matrix-fracture-conduct), a condition seen in most large caves and aquifers in the world (FORD; WILLIAMS, 2007). Due to these characteristics, groundwater velocity can vary by many orders of magnitude, even resulting in turbulent flows. In other words, depending on the development of the pipeline network, the height of the hydraulic gradient and the degree of confinement of the aquifer, the water flow may even resemble that of a small river or stream, reaching speeds of up to a few kilometers per day, as seen in Dinaric karst regions, in Herzegovina (5,184 m/day) (GOLDSCHEIDER; DREW, 2007), or in Pains, in Minas Gerais (840 m/day) (FERRARI *et al*., 2018).

Karst aquifers are more sensitive and vulnerable to contamination. This is due to the thin soils, flow concentration in the epikarst (upper layer, often intensely fractured and karstified) and the type of recharge, mainly autogenic, in which contaminants can easily reach the water table, transported quickly by conduits over great distances. Furthermore, flow paths in a karst aquifer can be connected to surface water. Therefore, a contaminant in a network of conduits, in addition to reaching greater distances in less time, is less degraded or retained by capillarity, different of what would happen in fissure and granular aquifers (RYAN; MEIMAN, 1996).

Subsidences are quite common in karst regions. These events can be natural (by rock dissolution or cave-in collapse), usually occurring over a geological period, or be induced or accelerated by human activities, which can generate catastrophic collapses (GALVÃO; HALIHAN; HIRATA, 2015). Induced geotechnical problems are usually caused by: a) excessive extraction of groundwater; b) by construction activities; and c) a combination of both, where agriculture, mining, roads and railways, urban and industrial construction are potential influencers. In the case of urban karst aquifer exploration, the dry periods are the most dangerous, as there is an increase in the demand for groundwater, which leads to the formation of drawdown cones in mile-long dimensions. Inside these depression cones, wells, springs and streams can dry up or have their flows significantly reduced, with the general direction of water flow being significantly altered (GALVÃO *et al*., 2017).

These characteristics make karst aquifers extremely heterogeneous and anisotropic, making it difficult to describe and quantify the characteristics of the underground flow. Several methods can be applied to the hydrogeological characterization in karst, from simpler techniques used in granular and fractured aquifers (field mapping, photo-interpretation, pumping, geophysics, etc.), to more modern approaches, such as isotopes and numerical modeling. Other complementary methods can be used, such as: use of fluorescent tracers, hydrographs and kymograms of karst springs, filming of wells to typify karst zones, pumping (in this case, long-term), speleological mapping etc.

Despite the complexity of exploring and exploiting karst aquifers, it is precisely because of the challenge of understanding their peculiarities that every year the interest of professionals from different fields has been progressively growing, which makes this hydrogeology field the one that presents the most technical and conceptual innovation.

Figure 14 – Initial process of karstification in limestone rock in enlargement in the bedrock planes (discontinuity sections), through which the flow of acidified water circulated
Photo by Paulo Galvão.

Figure 15 – Cave entrance in Pains/MG, indicating the water level in the deepest portion. An example of the connection between groundwater and surface water

Photo by Paulo Galvão.

Classification of aquifers, according to water storage pressure

Aquifers can also be classified according to the pressure of water storage inside them, as: *a) uncontained*; and *b) contained* (Figura 16), although there are intermediary conditions differing between these two types, such as *semi-contained*, *covered* or *suspended* aquifers. In *uncontained* aquifers, the upper limit is constituted by the water level, which corresponds to the top of the saturated zone (phreatic surface), in equilibrium and under the same atmospheric pressure conditions. *Contained* aquifers are restricted at the base and top by non-aquiferous units (aquicludes) or by partially impermeable rocks (aquitardes), where water is stored under pressure. The intermediate situation is the *semi-contained* aquifers, where the layers that limit them have low permeability, conditioning the water to cross them, however, slowly.

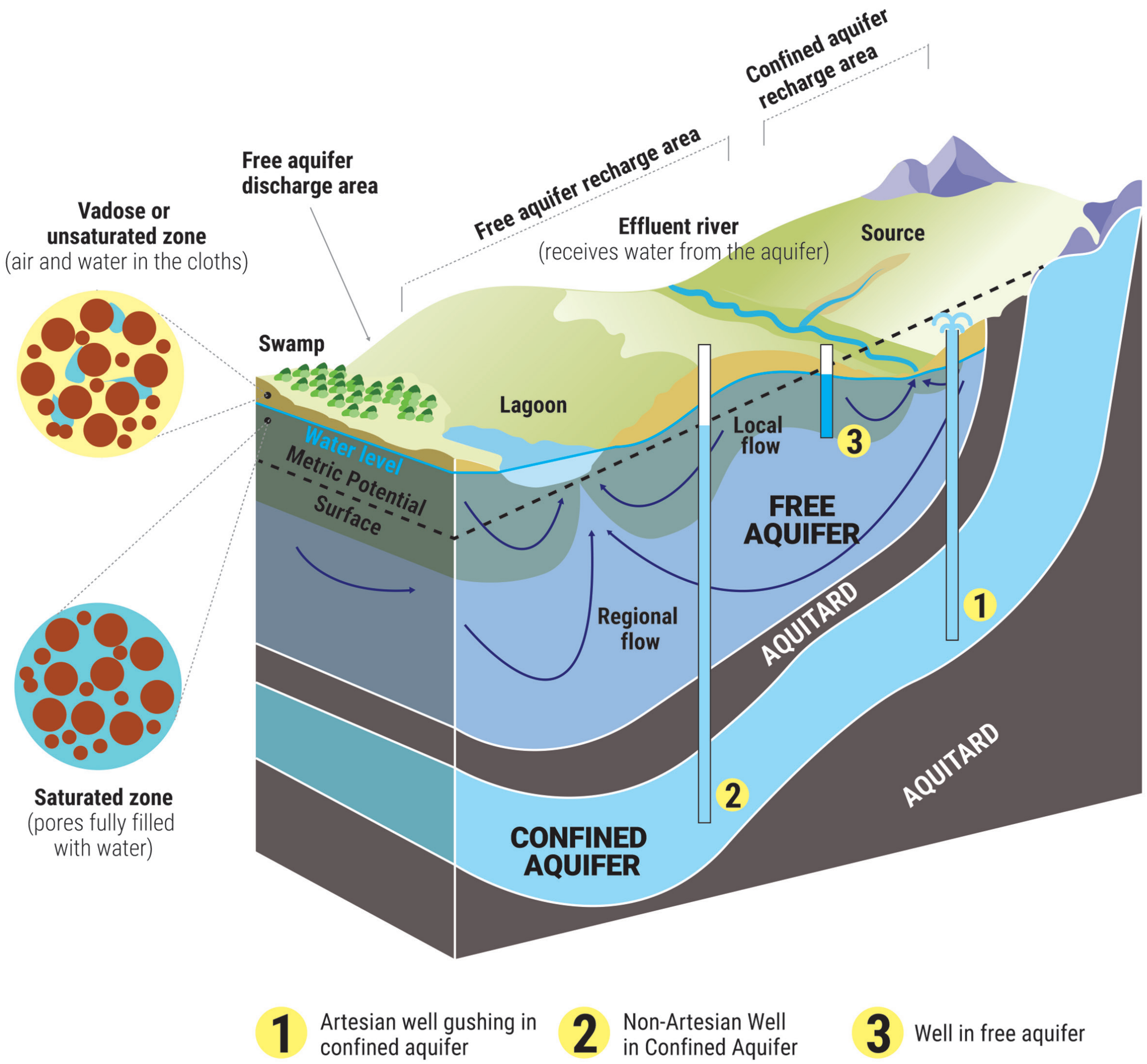


Figure 16 – Operation of an aquifer

Source: Cabral (2008), adapted by Dora Atman.

Water in contained or semi-contained aquifers is subjected to pressure greater than atmospheric pressure. Therefore, when the aquifer is drilled by the well, the water rises and reaches piezometric equilibrium positions above the top of the aquifer layer (reservoir) (Figure 16). In some cases, depending on the topographical surface and the pressure of the aquifer, this water can rise above the surface, forming artesian (gushing) wells.

Groundwater flows slowly towards the lower areas as it percolates through the vadose zone (Figure 16). While the surface water flow moves for miles in a few days, the underground flow advances by millimeters or inches every day. The movement of groundwater takes place through the filling of empty and connected spaces of the rocks and the slow displacement in the saturated zone. This difference in flow velocity allows water that infiltrated tens, hundreds or even thousands of years ago to still be moving in the underground environment. When compared to rivers, the aquifer stands out for its storage rather than high production.

The volumes stored in free aquifers fluctuate seasonally or over multi-annual cycles, demonstrating that part of the incident and infiltrated rainfall at the surface reaches the aquifer (recharge) and leaves it (discharge) over time. Due to their size and recharge dynamics, even small aquifers can have water stored for decades and even thousands of years.

Fluctuations in the volume stored in aquifers configure a dynamic equilibrium sustained by variations in precipitation along climatic seasonalities and by internal changes in recharge and discharge rates resulting from variations in the hydraulic gradient. When the water level of the aquifer rises over time through increased recharge, there is a natural tendency to increase water outflow rates by an increase in discharge – for example, through an increase in groundwater flow that reaches the rivers. When, however, the water level of the aquifer decreases due to reduced recharge, there is a tendency to reduce discharge rates. Therefore, throughout geological time, the aquifer trends toward a state of dynamic equilibrium, in which future discharge rates will be set according to today's recharge rates.

Exploitation through wells is a discharge imposed on a system that was previously in dynamic equilibrium. The intensity of pumping and the time of exploration, in conjunction with the size and hydraulic characteristics of the aquifer will define the consequences of this interference in the rates of recharge, discharge and storage.

2.3 INTERACTIONS OF METEORIC, SURFACE, UNDERGROUND AND COASTAL GROUNDWATER

The adoption of the hydrographic basin as the water management unit transforms this space into a reference for the analysis of interactions between meteoric, underground, surface and coastal waters. The hydrographic basin is composed of a geological framework that provides the initial elements for its analysis, as well as directly influencing water availability. This geological framework is understood here as a mosaic and/or succession of rocks and unconsolidated material that make up the floor and subsoil of a hydrographic basin, to which relief forms and topographic variations are associated, resulting from the action, in geological time, of internal (endogenous) and external (exogenous) dynamics.

The geological framework can be constituted by different types of rocks (igneous, metamorphic or sedimentary), with different ages, compositions and possibilities of spatial relationship (stratigraphy), as well as the presence of geological structures (fractures, gaps, folds etc.). Older and deeper rocky packages, due to uplift, associated with weathering and erosion, may end up outcropping or being buried by more recent sedimentary sequences, formed in the most different geological environments. Rocks with or without cover, formed by unconsolidated material and soils, have characteristics of porosity and permeability (or hydraulic conductivity) that can facilitate or prevent the percolation of rainwater. The climate and its variations over geological time are equally determinant in the form of occurrence and dynamics of underground, surface and coastal water bodies. The climate controls the characteristics of the cycle and hydrological balances that are set in a given watershed. In a watershed, therefore, the geological framework defines the geometry of the aquifers and their relationships with other bodies of surface water (Figures 16 and 17). Rainfall, in turn, influences the amount of water available to be stored in aquifers.

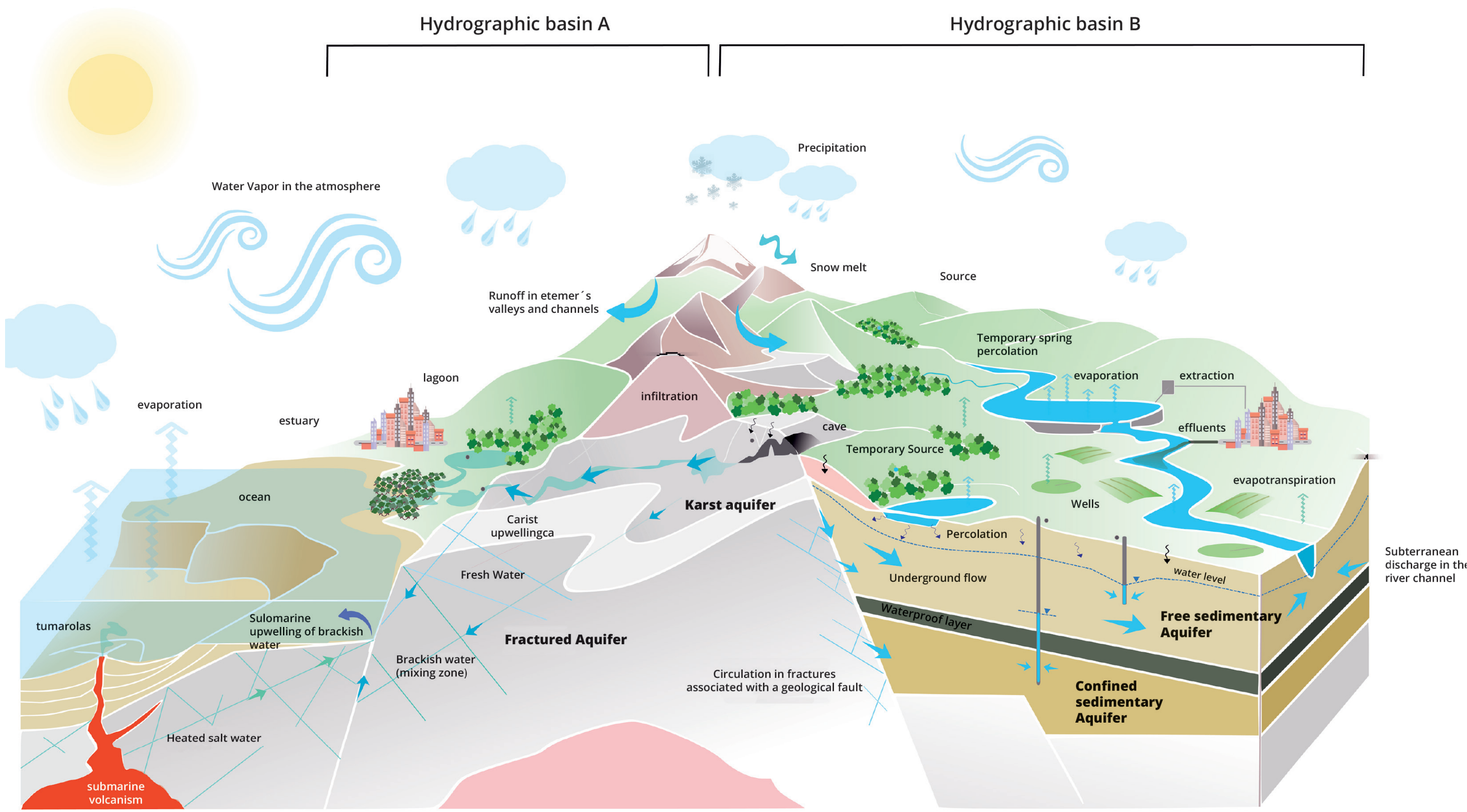


Figure 17 – The geological framework as a basic element for defining the territory of the basin and water storage

Authored and provided by Dora Atman.

The interaction between climate and the geological framework determine the natural organization of water resources in the territory (Figure 17). Rainfall is the main mechanism for water entry into the basin. Rocks will form the different types of aquifer and, in conjunction with topography, they will be decisive in defining the behavior of the waters, which can outflow superficially, infiltrate with the vertical and lateral sub-surface outflow, or even be absorbed by plants and return to the system through evapotranspiration.

The vertical sub-surface flow supplies the flow of groundwater, and part of this current generates springs and supplies to the interior of surface and/or coastal water drainage. In other cases, the opposite may occur, and the surface water bodies generate the recharges for underlying aquifers. Interactions between surface and groundwater occur both in the upstream and downstream parts of a watershed, depending on the geological framework, rainfall conditions and topography.

In crystalline terrain, it is common for springs to appear in the higher portions of the relief and form small watercourses, which join others as they reach the lower portions of the drainages, composing streams, creeks or other larger bodies of water. Therefore, they constitute a hydrographic basin, whose drainage pattern is generally controlled by the structuring of the rocks of the geological substrate. Throughout this trajectory, underground discharges occur to surface water courses, which are responsible for their perpetuation. Basins whose geological framework is formed by poorly permeable rocks and with pronounced topographic gradients present a large part of the flow dependent on surface outflow. Although aquifer interactions with water courses are minor, they should be considered in the elaboration of the water balance and management plans, as they can provide important contributions. On the other hand, in watersheds that drain sedimentary terrain or alluvial plains, aquifer interactions are highly relevant, as rivers receive a large volume of underground discharges, which makes them perennial during drought periods.

Between its recharge and discharge, groundwater moves along several paths, forming what is called a flow network, whose lines can conform to three situations: local, intermediate and regional (Figure 16) (TÓTH, 1963):

- *Local flow lines*: drain to discharge areas relatively close to the points where recharges took place, normally pointing to surface water bodies (rivers and lakes).
- *Intermediate flow lines*: have one or more local flow systems between their recharge and discharge area.
- *Regional flow lines*: they are deeper inside the aquifers and have transit over great distances with discharges to surface water bodies, namely: rivers, large lakes or even oceans.

Groundwater flows must be viewed from a three-dimensional standpoint, i.e., there may be subsurface and local flows overlapping deeper ones, which define regional flows. Consequently, it is possible that in the same aquifer there are local, intermediate and regional flows, and the use of these terms depends on the scale used (Figure 16). To quantify the integrated water availability of the basin, it is important to understand the dynamics of these flows and estimate their discharge rates.

Aquifer systems can even be larger than watersheds. Their recharge areas located in a basin can favor discharges into rivers in other river basins (Figures 17 and 18). Therefore, the same aquifer can participate in flows from more than one surface watershed (Figures 17 and 18), as well as supply water to the sea. If the discharge takes place at sea, the flow of fresh water from the aquifer is opposed to the flows of salt water, establishing a dynamic boundary between these waters, which are separated by a mixing zone.

There is an intrinsic connection between surface and groundwater, so its assessment must be done from an integrated and joint approach. Surface water can become groundwater through infiltration, while groundwater can become surface water through discharge from aquifers.

It is therefore necessary to understand, in space and time, the way in which these transfer relationships that regulate the volumes and fluctuations of water available to ecosystems occur. This theme reinforces the idea of river-aquifer interactions, as in the case of the Urucuia Aquifer System and the São Francisco River Basin (ANA, 2017a) (Box 8). The extraction of groundwater through wells modifies the original hydraulic condition of the aquifer and the basin, causing both positive and negative impacts. Overall, this extraction generates social benefits as it increases regional water availability, allowing the development and supply of communities that often do not have another water source or need to complement the surface source. However, depending on the volumes extracted, overexploitation can occur, which reduces aquifer discharges to surface water bodies or to the sea, culminating in negative environmental and economic effects.

Box 8 – River-aquifer interactions: the importance of the Urucuia Aquifer System for the São Francisco River Basin

Didier Gastmans
Camila de Lima

Surface waters present in different continental reservoirs, such as rivers, lakes, reservoirs, wetlands and estuaries, etc., interact with groundwater stored in aquifers. This interaction occurs both through the loss of water from surface water bodies to aquifers, and by the discharge of groundwater, which feeds surface water bodies, and it is fundamental to the balance of water of continental reservoirs (BRUNNER *et al*., 2017; WOESSNER, 2020). Understanding the processes that govern these interactions, as well as their quantification, are issues that must be part of the agenda of debates around the establishment of rational policies for the management of water resources, as a way of minimizing the effects caused by water scarcity or loss of quality of bodies of water, both on the surface and underground (MANZIONE, 2015; WOESSNER, 2020).

Usually control in the interaction between groundwater and a surface watercourse depends on the difference in elevation of water levels in the river and in the aquifer. If the elevation of the water table is greater than the elevation of the water in the river, it is called an **Effluent River** (Figure 18a and 18d), and conversely, if the height of the water table is lower than that of the river, it will be an **Influent River** (Figure 18b and 18c). For **Influent Rivers**, two situations of hydraulic connection are observed in nature: one in which there is a connection between the water table and the river (Figure 18b), and the other in which the river is disconnected from this surface, a typical characteristic of **Intermittent Rivers** (Figure 18c) (HEALY, 2010; POETER *et al*., 2020; WINTER *et al*., 1999; WOESSNER, 2020).

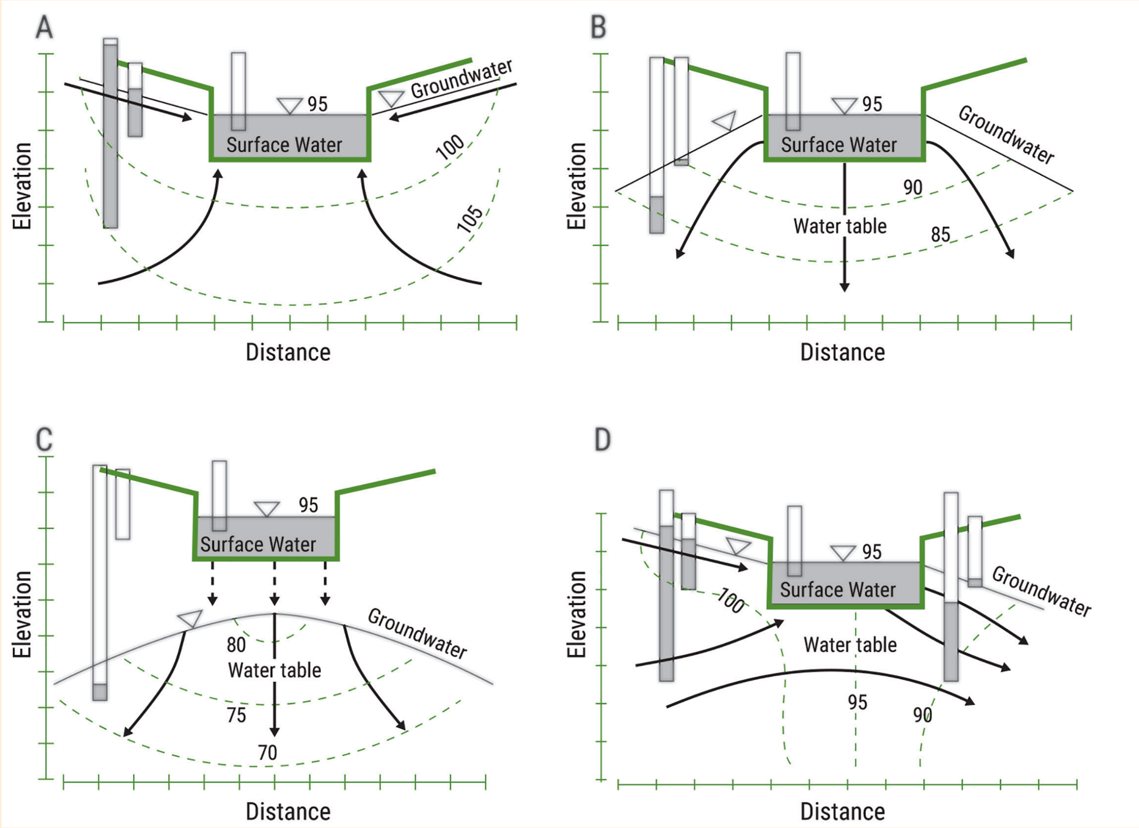


Figure 18 – (A) Conceptual model for effluent rivers; (B) Conceptual model for influent rivers, scenario in which the rise in the water level that separates the saturated from the unsaturated zone is connected with the river; (C) Conceptual model for influent rivers, scenario in which the rising water level that separates the saturated from the unsaturated zone is disconnected from the river; (D) Conceptual model of direct flow

Source: Woessner (2020), adapted by Didier Gastmans and Camila de Lima.

Different areas of knowledge are interested in knowing and quantifying these interactions, which are important not only for hydrology, but also for understanding the functioning of ecological systems dependent on the aquatic environment and the transfer of contaminants. Due to the complexity of these interactions, studies often require extensive and complex instrumentation, as well as an interdisciplinary view, in order to promote an assessment of multiple parameters and the combination of techniques (WOESSNER, 2020; KALBUS; REINSTORF; SCHIRMER, 2006).

The connections between surface and groundwater in Brazil are important for several hydrological regions, some of them extremely sensitive, such as the Pantanal Matogrossense, or hydrographic basins of national dimensions. This is the case of the São Francisco River Basin, the largest exclusively Brazilian watercourse, which through numerous transposition works intends to ensure water security for around 12 million people, including in the Northeastern Semiarid region, in addition to maintaining hydroelectric plants and population growth, estimated at up to 20.5 million by 2035 (CBHSF, 2016).

In the middle portion of the São Francisco River Basin is located one of the main Brazilian aquifers – the Urucuia Aquifer System (SAU) – which constitutes a strategic source of regional importance for the Brazilian Northeast, which is harshly affected by droughts. In addition to meeting the growing demand for water for the economic development of the region, this aquifer contributes significantly to the base flow of tributaries on the left bank of the São Francisco River, especially during dry periods (Figure 19).

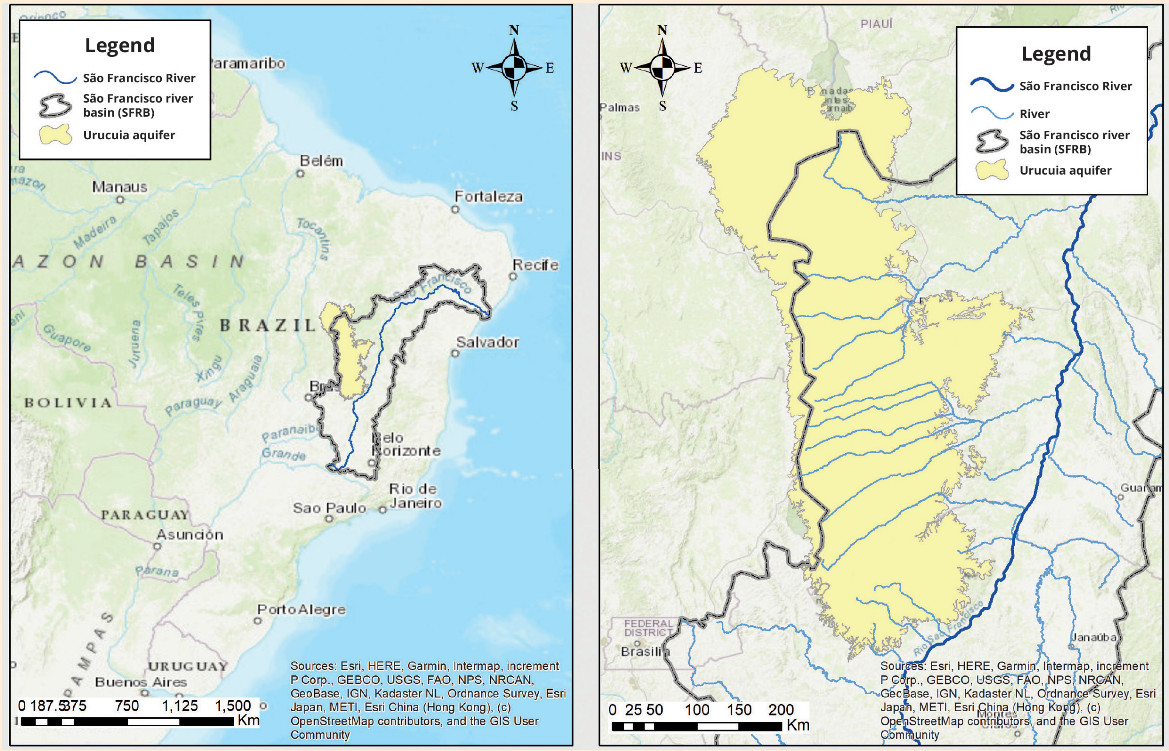


Figure 19 – The São Francisco River Basin and the Urucuia Aquifer System (left), and the relationships between the SAU drainage networks and the São Francisco River (right)

Source: Gonçalves, Engelbrecht and Chang (2016), adapted by Didier Gastmans and Camila de Lima.

The SAU is a porous aquifer, composed of Neo-Cretaceous fluvio-aeolian sandstones associated with the Urucuia Group, which occupy an area of 125,000 km². The aquifer constitutes an extensive plateau on the left bank of the São Francisco River, with altitudes above 900 m, which slopes moderately to the east, reaching altitudes of approximately 600 m.

There are uncertainties regarding the total thickness of the rocky package that forms the aquifer. Some authors, such as Chang and Silva (2015) and ANA (2017a) estimate, based on geophysical data, that preserved thicknesses does not exceed 400 m. However, higher thicknesses are reported in stratigraphic wells drilled in the region by the Geological Survey of Brazil (SGB-CPRM) and by the National Petroleum, Natural Gas and Biofuels Agency (ANP) (ANA, 2017a). Aquifer recharge rates represent about 18-20% of annual precipitation averages (GONÇALVES; ENGELBRECHT; CHANG, 2016), which are on the order of 22.37 km³.year-1, and which are added to the storage of the order of 1,327 km³ (ANA, 2017a). Such volumes represent almost half of all underground water availability in the São Francisco River Basin (ANA, 2017a; CBHSF, 2016).

The abundance of water and the favorable climatic conditions in the area of occurrence of the SAU made the area flourish in the west of the state of Bahia, from the 1980s, an important agricultural activity, which replaced the native vegetation (Cerrado, for the most part) by extensive agriculture areas (BRANNSTROM et al., 2008). In addition to changes in land use and occupation, this agricultural expansion requires intense use of water resources for irrigation of crops and animal watering.

Based on warnings concerning the decrease in the flows of the rivers that cross the region, the understanding of the relationship between the SAU and surface waters became the study agenda. Although there is no physical connection between the SAU and the São Francisco River, their waters are connected through the discharge of groundwater into the watercourse network that drains the plateau (Figure 20), and are responsible for approximately 35% of the total average flow of the São Francisco River (CBHSF, 2016). These discharges are crucial during the driest period, when the contributions of the UAA, in the form of discharge to the tributaries of the left bank of the São Francisco River, represent 80 to 90% of the flow in these rivers, representing an important source of water for the maintenance of flows in this stretch of the São Francisco River, in addition to being essential for the preservation of most ecosystem functions related to downstream waters (GONÇALVES; ENGELBRECHT; CHANG, 2018).

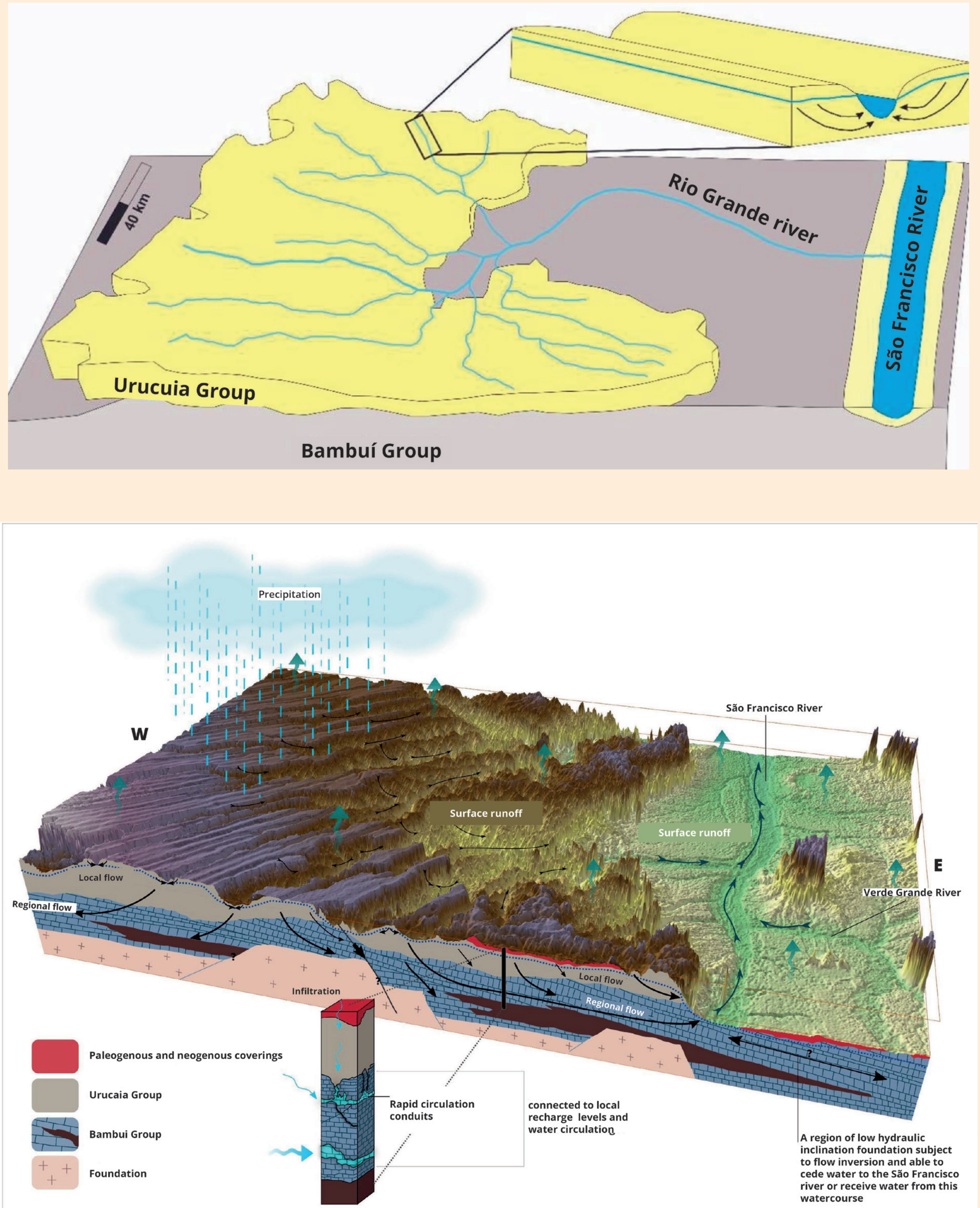


Figure 20 – Scheme of the hydraulic functioning of the SAU, the drainage network of the plateau and the form this water reach the São Francisco river

Source: Gonçalves, Engelbrecht e Chang (2016).

The regional intensification of land use, which leads to an increase in the irrigated area in the region, combined with qualitative and quantitative monitoring, under construction and expansion in the SAU, impair a more accurate analysis of the situation of water resources and their impacts on the water resilience of the region, as well as the development of management strategies that combine land use planning with the correct use of water resources. Integrated monitoring of water resources in the region has been implemented through the installation of monitoring wells by the Integrated Groundwater Monitoring Network (RIMAS/SGB-CPRM), operated in this aquifer system by the Geological Service of Brazil (SGB-CPRM), in a partnership with ANA. ANA and SGB-CPRM even established a partnership in the operation of the integrated network of the Urucuia Aquifer System. Therefore, 63 RIMAS wells, installed in this aquifer, are already part of the National Hydrometeorological Network (RHN), constituting the first region in the country that includes integrated monitoring (rain-river-aquifer). Monitoring actions take time to allow understanding of the interactions between rivers and aquifers, but they are a basic tool for good management of water resources, which must also consider the participation of all actors involved, including land users.

2.4 GROUNDWATER IN BRAZIL

Unlike surface water, the spatial determination of the occurrence of groundwater and aquifers is not something that can be verified by mere observation of the territory. Identifying their presence requires availability of data, maps and models that contemplate rock-water interaction. Most citizens are unaware that they live in areas with the presence of aquifers, even when supplied by underground sources.

The invisibility of groundwater makes it difficult to determine its occurrence, limits, movement, quantity and quality. Its delimitation represents the projection of the way water is organized in a mosaic of rocks, whose formation, transformation and configuration result from several geological processes that started millions of years ago. This process requires the interpretation of data, which is scarce, and specific methodologies, which have limitations. It also worth noting that there is little investment in hydrogeological studies in the country. For example, the State Fund for Water Resources of São Paulo (FEHIDRO) invested less than 1% of its budget in projects aimed at solving problems that affect groundwater (ALBUQUERQUE FILHO, 2015). This technical and financial challenge is added to the social challenge, which is to disseminate knowledge in order to build better water policies and establish a link between society and aquifers.

The delimitation of aquifers and the analysis of groundwater characteristics and flows are intrinsically related to the rock. Therefore, the first action to outline aquifers refers to geological mapping. Usually, aquifers are named after the geological formation that constitutes them, and which has the best aquifer characteristics. In Brazil, some aquifer systems received denominations unrelated to the name of the formations, as in the case of the Guarani Aquifer System (SAG). Although known for the aquifer potential of its Botucatu and Piramboia formations, it was renamed SAG to accommodate other geological formations and pay tribute to the Guarani people who inhabited this space. Another example is the Amazon Aquifer System.

From the 1980s onwards, the first cartography work was built to identify the interaction between rock and water in the national territory: *the Map of Brazilian Hydrogeological Provinces*, *1/2,500,000 scale* (MENTE; PESSOA; LEAL, 1981) and *1/5,000,000 scale* (DNPM/CPRM, 1983 *apud* DINIZ *et al*., 2014). These maps sought to aggregate geological regions with "similar general characteristics in terms of main groundwater occurrences." (PESSOA; MENTE; LEAL, 1980, p. 461). The territory was divided into 10 hydrogeological provinces (Northern Shield, Amazonas, Central Shield, Parnaíba, São Francisco, Eastern Shield, Paraná, Southern Shield, Midwest and Coastal Shield) and 15 sub-provinces.

The representation of this information has evolved with the advancement of geological knowledge. Based on the review of the Geological Map of Brazil, scale 1:1,000,000 (CPRM, 2004), *a Map of Hydrogeological Domains/Subdomains of Brazil*, *scale 1:2,500,000* (CPRM, 2007) was prepared. Hydrogeological domains are comprised of a group of "geological units with hydrogeological affinities", whose main basis is "the lithological characteristics of rocks." (BOMFIM, 2010, p. 1). The 2,338 lithological units were grouped into seven domains (Cenozoic formations, sedimentary basins, porous/fissural, metasediments/metavolcanic, volcanic, crystalline and carbonates/metacarbonates) and 30 hydrogeological subdomains. The difference between these products is that the hydrogeological provinces incorporate aspects related to tectonics, morphology, physiography and rock lithology, while the domains focus on lithology (BOMFIM, 2010).

In 2014, using a methodology aligned with international standards of Hydrogeological Cartography, and based on Geographic Information System (GIS) techniques, the SGB-CPRM launched the *Hydrogeological Map of Brazil to the Millionth* (DINIZ, 2014, p. 20). This Cartography incorporated a wide spectrum of data, such as: soil infiltration capacity, electrical conductivity, hydrolithological domains, relief, hypsometry, pluviometry, density of wells and annual explored volumes. Another important feature of this technique is the promotion of information from contained aquifers and not only from outcrops. In this map, the lithological units were reorganized into 202 hydrostratigraphic or aquifer units, of which 164 are outcrop units and 38 are non-outcrop units (DINIZ, 2014, p. 20).

To see this map click on:
https://rigeo.cprm.gov.br/jspui/handle/doc/15556.

Based on the systematization carried out by ANA (2013), the *Map of Outcropping Aquifer Systems in Brazil* was created, in a scale of *1:1,000,000*. ANA (2013) distributed the Brazilian groundwater potential in 181 aquifers and outcropping aquifer systems (Figure 21), of which 151 are sedimentary aquifers, considered the most productive, such as the Guarani, Bauru-Caiuá, Barreiras, Urucuia /Areado, Solimões, Alter do Chão, Açu, Barreiras and Beberibe. The karst domain is formed by 26 aquifers, among which Bambuí and Jandaíra stand out. The fractured domain, on the other hand, has reduced water potential and was grouped into four large blocks: Semi-arid Fractured Aquifer System, Northern Fractured Aquifer System, Central-South Fractured Aquifer System and Serra Geral Aquifer (ANA, 2013, pages 54-56).

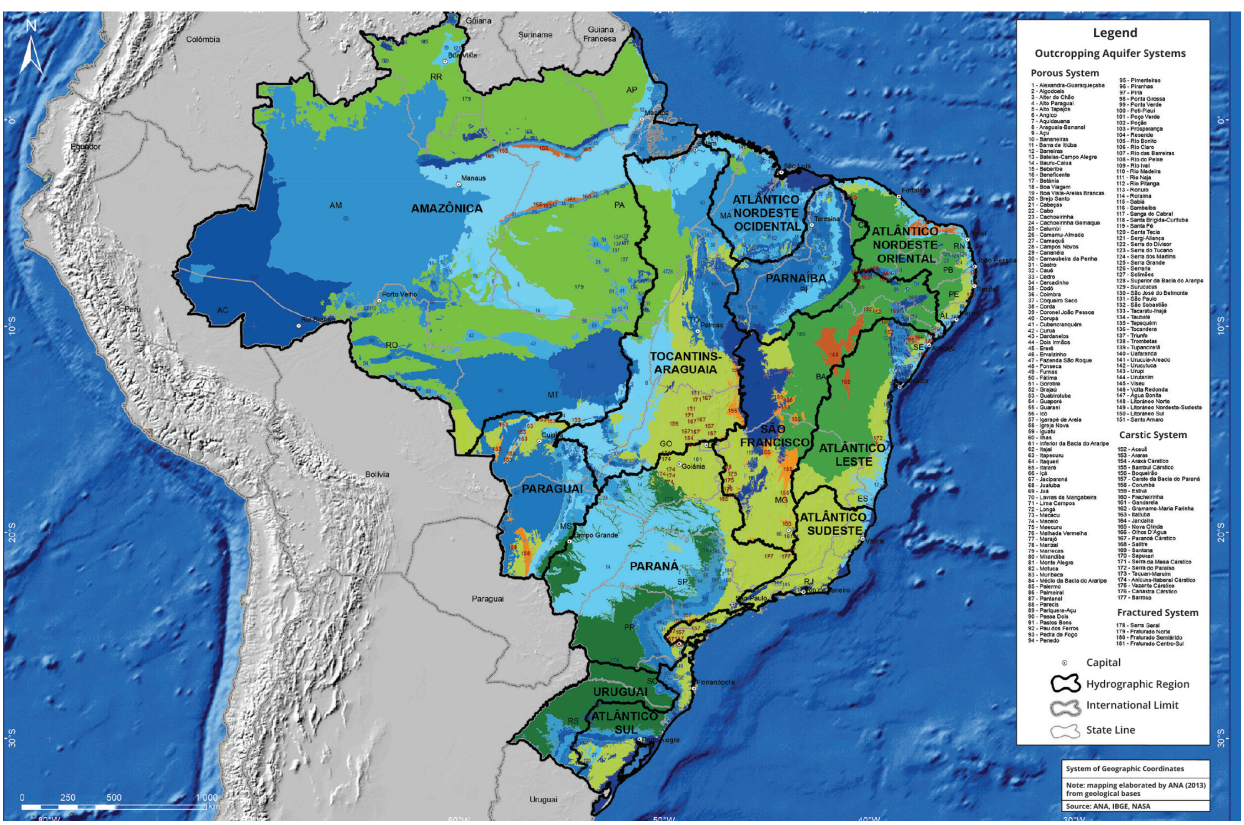


Figure 21 – Brazilian aquifer systems, according to ANA
Source: ANA (2013).

Much of the Brazilian territory is served by aquifers, although the productivity of wells in fractured areas is lower than those associated with sedimentary units. Figure 22 shows the main Brazilian aquifer systems, which are found in sedimentary basins and which stand out due to the use and quality of their water.

Figure 22 – The main Brazilian aquifers
Source: ANA (2007, p. 72).

The observation of maps allows us to understand that the territoriality of aquifers does not always correspond to that of water courses, hydrographic basins or hydrographic regions. Aquifers, in addition to being three-dimensional bodies, are also geological units associated with their lithology. Therefore, there may be different overlapping aquifers, sometimes with little or no hydraulic relationship between them, as in the case of the Bauru, Serra Geral and Guarani aquifer systems, which have different characteristics, but have an area of territorial convergence.

Bauru is an uncontained to semi-contained sedimentary aquifer that overlaps the rocks of the Serra Geral Formation. The Serra Geral is a fractured aquifer when it outcrops, but when covered by the Bauru-Caiuá, it is configured as an aquiclude and, therefore, it contains the Guarani. In many cases it is difficult to spatially limit the flow from one aquifer to the other, especially because the same geological formation can present very different hydraulic characteristics and behaviors. Consequently, although the stratigraphy and classification of lithological units can serve as a basis for the definition of aquifers (from the hydrostratigraphic point of view), they must be evaluated more broadly (considering their hydrogeological properties) and related to the hydrological cycle itself (areas charging, discharging, for example). This reason makes some hydrogeological maps try to classify the units by the type of porosity of the rock or sediment (fractured, porous, granular or karst), while others try to characterize the units by their production (hydrogeological potential), especially in cartographic representations of regional expression.

These maps demonstrate that the boundaries of the aquifers are still under construction and that, despite not converging with the watersheds, there is a great interaction between surface and groundwater. Especially, due to local flows, the highest rate of recharge and discharge of aquifers usually occurs in the basin.

2.5 HOW AND WHERE IS GROUNDWATER USED IN THE COUNTRY?

It is estimated that Brazil has 1.1 trillion m^3/year in groundwater reserves (ANA, 2020, p. 8). The availability of water, in turn, would be approximately 14,650 m^3/s, however, the distribution and productivity of aquifers happen unevenly through the territory (ANA, 2020, p. 23).

In the global context, Brazil is the 9th largest user of groundwater (HIRATA *et al.*, 2019, p. 47). The actual number of wells is unknown, despite the obligation to grant the right of use or registering them. Unfortunately, the overwhelming majority of users are irregular, preventing the establishment of a reliable profile of users and the amounts extracted, or their economic importance.

The number of well users grows every year and, according to ANA estimates (2021), there are approximately 2.6 million wells in Brazil. The Groundwater Waters Information System (SIAGAS), of SGB-CPRM, however, had recorded in March 2022, only 348,283 wells. In turn, the database supplied by the Federative Units recorded only 101,074 wells granted (ANA, 2020). To Hirata *et al.* (2019), these more than 2.5 million wells apparently have an extraction capacity in excess of 17,580 Mm^3/year (557 m^3/s), which corresponds to the volume necessary for supplying the entire Brazilian population for a full year (HIRATA *et al.*, 2019). This infrastructure of driven wells represents an investment of approximately R$ 75 billion in drilling and complementation services, in addition to pumping equipment (HIRATA *et al.*, 2019).

Groundwater, therefore, is essential for domestic and public supply, in industrial processes, in the provision of various types of services and in agricultural activity.

Among the advantages of groundwater over surface water, the following can be highlighted:

- the good natural quality of the water which, in most cases, only requires chlorination/fluoridation;
- lower costs related to obtaining water, extracting, maintaining and operating the extraction compared to classic sources of surface water systems;
- the autonomy of driven wells, which work in an automated way, requiring little maintenance;
- the exclusivity of owning a water source and control its use;
- the lowest environmental impact of underground abstraction. The deep driven well is considered to have a low impact compared to surface extraction, which involves treatment plants, distribution stations and dams;
- the ease and speed of the infrastructure required to make the extraction viable. The execution time of a well is from days to weeks, on the other hand, dams and water treatment plants require years;
- the implementation of the underground water extraction system can be carried out gradually, rationalizing investments in water withdrawal;
- groundwater does not imply expropriation of large areas, which represent substantial financial expenses;
- the possibility of organizing a sector-based distribution, with exploration groups, constituting isolated or interconnected systems and, many times, close to the demand, reducing the construction of long pipelines;
- less susceptibility to climatic conditions, as the storage capacity of the aquifers makes the flow stable even during droughts.

Figure 23 shows the profile of users based on SIAGAS data, according to the following classifications: agriculture and livestock (wells dedicated to irrigation or watering animals); domestic supply (urban residences); public supply (provided by water service utility providers); manufacturing supply (wells that supply industries); multiple use (wells that serve more than one purpose, the latter being mostly for urban services); and others (wells for purposes not listed in the other categories, such as leisure). We note that household supply characterizes the profile of the main user (30%), followed by agricultural use (24%), urban public supply (18%), multiple supply (14%), industrial supply (10%), and others (4%) (HIRATA *et al*., 2019).

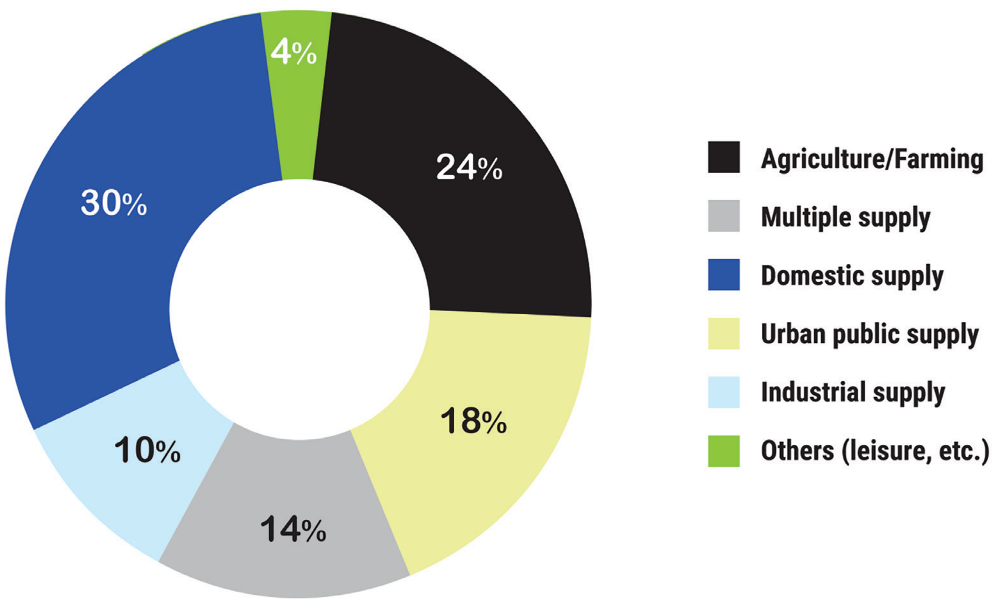


Figure 23 – Profile of groundwater users in the country
Source: Hirata *et al*. (2019, p. 15).

According to data from Hirata *et al.* (2019), of the total groundwater extracted in the country (557 m^3/s), only 10% (53 m^3/s) serve public supply of cities through public utility concession holders and municipal services. Although these flows are low, this resource is essential for public water supply in small (< 10,000 people) to medium- (< 100,000 people) sized cities. Almost half of the municipalities with a population less than 10 thousand are totally dependent on groundwater. They represent the only source in 36% of Brazilian municipalities and in a complementary way (mixed systems) in 16%. Therefore, 52% of municipal seats depend to some degree on this resource (Figure 24) (ANA, 2010).

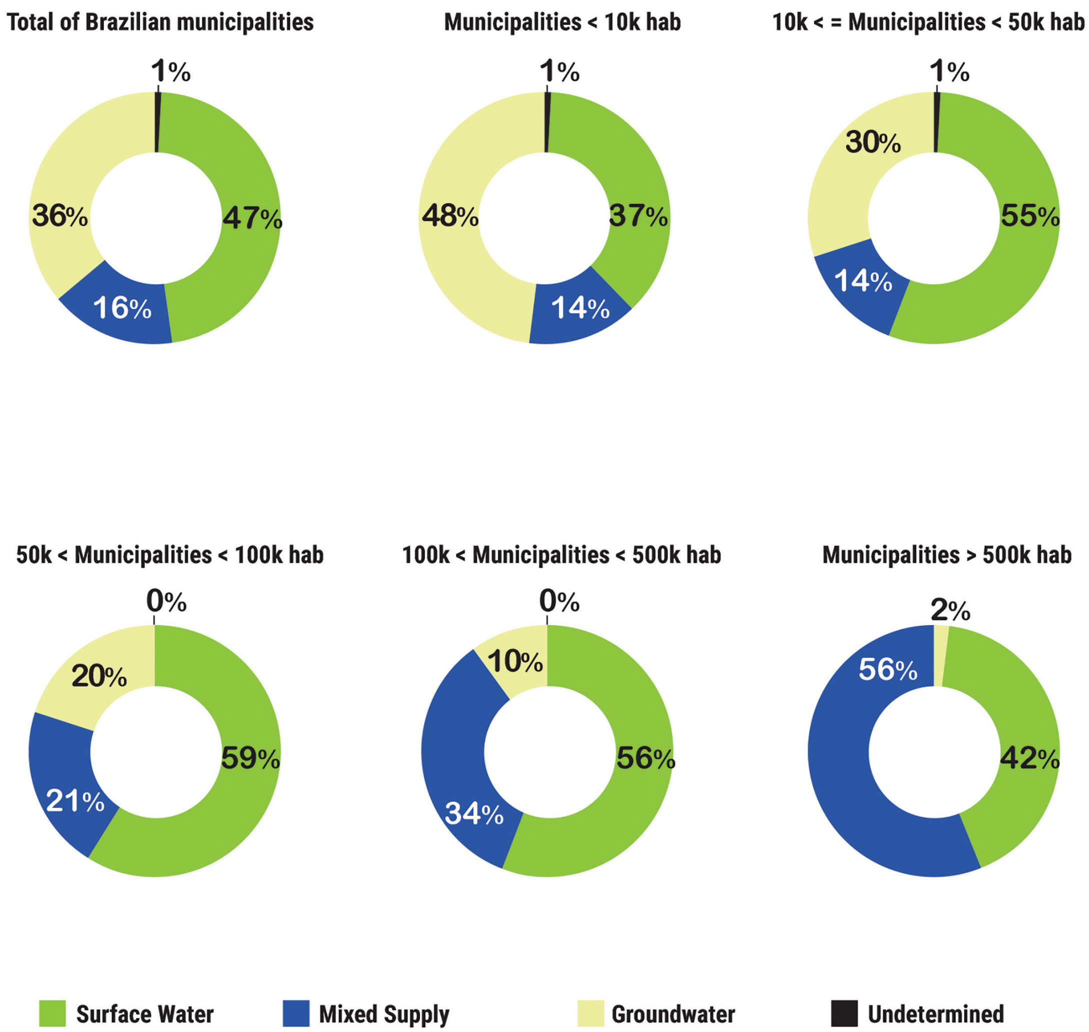


Figure 24 – Distribution of Brazilian municipalities (total and by population size) according to the type of supply source

Source: Hirata *et al*. (2019).

The new Sanitation Framework (Law No. 14,026/2020) tends to promote an increase in public demand for water, given that it determines that 99% of the population will have drinking water by 2033 (Article 11-B of Law No. 11,455/2007, included by Law No. 14,026/2020). Groundwater can contribute to achieving this goal. It is already used intensively by important urban centers, such as Mossoró (RN), Natal (RN), Maceió (AL), Recife (PE), Barreiras (BA) and Ribeirão Preto (SP), and is an alternative source in areas which do not have access to the public water network or have it only on a precarious basis.

Figures 25 A and B show the most dependent states in relation to the use of these resources. For urban use, the states of São Paulo, Piauí, Ceará, Rio Grande do Sul, Bahia and Paraná stands out, which shows its importance for the Northeast and South Regions, as well as the intense use in the state of São Paulo. For rural use, the main user state is Minas Gerais, followed by São Paulo, Bahia, Tocantins and Rio Grande do Sul (HIRATA *et al.*, 2019). Although the Northeast does not appear as a major rural user, these waters are very important for the populations of the Semi-arid region, especially with the encouragement of the use of brackish aquifers and filtering technologies, as in "Programa Água Doce" [Fresh Water Program].

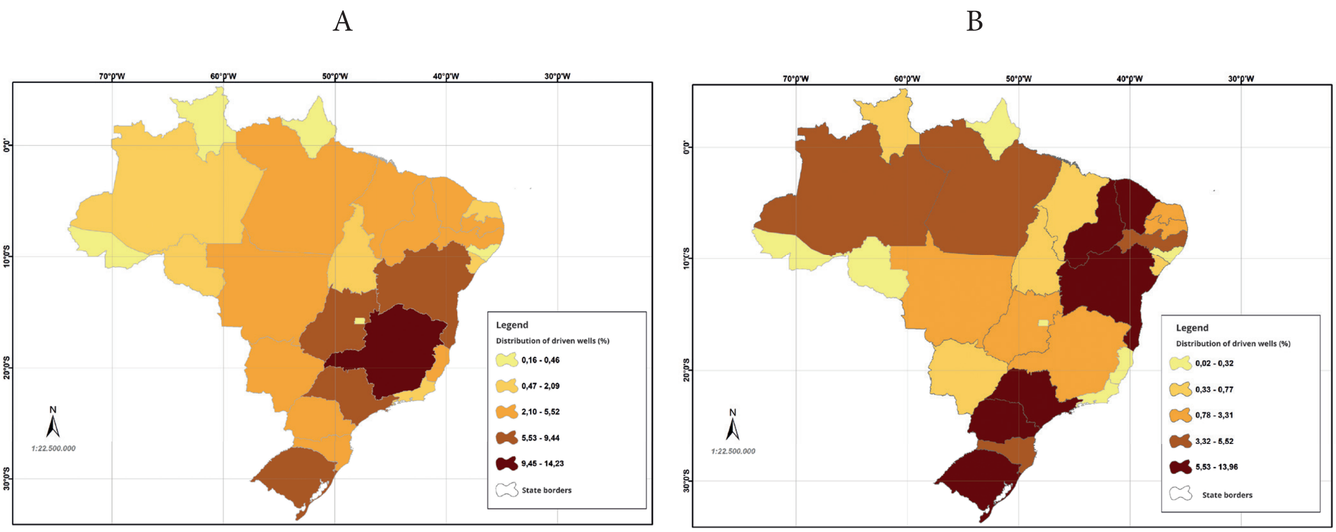


Figure 25 – Dependency of Brazilian states on groundwater, according to the distribution of driven wells (A: urban use; B: rural use)
Source: Hirata *et al*. (2019, p. 17).

Groundwater still has a little recognized importance in rural areas (ALY JÚNIOR, 2019). This source, however, is used to supply homes and rural enterprises, irrigation and animal watering. According to the IBGE Agricultural Census (2017), there are approximately three million extractions from excavated wells and springs, as well as 1.03 million rural properties equipped with at least one driven well. Although dug wells and springs have a low flow rate, they are the main source of water in the peripheral regions of cities that do not have a water network, in villages in mountains and in small rural properties. This reality must be maintained since Law No. 14,026/2020 did not provide any guidelines for the provision of public sanitation services in rural areas which will continue to depend on alternative water systems with high dependence on wells and springs.

The use of these waters in irrigation should is also likely to increase, as it ensures a perennial supply of good quality water, safeguarding agricultural production from the growing instability of the climate regime (HIRATA; VARNIER, 1998). This use is already important, which becomes explicit when analyzing the uses available in the official databases. In 2015, the largest number of valid grants were to the urban and rural supply sector, followed by manufacturing (Figure 26 A) (ANA, 2016). However, when analyzing the average extraction flow among users (relative to the number of grants/flow), we note that the main user was agribusiness (48.6 m^3/h), followed by manufacturing (20.86 m^3/h) and supply (17.89 m^3/h) (Figure 26 B) (ANA, 2016). In other words, proportionally considering, rural users use greater amounts of groundwater than other sectors. Intense irrigation can compromise the base flow of rivers and harm several ecosystem services, which demonstrates the need to promote studies on this topic, still little explored by national literature (ALY JÚNIOR, 2019).

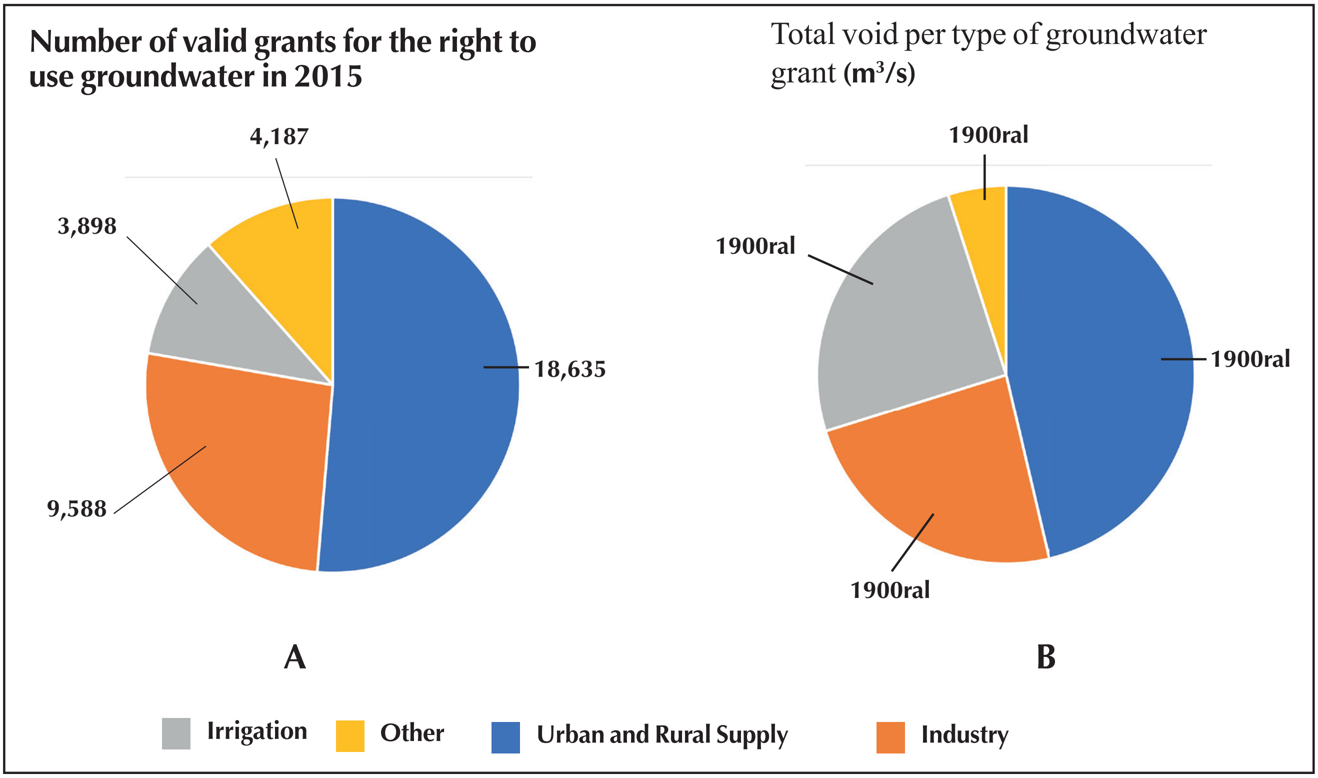


Figure 26 – (A) Number of valid grants of the right to use groundwater; (B) Total flow by type of grant of the right to use groundwater (m^3/s) (2015)

Source: Hirata *et al*. (2019, p. 50).

Groundwater is also critical to the manufacturing industry. In the group of wells of SIAGAS, this sector represents only 10% of users, however, within the scope of grants of right to use, it constitutes 25%, with an average flow slightly higher than the supply. Several manufacturers use this source, even in areas equipped with a water network infrastructure, as a way to save money and have their own source of input (HIRATA *et al*., 2019). Furthermore, we cannot forget its use by the beverage and mineral and drinking water industry.

The use of groundwater tends to intensify due to the increase in the demand for water resulting from the growth in consumption, increase in population, increase in exports of agricultural commodities, degradation of surface water sources, increased periods of drought, the need to meet the target the universalization of water and the problems arising from global climate change, which tend to affect surface waters more (HIRATA; CONICELLI, 2012).

2.6 THE ENVIRONMENTAL ROLES OF GROUNDWATER IN THE HYDROLOGICAL CYCLE

Groundwater in the hydrological cycle provides several ecosystem services, as they are linked to the processes that regulate the volume, distribution and quality of water available on the planet. The concept of ecosystem services and their relationship to aquifers and groundwater are detailed in Box 9. The importance of these resources goes far beyond the supply of water to human beings. Among its multiple ecosystem functions, the following stand out: *a)* storage, regularization and perpetuation of the hydrological cycle on the planet; *b)* treatment of the soil-aquifer system and groundwater quality; and *c)* maintenance of life and ecosystems.

Box 9 – Ecosystem Services (SEs) of aquifers and groundwater

Osvaldo Aly Júnior

The term Ecosystem Services was introduced by Erlich and Erlich (1981), adopted by ecological and environmental economics from the 1990s onwards (GÓMEZ-BAGGETHUN *et al*., 2010). SEs are defined as assets and benefits provided free of charge by ecosystems to human beings, promoting their well-being (BERGKAMP; CROSS, 2015). Its origin is based on the different roles in natural systems that form a complex relationship that supports human life. This concept considers that there is a positive correlation between human well-being and environmental well-being. Several studies seek to identify and monetarily quantify its importance and role.

The United Nations Environmental Program (UNEP) released the Millennium Ecosystem Assessment Report (MEA, 2005) which considered the "ecosystem (as) a complex made up of plant, animal, microorganism communities and their respective environment that interact as a functional unit." The SEs result from the interactions between the different ecosystem functions and may result from one or more functions, moreover, an ecosystem function may generate more than one ecosystem service (CONSTANZA *et al*., 1997).

MEA considers human beings to be those who integrate and interact with ecosystems, directly and/or indirectly interfering with its functioning. The concept of SE can be subdivided into four categories: *i*) *regulation*, relative to the regulatory characteristics of ecosystems; *ii) provision*, relating to "products supplied, obtained or extracted from ecosystems", including water; *iii) support*, understood as "services necessary for the production of other ecosystem services"; and *iv) cultural*, which comprises the "intangible benefits that people obtain, including cultural diversity, religious and spiritual values, knowledge, educational and aesthetic values etc.." (MEA, 2005).

Groundwater is essential for maintaining the good health of ecosystems and the quality of human life. In addition to being a source of supply and productive input for industry, services and agriculture, many SEs have a direct connection with the storage of groundwater, its recharge and recharge or discharge. These waters allow the storage of rain and water-thawing, in addition to fulfilling an important environmental function by providing the base flow of rivers, lakes and wetlands, ensuring the integrity of these terrestrial, aquatic and estuarine ecosystems, especially in periods of drought. These waters are still associated with culture and tourism and are recognized for their therapeutic, medicinal or even scenic beauty properties.

Consequently, groundwater guarantees geological stability, since by maintaining the structure of the aquifer pores, they prevent the subsidence of land and cave ecosystems. Aquifers, on their turn, sustain part of the landscape, biodiversity and watersheds, which includes riparian areas, terrestrial ecosystems and the tops of watersheds. Moreover, in some regions they allow the production of geothermal energy. Figure 27 summarizes the main SEs provided by these waters (GRIEBLER; AVRAMOV, 2015).

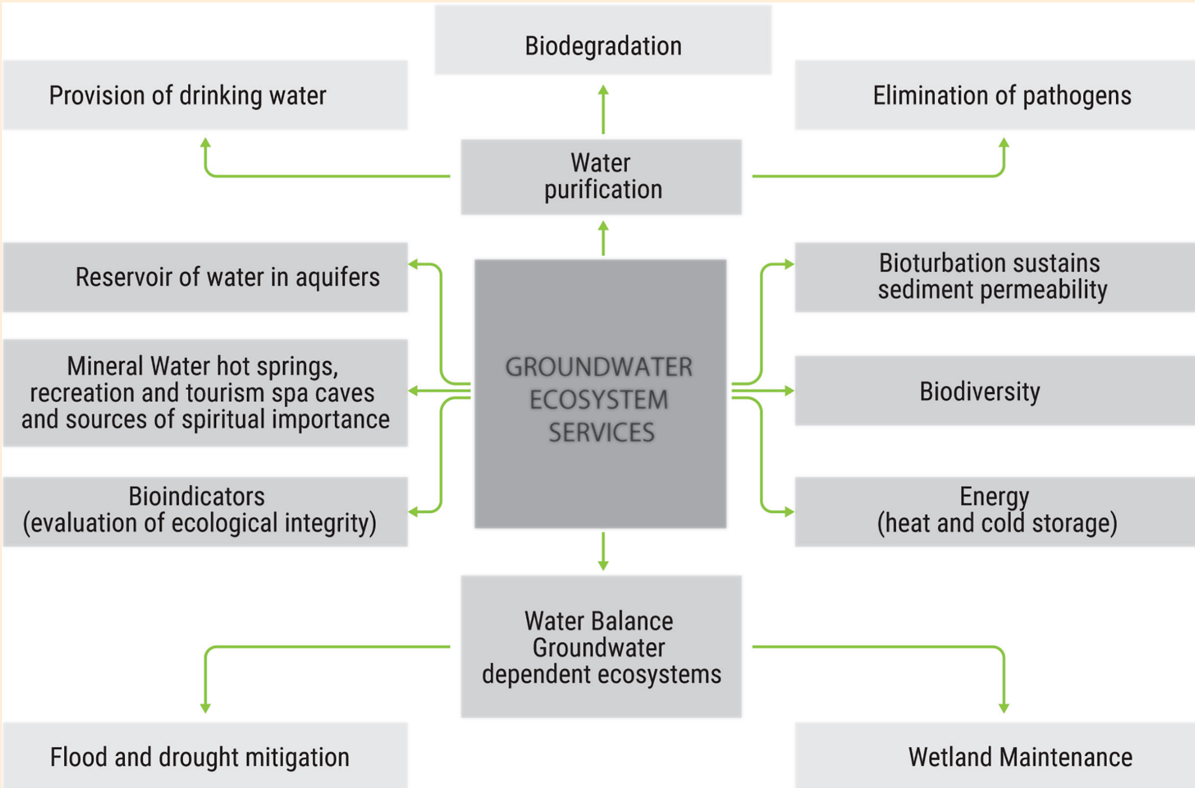


Figure 27 – Main ecosystem services provided by groundwater
Source: Griebler and Avramov (2015, page 356).

Groundwater sustains SEs that are essential for the life and well-being of the population and ecosystems. Despite that, human activities have generated serious impacts (contamination, overexploitation, waterproofing, changes in the climate regime etc.), which threaten its continuity. The more complex and technologically advanced human societies are, the more the unrealistic notion of their independence from natural systems develops. Currently, the consumption of SE is on an unsustainable scale and interferes with the functioning of ecosystems.

The scenarios studied by MEA (2005) reveal the need to improve public policies, institutions and ways to mitigate the negative consequences of pressure on ecosystems. Brazil should estimate the importance of SE provided by aquifers for different types of use, as well as intensify actions for their conservation and sustainable use to ensure that such SEs are maintained.

2.6.1 Perennialization and regularization of the hydrological cycle on the Planet

Groundwater functions as water reserves for rivers and lakes, as it is continuously contributing to the maintenance of the surface flow, which sustains most water courses. The rates of discharge from aquifers are more regular than the distribution of precipitation, which ensures a constant minimum flow to surface water courses, providing stability to water systems. Therefore, aquifers have a regulatory function of the hydrological cycle in hydrographic basins and even on a planetary scale. In Brazil, more than 90% of watersheds have rivers fed by groundwater discharge (ANA, 2017b, p. 37), which is responsible for the rivers' perennialization, even in places where there are climatic regimes with dry periods. This service extends to lakes, swamps and mangroves. Despite these characteristics, it is necessary to assess how climate change may affect these resources (Box 10).

2.6.2 Treatment of the soil-aquifer system and the excellent quality of groundwater

The water that percolates into the aquifer goes through a process similar to that of a filter along its underground path. During infiltration and percolation in soils, part of the water and dissolved substances is absorbed by plant roots and adsorbed to solid particles. Throughout the hydrogeological cycle, water acquires different chemical characteristics, which vary according to the proportion and type of dissolved solids. The amounts of chemical elements in groundwater depend on the climate in the recharge areas, the chemical conditions of the vadose zone, and the geology of the groundwater system through which it flows. The interaction of water with the particles of soils and rocks, normally, allows its enrichment due to the dissolution of minerals. This process tends to increase with the time of interaction between water-rock and the reactivity of the solid material itself. In many cases, the journey to the discharge points results in water of excellent quality and rich in mineral salts. In others, however, the dissolution of these minerals can generate quality problems, including natural anomalies that can compromise the potability of the water.

2.6.3 Maintainer of life and ecosystems

The supply of water from aquifers is essential for the maintenance of ecosystems, especially in areas where there is interaction between groundwater and surface water. Groundwater discharges into surface water bodies contribute to the maintenance of surface water flows, the regulation of water temperature, the exchange of nutrients and other hydrochemical parameters, influencing the balance of conditions that allow for life of animal and plant species.

Groundwater does not show sudden changes in temperature or in its physical-chemical qualities, so the underground inflow provides a stable habitat for aquatic plants and animals. Furthermore, the discharge of aquifers is essential to maintain coastal lagoons and mangroves, as it allows to dilute the salinity of marine influences, distributes nutrients and regulates physical-chemical conditions.

Even in cases where there are no outcrops, groundwater is relevant to ecosystems. For example, despite the absence of water courses and springs, it is common to find lush vegetation on the bottom of the valleys. This is explained because the water table in a valley is closer to the surface and the water level does not fluctuate as much. In the absence of rain, the water level in the higher parts drops considerably, but in the valleys there may be no variation, as the water infiltrated in previous rains is still moving slowly towards it (POETER *et al.*, 2020). That way, vegetation has access to water throughout the year.

These waters also support extensive semi-arid and humid terrestrial ecosystems without water mirrors, but with deep-rooted vegetation, which extracts moisture directly from the water table. In the Cerrado Region there are found several species that have developed deep roots to absorb water from aquifers. There is also a whole flora and fauna associated with hydrothermal springs, which are the places where the heated and mineral-enriched waters emerge from a long underground path.

Finally, groundwater contributes to geological stability, as it ensures the maintenance of the pore structure of rocks, preventing or reducing the risk of subsidence of land or cave ecosystems.

Box 10 – Climate change and groundwater

Adivane Terezinha Costa

Global Climate Change (GCC) refers to significant changes in the hydrological cycle, rainfall regime, temperature, evaporation and humidity in relation to the historical values of a region (HIRATA *et al*. 2019). These changes are associated with the warming that the planet has been experiencing as a result of increasing greenhouse gas emissions derived from human activity, especially in the last three decades (IPCC, 2018). Changes in the hydrological cycle caused by GCC interfere in the entire process of recharge of springs, whether surface or underground, and can generate direct impacts on groundwater, such as the reduction of aquifer recharge, and indirect, through the reduction of supply of surface water, inducing a greater exploitation of groundwater (more well drilling), which can culminate in the overexploitation of aquifers, if there is no efficient strategic planning in place.

Smerdon (2017) presents a synopsis of articles published between 2011 and 2016, where he makes several mentions about the state of climate change and groundwater, considering future predictions of recharge conditions. Studies indicate that the distribution uncertainty and the trend in future precipitation of the most used climate models, such as the General Circulation Models (GCMs), result in varied recharge predictions. Modeling studies are often unable to predict the magnitude and direction (increase or decrease) of future recharge conditions because the GCMs themselves are not unanimous. Despite this fact, these studies indicate that the regions most sensitive to climate change will be mountain areas and arid zones, where subtle changes in the timing and duration of seasonal climate can significantly change recharge levels.

Brazil is vulnerable to current climate changes and even more to those that are projected into the future, especially regarding climatic extremes, with forecasts of heavy and intense rains during the wet season and reduced and spatially irregular rainfall in the dry seasons (HIRATA *et al.*, 2019). According to Marengo (2008), climate projections indicate that in the Amazon and in the Northeast rainfall may be reduced by up to 20% at the end of the 21st century, in a scenario of high emissions. As a result, southern Brazil will experience an extreme increase in rainfall.

These climate changes can act as an additional source of pressure for the demand for water for consumption and irrigation, which impacts the socioeconomic sector. In this context, cities dependent on underground resources are more resilient to drought and are better able to face the challenges posed by global climate change (HIRATA *et al*., 2019) although the risk of overexploitation is underscored.

In regions subject to long dry periods, such as the Brazilian semiarid region, the critical situation of emptying reservoirs has been overcome with the implementation of alternative water supplies, especially groundwater. In response to seven years of drought, the state of Ceará drilled more than three thousand wells between 2015 and 2018, exclusively to supply populations in cities and rural areas (TEIXEIRA, 2018). Projections for 2050, according to IPCC and INPE reports (MARENGO, 2008), indicate that the semiarid region tends to become more arid with climate change, increasing the frequency and intensity of droughts and reducing the availability of water resources.

It is worth noting that in Brazil there are still few studies on forecasts regarding the impacts of climate change on groundwater, including how these impacts will affect the relationship between surface waters and aquifers, which are hydraulically connected (KUNDZEWICZ *et al*., 2007; PBMC, 2014).

According to the report of the Brazilian Panel on Climate Change (PBMC, 2014), future perspectives regarding the impacts of climate change on groundwater resources in Brazil indicate that the Northeast could have a 70% reduction in recharge by 2050 (DÖLL; FLÖRKE, 2005; PBMC, 2014). In the Guarani Aquifer System, forecasts indicate that almost 70% of the climate scenarios generated variations in groundwater levels below those measured in monitoring between 2004 and 2011 (MELO, 2013).

Studies carried out point to climate change as possible causes of problems related to the variability, availability, quantity and quality of water resources. In this context, it is projected that the poorest populations are the most vulnerable, as they are exposed to water scarcity. Faced with future uncertainty regarding the availability and demand of groundwater and the possibility of more frequent and severe extreme hydrological events, it is important to have technical capabilities aimed at the elaboration of an integrated map of vulnerability to climate change, adequate planning and instruments cooperation between entities from different levels and sectors, in addition to broad dissemination of the theme to society.

2.7 THREATS TO BRAZILIAN UNDERGROUND WATER RESOURCES

Aquifers, although more protected than surface water bodies, are also subject to impacts resulting from excessive use of water and human activities, presenting problems related to quantity, such as overexploitation or reduced recharge; and as for quality, such as contamination.

2.7.1 Overexploitation of aquifers

The extraction of water from an aquifer generates its lowering and modification in the hydrodynamic flow of recharge and discharge and, in some cases, changes in the geochemistry of its waters. The consequences of overexploitation are not immediately noticeable, but appear over a period of time which varies according to aquifer dimensions, storage capacity and the usage scenario. The storage potential of aquifers makes long-term storage possible through extraction of groundwater, even in periods of drought, without generating a scenario of overexploitation.

Hydraulic and chemical changes in aquifers take years or decades to be noticed by users or the Government. For this reason, it is necessary to monitor these extractions to prevent them from generating externalities, whose recovery can be complex, costly and time-consuming to reverse.

The lowering of the water level of the aquifer by itself does not characterize a situation of overexploitation, but it materializes when the impacts of extraction cause financial, ecological or social losses that cannot be compensated by the benefits of exploitation. This term comprises various phenomena and impacts caused by extraction or changes in recharge, which reduce water availability, harming users or the environmental and social roles of groundwater. Despite being considered imprecise by the scientific community, the term overexploitation is widely used by managers due to its ability to convey to society the idea that the aquifer is at risk (CUSTÓDIO; LLAMAS, 2001).

Overexploitation can affect part of an aquifer or the entire system. This phenomenon goes beyond a problem between balance and water withdrawal superior to recharge, as it comprises a series of negative effects. Due to the low velocity of the underground flow, the evaluation of the effects of overexploitation can take years to manifest, despite its causes having occurred a long time ago.

In the case of fossil aquifers, that is, those where water restitution in the exploited portion is greater than tens of thousands of years, overexploitation is inevitable, as the loss of level will be determined by the rate of extraction. Therefore, it is necessary to plan its use, considering whether the socioeconomic gains of the extracted water compensate for the depletion of the aquifer in the long term and its loss for future generations (FOSTER *et al.*, 2002).

If overexploitation is a problem, the abandonment of wells and their exploitation can also generate negative impacts relative to the rising of the water table level. When the exploitation of an aquifer is reduced, water levels recover the original situation or even exceed it, as cities can increase recharge levels due to water losses from the water and sewage network. Many buildings, canals, tunnels, galleries and the subway network have underground structures that were built when those portions were dry (unsaturated zone), requiring water to be drained. If the foundations of buildings were built on dry ground, the resumption of the water table causes their vertical movement, which can impact structural stability. The reestablishment of this natural condition ends up generating a series of losses that will befall the owners of the asset or infrastructure.

Unlike surface waters, it is not possible to directly visualize the processes that occur inside the aquifer. Therefore, the challenge of its management is to measure and establish when its exploitation is considered harmful enough to characterize it as such. Overall, overexploitation is understood as changes in the hydrological cycle that cause one or more of the following impacts:

a) **reduction of aquifer levels through water extraction**. The withdrawal of water can deplete the aquifer, that is, create such a pronounced reduction in potentiometric levels that it no longer allows its use, either because of the excessive hydraulic difference (head height) to be overcome by the well pumps, or because of the reduced saturated thickness of the aquifer, which prevents pumping, or even the elimination of natural sources and surges;

b) **reduction in water contribution from base flows in surface water bodies**. The decrease in water input damages the availability of surface water and dependent ecosystems, such as rivers, lakes, swamps and mangroves;

c) **increase in water exploitation costs due to the lowering of the dynamic levels of the wells and/or the adjustment of extraction infrastructure**. In this case, the origin may be: a) the imbalance between aquifer recharge and long-term extraction (decades); or b) interference between wells, whose proximity causes hydraulic interference and strong drawdowns. Extraction costs are more associated with pumping, which requires energy to bring water from the aquifer to the surface than to the work itself. Despite this, the design of a well must be compatible with the flows to be exploited, therefore, reductions in the water level can render extraction unsuitable for this purpose. If the extraction costs exceed the economically acceptable levels for a given situation, the aquifer is considered to be overexploited;

d) **loss of shallower wells or springs preventing equitable access to water**. The use of groundwater through dug wells or even shallow driven wells, by poor and socially vulnerable populations is a common practice in rural areas or urban-perimeter regions. In many cases, they constitute the only source of water available to guarantee the water and food security of these populations. Depending on the hydraulics of the aquifer, the installation of deep wells of high production can cause the lowering of the water level and dry the shallower wells and springs. In most cases, the deepest well is legalized, unlike other well users, however, this use can generate a problem of social inequality and violate the principle of multiple uses of water. It is common for owners of wells that have dried up not to correlate the loss of the well with the overexploitation of the aquifer;

e) **land subsidence**. The use of some aquifers, such as those associated with karst or sedimentary systems, can create land subsidence and impact civil works, causing social and economic damage, such as the collapse of buildings and changes in urban water flows;

f) **infiltration of contaminated or saline water into the aquifer due to excessive pumping or reduced recharge**. The extraction of water from an aquifer or even human occupation of the surface changes the hydrological cycle, modifying recharge rates and subsurface flow directions. In some cases, these changes can bring low quality water to aquifer use areas. For example, pumping from wells induces contaminated water from groundwater aquifers or rivers to enter the aquifer. Contamination by the induction of low quality water through pumping must be faced with the control of the operation and exploitation of wells; and

g) **saline intrusion into coastal aquifers**. In coastal aquifers in equilibrium, there is a hydraulic gradient conditioning the flow of fresh water from the continent to the ocean. This flow can be reversed due to the characteristics of tidal and climate variations, for example, mixing fresh and salt waters. This water mixture is conditioned by hydrodynamic dispersion, with fresh water, less dense, tending to flow closer to the surface, while the denser saltwater advances towards the aquifer, forming a saline wedge (FEITOSA *et al.*, 2008). Excessive extraction of coastal aquifers allows the advance of the saline wedge towards the continent, as the pumping reverses the flow directions of these waters, causing a hydrodynamic imbalance in the system and compromising the quality of aquifer waters. This process is detailed in Box 11.

Box 11 – Saline intrusion into coastal aquifers

Roberto Eduardo Kirchheim

Excessive extraction of groundwater in coastal areas, close to the coastline, can promote a decrease in freshwater discharges in coastal ecosystems and the advancement of saline intrusions (in the form of wedges) into the aquifers. The existence of fresh water discharge towards the sea is what limits the advance of these intrusions inland.

Saline intrusion is defined as the movement of salt water into freshwater saturated aquifers. This scenario is reported in several coastal regions, being the object of studies around the world over the last 50 years. This is a situation complex and costly to reverse that inevitably leads to the abandonment of the extraction infrastructure. Salt water has high concentrations of Total Dissolved Solids (TDS) and inorganic constituents, which makes it unsuitable for human consumption and other human uses.

Under natural conditions of the coastal aquifer, there is a hydrodynamic balance between the fresh waters that are juxtaposed on salt and dense waters. In simple terms, the thickness of the freshwater column above the saltwater interface can be estimated as a function of the ratio between the respective densities (Ghyben and Herzberg relation) (KRESIC, 2006) (Figure 28). This expression can be summarized by the equality ($z=40$ h), i.e., for every 1 m of freshwater column above sea level there are another 40 m of water column between sea level and the interface with salt water. If the height (h) decreases, it becomes evident that the line that limits this interface ends up rising to maintain this balance.

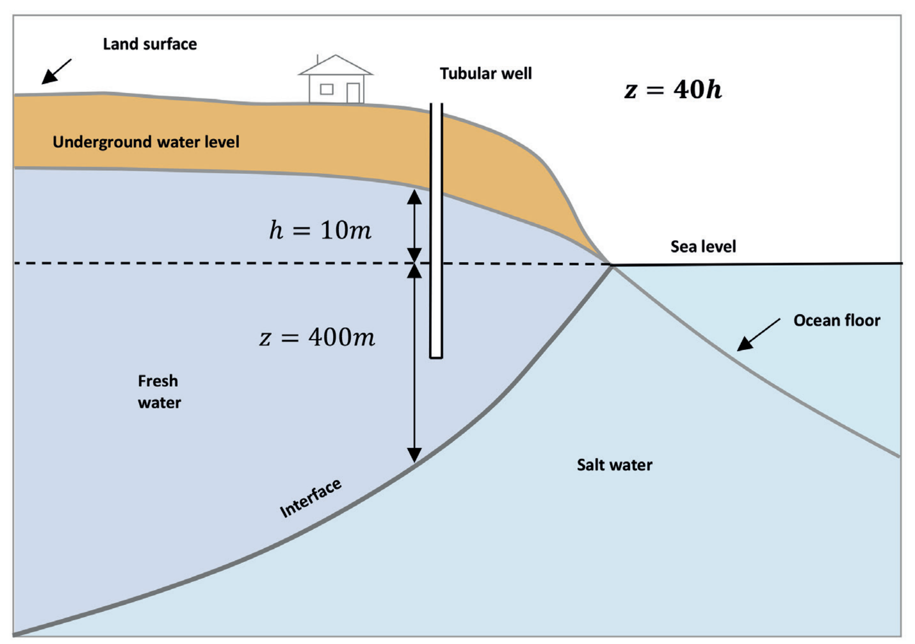


Figure 28 – Schematic illustration of the hydrostatic relation between fresh water and salt water in a coastal aquifer
Source: Kresic (2006), adapted by Roberto Eduardo Kirchheim.

Although quite valid as a first mathematical approximation, this equation adopts a simple scenario of isostatic equilibrium and no advective water motion. The true dynamics of groundwater in coastal regions, however, implies the discharge of fresh groundwater with percolation velocity, creating a true transition zone in which the waters mix through mechanisms of dispersion and molecular diffusion. This mix is caused and influenced by heterogeneities in the geometry and hydraulic properties of the aquifer, as well as by dynamic forces operating at various time scales, such as daily tidal effects, seasonal and/or annual variations in recharge rates in coastal aquifers, or variations in shoreline position. These dynamic forces move the entire mixing range between fresh and salt water from one side to the other. When the natural conditions of a coastal aquifer are altered due to pumping, the position and shape of the sweet-salt interface, as well as the geometric properties of the mixing zone, change in three dimensions, resulting in saline intrusions. The presence of multi-layered aquifers and discontinuous aquitards, associated with extractions from different aquifers with different depths, makes the space and time relations between fresh and salt water complex.

Technical literature suggests a series of methodologies aimed at diagnosing intrusion scenarios, from geological, geochemical and geophysical surveys to demarcate the salt and freshwater interface to the use of isotopic tracers and mathematical modeling techniques. All of them lack the results of systematic monitoring of levels and quality. Several mitigation techniques can be employed, involving artificial recharges, rearrangement of production wells and conformation of hydraulic barriers.

The coastal zone of Brazil has the highest population densities and high demand for water resources; nevertheless, diagnostic studies, monitoring and mitigation of saline wedges are incipient. The coastal zone in the state of Rio de Janeiro and some capitals in the Northeast region have studies that, at least, involved stages of diagnosis and modeling of salt wedge advance. The scenario in Recife stands out, and it is being examined by the Coqueiral Project, which involved several national and international institutional actors, such as: CEPAS (IGC- USP), EESC-USP, UFPE, SGB-CPRM, Geohyd, CeRIES and BRGM (Figure 29).

The extraction of water to supply the Metropolitan Region of Recife (RMR), which forms the fourth largest Brazilian population cluster, with 3.7 million inhabitants, resulted in a significant drop in the potentiometric levels of aquifers, their salinization and contamination (HIRATA *et al.*, 2012). Degradation is linked to the increase in water demand, occasionally amplified by periods of drought, as well as the fact that thousands of tube wells are not legalized and operated by private users (HIRATA *et al.*, 2012).

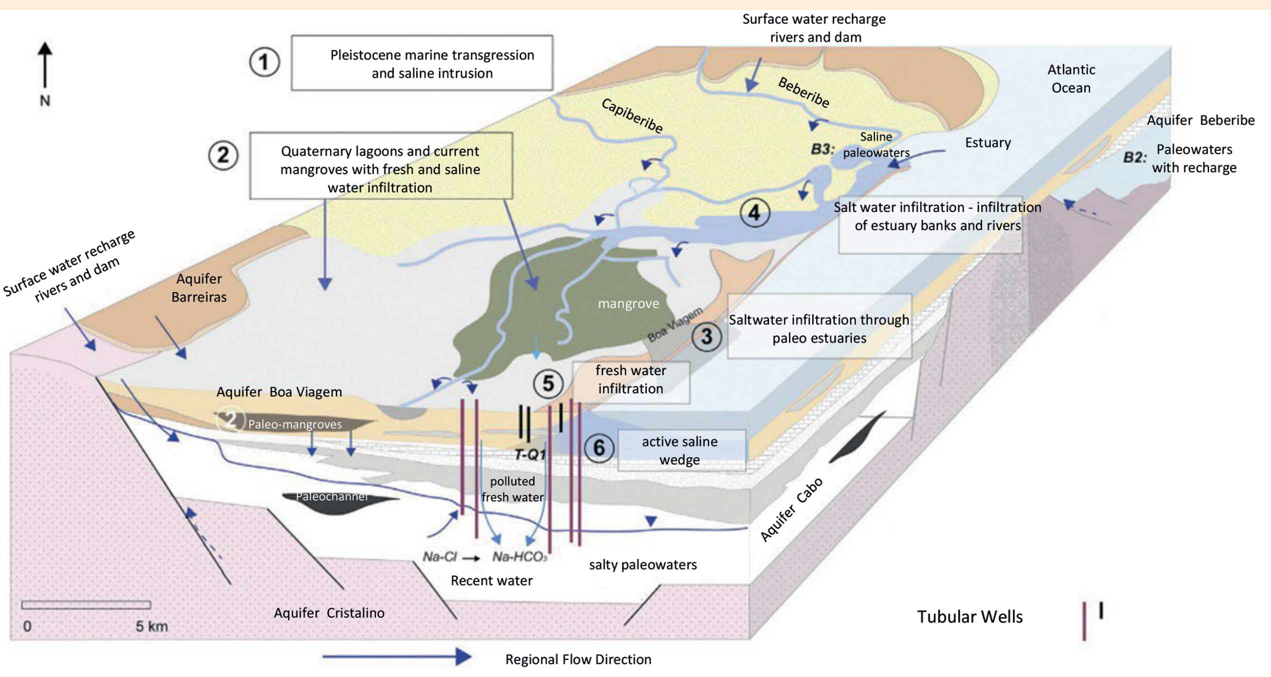


Figure 29 – Conceptual model of the RMR aquifers and their various salinization processes
Source: Cary *et al.* (2015).

The dependence on groundwater in the region is known, with wells drilled in the Aquifer System of the Planície do Recife (SAPRe), composed of Beberibe and Cabo (contained) and Boa Viagem (phreatic, overlapping the previous ones). Since 1970, there has been an increase in the levels of salts in SAPRe (COSTA FILHO *et al.*, 1998; COSTA; COSTA FILHO; MONTEIRO, 2002; MONTENEGRO *et al.*, 2010). The main regional salinization processes (Figure 29) found in the region are: *i)* past marine transgressions;

ii) the presence of quaternary mangroves where seawater and freshwater evaporate and mix before infiltration and interaction with clays and organic matter; *iii)* paleo-estuaries as preferential routes for the intrusion of current seawater into the surface aquifer; *iv)* a current estuary that favors the mixing of sea water and fresh water and the infiltration of the river banks; *v)* infiltration of fresh water from the surface; and *vi*) the current seawater intrusion into the surface of Boa Viagem aquifer.

2.7.2 Contamination of soil and groundwater

Contamination of soil and aquifers occurs mainly through incorrect disposal of effluents and solid waste, handling and storage of hazardous substances or accidents. The unsaturated zone represents the first line of natural defense against pollution and has a certain ability to attenuate and eliminate pollutants (FOSTER; HIRATA, 1988). Despite this, several activities generate contaminant loads that exceed the retention and degradation capacity of the unsaturated zone, leading to soil and groundwater contamination. According to Foster and Hirata (1988), contamination can be:

a) **punctual**: when the source of contamination is restricted to a small area, which facilitates its identification, extension and monitoring, for punctual contamination usually causes plumes of reduced extension and high concentrations. These are the typical cases of areas of sanitary landfills and dumps, buried tanks, effluent ponds, piles and deposit of hazardous products, among others; and

b) **diffuse or multi-point**: when the source of contamination extends throughout the territory and the pollutants are released in a sparse way, the pollutants become difficult to identify since well-defined plumes of contamination are not perceived. In this case, there are agricultural areas which have excessive application of pesticides and fertilizers, urban areas with leaks in sewage networks or that use rudimentary and septic tanks, among others.

Potential sources of contamination may be related to activities in the urban, urban-perimeter or rural region, including those resulting from the urbanization process, the deposition of solid and liquid waste, manufacturing, mining, agriculture and livestock. In principle, all human activities that generate, handle or store hazardous products can contaminate groundwater. Among these activities, however, there are those that can cause greater impacts or are more frequent (FOSTER; HIRATA, 1988; FOSTER *et al*., 2002). It is incumbent on management to identify, distinguish and classify these anthropic activities, allowing public bodies and society to set their policies.

There are few publications on the subject, however, Foster and Hirata (1988) and Foster *et al*. (2002) emphasize that polluting activities are not necessarily linked to large enterprises. Occasionally, small enterprises can generate even greater concern, as they handle dangerous products without the necessary control and are responsible for major impacts. This is the case of the Industrial District of Jurubatuba (São Paulo), detailed in the case gallery addressed in Chapter 4. In this region, an enterprise with just over hundreds of square meters generated serious contamination, for it handled chlorinated solvents (such as degreasers for the production of batteries) without proper care. For this reason, the contaminating potential of the activities must be analyzed mainly from two aspects: *a)* the type of product produced, handled and stored; and *b)* if the entry into the soil is made with some associated hydraulic load as there is no way for a contaminant to enter the aquifer if not through fluid.

Contaminants must be analyzed based on their toxicity, mobility and persistence in the subsurface. Chlorinated solvents have these characteristics and are therefore problematic. Nitrogen, although it has low toxicity, has a wide occurrence, which makes it a challenge to management. It is present in fertilizers used in agriculture and in domestic effluents that seep into the aquifer, via septic or rudimentary tanks, and via leaks from the sewage system.

Brazil has a particularly vulnerable situation in relation to the lack of sanitary sewage, with 39% of the generated sewage not being collected; 12% are destined for individual in situ treatment systems (septic tanks); and 27% are released mostly into the ground through rudimentary pits and sinkholes (99%) or into surface waters (1%) (HIRATA *et al*., 2019, ANA, 2017b, IBGE, 2008). In areas with sanitation infrastructure, there is a lack of maintenance of sewage networks which allows the leakage of expressive volumes that can exceed 10% of the total sewage collected (HIRATA *et al.*, 2019).

Although Brazil is a country with thriving agricultural activity and uses large amounts of inorganic fertilizers and pesticides, there are no systematic studies evaluating the impacts or occurrence of this type of contamination even in the academic environment. The application of nitrogen fertilizers is the main cause of agricultural contamination in North America and Europe, which report countless cases of extensive contaminated areas.

Another problem is that the wells or extractions are built without following technical standards, their location is inadequate (close to potential sources of contamination) or they are not properly maintained, which can lead to aquifer contamination. Technical diligence prevents, for example, microbiological pollution, which is very common in wells installed close to pits. The well, therefore, must be located at safe distances from potentially polluting sources, recommending the adoption of well protection perimeters, as well as periodic chemical analysis.

In Brazil, information concerning the situation of contaminated areas is scarce. The National Database on Contaminated Areas (BDNAC)[6] only has information concerning the states of Minas Gerais, Rio de Janeiro and São Paulo.

2.7.3 Reduction of aquifer recharge due to changes in land use and occupation

Changes in urban and rural land cover patterns directly affect groundwater recharge, as they influence rainfall distribution, temperature, surface outflow, evapotranspiration and aquifer recharge (TANG *et al.*, 2005). The main causes of these changes in aquifer recharge are related to the following aspects: *a)* sealing by impermeable surfaces (JACOBSON, 2011); *b)* compression (PITT *et al.*, 2003); and *c)* reduction of tree coverage (ANDJELKOVIC, 2001). Sealed areas are more present in urban areas and include all paved and edified spaces with structures built for preventing water infiltration. Compaction is the affectation of the physical properties of the soil, to reduce its porosity, being caused, for example, by the movement of earth or the passing of heavy machinery. The reduction of tree coverage causes impacts related to the loss of evapotranspiration, changes in the albedo of the land surface, the increase in temperatures and the intensification of erosion and desertification processes (TANG *et al.*, 2005). Moreover, forests prevent soil disturbances, and their roots and associated ecosystems contribute to improving the porosity of the land (ARTAXO, 2014; AZEVEDO, 2019). In cities, eventually, there may be compensation for the loss of natural recharge due to leaks in the water, sewage and rainwater drainage network (HIRATA; FOSTER; OLIVEIRA, 2015).

6. BDNAC was implemented by Coname Resolution 420/2009. For more information, see: http://ibama.gov.br/residuos/areas-contaminadas/banco-de-dados-nacional-sobre-areas-contaminadas-bdnac.

Box 12 – The importance of forest cover in aquifer recharge: lessons learned in the Alter do Chão Aquifer System

Júlio Henrichs de Azevedo
José Eloi Guimarães Campos

Tropical ecosystems are related to the control of infiltration, evapotranspiration and recharge rates under different rainfall conditions in tropical regions (KRISHNASWAMY *et al*., 2013), and this a topic that requires deeper study in Brazil, particularly in the Amazonian region (CARVALHO, 2012). The dense rain forest, which covers more than 80% of the formation of the Alter do Chão Aquifer, plays an important role in maintaining the rainfall regime, in regulating infiltration and in maintaining the recharge rates of this aquifer (CARVALHO, 2012). The loss of water by evapotranspiration, normally subtracted from the balance of the recharge rate of an aquifer (HEALY, 2010), ends up being compensated by the tropical forest, which has the role of optimizing the infiltration processes (fast flow) to the detriment of surface outflow, and maintain the rainfall regime.

Research by Azevedo, Freitas-Silva and Campos (2020) and Azevedo and Campos (2021) on circulation patterns and quantification of water recharge in the Alter do Chão Aquifer System, from bauxitic lateritic plateaus, developed in the Saracá National Forest -Taquera, in Porto Trombetas, Oriximiná/PA (Figure 30), based on potentiometric, hydrochemical, isotopic, pedological and structural geology studies, which are established tools for the studies of groundwater flows (JIE *et al*., 2011; GASTMANS; CHANG; HUTCHEON, 2010; HEALY, 2010; FEITOSA *et al*., 2008); these studies substantially corroborates the importance of vegetation cover in controlling the recharge of the Alter do Chão Aquifer.

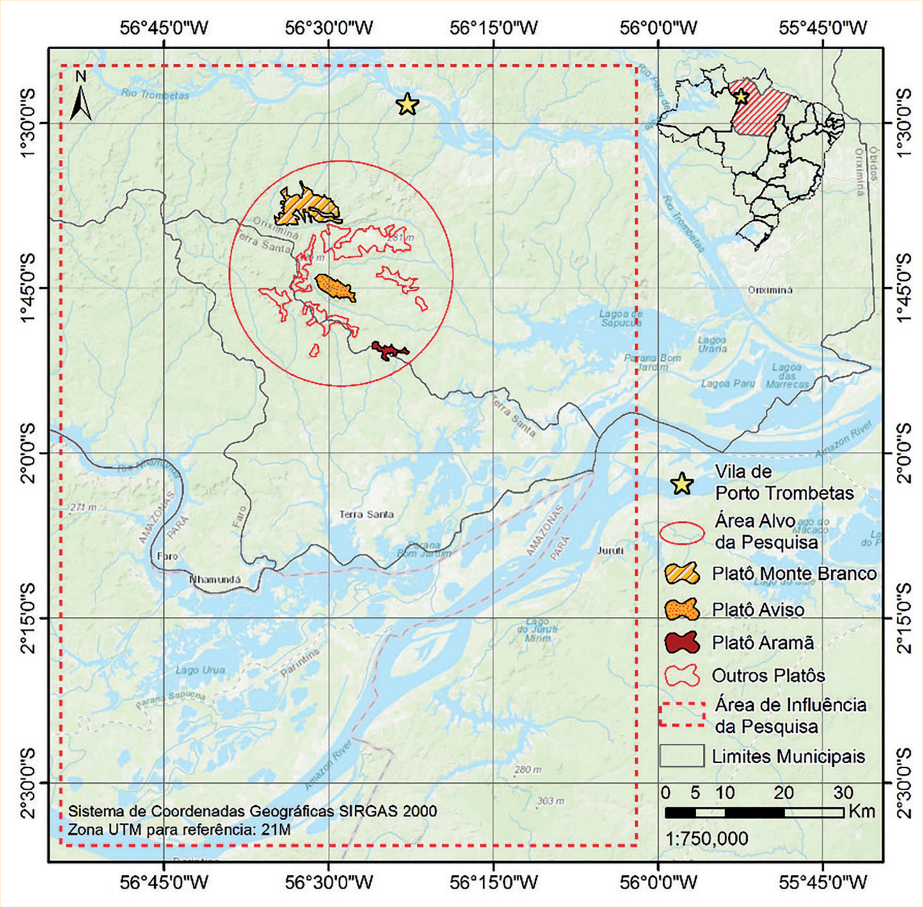


Figure 30 – Areas surveyed in lateritic plateau environments of the Alter do Chão Formation
Source: Azevedo, Freitas-Silva and Campos (2020).

The mineral layers of these plateaus maintain alternating values of hydraulic conductivity, which, in principle, would limit the vertical flow of water in the profile and, consequently, the recharge of groundwater. The bioturbations promoted by the roots interact with the layers of the lateritic profiles and cause preferential flow zones, contributing to an increase in permeability. Figure 31 details the effect of bioturbation of the roots, which can reach up to 15 meters deep. In this range, the geological material presents low hydraulic conductivity (on the order of magnitude 10^{-7} m/s).

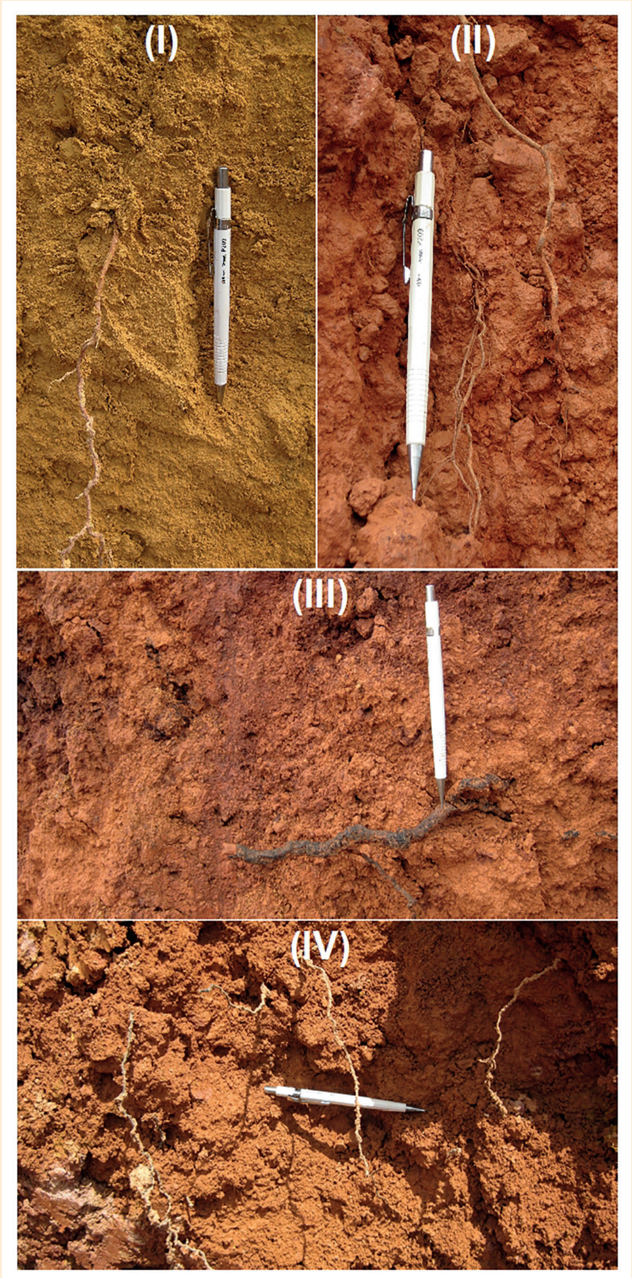


Figure 31 – Detail of the roots crossing the different layers of the lateritic profile: I – Yellow Latosol ± 4 m; II – Bauxite nodules ± 6 m; III – Solid Bauxite ± 7 m;and IV – Variegated Clay ± 15 m

Source: Azevedo and Campos (2021, p. 8).

The interpretation of the positive effects of the vegetation cover and the resulting bioturbation comes from the comparison of the potentiometric levels of three research areas and with different uses, namely: *i)* area with original vegetation cover of dense ombrophilous Forest; *ii)* area deforested for the purpose of mineral activity (bauxite extraction); and *iii)* mined area in the initial stage of environmental recovery (Figure 32). The area with original vegetation cover was the one that maintained the greatest regularity in the aquifer levels (less seasonal variation) when compared to the other areas. Regarding the recharge rate, there was no significant difference between the area with original forest cover and the area recently deforested for mining purposes. The data, however, indicate a reduction in this rate by almost 50% in areas that have been altered for a longer time (mining). And, despite being in the initial process of environmental recovery (land reconfiguration and reforestation), the areas have not yet reached the expected reestablishment of the hydrological and hydrogeological processes of the vadose zone (GRIGG, 2016).

Figure 32 – (I) Area with original vegetation coverage;
(II) Area deforested for starting the bauxite
mining activities; and (III) Area in post-mining environmental recovery process
Source: Azevedo (2019).

The hydrogeological studies conducted in Saracá-Taquera National Forest contribute to the consolidation of the understanding that groundwater recharge processes are not necessarily contingent on the responses of the physical properties of the underground environment and on the geomorphological patterns of climatic conditions, but rather on the relationships established between the environmental components of an abiotic, biotic and anthropic nature. Vegetation cover and subsurface bioturbations must be adequately considered. Figure 33 illustrates some of these relationships in the bauxitic lateritic plateau environments developed over the Alter do Chão Formation.

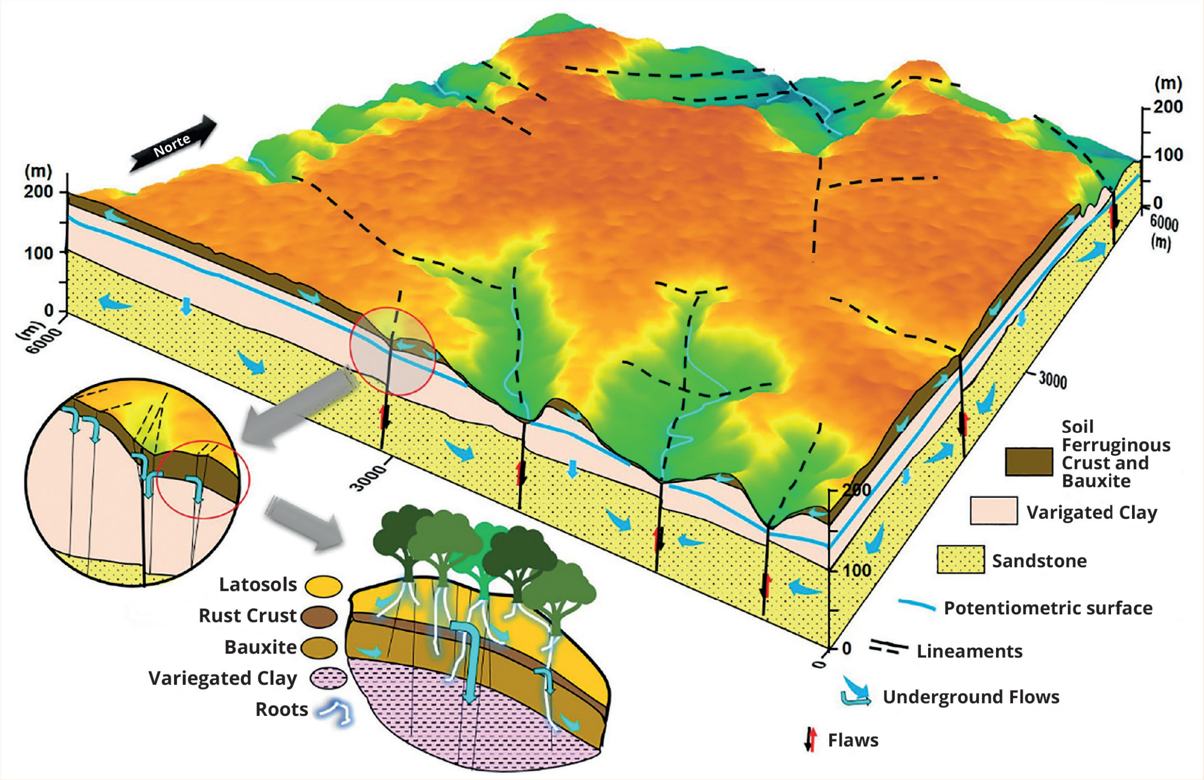


Figure 33 – Diagram block illustrating abiotic (soil and geology) and biotic factor relations (vegetation coverage, radicular systems) with effects on the hydraulic connection and on the patterns of underground flow in lateritic plateaus of the Alter do Chão Formation

Source: Azevedo, Freitas-Silva and Campos (2020, p. 59).

There are many gaps in the knowledge of recharge processes in tropical environments which, in addition to having notable scientific relevance, must be understood as strategic for the establishment of best practices for the conservation and management of aquifer recharge areas, as well as for the establishment of mechanisms increasingly sustainable management of groundwater reserves. Everything indicates that the preservation of native vegetation and the recomposition of modified ecosystems contribute to the water production not only of surface water courses, but also for uncontained aquifers or with aquifers with low degree of containment.

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Rio Roda Velha formed by springs of the Urucuia Aquifer, São Desidério (BA)

Photo: Vagney A. Augusto / ANA Image Database

Chapter 3

MANAGEMENT OF GROUNDWATER: FROM THEORY TO PRACTICE

3.1 WATER RESOURCE PLANS

The water resources plans were provided by Law No. 9,433/1997, and the constitute the main instrument for "building consensus on the hydrographic basin" (PORTO; PORTO, 2008, p. 51). The application of these plans goes beyond traditional planning, since the construction of the plan takes place through participatory processes that bring together the Government, civil society and economic agents (PORTO; PORTO, 2008). These plans are, therefore, defined by law as "master plans that serve to support and guide the implementation of the National Water Resources Policy and the management of water resources." (Article 6 of Law No. 9,433/1997).

The plans' application takes place at three levels of action: federal, state and hydrographic basin (Article 8 of Law No. 9,433/1997). Therefore, we have: *a)* the National Water Resources Plan; *b)* State Water Resources Plans; and *c)* the Hydrographic Basin Plans, which are subdivided into two categories, according to the type of basin (state and interstate): River Hydrographic Basin Plans under state control, and River Hydrographic Basin Plans under federal control (LANNA; PEREIRA; HUBERT, 2002). Each of these plans incorporates the aquifers correlated to the respective hydrographic basin. Figure 34 summarizes the types of plans according to the policy (national or state), their geographic scope and the board-based entities responsible for approving water resources planning in Brazil.

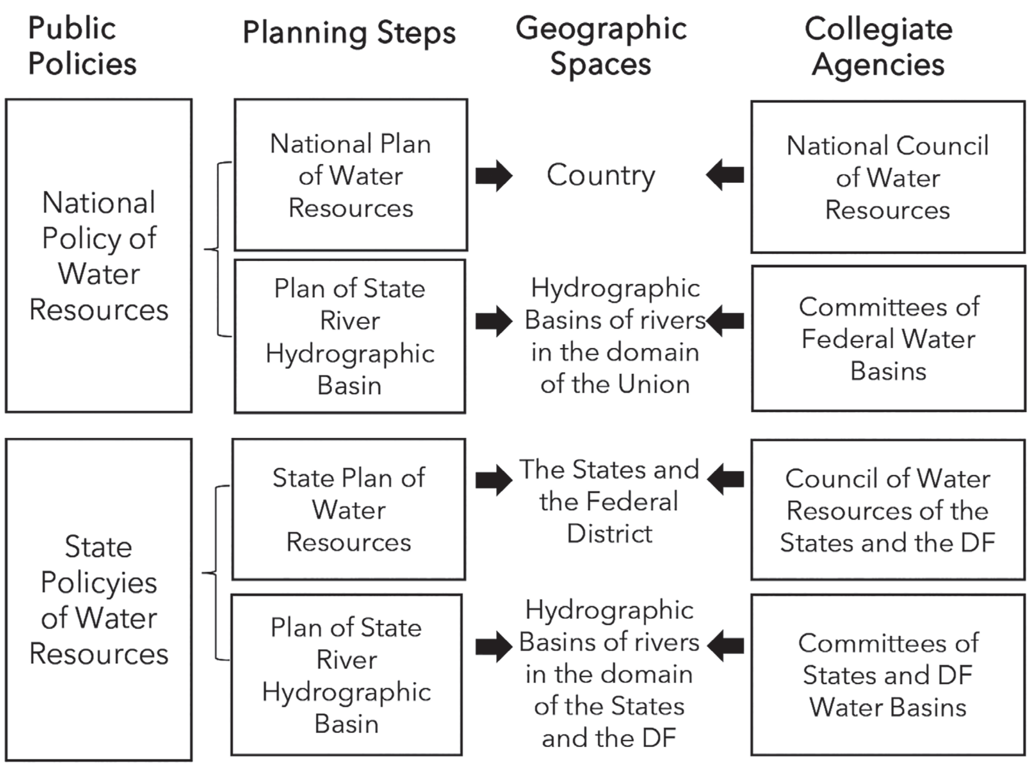


Figure 34 – Public policy, types of plans, geographic scopes and coordinating entities in the water resources planning process in Brazil

Source: Lanna, Pereira and Leite (2002, p. 110).

In the same watershed, different scales of water resources plans can coexist, as in the case of the São Francisco River Watershed (BHRSF). The National Water Resources Plan and the State Water Resources Plans, respectively, provide specific guidelines for the interstate basin and the state sub-basins of the São Francisco River. These guidelines must be observed by the water resources plans of the interstate watershed and by the state water resources management units. BHRSF is under the jurisdiction of the São Francisco River Basin Committee (federal) and the Peixe Vivo Agency, which prepared the Water Resources Plan for the São Francisco River Basin from 2016 to 2025[1]. Concurrently, the States' CBHs, made up of sub-basins of the BHRSF, operate, as is the case of CBH Velhas, which was established by the state of Minas Gerais and organized the Master Plan for Water Resources for the Rio das Velhas Basin[2].

3.1.1 National Water Resources Plan (PNRH)

The first National Water Resources Plan (PNRH) was approved in 2006 by CNRH Resolution 58, of January 30, 2006, valid until 2020 and periodic reviews every four years, hereafter referred to as PNRH 2006-2020. Since its conception, two reviews have been carried out to set priorities for the 2012-2015 and 2016-2020 cycles. CNRH Resolution 216, of September 11, 2020, postponed the expiration of this last implementation cycle to December 2021.

The National Water Security Department (SNSH), operating under the MDR [Regional Development Ministry], with technical support from ANA and in articulation with CNRH, has been debating the new National Water Resources Plan (PNRH 2022-2040), whose role is to guide the preparation of Federal, State or District Multi-Annual Plans (PPAs) and their respective annual budgets. The structure of the 2006-2020 PNRH is comprised of four volumes: i) Overview and State of Water Resources in Brazil (v. 1), which addresses diagnosis of water; ii) Waters for the future: scenarios for 2020 (v. 2), which outlines reference scenarios for planning; iii) Guidelines (v. 3); and iv) the National Programs and Goals (v. 4) (Article 1 of CNRH Resolution 58/2006).

In parallel with PNRH 2006-2020, ANA prepares, on an annual basis, the report named *Framework of Water Resources in Brazil*. This report serves as a substantiation for various government actions that include monitoring the PNRH 2006-2020, monitoring the Federal Government's Multi-Annual Plan and analyzing the System of Environmental Economic Water Accounts. This Report summarizes the main data on water in the country, however, the availability of information on groundwater is reduced when compared to surface water.

The 2006-2020 PNRH has several programs and subprograms that are detailed in volume 4. Altogether, seven national and six regional programs are provided. The national programs are: Program I – Strategic Studies of Water Resources; Program II – Institutional Development Program for IWRM in Brazil; Program III – Development and Implementation of Water Resources Management Instruments; Program IV – Technological Development, Training, Communication and Dissemination of Information in IWRM; Program V – Inter-Sector, Inter-Institutional and Intra-Institutional Articulation Program for Water Resources Management; Program VI – Multiple Uses and Integrated Management of Water Resources Program; and Program VII – Sector-Based Programs focused on Water Resources. Groundwater is included in the subprograms and priority actions are set in these programs, and they are also part of the National Groundwater Program (Program VIII) which, despite having a national and transboundary scope, was included in the component of regional water resources programs. Program VIII was divided into three subprograms: *i*) Expansion of Basic Hydrogeological Knowledge; *ii*) Development of Institutional and Legal Aspects; and *iii*) Training, Communication and Social Mobilization (CARDOSO, 2009).

1. The plan is available at: https://cbhsaofrancisco.org.br/plano-de-recursos-hidricos-da-bacia-hidrografica-do-rio-sao-francisco/.
2. The plan is available at: https://cbhvelhas.org.br/plano-diretor-cbh-velhas/.

Table 4 presents the actions considered priorities for each hydrographic region.

Hydrographic Region and States	Priority Actions for Hydrographic Regions considered in the Groundwater Program
Hydrographic Region of Uruguai (RS and SC)	– Implementation of Basin Plans, classification and collection; – basins revitalization and soil conservation programs; – hydrometeorological monitoring network; – user registration.
Hydrographic Region of Tocantins – Araguaia (GO, MT, TO, MA, PA and DF)	– Implementation/increase of SIAGAS in the states; – AS management program for transboundary aquifers; – expansion and consolidation of the AS monitoring network; – criteria for issuing groundwater grants; – implementation and dissemination of "RIMAS" and expansion of the AS quality and quantity monitoring network; – registration of AS users; – preparation and dissemination of state hydrogeological maps; – establishment of agreements and terms for technical cooperation; – projects to protect aquifer recharge areas; – review of the policy on mineral water and water resources; – development of studies on thermal waters.
Paraguai Hydrographic Region (MT and MS)	– Expansion of the AS quality monitoring network; – development of hydrogeological maps; – establishment of an agreement and cooperation document; – projects to protect aquifer recharge areas; – registration of groundwater users; – development of the AS inventory; – standardization of groundwater management standards; – implementation of groundwater grants; – AS studies, prioritizing wetland aquifer; – campaigns for the technical adequacy of the AS extration infrastructure.
Eastern Atlantic Hydrographic Region (AL, CE, PB, PE and RN)	– Encouraging the drafting of specific legislation for AS; – assessment of AS' reserves, potential and availability; – monitoring of AS and its protection areas; – aquifer vulnerability studies; – development of AS desalination technologies; – training of personnel for the management of groundwater infrastructure; – promotion of shared management of aquifers; – studies of support capacity (quantity and quality) of the AS; – articulation of water management with land use and occupation plans; – regulation of water use in agriculture, livestock and shrimp farming.
Southeast Atlantic Hydrographic Region (ES, RJ, SP, MG and PR)	– Development of studies for the implementation of a groundwater monitoring network in the Ribeira basin.
South Atlantic Hydrographic Region (SC, RS, PR and SP)	– Execution of plans, programs and actions proposed by the Guarani Aquifer Project; – zoning of land use and assessment of its interference in the main aquifers (Serra Geral, Alto Tietê, Guarani and sedimentary coastal aquifers); – implementation of a state-monitoring network; – information systems for underground springs.
Amazon Hydrographic Region (AC, AM, AP, MT, PA, RO and RR)	– Implementation and expansion of the integrated AS monitoring network; – guidelines and measures against overexploitation and contamination of AS; – development of state hydrogeological maps; – establishment of agreements and documents for technical cooperation; – promotion of training programs for shallow well drillers.

Hydrographic Region and States	Priority Actions for Hydrographic Regions considered in the Groundwater Program
East Atlantic Hydrographic Region (BA, SE, MG and ES)	– Registration of wells and integration of databases; – carrying out and expanding hydrogeological studies; – studies on the availability of AS; – creation of AS monitoring networks and strengthening of inspection; – identification, mapping and dissemination of sources of AS degradation; – strategies for sustainable use of AS; – creation of decision-making support systems to assist in SA planning and management. – training of professionals in the field of drilling and operation of deep driven wells and in measuring the flow of streams and rivers; – strengthening of AS management; – inspection of wells and providing education and awareness campaigns.
Western Atlantic Hydrographic Region (MA and PA)	– Exchange with countries experienced in AS management; – guidelines for regulation and definition of recharge areas; – feasibility studies for the implementation of SA charging; – training programs in the use, conservation and management of AS.
Paraná Hydrographic Region (DF, GO, MG, MS, PR, SC and SP)	– Guidelines and measures against overexploitation and contamination of AS; – zoning of potential AS restriction and control areas; – AS monitoring network and its articulation with the states; – expansion of hydrogeological knowledge: *a)* transboundary and interstate aquifers; *b)* local scale studies; and *c)* qualitative-quantitative groundwater monitoring.
Hydrographic Region of São Francisco (AL, BA, DF, GO, MG, PE and SE)	Studies on the potential, availability, demands and vulnerabilities of aquifers; – database of wells; – expansion of the qualitative-quantitative AS monitoring network; – preparation of the Atlas of AS of the São Francisco River Basin; – construction of a decision-making support system to assist in the management of AS; – user registration; – studies on the recovery and remediation of aquifers; – studies to define criteria for the artificial recharge of aquifers; – classification of AS into classes of use; – training of personnel to manage, monitor and supervise; – feasibility studies for the implementation of charging for the use of AS; – definition of recharge protection perimeter areas; – studies to define the interference distances between the wells.
Parnaíba Hydrographic Region (MA, PI and CE)	– Programs focused on the use and knowledge of explorable reserves; – program for the control and rational use of AS and protection of recharge zones; – studies for the protection and sustainable exploitation of aquifers.

Table 4 – Priority Actions for the Hydrographic Regions addressed in the National Groundwater Program
Source: BRASIL (2011, p. 58 to 120).

These actions are among the priorities and goals set forth in the PNRH 2006-2020, relative to groundwater, which act both in national and regional levels and in specific basins. There is a recommendation that several of these actions be continued in the 2022-2040 PNRH. The expansion of the Integrated Groundwater Monitoring Network (RIMAS) by 100% was one of the national goals, but it was not achieved due to budgetary constraints. Notwithstanding, the network was expanded from 369 to 409 wells (MDR, s.d). Part of these monitoring wells started to be operated jointly by SGB-CPRM and ANA, adding these piezometric data in the National Hydrometeorological Network (RHN), which contributed to promote the integrated management of surface and groundwater, allowing for analysis of the aquifer x river relationship, as in the case of the Urucuia and São Francisco River Aquifer System.

The preparation of studies on the aquifers of the Amazon Region was one of the regional goals achieved and which gave rise to the execution of the project *Assessment of Aquifers of the Sedimentary Basins of the Amazon Hydrogeological Province in Brazil (Scale 1:1,000,000) and Pilot Cities* (Scale 1:50,000) (ANA, 2015). Examples of initiatives in federal basins are the implementation of the project *Studies for the Implementation of Integrated Management of Surface and*

Groundwater in the São Francisco River Hydrographic Basin: Sub-Basins of the Verde Grande and Carinhanha Rivers (BA/MG), scheduled to end in mid-2023, in a partnership between ANA and SGB-CPRM. It is also worth mentioning the survey of technical data on groundwater in the Verde Grande and Paranapanema river basins, carried out by ANA (MDR, s.d).

3.1.2 State Water Resources Plan (PERH)

The State Water Resources Plans (PERHs) have their jurisdiction limited to the scope of each Member State and Distrito Federal, and they are responsible for portraying the situation of water resources under state jurisdiction. Their main objective is to guide water management through guidelines and criteria on a state level to address the needs specified in the basin plans. Their preparation, updating and implementation are the responsibility of the entities that comprise the State Water Resources Management Systems, as provided by state legislation.

Each state, based on its State Policy on Water Resources, sets guidelines and criteria for the preparation of the PERH, covering the following aspects:

- guidelines, objectives, criteria and goals for state water management;
- financial priorities in promoting regional programs for the management of water resources;
- strategies for coordinating inter-basin issues;
- diagnosis and monitoring of the macro situation of water resources in the state (availability, quality, demand, uses and conflicts);
- state programs, projects and actions for water resources;
- guidelines for the application of water resources management instruments within the scope of state hydrographic basins.

Due to the state domain of groundwater, PERHs are key elements in stimulating aquifer management. Among the information to be covered by this instrument, is included: data on the availability, demand and quality of groundwater; proposal of areas for the exploitation of these waters or protective measures, such as areas of restriction to the use of groundwater; identification of priority points for monitoring; stimulation of coordination mechanisms between CBHs that share the same aquifer; definition of specific state programs for groundwater etc. (VILLAR; HIRATA, 2022).

3.1.3 Water Resources Plans for Hydrographic Basins

As the name implies, this instrument addresses the hydrographic basin as a territorial unit. This is the main management instrument provided by water resources policies, applied to small, medium and large hydrographic basins. It is also called *Water Master Plan, Water Resources Master Plan, Integrated Water Resources Plan and Hydrographic Basin Plan*, whose name became common after the implementation of the State Water Resources Policies (PERH) that began in 1991 (SÃO PAULO, 1991), and the issuance of the National Water Resources Policy (PNRH).

The Water Resources Plan for Hydrographic Basins is defined in Article 2 of Resolution 145, of December 12, 2012:

> [...] instruments for long-term management of water resources, provided by Law No. 9.433, of 1997, with a planning horizon compatible with the period of implementation of its programs and projects, whose objective is supporting and guiding the implementation of the National, State and District Water Resources Policies and the management of water resources within the scope of the respective hydrographic basins.

The document sets the strategic planning of water management, with legal provision and regulation supported by Law No. 9.433/1997 and several CNRH Resolutions, especially articles 10 to 13 of CNRH Resolution CNRH 145/2012, which sets its stages and minimum content: *i*) **Diagnosis of the Situation of Water Resources**; *ii*) **Prognosis**; and *iii*) **Action Plan** (Figure 35). The watershed plans must contemplate the guidelines of the other water resources plans (national, state or other hydrographic basin plans that eventually overlap).

The Water Resources Plan for Hydrographic Basins must contain the multi-annual action program, whose term is usually 12 years. The document sets the investment program (short, medium and long-term), and contains: name of the planned action; programmatic lines of the managing board; goal set; term (year) of execution; coverage area of the action; execution priority; naming of those responsible for the execution; executor of the action; estimated cost for the action; and sources of the necessary financial resources.

Figure 35 – Guidelines for preparation of the Water Resources Plans for Hydrographic Basins

Source: CNRH (Resolution 145/ 2012).

3.1.4 Content of Water Resources Plans for Hydrographic Basins

The methodological protocol for preparation of a Water Resources Plan is set according to the definition of the work method, activities, results and products to be yielded. These points are included in a Reference Document, defined based on articulation between the water resources management entity and the Hydrographic Basin Committee (CBH) according to the specificities of the basin. These products are elaborated sequentially according to the diagnosis, prognosis and action plan stages. Each of these steps must include the contents presented in Figure 35, setting goals (short, medium and long-term) and actions for implementation, as recommended by CNRH Resolution CNRH 145/2012.

The Diagnosis stage characterizes the situation of water resources, based primarily on available data and information (secondary data), notwithstanding the possibility of using primary data (see Article 11 of CNRH Resolution CNRH 145/2012). It is important to clarify that CNRH Resolution 145/2012 presents the minimum structure of the plans; however, this must be done within the scope of concurrent and common jurisdictions, and states can incorporate additional elements, as in the case of the state of São Paulo. The diagnosis sets the general reference framework of the study unit and constitutes the basis for identifying critical aspects of management, as well as subsidizing the development of subsequent activities.

Art. 12 of CNRN Resolution 145/2012 defines the minimum content of the Prognosis stage, which comprises the characterization of scenarios to be built based on aspects directly and indirectly linked to the situation of water resources, according to the planning scenarios adopted (Figure 35). Therefore, it is possible to prioritize interventions to improve the conditions of water resources.

Finally, there is the Action Plan which, according to Article 13 of CNRH Resolution CNRH 145/2012, seeks to "mitigate, minimize and anticipate problems related to surface and underground water resources", focused on meeting the guidelines and principles, as well as achieving objectives set forth in the National Water Resources Policy.

3.1.4.1 Diagnosis and Prognosis of a Basin Plan in the state of São Paulo

States can regulate the content of their watershed plans so long as they comply with national guidelines and may even set additional requirements as a result of the regional reality. In the case of the state of São Paulo, the State Council for Water Resources (CRH) issued Deliberation CRH 146/2012, which sets the guidelines for the preparation of hydrographic basin plans, determining the minimum content of the Diagnosis and Prognosis stages. The Diagnosis must contain, at a minimum, the following topics:

- General Characterization of the Basin
- Physical Characterization
- Availability of Water Resources
- Demands for Water Resources
- Balance: Demand *versus* Availability
- Water Quality
- Sanitation
- Drinking Water Supply
- Sewer System
- Solid Waste Management
- Stormwater Drainage and Management
- Management of the Territory and Areas Subject to Special Management
- Land Use and Occupancy
- Remnants of Natural Vegetation and Protected Areas
- Areas susceptible to erosion, gullies, landslides and silting.
- Areas Susceptible to Flood, Flooding or Flooding
- Environment pollution
- Assessment of the Hydrographic Basin Plan
- Diagnosis Synthesis

The content proposed by the CRH included aspects aimed at evaluating the existing Hydrographic Basin Plan and its implementation by the hydrological management unit, as well as a summary of the diagnosis made. These elements are important to substantiate the current planning framework and its implementation in the management unit, which makes it possible to review, redirect and improve planning focused on following up on the actions to be subsequently developed.

Deliberation CRH 146/2012 also establishes detailed procedures for the Prognosis stage. The objective is to establish state of the art of knowledge about existing planning instruments and those being implemented (plans, programs, projects, actions and enterprises etc.), linked directly and indirectly to aspects of interest for the management and management of water resources (surface, underground or coastal), in the three branches of government (federal, state and municipal). Also, according to CRH Resolution 146/2012, the Prognosis stage must contain, at least, the following topics:

I. Plans, Programs, Projects and Enterprises Affecting the UGRHI

II. Planning Scenario:

1 Socioeconomic dynamics

2 Demands for water resources

3 Availability of water resources

4 Balance: demand versus availability

5 Water quality

6 Basic sanitation:

6.1 Drinking water supply

6.2 Sewer System

6.3 Solid waste management

6.4 Drainage and management of urban rainwater

III. Management of UGRHI's Water Resources:

1 Legislation relevant to water resources

2 Grant for the use of water resources

3 Environmental licensing

4 Charge for the use of water resources

5 Classifications of bodies of water

6 Qualitative-quantitative monitoring of water resources

7 Information system on water resources

IV. Critical Areas and Priorities for Water Resources Management:

1 Delimitation of critical areas for the management of water resources

2 Establishment of priorities for the management of water resources

V. Intervention Proposals for UGRHI's Water Resources Management

The *Diagnosis* and *Prognosis* stages make it possible to build scenarios and identify critical areas for the management of water resources, as well as improve the synergy of actions, regardless of responsibility for execution in order to integrate an action plan for the hydrological unit.

3.1.5 Minimum Content on Groundwater in Water Resource Plans

CNRH Resolutions 15/2001, 22/2002, 92/2008, 145/2012 and 202/2018 establish the guidelines for the inclusion of groundwater in the Water Resources Plans of the Hydrographic Basins. Figure 36 details the minimum content that must be included in basin plans relative to groundwater.

The water resources plan must adopt a holistic view, integrating ground, surface and atmospheric water. The inclusion of groundwater in this instrument requires methodological procedures that promote the knowledge and characterization of physical aspects (nature of the environment, architecture of the component units, spatial distribution, hydraulic interconnections between adjacent units, flow patterns, parameters of hydrodynamic control, reserves, among others); chemical properties (water quality, contamination, vulnerability to pollution, among others); and regional socio-environmental aspects (demand, types of use, land use, regulatory frameworks, among others). Moreover, the plan must set guidelines for their integrated management, considering the environmental and social dimension of water, as well as seek ways to ensure sustainable use, protection, prevention, remediation or mitigation of risk situations, such as overexploitation and contamination. Brazil needs studies that assess whether the basin plans have incorporated the requirements provided by CNRH Resolutions on groundwater.

Minimum Content of Basin Plans for Groundwater (AS)	▸ Space characterization. ▸ Computation of AS in water balance. ▸ Estimate of recharges and discharges and exploitable reserves. ▸ Physical, chemical and biological characterization of AS. ▸ Measures for use and protection of aquifers.
Monitoring of quantity and quality, with results presented in maps	▸ Monitoring network of aquifer water levels and their quality. ▸ Density of monitoring points. ▸ Parameter monitoring frequency.
Potentially impacting actions and protection or mitigation, including emergency measures	▸ Description and forecast of estimated socioeconomic and environmental pressures on availability. ▸ Estimate of point and diffuse sources of pollution. ▸ Evaluation of soil characteristics and use. ▸ Analysis of other human activity impacts related to AS.

Potentially impacting actions and protection or mitigation, including emergency measures	▸ Maximum Protection Areas.
	▸ Well Protection Perimeters.
	▸ Restriction areas and AS use control.
	  ▪ HR availability considering the base discharge of rivers.
	  ▪ Risk of geometric instability and soil use and occupation.
	  ▪ Sustainability of exploitation in coastal areas.

Integrated hydrological evaluations	▸ Delimitation of recharge and contribution areas of aquifers to directly connected nodes. ▸ Contribution of aquifers to the rivers base flow. ▸ Recharge and exploitable and renewable reserves. ▸ Integrated underground and surface water availability for different uses.

Figure 36 – Groundwater in basin plans, based on CNRH Resolutions

Source: CNRH (Resolutions 15/2001, 22/2002, 92/2008, 145/2012 and 202/2018).

Basin plans need to incorporate detailed analysis of aquifers and their relationship to surface water resources. Without this data, the disorderly extraction of groundwater can compromise the base flow of rivers, reduce the availability of surface bodies and cause damage to the environment and users. Interstate basin plans have sought to build this approach through the Integrated Water Resources Plans (PIRH); however, there is still a long way to go considering the lack of data or problems relative to implementation of management instruments. Box 13 discusses this experience in the Paranapanema Basin.

Box 13 – Integrated Water Resources Plan (PIRH) of the Paranapanema Water Management Unit (PIRH Paranapanema)

Malva Andrea Mancuso

The Integrated Water Resources Plan (PIRH) of the Paranapanema Water Resources Management Unit (PIRH Paranapanema) is a strongly agreed-upon and integrated planning and management instrument, developed with the main objective of allowing the effective management of surface water resources and groundwater for the benefit of present and future generations (ANA, 2016).

A consistent institutional arrangement was required for consolidating an integrative vision that guided the preparation of the PIRH Paranapanema and the guidelines of the Management Instruments that respect the domains and sociopolitical contexts. Moreover, it was necessary to include the specificities of the current legislation of the states of São Paulo, Paraná and the Federal Government. The Plan thus presents, and when necessary, different approaches for the federal and state levels. ANA was responsible for its preparation and, therefore, it counted on monitoring by state management bodies: Department of Water and Electricity of São Paulo (DAEE/SP), Águas Paraná, CBH-Paranapanema (with the committees of the state management units) and with the support of the consulting company Profill Engenharia e Ambiente Ltda., which carried out the studies and issued technical reports. The monitoring of the preparation of the Plan was coordinated by the Work Group (GT-Plan) and the Technical Integration (CTIPA) and Institutional and Legal Chambers (CTIL) (ANA, 2016).

The Paranapanema PIRH was concluded in 2016 and seeks to constitute elements for the management of multiple uses of water, considering the goals to be achieved and integrated with the conservation of existing water resources. According to the Diagnosis, there are no generalized problems regarding water resources, but in terms of quantity, deficits related to irrigation were identified (main user). Regarding the quality of surface water, the Paraná spring has a higher occurrence of stretches with worse quality standards (classes 3 and 4) relative to water uses. This situation is characterized by the lowest rates of sewage collection relative to the state of São Paulo (ANA, 2016).

The Paranapanema Basin has high groundwater potential, which has not yet been explored, however, specific actions were indicated in view of the need to overcome several gaps in knowledge. Among these actions studies are being carried out for identifying areas with groundwater potential based on the mapping of critical areas, as well as defining the conditions for exploring the aquifers. Thus, actions to expand and consolidate the underground qualitative data monitoring network are recommended. One of the goals of studies on groundwater is the refinement of information on availability (integrated with surface water) and on demands by expanding the registration of wells. The need to design and propose incentives for the use of underground springs, in case of availability, to meet current or projected water demands, is present in a specific action. The *Diagnosis* also underscored the punctual need for creating Conservation Units (UCs) and special attention to erosion control in urban and suburban areas and soil conservation in rural areas (ANA, 2016).

As a *Prognosis* of Water Resources, three scenarios were presented, one of them being a trend and two being alternative (accelerated and stagnant). These scenarios allowed the inference that, if there are no improvement and control interventions, existing problems or situations can either cause or exacerbate conflicts, both in quantitative and qualitative aspects (ANA, 2016).

The strategy proposed to achieve water sustainability of the system, which was the basis for the Action Plan, structured on three lines of action: Increase in Water Availability; Regulation on Water Demands; and Regulation of Polluting Loads (ANA, 2016).

Regarding Water Resources Management Instruments, guidelines were set for surface waters under the jurisdiction of the Federal Government and general recommendations for surface waters under jurisdiction of the States, however, there are no recommendations for groundwater. Among the guidelines for the Grant, we highlight the joining of the reference flow for the Water Resources Management Unit (UGRH) of Paranapanema and, as for Charges, guidelines and recommendations common to bodies of water under jurisdiction of both the states and the Federal Government. Furthermore, was also proposed a progressive implementation of the Water Agency (ANA, 2016).

The Programs (12 in all, with 37 sub-programs) and Actions (123 in all) structure their foundations on two components: a) Management of Water Resources; and b) Interventions and Articulation with Sector-Based Planning. Its focus is the integrated and participatory management of water supply and demand (considering quantitative and qualitative aspects of surface and underground sources). The budget provided for resources to be invested over the course of 20 years (ANA, 2016). PIRH Paranapanema's main legacy was bringing together the efforts of institutions and actors that participated directly or indirectly in the management of water resources at UGRH Paranapanema, defining common and technically-based objectives, and strengthening the premise that water resources management must be marked by the integration of the various entities and committees (ANA, 2016).

3.1.6 Specific groundwater management instruments

Conama Resolution 396/2008 determines that environmental agencies, in conjunction with water resources management agencies, establish Aquifer Protection Areas, Supply Wells Protection Perimeters and Groundwater Use Restriction and Control Areas (Articles 20 and 21). CNRH Resolution 22/2002, in turn, states that Basin Plans must provide measures for the use and protection of aquifers (Article 3, part VI), whereas CNRH Resolution 92/2008 provides the definition of aquifer protection zones, restriction and control areas, and well protection perimeters based on hydrogeological studies (Article 2, parts I, II and III);

Aquifer Protection Areas (APA) are intended to protect groundwater recharge zones, however, as they presuppose restrictions on land use and occupation, the instrument was not used, including whether it could be applied without the support municipalities, which have exclusive jurisdiction over municipal territorial planning.

Well Protection Perimeters (PPP) are intended to protect groundwater abstraction and have been regulated by several states. Mineral legislation requires water classified as mineral or drinking water establish protection areas or perimeters, as provided by Articles 12 and 13 of the Mineral Water Code and DNPM Ordinance 231/1998. The PPPs are explained in Box 14.

Restriction and Control Areas (ARCs) are measures of an exceptional and temporary nature, which aim to restrict the use or abstraction of water in situations where quality or quantity is compromised. Restriction areas for groundwater use can be used based on the following criteria: density of abstraction wells; number of potentially polluting enterprises; critical levels of underground water availability; occurrence of changes of the natural quality; and presence of contaminated areas. Box 15 presents ARC's case regarding use of groundwater in Ribeirão Preto – SP.

Box 14 – Well Protection Perimeters (PPP)

Mara Akie Iritani

The experience of other countries, especially Europe, shows that establishing a protection perimeter around public supply wells, especially those located in open aquifers, is an efficient strategy to minimize the danger of contamination of groundwater supplied to the population. (NAVARRETE; GARCIA, 2003).

The concept of Well Protection Perimeters (PPP) is based on the control of potentially contaminating activities and the application of restrictions to the use of the soil around the well, where the aquifer recharge area is located. The measures with the highest restrictive levels are applied to zones bordering the innermost perimeters, located closer to the extraction zone (Figure 37). In some cases, the PPP may aim not only at protecting quality, but also the quantity of water to ensure the sustainability of the reserve destined to supply the population (NAVARRETE; GARCÍA, 2001).

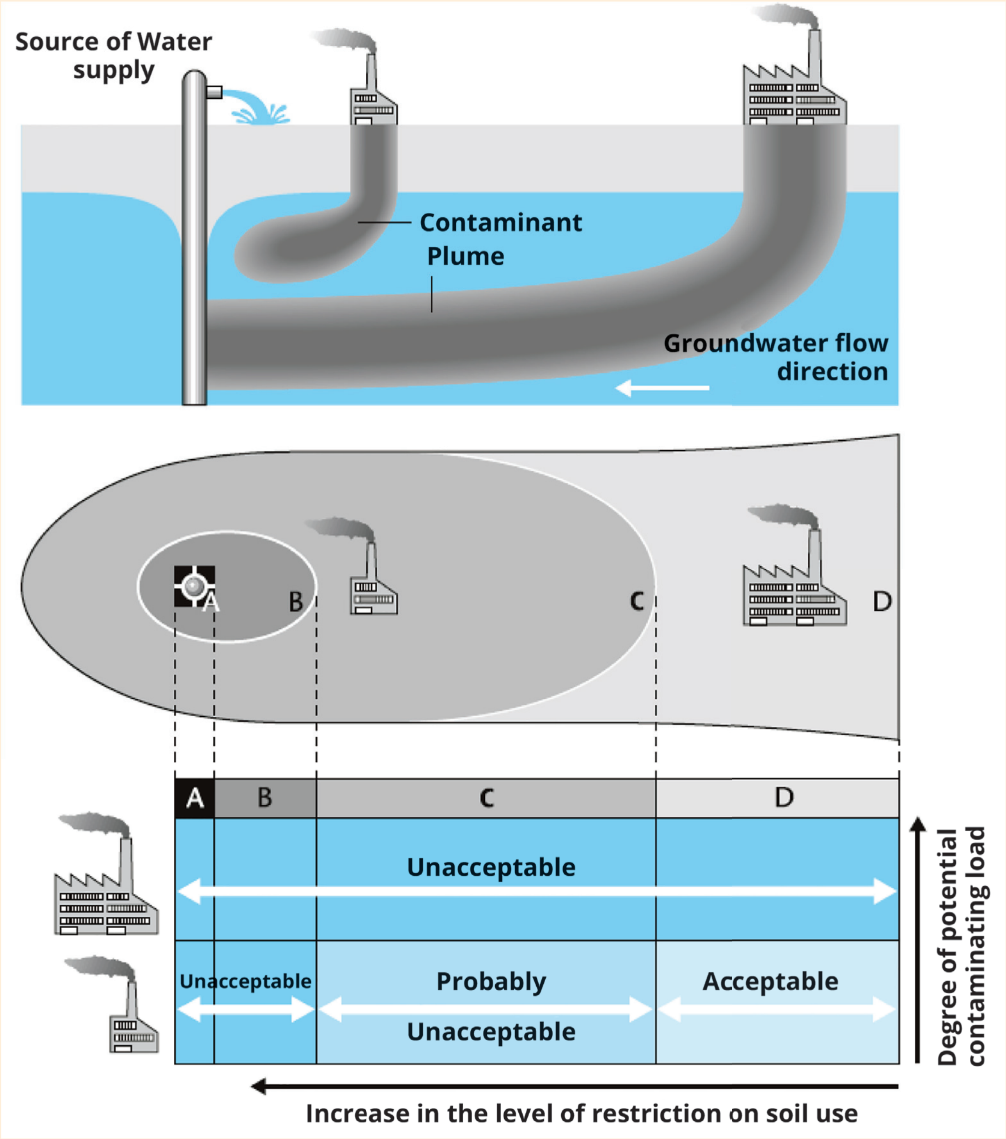
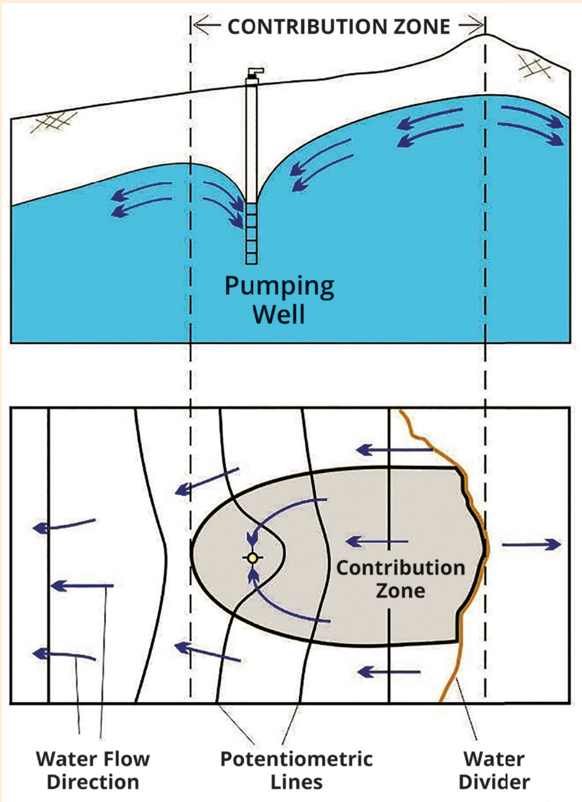


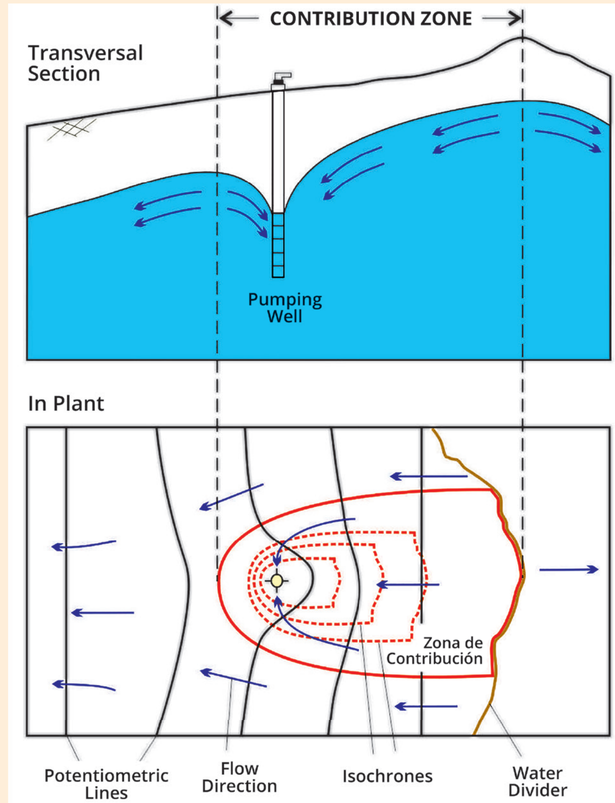
Figure 37 – Well Protection Perimeter Concept
Source: Foster *et al*. (2006, p. 9).

PPPs are established in the Contribution Zone (CZ) of the well and take into account non-conservative contaminants (they undergo degradation over time) and conservative contaminants (there is no degradation, and the decrease in concentration is mainly due to the dilution along the underground flow) (FOSTER *et al*. 2002).

The CZ is the area where aquifer recharge occurs and groundwater flow converges into the well (Figure 38A). Its extension depends on the characteristics of the aquifer (permeability, porosity, viscosity and recharge) and on the constructive and operational conditions of the well (depth of penetration into the aquifer, flow and operating time). The delimitation of protection perimeters can be based on different criteria, such as: a) longitudinal distance from the well; and b) time traveled by the water in the aquifer until it reaches the well (called *transit time*). Points with the same transit time of water in the aquifer draw an isochron, which is used to delimit the protection perimeter. The zone inside the isochron is called the *Transport Zone* (Figure 38B).



(A)



(B)

Figure 38 – Contribution zone and transport zone of a well in an uncontained aquifer

Source: Iritani e Ezaki (2012, p. 3 and 5).

These criteria can be associated with hydrogeological features that affect the flow of water in the aquifer, such as the presence of a watershed, gaps or contacts between geological formations and others.

There are several methods to delimit protection perimeters, which can be found in USEPA (1987, 1994), Navarrete and García (2003), Strobl and Robillard (2005), Environmental Agency (2019) and Liu, Weisbrod and Yakirevich (2019). The method to be adopted must consider the complexity of the aquifer, the constructive and exploration characteristics of the well, hydraulic interferences and use of the soil. This choice also depends on the quantity and quality of the existing data, the importance of the extraction to supply the population served and the financial resources available.

The identification of the CZ can be difficult and, consequently, add greater uncertainty to the delimitation of PPPs due to the presence of complexities (FOSTER; SKINNER, 1995; FRANKE *et al*., 1998; PARIS *et al*., 2019), such as: *a)* multi-layered, fractured or karst sedimentary aquifers; and *b)* areas with interference from wells or influence from surface water bodies. In these situations, numerical modeling presents better accuracy (GÁRFIAS; EXPÓSITO; LLANOS, 2008; CARVALHO; HIRATA, 2012), however, this modeling costs more, requires more time and data for its application. The objective of the PPP to be established must also be considered. For example, for short transit times, uncertainties associated with the more simplified methods may be acceptable since the perimeter covers a small area and the result does not present great variation relative to more complex methods (FOSTER *et al*., 2002; CARVALHO; HIRATA, 2012).

Delimitation of well protection perimeters

Protection perimeters of public supply wells and the restriction and control measures to be adopted must be supported by legal regulations. In European Community countries, for example, the legal grounds are found in Directive 2000/60/EC (DOVERI; MENICHINI; SCOZZARI, 2015). In Brazil, the support for the delimitation of areas of protection of wells is linked to the state legislation that deals with the management of water resources or to specific legislation on groundwater, as, for example, in Minas Gerais (Law No. 13,771/2000), Acre (Law No. 1,117/1994), Pernambuco (Decree No. 20,423/1998); Piauí (Law No. 5,165/2000), Roraima (Law No. 547/2006), São Paulo (Decrees No. 32,955/1991 and No. 63,261/2018) and Distrito Federal (Decree No. 22,358/2001). Carvalho and Hirata (2012) and García and Navarrete (2005) conducted a survey of the protection perimeters of wells adopted in several countries and showed that, usually, between three and four protection zones are adopted.

The innermost zone of the well is called the operational zone, where only activities associated with the well operation are allowed (FOSTER *et al*., 2002) (Figure 39). For fully protecting an uncontained aquifer abstraction, the authors suggest delimiting other perimeters (Figure 39) and they highlight, in terms of public health, the importance of the protection zone for non-conservative contaminants. In Germany, Netherlands and in the United Kingdom, the criterion for delimiting this perimeter is a transit time of 50 days (GARCÍA; NAVARRETE, 2005; ENVIRONMENTAL AGENCY, 2019).

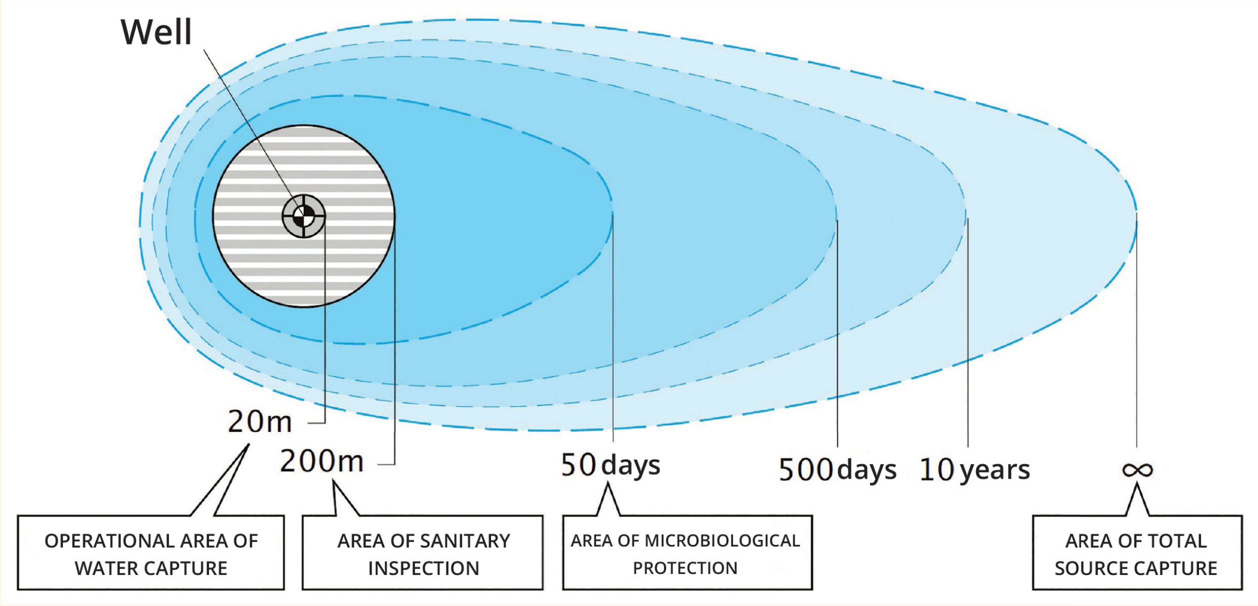


Figure 39 – Scheme designed for the delimitation of well protection perimeters in and uncontained aquifer

Source: Foster *et al*. (2006, p. 35).

This criterion is also adopted for the Alert Perimeter, established by legislation relative to protection of groundwater in the states of São Paulo and Pernambuco. Iritani and Ezaki (2012) listed simple methods to support the calculation of the Alert Perimeter, which was applied in the state of São Paulo (2016) in a study developed with the Bauru Aquifer System (SÃO PAULO, 2016).

Control and restriction of human activities depend on the danger they pose to the well (Figure 37). The approach and methodologies proposed by Foster *et al*. (2002) help identifying the danger of contamination and define the measures to be imposed in each well protection perimeter.

In addition to the technical foundations, implementation of well protection areas needs to be a participatory process that involves users and society in general. In the state of São Paulo, for example, legislation requires that such actions be based on studies and approved by the State Council for Water Resources.

Box 15 – Establishment of Restriction and Control Areas for the Use of Groundwater as a Management Instrument for the Exploration of the Guarani Aquifer System (SAG), in Ribeirão Preto, SP

José Luíz Albuquerque Filho

Deliberation 052, of April 15, 2002, of the Water Resources Council (CRH) of the state of São Paulo established "[...] within the scope of the Integrated System of Management of Water Resources (SIGRH) guidelines and procedures for the definition of restriction areas and control of the extraction and use of groundwater".

This management instrument was implemented by 6.134, of June 2, 1988 (Article 7), which provides for the preservation of natural groundwater deposits, and regulated by Decree No. 32,955, of February 7, 1991, and by CRH Resolution 52, of April 15, 2005. The Restriction and Control Areas (ARCs) for the use of groundwater are "[...] those where there is a need to regulate activities that may cause changes or negative effects on the quantity or quality of groundwater" (Article 1) of CRH Resolution 52/2005).

The city of Ribeirão Preto, located in the Northeast region of the state of São Paulo, with a population of 676,440 depends exclusively on the underground spring constituted by the Guarani Aquifer System (SAG), according to the *Water Resources Situation Report* (CBH PARDO, 2020). According to professor and researcher Osmar Sinelli, a hydrogeologist who has been working in the region for a long time, the use of groundwater in the SAG dates back to the 1930s. The growing demand for water shows an imbalance between the volumes extracted, the reduction of available underground reserves and the drawdowns in the groundwater levels of the aquifer.

Based on this scenario, the Pardo River Basin Committee (CBH Pardo) proposed the CBH Pardo Deliberation 04/06 (approved on 06/09/2006), which established "Areas of Restriction and Control of Catchment and Use of Groundwater in the urban area of Ribeirão Preto". The Ribeirão Preto ARC seeks to contain the lowering cone of the groundwater level caused by the intensive pumping of the existing wells. This decision was submitted to the State Water Resources Council (CRH) and ratified through CRH Resolution 065/06 (approved on 09/04/2006). The decision has been revalidated by CBH Pardo and CRH, based on technical hydrogeological studies. The latest version is CBH Pardo Resolution 300, of September 17, 2021, which was ratified by CRH Resolution 260, of December 16, 2021.

Figure 40 shows the delimitation of the Area of Restriction and Control of the Use of Groundwater of the Guarani Aquifer System (SAG) in the Municipality of Ribeirão Preto (SP), which establishes the following zones and their technical criteria relative to the drilling of new wells and use of groundwater:

- **Zone 1 – Urban area in the inner zone of the drawdown cone**: only new drilling of deep driven wells are allowed to replace existing wells, intended for the water supply system for human consumption under the responsibility of the Municipal Government;
- **Zone 2 – Densified urban area**: replacement of deep driven wells, such as in Zone 1, or the drilling of new wells intended for the water supply system for human consumption under the responsibility of the municipal government; and replacement of existing wells with subsequent plugging of the existing well, or deepening of existing deep tube wells for any purpose, are the responsibility of the private user; and
- **Zone 3 – Urban expansion area**: substitutions of deep tube wells are allowed, such as in Zone 1; deepening or replacement of existing deep tube wells, for any purpose, are the responsibility of private users; and new deep tube well drilling for any purpose of use.

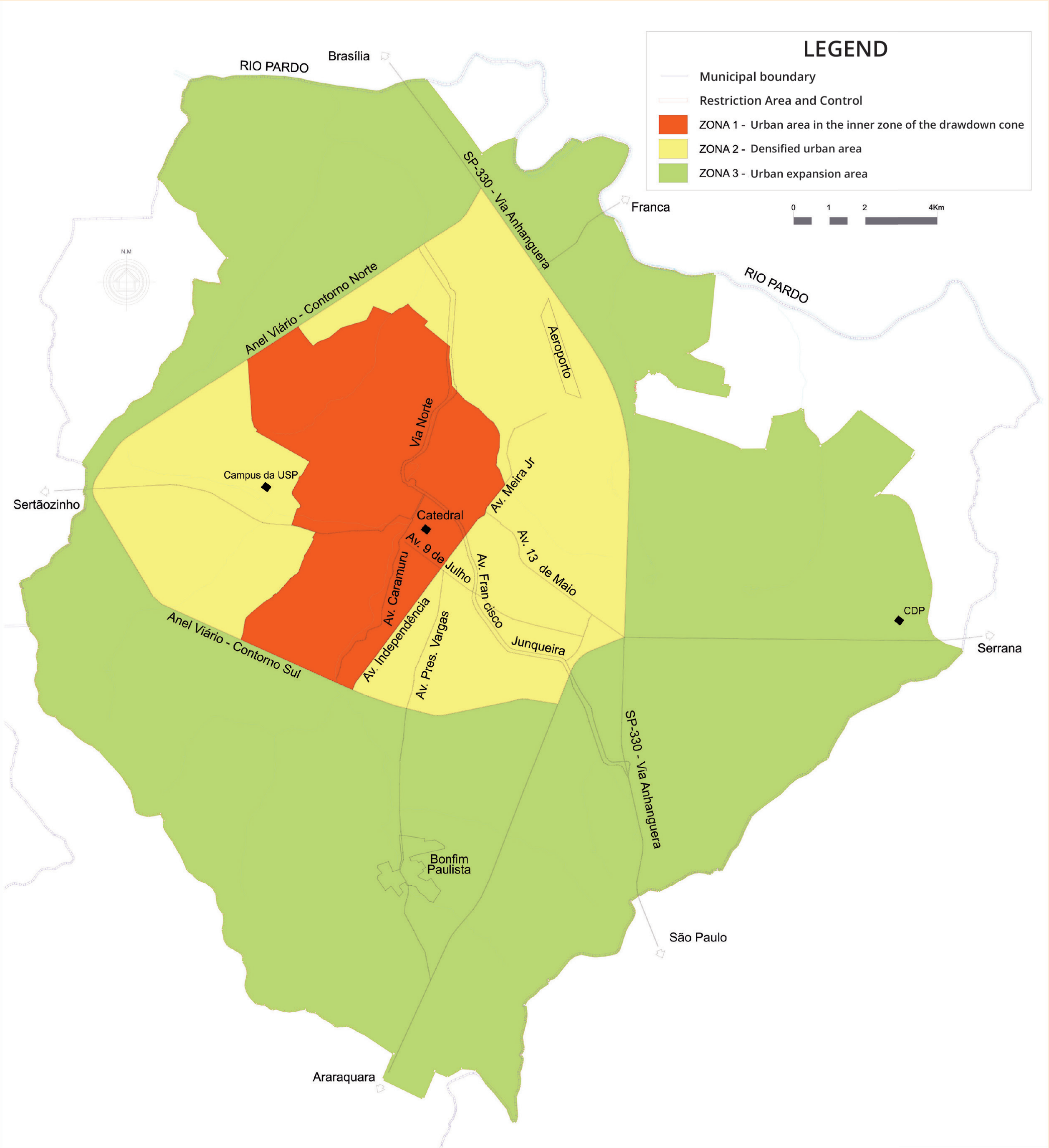


Figure 40 – Restriction Area and Control of Use of Groundwater in the Guarani Aquifer System (SAG) in the Municipality of Ribeirão Preto, SP

Source: CBH Pardo (Deliberation 04/06).

ARCs are a water resources management tool dedicated to correcting distortions in the use of aquifers, which may compromise the quality or quantity of water. The reversal of these situations is a complex process, which demands the monitoring of the evolution of the identified situation, as well as the articulation of the collegiate managers (Water Resources Committees and Councils) with the Government and the negotiation and actions between the actors involved.

3.2 FRAMEWORK OF GROUNDWATER BODIES, ACCORDING TO THE PREDOMINANT USES

The classification of water bodies into classes, according to the predominant uses of water from aquifers, is regulated by Conama Resolution 396/2008 and by CNRH Resolution 91/2008. Art. 29 of Conama Resolution 396/2008, determines that the framework of underground water bodies must consider, at least, the following aspects:

I. hydrogeological and hydrogeochemical characterization;

II. characterization of vulnerability and pollution risks;

III. registration of existing and operating wells;

IV. land use and occupation and its history;

V. the technical and economic feasibility of the framework;

VI. the location of potential sources of pollution;

VII. natural quality and groundwater quality condition.

Based on these criteria, groundwater is classified into classes, as defined in Article 3 of Conama Resolution 396/2008, detailed Table 5.

Classes	Uses
Special Class	Aquifer waters, a set of aquifers or a portion thereof intended for the preservation of ecosystems in full protection conservation units and those that directly contribute to the stretches of surface water bodies classified as Special Class.
1	Water from aquifers, set of aquifers or portions thereof, without changes in quality due to human activities, and that do not require treatment for any predominant uses due to their natural hydrogeochemical characteristics.
2	Water from aquifers, a set of aquifers or a portion thereof, without changing their quality due to human activities, and which may require adequate treatment, depending on the predominant use, due to their natural hydrogeochemical characteristics.
3	Aquifer waters, a set of aquifers or a portion thereof, with changes in their quality due to human activities, for which treatment is not necessary due to these changes, but which may require adequate treatment, depending on the predominant use, due to their natural hydrogeochemical characteristics.
4	Water from aquifers, a set of aquifers or a portion thereof, whose quality has been altered due to human activities, and which can only be used, without treatment, for the predominantly less restrictive use.
5	Aquifer waters, set of aquifers or portions thereof, which may have their quality changed due to human activity, intended for activities that do not have quality requirements for use.

Table 5 – Classes for the characterization of groundwater

Source: Conama (Resolution 396/2008).

Conama Resolution 396/2008 determines that groundwater classified in the Special Class must "have its natural quality conditions maintained" (Article 5). The standards of Classes 1 to 4 are based on the Quality Reference Values (VRQs) and the Maximum Allowed Values (MPVs) for each predominant use (Article 4), observing the Practical Quantification Limits (LQPs), presented in Appendix I of Conama Resolution 396/2008. VRQs must be defined by the competent body, which may be Conama or state bodies, however, such standards have still not been determined. Table 6 presents the standards for each of the classes:

Classes	Uses
Special Class	They must maintain their natural quality conditions.
1	They present, for all parameters, a Quality Reference Value (VRQ) below or equal to the Most Restrictive Maximum Allowed Values (VMPr+) of the predominant uses (Article 7 of Conama Resolution 396/2008).
2	They present, in at least one of the parameters, a Quality Reference Value (VRQ) higher than their respective Most Restrictive Maximum Allowed Value (VMPr+) of the predominant uses (Article 8 of Conama Resolution 396/2008).
3	They must meet the Most Restrictive Maximum Allowed Value (VMPr+) among the preponderant uses, for each of the parameters, except when it is a natural condition of the water (Article 9 of Conama Resolution 396/2008).
4	They must meet the least Restrictive Maximum Allowed Values (VMPr-) among the predominant uses, for each of the parameters, except when it is a natural condition of the water (Article 10 of Conama Resolution 396/2008).
5	They will not have quality conditions and standards, according to the criteria used in Conama Resolution 396/2008 (Article 11).

Table 6 – Standards for groundwater classification
Source: Conama (Resolution 396/2008).

The procedure for classifying surface and underground bodies of water is defined by CNRH Resolution 91/2008. The steps of this procedure are divided into: *i*) diagnosis; *ii*) prognosis; *iii*) proposal of goals relative to classification alternatives; *iv*) deliberation by the Water Resources Committee and Council; and *v*) implementation of the classification program (Figure 41).

The first three stages are technical in nature, which requires social participation through public consultations, technical meetings, workshops and others (Article 3, § 2 of CNRH Resolution 91/2008). The process of issuing the deliberations and implementation of the classification program, in turn, have a more political/decisional nature, and should be conducted by CBH in conjunction with its Technical Agency (COSTA *et al.*, 2019, p. 45). So far, this instrument has not yet been used relative to groundwater.

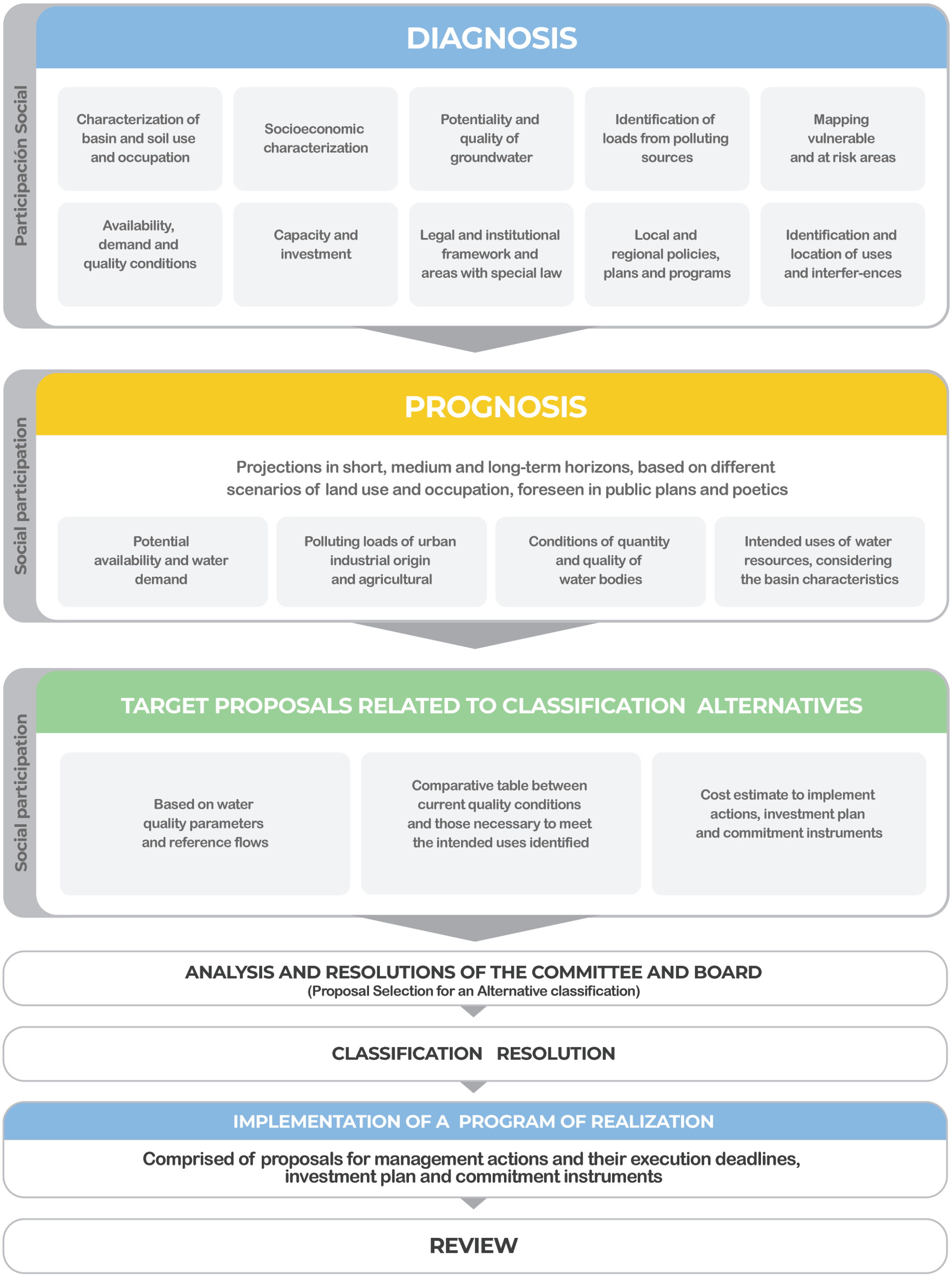


Figure 41 – Steps in the procedure of classification of superficial and underground bodies of water, defined by CNRH Resolution 91/2008.

Source: CNRH (Res. 91/2008).

3.3 GRANT OF THE RIGHT TO USE GROUNDWATER RESOURCES

Law No. 9.433/1997, in Article 5, Part III, established the granting of the right to use water resources, defined as "the administrative act through which the granting authority grants the grantee previously or through the right to use water resources for a given period pursuant to the terms and conditions stated in the respective decision, considering the specific legislation in force" (Article 1 of Resolution CNRH 16/2001). This instrument makes it possible to reconcile the public nature of water with its private use through the role of the State manager (ANA, 2007). The priorities for the grant are included as a requirement of the minimum content of the Hydrographic Basin Plans (Article 7, part VIII, of Law No. 9,433/1997), to be approved by the CBHs.

Lanna (2000, p. 89) states that the "role of the grant will be to apportion the available water between existing or potential demands, so the best results are delivered to society." This instrument is a reflection of the State's Police Powers since it regulates the use of water resources through the granting of formal authorization to the user who intends to use the water privately, for a specified period and in accordance with the established conditions (PORTO; PORTO, 2008).

The maximum term of the grant of the right to use water resources is 35 years following the date of publication of the respective administrative decision (Article 16 of Law No. 9,433/1997). This period, however, may be extended by the concession granting authority provided the priorities set forth in the Hydrographic Basin Plans are respected (article 6, § 1 of CNRH Resolution CNRH 16/2001).

The granting of the concession does not imply the disposal of the water, but rather a right of using it (Article 18 of Law No. 9,433/1997). Therefore, it seeks to balance water availability with the demand, allowing the Government to control the use of water to ensure management objectives and, at the same time, ensure the user access to water (LEAL, 1998). It is an instrument of "quantitative and qualitative control of water uses" and a condition for the "exercise of rights of access to water" (Law No. 9,433/1997, Article 11). The uses that depend on the grant were listed in Article 12 of Law No. 9,433/1997, which determines as follows:

> Article 12. The rights of the following uses of water resources are subject to granting by the Government:
>
> I – derivation or extraction of a portion of the water existing in a body of water for final consumption, including public supply, or input of the production process;
>
> II – extraction of water from underground aquifer for final consumption or production process input;
>
> III – discharge of sewage and other liquid or gaseous waste, treated or not, into a body of water for the purpose of diluting, transporting or final disposal;
>
> IV – use of hydroelectric potential;
>
> V – other uses that change the regime, quantity or quality of water existing in a body of water.

Law No. 9,433/1997 expressly included the need to grant the right of use for the "extraction of water from underground aquifers for final consumption or production process input" (Article 12, part II). Due to states' jurisdiction over groundwater, states and the Distrito Federal are responsible for regulating the granting of the right to use these resources, always complying with national standards. In addition to extracting water from wells, some states, based on Article 12, Part V, require this instrument in cases of lowering of the water table in buildings and civil construction projects or of the water level in mining activities (in this case, see CNRH Resolution 29/2002). In these two situations, the focus is not on the use of groundwater, but on the effect that these activities can have on the aquifer.

Due to the exclusive federal jurisdiction to legislate on water matters, the requirement of this instrument can only be waived by the states and the Distrito Federal in the events detailed in Article 12, paragraph 1 of Law No. 9,433/1997:

> § 1 Do not depend on granting from the Government, as defined by regulation:
>
> I – the use of water resources to satisfy the needs of small population centers distributed in rural areas;
>
> II – derivations, funding and entries considered insignificant;
>
> III – accumulations of water volumes considered insignificant.

In the situations mentioned in Article 12, § 1, the request for granting the right of use is waived, however, it is necessary to comply with other administrative conditions imposed by the states, such as: a) registration in the registry of wells or users; and b) obtaining a document attesting to the character of exempt or immaterial use. It incumbent on the CBHs to propose guidelines and criteria to establish the uses considered insignificant, and on CERHs approving them. In the event of lack of determination of these criteria by CBH or absence of this entity, the state granting authority will issue a definition on a provisional basis (see CNRH Resolution 184/2016).

The volumes considered exempt, therefore, may vary between basins or in specific regions of the same basin.

The definition of uses considered insignificant must take into account the following criteria: *a)* the "percentage of the volumetric reference of a certain portion of the aquifer as an individual limit of extraction"; *b)* the "percentage limit of quantitative collective commitment of aquifer portions"; and *c)* the "cumulative effect, in the same water body, of all derivations, abstractions, releases or accumulations of small volumes of water, considered insignificant" (Article 6 of CNRH Resolution 184/2016).

The granting of the right to use groundwater must ensure the integrated management of water to "avoid the qualitative and quantitative compromise of aquifers and surface water bodies connected to the aquifers" (Article 3, part III of CNRH Resolution 15/2011). Therefore, the decision must be based on the hydrogeological studies described in Article 2 of CNRH Resolution 92/2008 (represented in Figure 42), which constitute the bases of the basin plans. It is important to emphasize that there are no guidelines in the country for granting concessions in fossil aquifers.

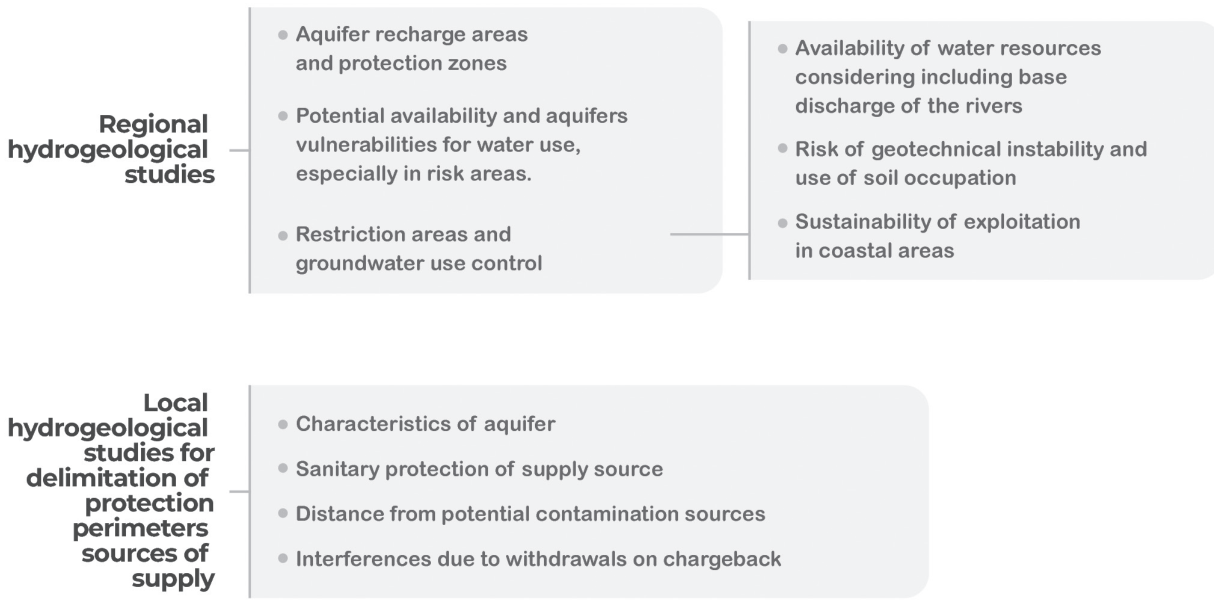


Figure 42 – Hydrogeological studies and granting of the right to use groundwater
Source: CNRH (Resolution 92/2008), prepared by the authors.

Note that the granting of the right of groundwater use should take into account not only the characteristics of the aquifers and the needs of users, but also the following criteria: *i*) interference between wells and maximum allowed drawdown levels; *ii*) saline intrusion; and *iii*) management of demand between users of groundwater and superficial water, as well as articulation with soil management (COSTA *et al.*, 2011).

The most serious problem, however, goes back to the very low adherence of users to the instrument. It is estimated that the absolute majority of wells are either illegal or irregular. Illegal wells "are those whose drilling and use of groundwater are not supported by law, therefore, their existence is prohibited and, consequently, if the concerned party requested a grant request, it would be denied" (VILLAR; HIRATA, 2019). Irregular wells "are those whose drilling and use of groundwater is supported by law, however, compliance with certain procedures is required or restrictions or conditions are imposed for this use, which were not met by the owner of the well" (VILLAR; HIRATA, 2019).

According to the ANA database (2021), there are 115,354 underground extractions regularized by the States, including the modalities of granting the right to use and insignificant uses. This number is much lower than that found in other databases, such as those of SGB-CPRM or IBGE. The Government does not know the actual number of existing wells or the use of the resource, which compromises the entire management process (HIRATA *et al.*, 2019; ANA, 2020).

Irregular use of water "allows the appropriation of an asset intended for common use by the people and diverts water resources from their legitimate users, changing the ownership regime of the water and causing various environmental and social impacts" (VILLAR, 2016, p. 92). The irregular status also hinders the application of other instruments. Without an estimate of the real demand for the use of groundwater resources, the diagnoses, prognoses and action programs of the hydrographic basin plans are hampered. Moreover, without the grant, there is no way to charge for the use of these resources.

Unfortunately, in the case of legal uses, most of the grants are issued without the necessary hydrological assessments or are not based on appropriate methodologies. ANA (2013, p. 64) recommends that the calculation of underground water availability be guided by the concepts of:

- **Direct Potential Recharge (RPD)**: portion of the average annual rainfall that infiltrates and effectively reaches the free aquifers, thus constituting the renewable or regulatory reserve;
- **Sustainability Coefficient (CS)**: maximum percentage recommended to exploit the RPD, in order to avoid adverse effects on the aquifer or decrease in the base flows of interconnected rivers;
- **Estimated Explorable Potential Reserve (RPE)**: corresponds to the portion of the RPD indicated by the CS.

The state of Mato Grosso do Sul uses this methodology to delimit the volumes available for the grant, however, there are other ways to determine these values. The precariousness of the implementation of this instrument jeopardizes the objectives of the water policy because without the control of its use, there is no way to ensure the availability of water for present and future generations or the rational and integrated use, much less prevent and mitigate hydrological events or critical consequences arising from the inappropriate use of water. Therefore, investing in user awareness campaigns, grant incentive mechanisms and in inspection actions is a priority.

Box 16 seeks to explain the reasons for illegal wells, while Box 17 explains the most frequent criteria used to determine grant-eligible flows. The lack of technical data and the application of appropriate methodologies for granting, in conjunction with the high number of irregular wells, creates a situation of vulnerability for groundwater, and makes it difficult to trace diagnoses, prognoses and action programs for aquifers.

Box 16 – Why do we have so many irregular wells?

Antonio Luiz Pinhatti

Irregular wells exceed regular ones in Brazil, which leads to the question: why are there so many irregular wells? The invisibility of the resource and the limited knowledge on the part of users, well drillers and management bodies contribute to this situation. Users do not have the perception that the irregular use of groundwater can interfere and harm their well or that of others, much less that it can impact the environment.

Users look to groundwater for an individual solution to their supply problem. This unknown collective of individual users that seeks to supply their private demand can lead to overexploitation of an aquifer. The number of irregular wells in Brazil portrays the typical case of the *Tragedy of the Commons* (HARDIN, 1968), in which there is "a situation in which individuals acting independently and rationally in accordance with their own interests behave contrary to the best interests of a community, depleting a common resource."

The lack of knowledge concerning the legal obligation or the lack of incentives to seek regularization through the grant, combined with the lack of inspection by both the water resources management bodies and the bodies that control the activity of drilling wells (the Regional Engineering and Agronomy Boards – CREA) contribute to the drilling of irregular wells and the use of groundwater without authorization. Well drilling methods are fast and relatively low-cost, making it possible to maintain and operate an irregular well unnoticed, which renders possible inspection actions difficult. In this sense, drilling companies are responsible for their work and for meeting legal requirements. For commercial reasons, the well is often built without proper authorization, which turns drilling companies into facilitators of the irregular use of groundwater.

Irregular use calls into question the management of water resources in Brazil and requires the adoption of actions with *stakeholders* to reverse this scenario. Table 7 summarizes the main factors that lead to the existence of irregular wells and their mitigating actions.

Social actors	Facilitating factors	Mitigating actions
Users	– Lack of knowledge regarding the technical and legal aspects of groundwater. – They see no problems or consequences in using water irregularly. – Lack of knowledge about the benefits of having the well regularized. – There are no financial or service incentives or compensation that make the regularization of the well attractive for the user; – There is no willingness on the part of the user to pay extraction fees without seeing a return on that payment. – Resistance to accept payment of the sewage fee proportional to the volume of water captured in the well; – There is an understanding that having an irregular well is a minor offense and does not harm society or the environment.	– Make users aware of the need and benefits of regularizing wells. – Provide technical information and groundwater availability to assist the user in prospecting and capturing the resource. – Offer compensation for regularized use. – For example, through technical operational guidance on energy and pump efficiency, water quality etc. – Look for ways to include the well owner as a partner in groundwater management.
Managing Bodies	– Lack of political will to monitor and control irregular wells and enforce the law. – Absence of institutional tradition and organizational stability; – Limited knowledge and data on aquifer behavior; – Inconsistent well records and insufficient groundwater availability information to help users or promote good management; – Low field operational capacity, which hinders effective inspection; – Sanctions are rarely applied to users of irregular wells, in many cases it is only required to carry out regularization. – Groundwater resources are not seen as a priority by managers or society. – The granting processes are usually complex, bureaucratic and time-consuming.	– Carry out effective inspection, identifying irregular wells, promoting regularization and enforcing the law and imposing the relevant penalties; – Use supervision and the application of penalties in an exemplary way, including disclosing these actions to demonstrate state action. – Create programs to regularize wells, especially in areas with intense use of groundwater, signs of overexploitation and conflicts between neighboring users.
Drillers	– Omission on the obligation of granting and the risks and consequences arising from the lack of authorization – Limited knowledge of hydrogeology to understand the impacts of irregular use; – There are drillers working without registration with the activity control body (CREA) or whose technical manager spends less time operating in that capacity as the minimum required for the position; – Lack of solid relations between the management bodies and those controlling the drilling activity, which could reduce the number of irregular wells.	– Establish a relationship between the water resources management agency and CREA, including the exchange of information. – Carry out the effective inspection and control of well-drilling activity. – Make drillers aware to perform only authorized drilling and in accordance with technical standards.

Table 7 – Main factors that lead to the existence of irregular wells and mitigating actions
Source: Foster, Hirata and Custodio (2021), adapted by the author.

Box 17 – Criteria for determining grant-eligible flows in underground springs

Vagney Aparecido Augusto

José Eloi Guimarães Campos

The determination of criteria for issuing grants or authorization for the use of groundwater aims to define, mainly, technical parameters concerning underground water systems that favor their proper use, defining acceptable limits for their exploration, so as not to cause damage to aquifers. They are also important to allow, in a balanced way, the different types of groundwater uses in the short, medium and long term, ensuring that users are not harmed due to out-of-balance use. To achieve these goals, actions must include all aspects involved in the water system, including the environment itself and the natural framework that constitute the aquifers.

Law No. 9,433/1997 defines the hydrographic basin as the base unit for managing water resources. This legal definition considers the relief as a delimiting factor for surface water flows and their accumulation; however, groundwater does not follow the same delimitation, flows and accumulation assumptions. Many aquifers extrapolate watershed areas, presenting unconnected underground flows to surface flows, and following totally different patterns, shape and timing for flows and accumulation. Thus, the definition of a base unit for the management of underground resources must consider at least three environmental conditions: climate, hydrogeology and aspects of surface hydrology that affect the unit, according to the concept of hydrogeoclimatic domains (AUGUSTO; CAMPOS, 2021).

The criteria for granting the right of use necessarily need to respect the differences between the types of aquifers. These different aquifers receive, store and allow water flows in their free spaces of very different shapes, volumes and speeds, which should imply also different criteria for their uses and, consequently, for the granting process. In this context, the criteria for granting groundwater must consider the current conditions of exploration of aquifers, the climatic factors that make water available over time and all surface interferences that affect or are affected by the aquifers.

On the aquifer scale, the term safety flow was first described by Lee (1915) as a rate of water that can be removed annually without danger of depletion of stored reserves. The author, therefore, already recognized that excessive pumping in an aquifer would affect surface waters. Meinzer (1920) and Conkling (1946) state that the amount of water to be extracted from aquifers must be equal to the rate of their natural recharge. Meinzer (1920) argues that safe rates of extraction from an aquifer, without depleting its supply, are the limitations of economic viability in extraction. Although the definition does not aim at sustainability, it reflects well what happened with depleted American aquifers. Theis (1940) incorporated the water balance and defined the perennial safety flow. To that end, was added to the flow available for use, a volume of recharge induced by pumping, plus a part of the natural discharges. Bear and Levin (1967) proposed the optimal flow based on economic, social, cultural and biotic purposes, with water resources being one of the variables. The optimal flow could overexploit aquifers as it does not aim to maintain the water system over time. In Brazil, the optimal flow could bring conflicts between the priority uses provided for by law or then, favor economic use at the expense of essential uses and low economic returns. Sophoclous (1997) defined safety flow as the achievement and maintenance of a long-term balance between the amount of groundwater withdrawn and the annual amount of natural recharge. For the author, the sustainable flow differs and must be smaller than the natural recharge, still considering that the natural discharges support the drainages, wetlands and dependent ecosystems. Fetter (2004) considers that explorable reserves refer to a regular and permanent extraction rate without causing permanent reserve depletion damage. Kalf and Woolley (2005) emphasize that it is necessary to separate the concept of sustainability of the aquifer system from the system's production performance. Sustainability must be based on the volume of recharge and discharge of the system and may consider the volumes of recharge induced by the pumping process. On the other hand, the safety flow can be sustainable if the sum of natural recharge flows is greater than the sum of discharges/withdrawals from the system. In regions with arid or semi-arid climates or in aquifers with a high degree of confinement, recharge is restricted and can lead to unsustainable use; however, there are still aquifers with large volumes of water stored with high water productivity. In these cases, the use of volumes greater than the recharge, even if justified, would be depleting a non-renewable volume, which would be a process of mining the water resource stored throughout geological time. In countries where water is a public asset, the use of non-renewable water resources would justify a deeper analysis of the relationship between socio-environmental costs and the private benefits generated by its use.

In natural conditions, before the production of groundwater, aquifers are in a state of dynamic equilibrium (ZHOU, 2009). Removal of water leads to a new balance, either through increased recharge, decreased discharge, loss of storage, or a combination of all these factors. Pumping can reduce evapotranspiration by lowering water levels and inducing additional recharge when aquifers have a shallow phreatic surface over wet humid weather or, also, via induction of recharge by adjacent surface bodies of water. The dynamic responses of an aquifer to pumping are relative and depend on the conditions of the drawdown cone generated, and its distances from natural recharge and discharge areas. If a new dynamic balance is established by a pumping rate lower than the natural recharge, i.e., supposedly safe, this can still cause levels to deplete, and not be sufficient to maintain dependent ecosystems. Furthermore, pumping can cause intrusion of poor quality water and land subsidence even without overexploitation of aquifers.

Groundwater sustainability is based on its development and use and can be maintained for an infinite amount of time without causing unacceptable environmental, economic or social consequences, according to the context of the complete hydrological system and over the long term (ALLEY; REILLY; FRANKE, 1999; ALLEY; LEAKE, 2004). The amount of groundwater available for use depends on how changes in recharge and discharge affect the surrounding environment and the acceptable trade-off between groundwater uses and these changes. The balance of these long-term variables is the central theme of the evolving concept of sustainability.

In Brazil, the term *safety flow* is seen as a *renewable or regulation reserve* (m^3/year). These reserves are renewed on an annual basis by the hydrological cycle and are directly related to rainfall, which causes them to vary over the years. Campos and Correia (2013) indicate that explorable and grant-eligible reserves, whose volume can be extracted without causing damage, may be greater than renewable reserves, considering the sum of the annual renewable reserve and part of the permanent reserve. Permanent reserve refers to the volume of groundwater stored in aquifers over geological time and does not change significantly in the annual cycle. These are important not only as strategic reserves, but because they constitute the basis for sustaining renewable reserves and the aquifer framework, allowing natural discharges related to rainfall cycles.

Among the *main technical criteria* used for determining the flow to be granted relative to groundwater, the following stand out: *i)* average aquifer flow; *ii)* well flow percentage; *iii)* base surface of superficial drainage; *iv)* safety flow; and *v)* lowering available and qualitative analysis of pumping test data (CAMPOS; CORREA 2013). Roedel (2017) and Campos and Correa (2013), based on numerical models and application of a geographic information system, proposed that the grant should consider the favorability and underground water potential, interference between wells and surface water resources, the average flow of the aquifer and impact analysis of the required flow, with the maximum grant-eligible flow below 90% of the natural recharge.

It is evident that the determination of flows attributable to aquifers must be based on previous hydrogeological studies, however, the criteria can be considered as basis for application in different conditions on the aquifer and on the well scale. For its application, however, local limitations and impacts must be considered:

- **Average Flow of Aquifer Wells**: determined from the values of flow of wells that were reached through different constructive characteristics but within the same aquifer. This flow can be obtained by arithmetic or weighted average of the depths, diameter of the wells or by the length of the filtering sections. It is based on the average productive capacity of the aquifer; therefore, its application depends on recharge conditions and renewable reserves to define acceptable limits of use.

- **Percentage of Individual Well Flow**: it is a fraction of the maximum flow obtained from pumping tests in the wells to be granted. This fraction must vary depending on the commitment of the region in which the grant is required and the circulation conditions (recharge and discharge). There must also be considered the risks of overexploitation and contamination to which aquifers are subjected. In the case of the existence of neighboring wells with mutual interferences, the grant-eligible flow must consider well systems as one single system.
- **Safety Flow**: are the values of renewable reserves multiplied by a safety factor. The factor is defined based on the water characteristics of each management unit (Hydrogeoclimatic Domains). The safety flow can be represented in an area unit (km2 or hectare) of the aquifers and it is intended to represent exploitable reserves based on the proportionality of their occurrence. In some cases, it may represent values above the renewable reserve, in others, lower values.
- **Surface Drainage Base Flow**: the grant flows are defined based on a percentage of the drainage base flow, applicable only in perennial drainages and where underground flows represent the only water source in dry periods. This criterion is difficult to apply, especially due to: *i)* the lack of data in many drainages; *ii)* the inapplicability of intermittent drainage; *iii)* cases when the existence of dams changes the natural flow pattern of rivers; *iv)* the existence of extractions and releases that change the natural recession flows; *v)* use and occupation of the soil that favor changes of superficial outflow among other aspects. Due to these difficulties, this criterion, when applicable, only allows for approximations.
- **Available Drawdown**: it is obtained from the pumping test, and it is related to aquifer viscosity, pump installation depth, static level depth, annual variations in the water table and potential interference between wells. The maximum drawdown available is that which the submergence of the pump reaches. From a sustainability point of view, this maximum available drawdown must be limited to a percentage of the aquifer's viscosity to preserve most of its saturated zone.
- **Qualitative Analysis of Pumping Test Data**: pumping data is used focused on specific capacity (ratio of flow exploited by the drawdown produced in the water level in the well). It is a criterion relative to the production potential with specific low capacities, when the flow granted is lower than the test flow. For high values, the flow rate granted can be close to that obtained in the pumping test. Other hydraulic data must also be considered when issuing grants, including: i) average specific capacity of the aquifer; ii) the par value of the downgrade; and iii) the 24-hour static level recovery time after the end of pumping. As for availability, the favorability of the aquifer should be considered in the following aspects: conditions of recharge and water circulation, and estimation of explorable water reserves. Different methods and criteria can be applied to the availability estimates; however, the most important thing is that the applied parameters are conservative, that is, optimistic relative to natural systems, and pessimistic relative to human projects.

3.4 CHARGING FOR THE USE OF WATER RESOURCES: FINANCIAL RESOURCES TO PROMOTE GROUNDWATER MANAGEMENT

The charge for the use of water resources is provided for in Article 5, Part IV of Law No. 9,433/1997. Art. 19 of the aforementioned Law and CNRH Resolution 48/2005 define that its objectives are:

I. to recognize water as a limited public good, with economic value, and give the user an indication of its real value;

II. to encourage the rationalization of water use and its conservation, recovery and sustainable management;

III. to obtain financial resources for finance studies, projects, programs, works and interventions included in the Water Resources Plans, which promote direct and indirect benefits to society;

IV. to encourage investment in depollution, reuse, protection and conservation, as well as the use of clean technologies that save water resources, according to the classification of water bodies in classes of predominant uses; and,

V. to induce and stimulate conservation, integrated management, protection and recovery of water resources, with emphasis on areas subject to flooding and recharge of aquifers, springs and riparian forests through compensation and incentives to users. (Article 2 of CNRH Resolution 48/2005).

This economic and control instrument is based on the polluter-payer and user-payer principles, and the amounts received bear the nature of a public price, since this is a consideration paid for the use of a public asset (GRANZIERA, 2015; VILLAR; GRANZIERA, 2020). The charge can be federal or state, depending on the jurisdiction over the water resource and the area of the Committee in question. In the case of interstate CBHs, the charge was levied on the following basins: Paraíba do Sul River Basin; in the Piracicaba, Capivari and Jundiaí River Basins; in the São Francisco River Basin; in the Rio Doce Basin; in the Paranaíba River Basin; and in the Verde Grande River Basin (ANA, 2019).

Groundwater is a resource under state jurisdiction, whereby it is incumbent on the States to regulate and apply the instrument. Based on legislation, in participatory form, CBHs set the charging mechanisms and suggest the amounts, which will be approved by CERH. In some states, in addition to this approval, a government decree is required for allowing the charging to be levied (VILLAR; GRANZIERA, 2020). Only users who are granted authorizations for the use of water resources are charged.

The charging by State Committees still has a long way to go, as it has not been levied in a large part of the national territory (Figure 43). Moreover, the irregular situation of groundwater users jeopardizes their effectiveness in the basins that charge for the use thereof. Regions with a high rate of exploitation of groundwater and equipped with CBHs have not yet implemented the instrument, as is the case of Rio Grande do Sul, Santa Catarina, Paraná, Mato Grosso, Mato Grosso do Sul and Goiás. The charge could help to implement various programs and projects aimed at improving water management, as well as strengthening the integrated management of surface and groundwater.

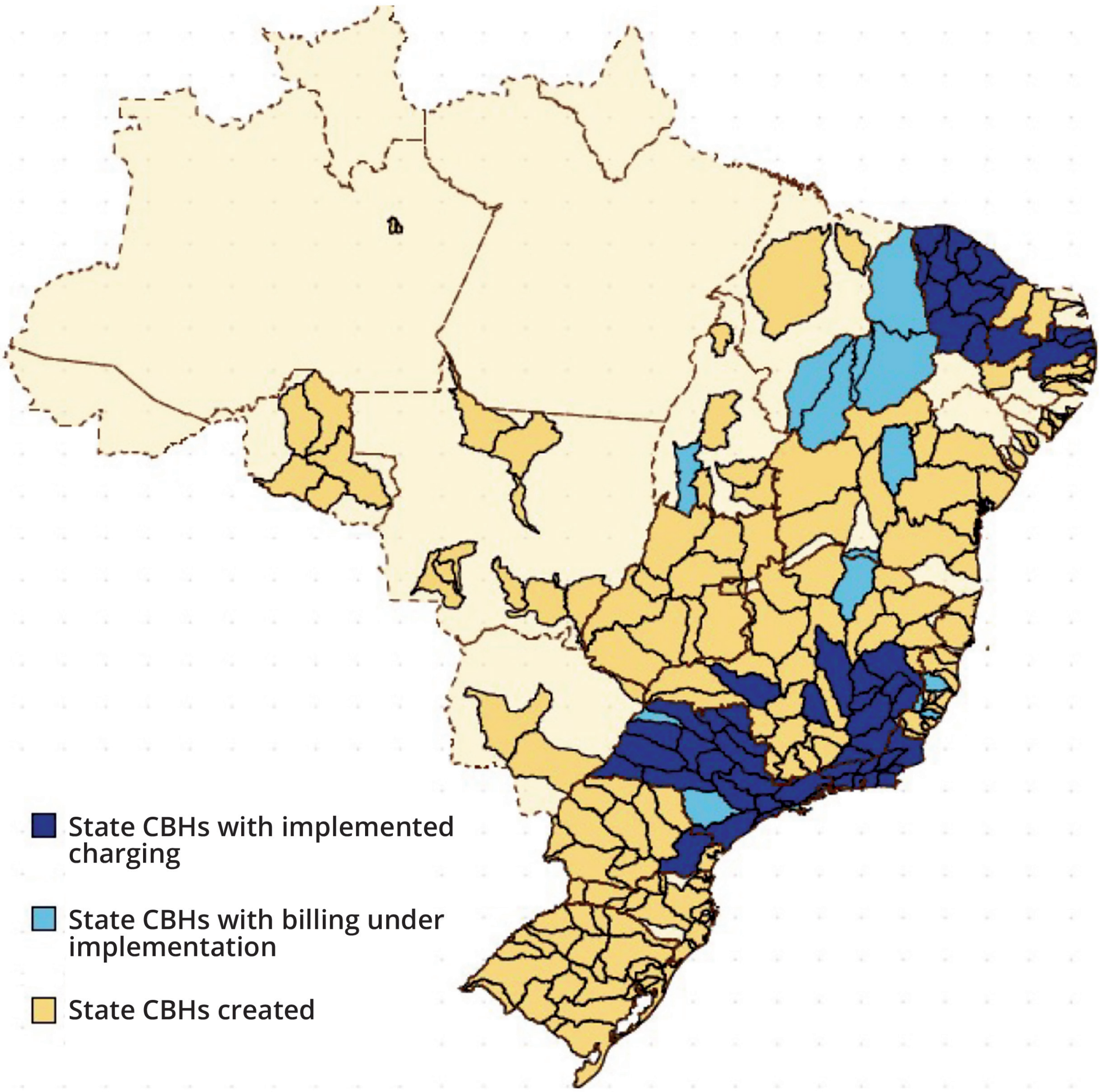


Figure 43 – Charge for the use of water resources in Brazil – State Committees

Source: ANA (2019, p. 26).

Table 8 presents the Basic Unit Price (PUB) applied in some state basins.

Basin	State	Amount charged for water	Legal grounds
Coreaú Hydrographic Basin; Coastal Hydrographic Basin; Curu Hydrographic Basin Committee; Metropolitan Watersheds etc.	CE*	The basins have a uniform charge regulated by the State. – The amounts range from R$ 0.00192 to R$ 2.93208/m³, depending on the user and type of extraction. – There is a specific value for extraction of mineral waters, of R$ 0.85233/m³.	Communication 01/2021/GECOM/DIAFI/COGERH, of 02/16/2021.
Rio das Velhas Hydrographic Basin	MG	– R$ 0.01415/m³ superficial and underground water extraction; – R$ 0.0283/m³ consumed; – R$ 0.09905/kg DBO released.	Normative Deliberation CBH-Velhas 3, 08/03/2020.
Hydrographic Basin of the Mining Affluents of the Pomba and Muriaé Rivers	MG	– R$ 0.01/m³ superficial and underground water extraction; – R$ 0.02/m³ consumed extraction; – R$ 0.07/kg DBO released.	Deliberation of the River Basin Committee of the Mining Affluents of the Pomba and Muriaé Rivers 37/2014.
Araguari River Hydrographic Basin	MG	– R$ 0.01/m³ superficial water extraction; – R$ 0.0115/m³ groundwater extraction; – R$ 0.02/m³ consumed extraction;	CBH-Araguari Resolution 12, of 06/25/2009.
Alto Iguaçu Basins and Alto Ribeira Tributaries	PR	– R$ 0.01/m³ superficial water extraction; – R$ 0.02/m³ groundwater extraction; – R$ 0.02/m³ consumed extraction; – R$ 0.10/kg/year of DBO released.	Resolution 5 of the Committee of the Alto Iguaçu Basins and Tributaries of the Alto Ribeira, of 07/11/2013.
Alto Tietê Basin	SP	– R$ 0.01/m³ water extration, extraction or derivation; – R$ 0.02/m³ consumed water; – R$ 0.10/kg of DBO 5.20 released.	Appendix 1 – Decree No. 56,503, of December 9, 2010.
Pardo River Basin	SP	– R$ 0.01/m³ water extraction extraction or derivation; – R$ 0.02/m³ consumed water; – R$ 0.10/kg DBO 5.20 released.	Decree No. 58,771 of December 20, 2012.

(*) In the state of Ceará, the collection values are decreed by the Governor for all basins, after the State Council for Water Resources (CONERH/CE) is heard. There are no statements from state CBHs regarding the collection (ANA, 2019).

Table 8 – Basic Unitary Price (PUB) of water applied in the charging for use of water resources in some Hydrographic Basins State Committees
Source: prepared by the authors.

The PUB is not the final price paid by the user, which is obtained through mathematical formulas that apply various weighting coefficients to this value. However, despite the application of these coefficients, the prices charged are low and do not necessarily encourage the rational use of water resources (OECD, 2015). The value of groundwater is much broader than the price charged for it. Box 18 presents the different types of values for environmental resources.

Box 18 – The different types of value of environmental resources

Osvaldo Aly Júnior

Environmental valuation uses different methods to economically quantify an environmental good, "estimating" the importance (and costs) of ecosystem services impacted or lost due to human action. By estimating the costs and values of environmental impacts, it is possible to assess the positive and negative consequences of public policies and private actions and understand to what extent people are willing to accept the preservation or restoration of the natural environment, and how much this will impact future generations. Unfortunately, the environmental valuation of groundwater is a subject of little exploration in Brazil.

One of the ways to estimate the value of the environmental resource is through the calculation of the Total Economic Value (VET). The calculation includes the *use value* (*right, indirect and option*) and *non-use values* (value of existence). The first set refers to the potential use (current or future), whereas the last one is related to the existence of the asset, regardless of its use.

Direct use value is attributed to an environmental resource where direct appropriation occurs via extraction or consumption. For example: extraction of drinking water for human consumption (bottled/tap); consumption of non-drinking water (irrigation, car washing and gardens); base flow that perpetuates rivers and guarantees irrigation, aquaculture, river transport and energy generation; tourism and leisure: hydro-mineral bathing, cave contemplation and landscape.

In turn, the indirect use value estimates the indirect benefits arising from ecosystem dynamics and the functioning of aquifers. For example: sewage dilution and sediment transport that prevent silting and flooding, filtration, purification and attenuation of contaminants (aquifer-soil system and river banks), artificial recharge/infiltration and underground storage, support for biodiversity, nutrient cycling.

Option value is attributed to the preservation of natural resources and ecosystems for direct or indirect use in the future. All services previously presented and not currently used have option value, as they may be used at some future time.

On the other hand, non-use values, such as existence value, seek to estimate values that are not associated with the direct or indirect use of the resource, but rather intangible aspects. Its value comes from aspects of a moral, cultural, ethical or altruistic nature relative to the right of existence of species other than the human species or of natural resources, even if they have no current or future use. Its measurement has a high degree of subjectivity, as they are usually obtained through opinion polls.

3.4.1 Actions for groundwater that could be funded by charging

In most cases, groundwater is not a priority for action plans and investments. Table 9 details the possible central themes for the preparation and execution of programs and actions that would contribute to promoting water management by water resource management bodies.

Central themes for executing PDGAS	Actions for the management of Groundwater (AS)
Technical Basis for Groundwater Management	– Registration of groundwater users throughout the basin.
	– Adaptation, improvement and regulation of the criteria for AS granting.
	– Hydrogeological, technical-economic assessment, monitoring and control of the drilling of deep driven wells to avoid overexploitation of aquifers.
	– Development of studies aimed at innovation and technological modernization applied to the water security of underground springs.
	– Studies to propose or update legislation affecting the AS or guidelines for regulating the use and occupation of land that affect areas where aquifers occur.
	– Development of studies on thermal waters (hydrothermalism).
	– Review of the policy on mineral water and water resources;
	– Preparation of groundwater management projects for transboundary aquifers.
	– Establishment of subsidies for AS in the State Water Resources Plan, Hydrographic Basin Plans and Evaluation Reports of State Water Resources Management Systems and Singreh.
– Quality Improvement and Protection of Aquifers	– Registration of actual or potential sources of pollution of aquifers and recharge zones.
	– Registration, study and characterization of diffuse sources of urban pollution and agricultural inputs.
	– Development of projects to protect aquifer recharge areas through the recovery and/or conservation of drainages and headwaters.
	– Preparation of the cartography containing the zoning of the natural vulnerability of the aquifers.
	– Execution of vulnerability and hazard mapping of the intrusion of saline wedges in coastal aquifers.
Development of Aquifer Information Systems	– Implementation/increase of SIAGAS in the states and Federal District.
	– Development and implementation of Decision Support Systems (SSD) to support the analysis of requests for drilling deep wells and granting the right to use groundwater in the states and the Federal District.
Implementation, operation and maintenance of RIMAS	– Expansion and consolidation of the groundwater monitoring network (e.g.: RIMAS).
	– Expansion of the groundwater quality and quantity monitoring network.
Training and dissemination in Groundwater	Execution of agreements and terms of technical cooperation with public research and teaching institutions (SGB-CPRM, Federal and State Universities, Federal Technology Centers, among others), academic support (Research Support Foundations, CNPq) and associations that work on groundwater (ABAS, ABRH, ABGE, APG, ABES, among others), as well as nongovernmental organizations that work on issues pertaining to groundwater.
	Drafting, publication and dissemination of the basic hydrogeological cartography of the states and the Federal District.
	Training of the general participants of the Hydrographic Basin Committees on the general aspects of groundwater and aquifers.
	Advertising campaigns for the dissemination and enhancement of underground springs, highlighting the connectivity of groundwater and the need to regularize the wells.

Table 9 – Proposal for the organization of Programs for the Development and Management of Groundwater (PDGAS)

Source: prepared by the authors.

3.5 INFORMATION SYSTEMS AND GROUNDWATER

Information systems are essential to substantiate the decision-making process. The application of water resources management instruments, provided for by Law No. 9.433/1997, depends on the availability of data that allow assessing the conditions of hydrographic basins and their respective aquifers (PORTO; PORTO, 2008). Water resources information systems can be national or statewide. In the case of groundwater, three information systems stand out: the National System of Information on Water Resources (SNIRH), the National Registry of Users of Water Resources (CNARH), which is a subsystem of the SNIRH, and the Information System of Groundwater (SIAGAS). The first two operate under ANA [National Water Agency], whereas SNIRH seeks to gather general information on water resources, while the CNARH focuses on the regularized uses of water resources. SIAGAS, which predates Law No. 9,433/1997, is exclusively dedicated to wells, analyzing constructive, geological and hydrogeological data (see Box 19).

SIAGAS operates independently of the systems coordinated by ANA. Although their integration is desirable, connecting them is a technical challenge given the different interfaces used. Coordination would facilitate institutional work and contribute to generating a consolidated database with information related to research, use and management; however, there is still no forecast for carrying out this integration. CNRH Motion 038, of December 7, 2006, recommended the adoption of SIAGAS by state management bodies, State Government Departments, the National Water Agency (ANA) and Users of Underground Water Resources, as a shared national basis for storage, handling, exchange and dissemination of information on groundwater.

In addition to these water-related information systems, the National Environmental Information System (SINIMA) and the National Sanitation Information System (SNIS), provided that Motion CNRH 039 of December 7, 2006 also recommended integration of these systems.

3.5.1 National Water Resources Information System (SNIRH)

SNIRH is provided in Articles 5, Part VI, and 25 to 27 of Law No. 9,433/1997, and it addresses the "collection, treatment, storage and retrieval of information on water resources and factors involved in their management." (Article 25). ANA is responsible for the organization, implementation and management of this system, which is intended for SINGREH entities, users, the scientific community and society in general[3]. The stored data provide the basis for the preparation of Water Resources Plans, where data can be found on: hydrographic division, water quantity and quality, water uses, water availability, critical hydrological events, water resources plans, regulation and inspection of water resources and programs aimed at the conservation and management of water resources. In the case of groundwater, it is possible, for instance, find the national and[4] and transboundary[5] aquifer systems.

3.5.2 National Registry of Water Resources Users (CNARH)

CNARH was established by ANA Resolution 317, of August 26, 2003, with the objective of "learning the demand for water use in the country to provide support for the implementation of the instruments of national and state policies on water resources, and for the supervision of uses and interference in water resources" (Article 1, § 2). This registry materializes a "record of users of water resources, uses and interferences regulated by the States and the Federal Government" (Article 1, § 1). Developed by ANA, in conjunction with the state water resources management authorities, CNARH is also part of the SNIRH.

CNRH Resolution 126/2011 set guidelines for the registration of users of water resources and for the integration of databases referring to the use of surface and underground water resources. In its Appendix, the aforementioned Resolution determines all the data that must be integrated by ANA and the States.

The idea is that the States will insert in this National Database data relative to water resources in this National Registry, allowing the states to disclose their users and uses, based on the different territories (local, regional or national). This Registry forms a bridge between the National System and the State Water Resources Information Systems regarding different types of uses of water resources. The bodies or entities managing water resources and state and federal granting-authorities are responsible for entering the register of users, uses and

3. This system can be accessed at: https://www.snirh.gov.br/.
4. Available at: https://metadados.snirh.gov.br/geonetwork/srv/por/catalog.search#/metadata/3ec60e4f-85ea-4ba7-a90c-734b57594f90.
5. Available at: https://metadados.snirh.gov.br/geonetwork/srv/por/catalog.search#/metadata/54891117-5f06-4cdc-b929-fcd4b50eec08.

interferences, plus the regularization acts, as provided by CNRH Resolution 126/2011. There are characterized as users of this Registry all individuals or corporate entities, public or private, using or interfering with water resources, whether or not eligible for granting, pursuant to Article 12 of Law No. 9,433/1997, and state rules in force" (Article 3, part III, of CNRH Resolution CNRH 126/2011)[6].

Box 19 – Groundwater Information System (SIAGAS)[6]

Valmor Freddo

Created in 1996 by the SGB-CPRM, the Groundwater Information System (SIAGAS) stands out in terms of information management and is the main collection of information on existing wells in Brazil. The main partners that support and contribute to the feeding and consistency of data are the managing bodies and stakeholders in water resources in the states of the Federation, well drilling companies and users of water resources.

SIAGAS aims to collect, make consistent, store and make available georeferenced hydrogeological data and information. Initially, its work aims to support the preparation of hydrogeological maps and, later, to meet the demands of users, coming from the area of Water Resources and related areas. It presents mechanisms that facilitate the collection, consistency and storage of hydrogeological data, acting in coordination with state management agencies and partner companies (public and/or private).

One of the main concerns, since the beginning of the development of this System, was to provide managers and decision makers with increasingly qualified and relevant information. Hence the philosophy adopted, which was to use the database approach, structured in a data model with comprehensive content, to allow greater flexibility, rationalization and interchange with other databases.

SIAGAS is an important decision support instrument, and its mission is:

- To give subsidies to the research, study and projects of Hydrology and Hydrogeology developed by the Geological Service of Brazil within the scope of its activities;
- To form a national database of wells to support the National Water Resources Policy; and
- To provide information for decision-making, with a view to increasing water supply, and serve as an instrument for the management of groundwater resources.

Among the main benefits generated from the SIAGAS Project, we may highlight:

- additional value to the Wells Database;
- instrument to support the rational management of groundwater resources;
- input for the preparation of Thematic Maps in Hydrogeology;
- support for the National Water Resources Policy.

With an interactive system and totally open to the public, SIAGAS allows access to registration, constructive, geological, hydrogeological data, pumping tests and chemical analysis of several wells throughout the national territory. Its content can be found on the SIAGAS Web electronic platform, with easy access to information, enabling hierarchical searches, both punctual and spatial. Moreover, SIAGAS enables users to employ it in a wide range of applications, from management, monitoring of groundwater, studies hydrogeological assessment and water supply[7].

6. The system can be consulted at: http://www.snirh.gov.br/cnarh-histo/publico/index.jsf.
7. All data is available on the website: http://siagasweb.cprm.gov.br/layout/.

3.6 LEGAL IMPLICATIONS OF IRREGULAR USE OF GROUNDWATER

National and state water resources legislation imposes a series of obligations on those who wish to use groundwater resources. Among them, the following stand out (VILLAR; GRANZIERA, 2020, pp. 128-129):

- Necessity of a license or authorization to drill wells;
- granting of the right to use water resources, granted by the competent authority, and use compatible with its prescribed terms;
- in the case of uses provided for in Article 12 of Law No. 9,433/1997, compliance with the procedures provided for in state legislation, such as obtaining the declaration of exempt use or insignificant use from the competent water resources management body and use of water within the prescribed limits;
- groundwater abstractions must be designed, built and operated in accordance with current technical standards;
- groundwater abstractions must be equipped with devices that allow water collection, level measurements, flow and volume captured to allow quantitative and qualitative monitoring;
- the uses of groundwater conceded in the grant are subject to collection if this instrument is in force in the basin;
- any activity or enterprise must take preventive measures to avoid damage to aquifers;
- the owner of abandoned or unproductive wells, or the operation of which causes harmful changes to the quality of groundwater, must take measures, in accordance with the procedure approved by the water resources management agency.

In the case of groundwater that is used as a mineral, thermal, drinking water or bathing water, the following obligations are highlighted (VILLAR; GRANZIERA, 2020, p. 129):

- obtaining research authorization and mining ordinance from the ANM in order to exploit the potential of groundwater related to the mineral, thermal, drinking water or bathing purposes;
- comply with the terms contained in the research authorization and in the mining ordinance issued by the ANM [National Mining Agency];
- establish mineral water protection perimeters;
- some states require obtaining a right of use grant or declaration of exempt use for this type of exploitation.

Failure to comply with any of these obligations may generate civil, criminal and administrative liability, pursuant to Article 14, § 1 of Law No. 6,938/81, and Article 225, § 3 of the 1988 Federal Constitution. There is abundant precedent from State Courts, that: a) authorizes the plugging of wells without the granting of the right to use or proof of their exemption; b) obliges polluters or landowners to remedy contaminated areas; and c) condemns irregular users of mineral waters to pay compensation to the Federal Government as financial compensation for the unauthorized use of a federal resource (VILLAR; HIRATA, 2019; VILLAR; GRANZIERA, 2020). However, in case law, the payment of indemnities to the State Government or third parties affected by the use of groundwater without the grant of the right of use was not found, however, in theory, this compensation would be viable from a legal standpoint.

Civil liability materializes whenever there is damage to an aquifer, and it unfolds in two aspects: *a)* repair, remediation or compensation for the undesirable alteration caused to the environment and its elements, to the aquifer and its waters; and *b)* compensation for the damage that this change caused to the health and interests of the people affected, such as legitimate users who lost their wells.

Administrative and criminal liability requires conduct characterized as such. Table 10 shows the main administrative infractions, listed by Law No. 9,433/1997 and Federal Decree No. 6,514/2008, relative to the use of groundwater. States also have the jurisdiction to establish other administrative infractions related to the use and protection of these waters. It is also worth noting that the Mineral Water Code establishes several administrative obligations and infractions relevant to the trade of mineral waters (Article 24 to 34). Most of these administrative infractions are punished with: a) written warning, in which deadlines are established for the correction of irregularities; b) fine, simple or daily; c) provisional embargo of the well for the execution of services and works necessary for the effective fulfillment of the granting conditions or for the fulfillment of norms referring to the use, control, conservation and protection of water resources; and d) definitive interdiction of the well or plugging.

Law No. 9,433/1997.
Article 49. It is a violation of the rules for the use of surface or underground water resources:
I. derive or use water resources for any purpose, without having a grant of the right of use;
II. initiate the implementation or implantation of an enterprise related to the derivation or use of surface or underground water resources, which implies changes in the regime, quantity or quality thereof, without authorization from the empowered bodies or entities;
III. (VETOED)
IV. use water resources or perform work or services related to them in violation of the conditions specified in the grant;
V. drilling wells to extract groundwater or operating them without proper authorization;
VI. defrauding the measurements of the volumes of water used or to declare values different from those measured;
VII. infringing the rules set by regulations of this Law and in the administrative regulations, including instructions and procedures established by the competent bodies or entities;
VIII. obstructing or hindering the inspection action of the competent authorities in the exercise of their functions.

Federal Decree No. 6,514/2008:
Art. 61. Cause pollution of any nature at such levels that it results in, or may result in, harm to human health, or that causes the death of animals or significant destruction of biodiversity:
Sole Paragraph. The fines and other penalties mentioned in the header will be imposed after a technical report prepared by the empowered environmental agency, identifying the dimension of the damage resulting from the infraction and in accordance with the level of the impact.

Article 62. The fines set forth in Article 61 will also be imposed on whomever:
[...]
III – causes water pollution that makes it necessary to interrupt the public water supply of a community;
[...].

Art. 63. Carries out research, mining or extraction of minerals without the competent authorization, permission, concession or license from the empowered environmental authority or in violation of the terms of the one previously granted:
Fine from R$ 1,500.00 (one thousand five hundred reais) to R$ 3,000.00 (three thousand reais), per hectare or fraction.

Art. 66. Builds, renovates, expands, installs or operates establishments, activities, works or services that use environmental resources, considered effectively or potentially polluting, without a license or authorization from the empowered environmental bodies, in violation of the license obtained or contrary to the relevant legal rules and regulations:
Fine from R$ 500.00 (five hundred reais) to R$ 10,000,000.00 (ten million reais).

Art. 82. Prepare or present information, study, report or environmental report that is totally or partially false, misleading or omitted, whether in official control systems, licensing, forest concession or any other environmental administrative proceeding:
Fine from R$ 1,500.00 (one thousand five hundred reais) to R$ 1,000,000.00 (one million reais).

Table 10 – Administrative infractions relative to the use of groundwater

Source: Villar and Granziera (2020, p. 130).

Table 11 presents the environmental crimes related to the use of groundwater, set by Law No. 9,605/1998. Moreover, the use of mineral waters without authorization from the ANM has been considered by several judges as a crime of usurpation of Federal Government assets, set forth in Article 2 of Law No. 8.176/1991.

Law No. 9,605/1998.
Article 54. Causes pollution of any nature at such levels as to result in, or may result in, harm to human health, or to cause the death of animals or significant destruction of flora:
Penalty – imprisonment, from one to four years, and a fine.
§ 1. If the crime is committed by gross negligence:
Penalty – detention, from six months to one year, and fine.
§ 2. If the crime:
[...]
III – causes water pollution that makes it necessary to interrupt the public water supply of a community;
[...]

Article 55. Carries out research, mining or extraction of mineral resources without the relevant authorization, permission, concession or license, or in violation of a previously obtained one:
Penalty – imprisonment, from six months to one year, and fine.

Article 60. Build, renovate, expand, install or operate, in any part of the national territory, potentially polluting establishments, work or services, without a license or authorization from the empowered environmental bodies, or contrary to the relevant legal and regulatory standards:
Penalty – imprisonment, from one to six months, or a fine, or both penalties, cumulatively.

Article 68. Failing – by whoever has a legal or contractual duty to do so – to comply with an obligation of relevant environmental interest:
Penalty – detention, from one to three years, and fine.
Sole Paragraph. If the crime committed though gross negligence, the penalty is from three months to one year, notwithstanding the fine.

Art. 69-A. Prepare or present, in the licensing, forest concession or any other administrative proceeding, study, report or environmental report totally or partially false or misleading, including by omission:
Penalty – detention, from 3 (three) to 6 (six) years, and fine.
§ 1. If the crime committed through gross negligence:
Penalty – detention, from 1 (one) to 3 (three) years.
§ 2. The penalty is increased from 1/3 (one third) to 2/3 (two thirds) if there is significant damage to the environment as a result of the use of false, incomplete or misleading information.

Law No. 8,176/1991:
Art. 2 It is a crime against property, in the form of usurpation, producing goods or exploiting raw materials owned by the Federal Government, without legal authorization or in violation with obligations imposed by the authorization.
Penalty: detention, from one to five years, and fine.

Table 11 – Environmental crimes related to groundwater
Source: Villar and Granziera (2020, p. 131).

3.7 OTHER POLICY INSTRUMENTS THAT CONTRIBUTE TO WATER GOVERNANCE

The idea of integrated management of water resources presupposes not only specific policies for the use and exploration of water resources, but also coordination with policies related to land use and occupation, user industries and environmental protection. The core nature of water for economic activities, ecosystems and the quality of human life makes this substance (or should make it) an important variable in the application of management instruments for other public policies, especially those related to the environment, sanitation, agriculture and urbanism.

Examples of national laws that provide management instruments related to water management are: National Environmental Policy (Law No. 6.938/1981), the Agricultural Policy (Law No. 8.171/1991), the National System of Nature Conservation Units (Law No. 9.985/2000), Urban Policy (Law No. 10.257/2001), National Basic Sanitation Policy (Law No. 11.445/2007), National Policy on Climate Change (Law No.

12.187/2009), National Policy Waste Management (Law No. 12.305/2010), Conama Resolution 420/2009 (contaminated areas), the "New Forest Code" (Law No. 12.651/2012) and the National Irrigation Policy (Law No. 12.787/2013).

According to their jurisdictions, states and municipalities must regulate and implement these instruments, including aspects relative to water (surface and underground) and the promotion of water security. The main management instruments that can have a positive or negative impact on water are (VILLAR; HIRATA, 2022):

- Master Plan;
- Legislation related to the subdivision, use and occupation of land;
- Environmental Zoning;
- Environmental Licensing of Potentially Polluting Activities;
- Licensing or administrative authorization for well drilling and drilling;
- Ecological Economic Zoning (ZEE);
- Conservation units;
- State Environmental Regularization Program (PRA);
- Permanent Preservation and Legal Reserve Areas;
- National Environmental Information System (Sinima);
- Climate Change Plans;
- Solid Waste Plans;
- Solid Waste Management Plans;
- Management of Contaminated Areas;
- Report of Contaminated Areas;
- Basic Sanitation Plans;
- Information System on Public Basic Sanitation Services;
- Spring Recovery Programs;
- Program for the Proper Management of Animal Waste;
- Irrigation Plans (PEI);
- Agroecological Zoning (ZA);
- Irrigation Information System.

These instruments have the potential to promote the management of groundwater as they guide and optimize the performance of users, protect water or elements related to the hydrological cycle, impose restrictions or limit the use and occupation of land, or condition the implementation of activities potentially polluters or users of natural resources. The greatest challenge, however, is that they are implemented effectively and efficiently, as well as encompassing groundwater. The Government has difficulty in preparing or implementing important planning instruments, such as the State Irrigation Plans, Agroecological Zoning and Ecological Economic Zoning. This situation is particularly worrying because Brazil is among the ten countries with the largest area equipped for irrigation, where agriculture is the main user in quantitative terms (ANA, 2021).

Another problem is the inclusion of aquifer protection in municipal land use planning. Groundwater is essential for public supply, especially for small municipalities. It is not usual, however, for municipalities to use urban policy instruments to protect recharge areas that contribute to guaranteeing local supply, or to carry out zoning that takes into account aquifer vulnerability.

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Violeta Well in Aquifers Cabeças and Serra Grande in Alvorada do Gurguéia (PI)
Photo: Vagney A. Augusto / ANA Image Database

Chapter 4

GROUNDWATER GOVERNANCE AND THE STRENGTHENING OF INTEGRATED WATERRESOURCES MANAGEMENT

4.1 ESTABLISHING A GROUNDWATER GOVERNANCE IMPLEMENTATION AGENDA

Historically, water governance in Brazil has always focused its efforts on surface waters. The Government, in this context, faces difficulty in including groundwater in the management, while the integration with estuarine and coastal waters remains in the debate, and that of meteoric waters is not even discussed. The integration of surface and groundwater is the first step towards the integrated management of water resources. This type of management demands joint actions that contemplate this cyclical movement of water, but also specific actions that consider the particularities of each dimension, otherwise society will lose social, ecological and economic opportunities. Table 12 presents the main distinctions between surface and groundwater.

Aspect	Groundwater	Surface water
Storage	Great	Small and medium
Resource area	Relatively unrestricted	Restricted to bodies of water
Flow speed	Very low	Medium and high
Permanence time	Usually decades/centuries	Usually weeks/months
Prone to droughts	Low	High
Losses due to evaporation	Low and located	High
Resource evaluation	High cost and uncertain	Low cost and right
Impacts of extraction	Long and scattered	Immediate
Water quality	Generally good	Variable
Vulnerability to Pollution	Variable natural protection	No protection
Persistence of pollution	Usually extreme	Usually transient

Table 12 – Main distinctions between surface and groundwater

Source: Tuinhof *et al*. (2006, p. 2).

Groundwater is not an accessory resource to surface water, on the contrary, it maintains surface water availability. Moreover, regardless of the climate change scenario or water crisis, these waters are essential for public supply, economic uses and for vulnerable groups that do not have another water source. Finally, their permanence time means that part of them is not considered a renewable resource, which requires a debate on how to maximize their use and the right of future generations to the resource.

The lack of knowledge about groundwater or its uses and strategic role is a threat to water resources (ground and surface), ecosystems, human beings and future generations. Moreover, the opportunity to stimulate the development of areas that could benefit from this water potential is lost.

Brazil faces increasingly frequent periods of drought and, consequently, reduced river flow and water availability from reservoirs, which can compromise water, energy, food and economic security. This scenario causes an increase in the use of aquifers, whether for supply, irrigation or industry purposes. In this context, there are three central problems that threaten groundwater (CONTI, 2017):

a) **Lack or inefficiency in the management and control of aquifer extractions**. Disorderly extractions generate socio-environmental damage and can compromise the only source of water available, especially in the case of vulnerable populations.

b) **Lack or inefficiency of actions to maintain the quality of the aquifer or to restore it.** Human activities can contaminate aquifers and render important water reserves unfeasible.

c) **Lack of strategic planning in the management of aquifers that incorporates the pressures arising from the global-local and local-global relationship.** Climate change, the loss of large forests and the international market form new realities of supply and demand for groundwater that need to be addressed. According to the structuring of this plan, groundwater can be used as a strategy for adaptation and mitigation, or else be degraded.

The solution to these problems comes from knowledge-based governance, inter-institutional coordination and the participation of multiple actors (institutional and social) involved in the use and management of water resources, and in territorial, environmental and socioeconomic planning. The particularities of groundwater reinforce the importance of governance, especially given the need to move beyond sectoral management actions and user engagement.

The existing hydrogeological knowledge in Brazil is incipient in view of the needs imposed by the management of water resources; however, it is only this knowledge that allows the "visualization" of aquifers. Groundwater moves through heterogeneous and complex geological structures, which makes access to information and the formation of a participatory and well-founded decision-making process difficult. Invisibility and ignorance also occur in relation to conflicts between users and between public policy governing water resources, environment, agriculture, sanitation, mining and economic development. Users do not correlate that well productivity losses or contamination may be caused by third parties, who are using wells incorrectly (or irregularly), or by the proximity of activities capable of contaminating the soil and aquifers. Without understanding what causes these problems, there is no social pressure on the managing Government (VILLAR, 2016; CONICELLI *et al.*, 2021).

In Brazil, command and control instruments are the basis of water management; however, in the case of underground resources, they have been showing limitations. The overwhelming evidence is the high number of irregular wells. If noncompliance with the law is, in and of itself a problem, another is the lack of knowledge of the existence of the real number of wells. In Brazil, 90% of abstractions are private and only 10% supply urban public networks (Hirata *et al.*, 2019). Most abstractions are invisible to public policies, and states have no idea of the economic dimension and socio-environmental role of these waters.

Due to the ease of exploitation, this source becomes increasingly popular for supplying various activities in the countryside and in the city, and is based on the following points: low cost of exploitation; speed in drilling wells (in some cases in less than a week); new technologies associated with the operation of wells, which allow collections to function almost autonomously; and availability in practically the entire Brazilian territory. The well is the solution where the problem exists without water distribution stations.

In this context, governance needs to jointly develop the answers to the following questions: how to protect an invisible resource unknown to society? Who extracts these waters, and how to control this extraction in order to make individual use compatible with collective interests? How to encourage aquifer protection actions? How to reveal and equate existing conflicts for use thereof? There are no right answers to these questions, because in each aquifer, within the context of the hydrographic basin itself, there is a need for a governance process that defines how it will be used in view of the socioeconomic and ecosystem functions performed.

The Government and water resources management bodies have a fundamental role in this process; however, it is necessary to mobilize other actors and stakeholders. Good governance makes it possible to move more holistically towards the challenges faced by groundwater management. Much more than surface water, the use of groundwater is spread across hundreds to thousands of abstraction points in just one location. Therefore, there will be no adequate management if users are not aware of their responsibilities and rights and, above all, if they do not participate in this process. Therefore, groundwater governance needs to overcome the following weaknesses:

- **Lack of hydrogeological knowledge and/or difficulty in incorporating this knowledge into the application of water governance**.

  Hydrogeology plays a fundamental role in the governance of aquifers insofar as this science is responsible for spatializing aquifers and determining the central aspects of management, such as: a) how much water can be provided; b) how extraction impacts the aquifer and dependent water resources; c) what is the quality of the water; d) how to conserve the aquifer; and e) how to recover an aquifer. In many cases, even with the existence of data demonstrating risk situations, there are difficulties in incorporating aquifers into public policies and management instruments.

- **Lack of studies on the social, economic and political dimensions of governance, management, appropriation, use and importance of groundwater**.

  The debate must go beyond the technical issues of geology and engineering and include topics such as: institutional and legal architecture of groundwater governance; value of these waters; social relations and power structures behind the logic of clandestineness, ignorance and invisibility; processes of social participation in relation to these waters; social conflicts and unequal resource appropriation; environmental education strategies etc.

- **Institutional and legal weaknesses to promote groundwater governance**.

  The institutions responsible for organizing the management of water resources face problems related to the lack of resources to promote technical studies and institutional campaigns, as well as operational and technical difficulties to implement management instruments or inspection actions. At the same time, the lack of regulation or its limitations make it difficult to implement management and its instruments, creating legal conflicts or simply preventing its operationalization.

- **Lack of horizontal and vertical[1] coordination between managing bodies for the implementation of public policies related to groundwater**.

  Brazilian federalism and the division of powers in matters of water, soil, mineral exploration and economic development require coordination between different sectors and levels of government to promote effective policies for the management of groundwater. Notwithstanding, there is a lack of initiatives that promote this coordination between the Federal Government, States, the Federal District and municipalities, and that correlate groundwater resources with the environment, territorial planning, mineral waters and sectoral policies, such as sanitation, agriculture and development.

- **Lack of user engagement and participation in groundwater management**.

  Groundwater users are not proactively involved in the management and monitoring of the aquifer, on the contrary, the vast majority of them are on the sidelines of this management, as they use water irregularly. Brazilian legislation does not encourage the formation of user organizations as in other countries, which restricts the role of users to participate in panel-based bodies (CBH, CERH and CNRH). Most of the time these users do not participate or are underrepresented.

- **Social ignorance about groundwater**.

  Civil society, users and even the Government do not promote the debate on aquifers. In panel-based bodies, discussions and investments prioritize surface water resources. Most nongovernmental organizations operating in the sector focus on surface water. The lack of knowledge about groundwater prevents participation, for social actors do not understand the importance of managing the resource or the consequences of not doing so. Ignorance does not allow a sense of relevance, urgency or priority for these waters to be established in the community.

The governance, administration and management of groundwater resources go through the following minimum agenda:

- regional recognition of potential aquifers and their main ecosystem functions through studies that incorporate the various roles played by groundwater, including its economic importance (quantifying it) and ecological importance (recognizing it). The works for this recognition must consider the hydrogeological cartography, based on the register of driven wells, surface geological map, map of the hydrographic network, areas of swamps, mangroves and lakes, regional water balances (in hydrographic basins), among others;

1. Horizontal coordination takes place between "organizations and political and bureaucratic actors that make up the same level of government", while the vertical is composed of "different levels of government" (SOUZA, 2018, p. 16).

- study on the relationship of aquifers with other bodies of water, quantifying groundwater discharges in the perenniality of rivers, lakes, mangroves and swamps, through analyzes in hydrographic basins and regional numerical modeling;
- identification of critical areas of groundwater resources, i.e., those with the greatest use of groundwater, both for public and private supply, or those where the greatest danger of contamination is identified (in the sense of Foster and Hirata, 1988), from the registration of potential sources of contamination and vulnerability to contamination;
- identification of the actors involved in the use and management of water, territorial and environmental resources; identification of vulnerable communities and groups that depend on groundwater;
- creation of specific hydrogeology groups in basin committees and other bodies that contribute to planning the use of water in the basins, especially in critical areas. These groups must define a particular investment agenda in order to identify priority areas and studies that seek solutions;
- once the basic hydrogeological studies have been carried out, the water resources management bodies, especially the collegiate ones, should establish interdisciplinary groups with the objective of proposing comprehensive strategic actions for a management committed to the needs of society and the environment, which takes into account topics including, for example, equity and social responsibility;
- creation of interdisciplinary research lines to promote groundwater for universities and research centers, private and consulting companies, in addition to organized civil society groups; technical training at various levels for different audiences, always in line with groundwater resources management and governance policies;
- promotion of environmental education and social communication initiatives on groundwater and aquifers in schools, unions, neighborhood associations, etc., prioritizing critical areas, in order to reduce the irregularity of abstractions and the risk of the use of contaminated groundwater. Entities such as CREA and the health surveillance should be involved in these initiatives;
- inclusion of contractual clauses for sanitation service providers, providing for environmental education actions related to groundwater, especially identifying irregular private users, making them aware of the importance of good use and protection and maintenance of their capture; search for incentive mechanisms to promote the regularization of wells;
- Fostering the establishment of user organizations that help the government in monitoring and inspecting water;
- promotion of partnerships with universities and research centers, the Brazilian Bar Association (OAB) and the Prosecutors' Offices to monitor the progress of state public policies related to groundwater;
- integration of information systems related to water, environment and user sectors, giving more visibility to groundwater;
- inclusion of groundwater in urban policies, sanitation plans, irrigation plans, solid waste management plans and irrigation plans;
- production of groundwater indicators that feed a process of communication with society about advances and failures in water management, as well as actions taken, considering what is planned, executed and long-term courses to improve the use of water resources, including underground.

Box 20 – The joint use of surface and underground water resources as a strategy for facing climate change

Bruno Conicelli

Groundwater is essential to face water crises. Based on official data, Hirata et al. (2019) found that cities supplied only with surface water were twice more affected by the crisis than those supplied only by groundwater. Such differences could be greater if there was a planned and managed use of groundwater, which is not the case in most cities.

Due to their storage capacity, aquifers can provide water even after long periods of drought, in which recharge is limited or even null. Level drops in an aquifer under exploitation are slow, which makes it possible to restore storage in periods when there is an abundance of rain. This feature contributes to coping with long dry periods, and the city or enterprise can, when necessary, make use of this "saving" of water from the hydrological cycle, and leave the surface source for the rainy season or even create mechanisms for the surplus water to be able to recharge the aquifer, compensating for withdrawals from the dry period. This type of use is known in Hydrogeology as the conjunctive use of surface and groundwater (FOSTER; STEENBERGEN, 2011).

The conjunctive use allows for a better and more balanced use of the hydrological cycle (and not just a resource), seeking the most available water, the cheapest economically and the one that causes less damage to the environment. Another important point is that in a city there are several types of water sources that can serve different uses. Deep urban aquifers have potable water and can be directly used for public supply, with little or no treatment. On the other hand, shallow aquifers, which in some places have their water extracted only to drain and keep underground civil constructions dry, can be used for less noble uses, such as cleaning, watering green areas or, when the project allows, for sanitary use (HIRATA; FOSTER; OLIVEIRA, 2015).

Artificially managed aquifer recharge is an important ally of connective use, which can help treated effluents to guarantee the restitution of overexploited aquifers. Therefore, the strategy of conjunctive use of water is the key to allow the sustainability of both cities and irrigated agriculture.

4.2 STRATEGIES TO PROTECT THE QUANTITY OF WATER AND THE OVEREXPLOITATION OF AQUIFERS

Aquifers have as their main characteristic the great storage of water. Therefore, withdrawals of volumes greater than the recharge could be allowed so long as there is compensation in the future. That, however, requires long-term planning, with clear rules for exploitation, based on technical studies and monitoring through an integrated monitoring network, in addition to user engagement. The extractions in aquifers should not be reduced to a simple arithmetic of inputs and outputs, which disregards their storage capacity or the fact that extractions can induce greater availability of groundwater (FOSTER *et al*., 2006). Ignoring these considerations means losing the opportunity that aquifers offer to provide more water or to regulate the balance between production and demand, especially in dry periods and prolonged droughts.

The formation of a long-term planning is hampered by the low investment in studies, which would allow accurately measuring the potential of aquifers. Moreover, the problem of overexploitation is associated with the large number of irregular or unknown wells, which makes it difficult to establish a realistic water resources management program.

The proper management of extractions and the use of an aquifer, an aquifer system or a specific part of an aquifer, must initially consist of the identification of critical areas, i.e., those where the use of groundwater is more intense or where their performed ecosystem services prove to be essential. The recognition of critical areas should have a regional character, ideally on a scale of 1:100,000 – 1:250,000, and encompass specific watersheds, in order to verify the surface resources that may be impacted. This will allow the planning of groundwater use actions and, above all, enable managers to identify priorities among critical areas.

The identification methods of critical areas must be based on: a) hydrogeological cartography to recognize aquifers and their hydraulic characteristics, supported by a register of wells, with tests and hydraulic data; b) identification of ecologically fragile areas (swamps, rivers and mangroves) of the underground flow; c) a register of urban centers dependent on underground water for public and private supply; d) records of conflicts between users; e) an inventory of areas with records of large losses of potentiometric levels of the aquifer, as reported by well drilling companies, users or operators of water supply systems; and f) a history of flow reduction in rivers, drainages and dry swamps or loss of springs and lakes.

The study of the characterization of critical areas must be developed in semi-detail, preferably on a scale of 1:50,000 or greater. The focus is to identify the areas of greatest use of the water resource, either due to the high density of wells, the sum of high flows or the presence of pronounced lowering of the potentiometric level, as well as in cases of conflict situations between users or where the use of resource involves vulnerable populations.

The method of detailing critical areas can be MetQ (HIRATA; FOSTER; OLIVEIRA, 2015), in which an area is squared in sizes of 500 m x 500 m or 250 m x 250 m, and the wells are located. The areas with the highest density of wells or where the sum of flow is greater will be considered of greater criticality. Such a tool can support the concession of a grant, as it allows the resource manager to establish areas where the use of groundwater can be encouraged or prohibited, or even where the grant must be conditioned to specific requirements.

From the identification and characterization of critical areas, it is necessary to transform this knowledge into institutional, political and legal actions. Usually, the most frequent action is the creation of groundwater restriction and control areas, whose objective is to limit the volumes captured or new drilling. This is the case of the area of restriction and control of capture and use of groundwater in Ribeirão Preto (SP), set forth in the previous chapter. The option for the regulation of restriction and control areas is a management policy foreseen in several Brazilian states and even internationally. The case of the Valle de Santo Domingo aquifer (Mexico) illustrates how this measure can stabilize extractions, although it warns of the difficulty of reversing the losses of an uncontrolled extraction prolonged for years. Moreover, this type of measure requires the involvement of the government and users. Management bodies need to monitor the evolution of aquifer water levels, engage users in the process of defining goals and ways of allocating water and monitoring compliance with the measure. To fulfill these obligations it is necessary to establish partnerships between the various levels of government (local, state and federal). Users, in turn, need to commit to reducing abstractions in order to achieve goals, monitor their wells and work together with the government to recover the aquifer.

Another option to recover the aquifer is the adoption of mechanisms for artificial aquifer recharge, detailed in Box 21. In this case, the structure can be implemented by the government, by users or by mixed models between the government and users. In Brazil, artificial recharge is not used as a public policy, although it is provided for in CNRH Resolution 153/2013. The states did not regulate this issue in the necessary detail, for example, by specifying the studies and procedures to be implemented.

The Case Gallery presents the Geneva Aquifer, which is a transboundary aquifer shared between France and Switzerland, which has implemented a joint system of artificial recharge. Although the aquifer is transboundary, this institutional arrangement came about from the initiative of the affected localities (Canton of Geneva, Switzerland, and the Department of Haute-Savoie, France), regardless of any action by the federal governments or bodies of the Ministry of Foreign Affairs. This paradiplomacy[2] scheme is considered the main successful experience in the management of transboundary aquifers. Local governments shared the cost of implementing the artificial recharge system and created a technical committee made up of hydrogeologists from both countries. Its technical determinations in relation to exploitation rates are binding on managing bodies and users of public supply, the main responsible for the overexploitation of the aquifer.

2. Paradiplomacy comprises international actions carried out by sub-national entities, such as states of the federation, NGOs, companies and municipalities.

Box 21 – Artificial aquifer recharge: an alternative for increasing water availability

José Eloi Guimarães Campos
Vagney Aparecido Augusto
Júlio Henrichs de Azevedo
Drielly Sousa Rodrigues

The most common process of natural groundwater recharge is that originating from the infiltration of rainwater from the surface and by its percolation in the soil profile to the saturated zone of the aquifers (VRIES; SIMMERS, 2002; SCANLON; HEALY; COOK, 2002; SCANLON; HEALY; COOK, 2002). Only part of the water infiltrated at the surface results in effective recharge, since this balance is affected by the evapotranspiration process, by the retention of water in the soil in the form of moisture and, sometimes, by the subsurface interflow, which occurs due to permeability contrasts in the infiltration section.

Artificial recharge of aquifers corresponds to any human action that results in the expansion of natural recharge, intentionally or not (FETTER, 2001). Historically, the term artificial recharge of the aquifers has been used to refer to projects that aim to increase infiltration and raise the top of the saturated zone of aquifers. In recent years, this terminology has been replaced by *Managed Aquifer Recharge* – MAR.

Artificial recharge can be carried out in three situations in relation to underground reservoirs: i) on the surface, through the spreading and induction of infiltration of rainwater, using basins, tanks, contour lines and terraces or, still, with directing drainage to natural depressions in the terrain (Figure 44); ii) in the unsaturated zone of aquifers (generally, inside the soils), from infiltration boxes (filled or coated), recharge trenches, subsurface drains or through drainage galleries (Figure 45); and iii) directly in the saturated zone of the aquifers, through shallow or deep wells (Figure 46).

The main objectives of artificial recharge are: to increase underground water availability; raise potentiometric levels; and recover aquifers subjected to overexploitation. The practice, however, can result in other advantages, such as: mitigation of the effects of saline wedge intrusion in coastal aquifers; in situ dilution of contaminants or natural salinity from aquifers; minimization of surface runoff of rainwater (with reduced risk of inundation and flooding); and regulation/stabilization of the physicochemical characteristics of groundwater.

The water used for recharge can come from the following sources: rainwater (generally captured on building roofs); water from surface bodies of water (rivers or lakes); water from other aquifers (generally pumped from greater depths); wastewater or reused water. The main condition to be observed is that the water used in artificial recharge must not effectively or potentially compromise the environmental quality of the waters of the aquifer to which it is directed (CONAMA, 2008; CNRH, 2013).

The implementation of artificial recharge involving a large area must be preceded by studies, with the construction of pilot systems and qualitative-quantitative monitoring. Only after the effectiveness of the proposed system is known should its implementation be extended to larger areas.

For the projects of artificial recharge of aquifers to reach the expected results, it is important to know the mechanisms and dynamics of natural recharge since the induced recharge must simulate the same paths of the natural flow. The implementation of pilot systems must be preceded by the following studies: hydraulic assessment of aquifers (determination of hydraulic parameters); determination of the boundary conditions of aquifers (thickness, porosity and limits); verification of water quality in aquifers and recharge; application of geophysical studies (to determine the ideal locations for the implementation of pilot systems); and other hydrogeological techniques (isotopic studies, tracers, hydraulic tests in the aquifer and *in situ* infiltration tests).

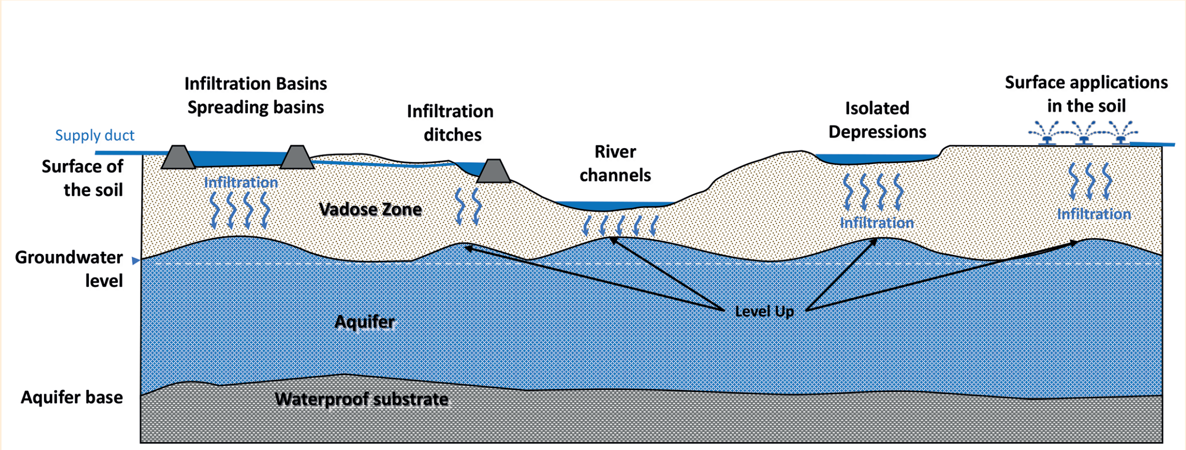

Figure 44 – Examples of surface recharge methods

Source: adapted from Topper *et al*. (2006, p. 77).

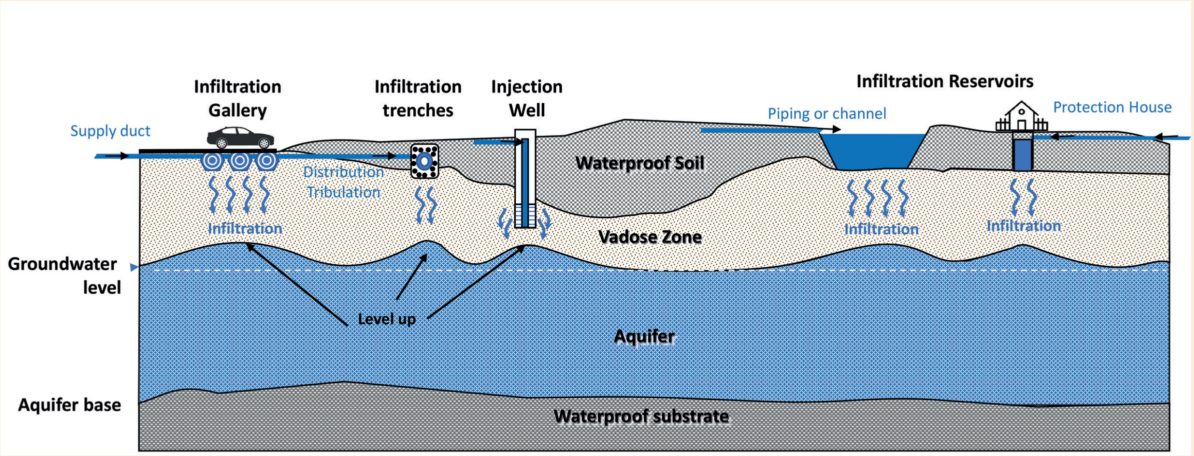

Figure 45 – Example Examples of methods of artificial recharge at depth in the unsaturated zone

Source: adapted from Topper *et al*. (2006, p. 81).

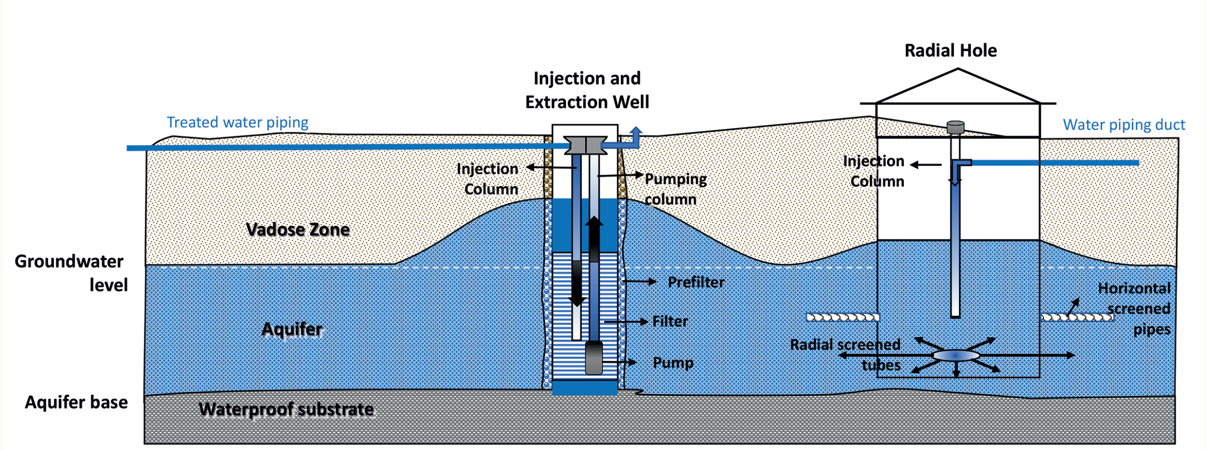

Figure 46 – Scheme of direct injection methods

Source: adapted from Topper *et al*. (2006, p. 82).

The natural recharge of aquifers is strongly controlled by soils (thickness and sand/clay ratio) and climate (total rainfall and rainfall distribution regime in time and space). In regions with greater water surplus, with more regular and abundant rainfall, the presence of thick soils favors recharge. On the other hand, regions with strong climatic seasonality, with a long period without rainy events (even with a high average volume of rainfall) present a large loss of water since natural recharge requires that adequate conditions be reached before the moisture plumes are transformed into effective recharge (mainly the replacement of water in the unsaturated zone of the soils). On the other hand, in semi-arid regions, with rainfall concentrated in some months of the year, the presence of thicker soils (if any) constitutes a barrier to natural recharge.

Artificial recharge, therefore, can be a way to minimize natural water losses due to climatic seasonality and intrinsic soil features. In this sense, if infiltration is carried out at greater depths, i.e., below the zone of greater root development, losses through evapotranspiration, soil moisture replacement and interflow are minimized with the consequent increase in recharge effectiveness.

The development of managed aquifer recharge is a common practice in the management of water resources in different countries around the world (DILLON *et al*., 2019). India and the United States are the countries that most practice this type of technique, followed by countries in Europe and Australia. In Brazil, this practice is incipient, being applied only in academic research and isolated initiatives.

The main projects that have advanced the knowledge of this type of technique in Brazil include: i) practice of artificial recharge in condominiums in the Federal District (CADAMURO, 2002; CADAMURO; CAMPOS, 2005); ii) recharge in an urban area of Recife (PE) to recover potentiometric levels (MONTENEGRO *et al*., 2005); iii) recharge of thermal aquifers in the region of Caldas Novas (GO) using water after circulation in swimming pools (ALMEIDA, 2011); iv) recharge aimed at optimizing the quality of groundwater in the south of the state of Tocantins (AZEVEDO, 2012); v) recharge of crystalline aquifers in the semi-arid region of Petrolina (PE) aiming at the dilution of dissolved salts (SILVA, 2016); and vi) recharge of contaminated aquifers in condominiums in the Federal District, aiming at *in situ* treatment by dilution (NUNES, 2016).

Growing urbanization (soil sealing), the conversion of natural areas for agricultural and livestock purposes (suppression of vegetation and soil compaction by trampling herds and motorcycle mechanization), among others, are anthropic factors that reduce natural recharge. Moreover, the trend towards a decrease in rainfall or, at the very least, a change in historical rainfall patterns, as well as the scenarios of increasing global temperature (potential changes in evapotranspiration rates), also converge towards a decrease in the natural recharge of aquifers.

Given the expected changes in weather patterns and the intensification of land use and occupation, the adoption of artificial recharge technologies can help to alleviate water crises, especially in urban environments.

In this context, it is necessary for water management to advance in discussions on legal and technical issues related to the development of artificial recharge projects or managed aquifer recharge. These discussions must be transversal and involve environmental and water management bodies, sanitation companies, municipal governments (responsible for land use planning), institutions representing the agricultural sector, academic communities and civil society. Moreover, to establishing general guidelines for artificial recharge in the country, it is important to determine the obligation to adopt this technique when it is characterized as a mitigation measure in specific situations, such as the dilution of contaminants in groundwater, compensation for the effects of waterproofing of land, reduction of the risk of flooding due to excess surface runoff, and replacement due to lowering of the aquifer by pumping.

4.3 STRATEGIES FOR PROTECTING THE QUALITY OF AQUIFERS

Strategies to protect the quality of aquifers should not be dissociated from those that aim to protect the quantity of their waters. Groundwater extraction can influence the entry of brackish water from deep aquifers or the sea, as well as contaminated water from surface water courses or groundwater aquifers, degrading the aquifer. Thus, the areas of restriction and control of groundwater use can also be considered instruments to protect aquifer quality, because by restricting the exploitation of groundwater, contamination is prevented from entering or spreading through the aquifer.

The water use concession programs must consider the quality of the resource and the danger of pollution, in order to avoid problems and risks to the users' health and facilitate the identification of contaminated areas in the aquifer. Prevention against the loss of quality of water resources focuses on two distinct strategies (FOSTER *et al.*, 2002): a) actions aimed at protecting the aquifer as a whole; and b) actions aimed at protecting water sources for public supply.

As a matter of priority, the protection of the aquifer takes place through the control of the use and occupation of the soil, in order to avoid generation of contaminating loads or their reaching the aquifer (saturated zone). This type of protection requires the application of instruments that: *a)* restrict certain uses in recharge areas; *b)* request authorization or permission for the use and occupation of the land, taking into account the vulnerability to contamination of aquifers; and *c)* adopt hazard management procedures to prevent or mitigate accidents. Brazilian legislation has established several instruments for such purposes, such as the case of environmental licensing, environmental zoning and municipal land use and occupation laws.

According to Foster and Hirata (1988) and Foster *et al.* (2002), the prevention of contamination can occur by reducing the danger of contamination of an area. The greatest danger occurs when there are high contaminant loads in areas of high vulnerability, such as, for example, the outcrops of a sandy and permeable sedimentary free aquifer. In contrast, the lowest hazard is associated with cases where there is a low or no contaminant load located in an area of low vulnerability.

Aquifer vulnerability can be mapped, and there are several methods available to do so. The GOD (FOSTER; HIRATA, 1988) and DRASTIC (ALLER *et al.*, 1987) techniques are quite popular in Brazil and Latin America. Both allow generating maps of a regional (1:100,000) to semi-regional (1:50,000) character. More recently, Foster, Hirata and Andreo (2013) reviewed the practical scope of vulnerability methods and concluded that such maps serve to identify three classes of aquifers: *a)* high vulnerability aquifers, where a wide spectrum of activities can contaminate groundwater; *b)* low vulnerability aquifers, i.e., those where an anthropic activity would hardly contaminate them; and *c)* medium vulnerability aquifers, which would encompass all those that do not fit into the first two categories. In this third case, the danger would be more conditioned to the type of activity and its operation than to the hydrogeological characteristic of the aquifer (FOSTER; HIRATA; ANDREO, 2013).

Another management approach is the protection of the most important water sources, such as those used for public supply or users who are more sensitive to the issue of quality, such as hospitals, clinics and schools. In this case, the strategy is to trace the Protection Perimeters of Wells or Springs (PPP) by mapping the areas around the abstraction, which are associated with its recharge, and preventing the installation of potential sources of contamination (CARVALHO; HIRATA, 2012; FOSTER *et al.*, 2002).

4.3.1 Management of contaminated areas and groundwater

When contamination occurs, it is necessary to resort to the Management of Contaminated Areas (GAC), which is a procedure regulated by Conama Resolution 420/2009 and by state legislation. The term contamination is defined in article 6, Part V, of Conama Resolution 420/2009 as:

> the presence of chemical substance(s) in the air, water or soil, resulting from human activities, in concentrations that restrict the use of this environmental resource for current or intended uses, defined based on a risk assessment to human health, as well as the assets to be protected, in a standardized or specific exposure scenario; [...].

From the perspective of the GAC, degradation becomes legally relevant when it exceeds contamination parameters previously set by legislation. According to Conama Resolution 420/2009, this procedure is guided by the Guiding Values (VOs), which are subdivided into the following categories:

Quality Reference Value (VRQ): is the concentration of a certain substance that defines the natural quality of the soil, being determined based on statistical interpretation of physical-chemical analyzes of samples of different types of soil (Article 6, XXII);

Prevention Value (VP): is the limit value concentration of a given substance in the soil, such that it is capable of sustaining its main functions, in accordance with article 3 (article 6, XXIII);

Investigation Value (VI): is the concentration of a certain substance in the soil or underground water above which there are potential risks, direct or indirect, to human health, considering a standardized exposure scenario (article 6, XXIV).

The characterization of contamination, therefore, presupposes the existence of certain concentrations in the soil or groundwater that, according to the legislation, would generate a potential or effective risk to human health or ecosystems. Once this situation is verified, it becomes mandatory to adopt a series of measures to restrict the use of soil and groundwater, as well as to recover and remedy the contaminated area. CNRH Resolution Conama 420/2009 regulates the Guiding Values (VOs), however, the states must regulate the GAC, defining its procedures, the competent body to carry them out and the Quality Reference Values (VRQ), in addition to establishing more restrictive VOs.

The protection of groundwater must be guided by prevention, as the damage is usually irreversible, and may even make the use of this water unfeasible, given that the cost of its recovery or remediation can be higher than the actions to avoid the damage. In many cases, even with high investments and application of the best available techniques, it is not possible to clean up the aquifer, but only to reduce contamination levels. This situation gave rise to several lawsuits in the state of São Paulo that discussed whether the recovery of contaminated areas should be guided by the criteria of the Guiding Values or by the duty of integral environmental repair (Box 22). The core of this legal debate concerns the cost-benefit analysis promoted by the GAC in the face of environmental damage and the technical capacity to decontaminate an aquifer. In other words, what would be an acceptable recovery from an environmental, economic and social point of view? Unfortunately, there are technological and/or economic limitations that prevent the full repair of the damage, i.e., restoring the natural geochemical characteristics of the aquifer, especially in the case of hydrologically complex aquifers (such as fractured, sedimentary, multilayered or deep aquifers) or when there is a presence of very toxic or persistent contaminants, such as organochlorine solvents.

Box 22 – Remediation of contaminated areas: guiding values *versus* full environmental reparation

Ana Carolina Corberi Famá Ayoub e Silva

Remediation of aquifers is complex. Most of the time, even applying the Contaminated Area Management (GAC) procedure, the full restoration of soil or water is not promoted, but only the remediation of resources to reach legal standards. The fact gave rise to the filing of actions by the Prosecutor General's Office of the State of São Paulo (MPSP), which even questioned the constitutionality of São Paulo Law No. 13,577/09, and is considered a precursor on the subject. The main legal discussion concerns the scope of the GAC, i.e., whether it should promote remediation through the application of Guiding Values or comprehensive environmental remediation (one of the principles of Environmental Law).

To understand this conflict, it is necessary to clarify the meaning and purpose of the terms remediation and reparation. Conama Resolution 420/2009 defines remediation as "one of the intervention actions for the rehabilitation of a contaminated area, which consists of the application of techniques, aiming at the removal, containment or reduction of concentrations of contaminants" (Article 6, part XVII). In a similar sense, State Law No. 13, 577/09, which "provides for guidelines and procedures for the protection of soil quality and management of contaminated areas" defines remediation of contaminated areas as "adoption of measures to eliminate or reduce risks in acceptable levels for the declared use" (Article 3, part XVIII). The term integral environmental repair, which aims to restore the environment, is defined by Law No. 9.985/2000, as the "restitution of an ecosystem or a degraded wild population as close as possible to its original condition" (Article 2, part XIV); In the same sense, the 1988 Federal Constitution, in its Article 225, paragraph 1, part I, in determining that essential ecological processes be restored, aims to achieve the pre-damage situation – *status quo ante*. Therefore, comprehensive environmental repair aims to restore ecological balance (PINHO, 2010; SILVA, 2019).

In the specific case of contamination, the premise for defining the application of full repair or remediation depends on the way in which the damage is treated. In other words, from an ecological point of view, environmental damage "violates the so-called 'ecology laws'", highlighting interdependence, self-regulation, self-regeneration and the ecological function. Legal damage occurs when there is an offense or threat to certain legal assets, in this case the environment (SILVA, 2012, 2019).

The repair of ecological damage seems to be ideal, as it aims to restore the environment, allowing the integral re-establishment of the "ecology laws". Leite and Ayala (2010), however, state that "nature, having its physical and biological compositions modified by aggressions that it cannot tolerate, can never be truly restored, from an ecological point of view." In this way, the purely legal view is adopted more frequently, in which remediation takes place following the criteria and limits of the viable parameters defined by standards.

The conflict of positions on contaminated areas was intensified with the filing of the Direct Unconstitutionality Action (ADI) 0210197-50.2011.8.26.0000, by the MPSP [São Paulo State Prosecutor General's Office], claiming the declaration of unconstitutionality of Article 10 and sole paragraph of São Paulo Law No. 13,577/09, which admits the possibility of exceeding the Prevention Values through assessment by the environmental agency and monitoring of the resulting impacts. In the MPSP's view, the device would transform environmental licensing from preventive to corrective, defying the State Constitution and the precautionary principle.

Despite the dismissal of the ADI, the MPSP filed several lawsuits (several still in progress) against the owners of contaminated areas. Therefore, it took a position contrary to São Paulo Law and Conama Resolution 420/2009, arguing that, by failing to provide integral repair of the ecological functions of the soil and groundwater, these norms contribute to the generation of environmental liabilities for present and future generations (LUTTI, 2012).

Among the numerous lawsuits filed, the decision that dismissed Civil Appeal 1096930-98.2016.8.26.0100 stands out, recognizing the "Impossibility of demanding the adoption of a technical solution different from that imposed by the environmental agency in dealing with the contaminated area." In a similar precedent (Civil Appeal 1032789-75.2013.8.26.0100), it was decided that "It is not reasonable to demand the adoption of a technical solution different from that imposed by the environmental agency, notably without the declaration of unconstitutionality of State Law No. 13,577/ 09 and Decree No. 59.263/2013." TJSP, 2016 [2020].

Based on these decisions, the tendency of the Judiciary of the state of São Paulo to guarantee the legal certainty of the procedures for the remediation of contaminated areas, based exclusively on the existing legislation is observed. Numerous lawsuits, however, are still ongoing, with room for the emergence of new understandings. The current position guarantees the legal certainty of the legal remediation procedures, which must be guided by the balance between the search for repairing the area and the existing limitations to achieve this objective.

The priority focus of the GAC in Brazil is directed to: a) the identification of the contaminated area; b) risk assessment to human and environmental health; and c) carrying out the rehabilitation process. The logic of this procedure is to establish goals for cleaning the soil or aquifer and carry out its rehabilitation to return to society an environment that offers a tolerable level of risk. Therefore, a contaminated area is understood to be one that offers a level of risk above the tolerated level and not just a physical-chemical or biological alteration of the environment compared to the original natural qualities.

Given the environmental and social costs of contaminated areas, environmental agencies must seek preventive protection of soil and aquifers through the following actions:

- establishment of environmental quality standards for soil, air and water, as well as for pollutant emissions;
- licensing and inspection of potential sources of contamination, based on pre-established legal norms;
- incentives for the development and application of best technological practices aimed at reducing or eliminating pollutant emissions.

The state of São Paulo is considered a national reference in the GAC, as it was the first state to implement it. This procedure was introduced in 1999, when the first *Contaminated Areas Management Manual* was published, and in 2002 the first report on contaminated areas was published. The GAC is provided by State Law No. 13,577/2009 and in its Regulatory Decree No. 59.263/2013. The Environmental Company of the State of São Paulo (CETESB) – a state agency with powers to prepare the GAC – regulated the procedure through Board Decision 38/2017. These legal grounds have inspired several regulations in the country.

From the identification of areas with probability of contamination, the GAC imposes a sequence of procedures and studies in order to characterize and prove this situation and act in the remediation of the problem when necessary. It starts with a preliminary assessment. The study aims to "find evidence, indications or facts that make it possible to suspect the existence of contamination in the area" through the collection of historical information and site visits (article 6, part II of Conama Resolution 009). Based on this, the confirmatory investigation plan is prepared.

Confirmatory investigation, unlike preliminary investigation, requires the collection of soil and groundwater samples, as well as other invasive or non-invasive techniques (such as geophysics). The purpose of the investigation is to confirm – or not – the existence of contamination. It is worth highlighting that this recognition is made by comparing the results of chemical analyzes of soils and water with the guiding values and quality reference values established by the environmental agency.

Once contamination is confirmed, a detailed investigation is carried out, whose objective is to "understand the dynamics of contamination in the affected physical environments and the identification of specific scenarios for land use and occupation, existing risk receptors, exposure paths and entry routes.." (article 6, part IX of Conama Resolution 420/2009). In this step, the degradation level and limits are established (mapping of the extensions of the contaminant plume), in addition to the quantification of the mass present, as well as the transport dynamics of these substances. This activity makes it possible to assess the degree of risk to which people and the environment are exposed. Once the contaminated area and the existing risks are defined, the process of rehabilitation of the area begins, which must include an **intervention plan**. With the approval of the environmental agency, the execution of soil and aquifer remediation begins. If the remediation meets its objectives, the **monitoring program** begins, which aims to ensure that the agreed targets were actually achieved. If the monitoring report confirms that the targets have been met, the area is declared by the environmental agency as **rehabilitated for its declared use**.

4.4 GROUNDWATER GOVERNANCE AS A MEANS OF ENSURING SOCIOECONOMIC DEVELOPMENT

The extraction of groundwater has contributed to social and economic development, as well as ensuring water and food security in various parts of the planet over the centuries. Population growth and consumption, the degradation of surface reserves, advances in the field of knowledge of Hydrogeology and well drilling techniques encouraged and expanded the use of these waters from the 1950s onwards (UN/WWAP, 2003). Groundwater, therefore, was, is and will always be an important source of water for humanity. Despite its importance for the use of supplies, agriculture and industry, the perception of population dependence and the benefits resulting from its exploitation were only highlighted in the literature from the 2000s onwards (FOSTER; HIRATA; ANDREO, 2013).

4.4.1 The historical use of groundwater

The use of groundwater dates back to ancient peoples, who developed techniques for its use and guaranteeing a source of quality supply. The ancient civilizations of the Assyrians, Greeks and Romans built aqueduct systems to transport water from springs to villages (DEMING, 2020). The oldest well record is found in the *Atlit Yam* region of Israel (8000 BC) (GALILI; NIR, 1993). Since year 5000 BC, the Chinese have been drilling deep wells with bamboo poles (REBOUÇAS, 2006), while the Persians have developed underground horizontal tunnel systems called "kanates," which have spread to countries that were part of the ancient trade routes, such as: Afghanistan, Spain, Morocco, Arabian Peninsula, North Africa, China, Saudi Arabia and Egypt (VILLAR, 2015). The first recorded "kanate" was located in northwest Iran, in the city of Nineveh, and was built around 800 BC. (SALIH, 2006; REBOUÇAS, 2006). With the Spanish colonization, the system of "kanates" was brought to Hispanic America, being used until the present day, as shown in Box 23.

Box 23 – Extraction of groundwater through "kanates" or filtering galleries: examples in Latin America

Jacinta Palerm

The filter gallery is an ancient technique used to obtain groundwater. Its origin is the Old Continent, but it has an important presence in the Americas, whether in relation to the galleries built during the Colonial Era or those of the present time.

In Mexico, the first known galleries were used for urban supply. Probably, the first constructions were made in the cities of Aguascalientes (1730), Guadalajara (1730), Parras de la Fuente (1825), San Luis Potosí (1828) and Querétaro (1 852). There are also reports of filtering galleries built in the 19th century by farmers who sought to guarantee water for cattle in the states of San Luis Potosí and Jalisco, as well as for agriculture in the Tehuacán Valley, located in the state of Puebla (PALERM, 2020).. Apparently, the galleries in the states of San Luis Potosí and Jalisco were built with a large investment of capital, and under the guidance of experts. In the case of the Tehuacán valley, the local peasant peoples have appropriated the construction technique and until the present day they implement filtering galleries. There are hundreds of filtering galleries in this region, which are managed by farmers.

There is a lot of uncertainty regarding the construction dates of the first filtering galleries in America, even suggesting the possibility of a pre-Hispanic origin, especially in the case of the Nazca galleries in Peru (BARNES; FLEMING, 1991). Evidence suggests, however, that the first "canates" date back to colonial origin.

Studies on the management of filtering galleries are limited, however, they do exist. For example, studies on the galleries in the Tehuacán Valley (CAMPOS *et al*., 2000), as well as a study on Pica, in Chile (CERNA, 2003), stand out. The technique of capturing groundwater by gravity has several regional names, for example: in Peru and Chile it is called *puquios*; in northern Mexico, from *tajos*. There are also variants of the technique, such as, for example, those that use groundwater located under the riverbed.

For more information, see: Barnes and Fleming (1991), Campos *et al*. (2000), Cerna (2003), and Palerm (2002, 2004 and 2020).

4.4.2 The role of groundwater as a means to achieve the Sustainable Development Goals (SDGs)

Groundwater was considered the fastest and cheapest way to reach the goals of access to water and the fight against hunger, considered in the Millennium Development Goals (MDGs) (LLAMAS; MARTINEZ-CORTINA, 2002), which were taken up by the Goals of Sustainable Development (SDG) (GUPPY *et al*., 2018).

The United Nations Summit, held in 2012 in the city of Rio de Janeiro, also known as Rio+20, committed to formulating a set of Sustainable Development Goals (SDGs) to guide global development (GLASER, 2012). As a result, the United Nations, in 2015, adopted Resolution 70/1 – *Transforming our world: the 2030 Agenda for Sustainable Development*. The 2030 Agenda is composed of 17 goals and 169 targets to be achieved by 2030. The 17 SDGs are detailed in Figure 47.

Figure 47 – Sustainable Development Goals (SDG)
Source: United Nations Brazil (2015).

The objective of the 2030 Agenda is to serve as a reference framework for the actions of countries and to integrate the economic, social and environmental dimensions. SDG 6 – *Ensuring the availability and sustainable management of water and sanitation for all* – is directly dedicated to surface and groundwater, and its main challenges relate to aspects of quantity and quality, access to drinking water and sanitation, actions of coping with water risks (droughts and floods) and transboundary waters (UNSDSN, 2013). Target 6.6 expressly mentions groundwater and aquifers, stating the following: “By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.”

Groundwater is essential to meet the goals set out in SDG 6, especially with regard to ensuring universal access to safe drinking water, sanitation and hygiene. Its importance, however, transcends these SDG. Although the SDG structure is organized through individual and independent objectives, there is a very present interconnection between them (BHADURI *et al.*, 2016). Water is a central element for sustainable development and fundamental to all other SDGs, especially SDGs-1, SDG-2, SDG-3, SDG-5, SDG-11, SDG-13, SDG-14 and SDGs -15.

Furthermore, groundwater contributes to the fight against poverty and to food, water and health security for thousands of people, mainly in rural, arid and semi-arid areas. People will also be less susceptible to climate variability, allowing for strategies to mitigate and adapt to climate change. And in some regions, these waters have the potential to generate geothermal energy.

The use of groundwater resources, however, to promote the SDGs requires a governance structure capable of implementing and integrating them through institutions, policies and management practices (BERNSTEIN, 2017), as well as a process management that promotes the sustainable use and protection of the resource. Groundwater has helped several countries to meet international goals related to expanding access to water. In the case of Brazil, the Água Doce Program can be highlighted, whose initiative promotes socioeconomic development and, through the use of brackish aquifers, access to water for the most vulnerable populations in the semiarid region. This experience is explained in detail in Box 24. The Program arose from the need to correct management errors in the Água Boa Program (PAB) and to reuse abandoned brackish wells.

The PAB was implemented by the Ministry of the Environment/Urban Water Resources Secretariat (MMA/SRHU) in the late 1990s, with the aim of installing desalination plants in water-critical areas, with brackish or saline wells. There were, however, problems of execution, either from an operational or social point of view. For example, there were failures in the destination of the saline concentrates generated, which contributed to the increase in desertification and erosion in the areas close to the extraction points. There was no provision for preventive maintenance or management of desalination systems, which resulted in the loss of water quality or the deactivation of part of the equipment (AZEVÊDO, 2015).

The PAB and PAD demonstrate that even brackish groundwater and aquifers with low flows can be used for supply, helping to guarantee the water security of populations, especially in situations of water crisis and in semi-arid regions. The desalination process of these waters is simpler than that applied to marine waters and does not require major infrastructure. Moreover, the process helps in the food security of populations.

Box 24 – Fresh Water Program

Wilson Rodrigues de Melo Junior

Alexandre Saia

The Água Doce Program (PAD) is an action of the Federal Government, coordinated by the Ministry of Regional Development (MDR), in partnership with federal, state, municipal institutions and civil society. Its objective is to establish a permanent public policy for access to quality water for human consumption through the sustainable use of groundwater, incorporating technical, environmental and social care in the implementation and management of desalination systems in the Brazilian semiarid region, taking into account the characteristic of the presence of salts in the groundwater of this region.

The formulation of the Program sought to build a methodology that would provide greater sustainability for the implementation of desalination systems. The program considered that many systems had already been implemented in the Brazilian semiarid region since the 1990s and that they lacked proper technical, social and environmental care. For that reason, in a short time many stopped operating and those that remained released their effluents into the environment without proper destination.

Bearing in mind that about 70% of the wells in the semi-arid region of Brazil have brackish or saline water, and that groundwater is often the only source available to communities, it was up to the Ministry of the Environment to structure a method so that this technology would be more successful in its implementation, and communities would permanently receive safe drinking water (Figure 48).

One of the main differentials of the Água Doce Program is the environmentally appropriate disposal of the effluent generated in the desalination process. In most cases, the effluent is released into a containment tank for evaporation, preventing soil degradation. However, depending on the physicochemical characteristics of this concentrate, it may be used for other uses, such as animal watering or irrigation in biosaline agriculture.

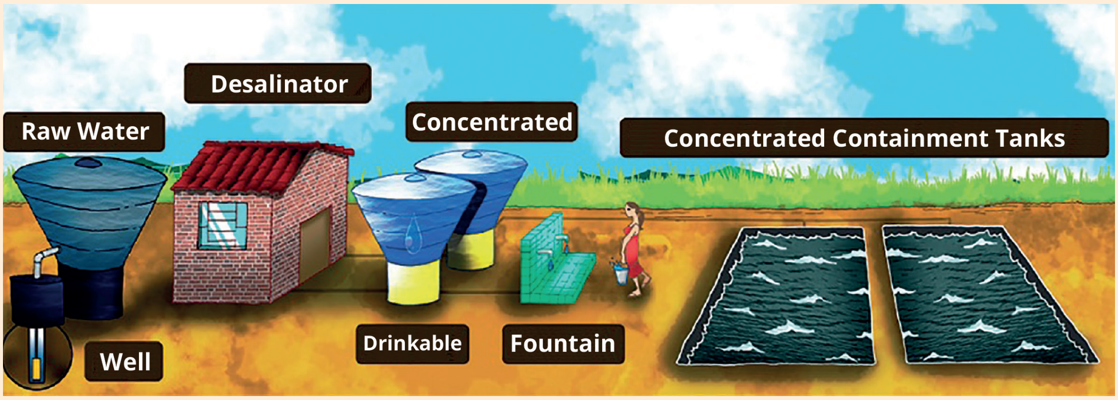

Figure 48 – Illustrative scheme of PAD infrastructures

Source: Images from the MDR database

Communities that have wells with flow rates greater than 5,000 l/h and soil depths greater than 1.00 m can receive an integrated production system. The system was developed by the Brazilian Agricultural Research Corporation (Embrapa) and uses the effluent resulting from the desalination process for the production of tilapia and irrigation of crops adapted to the salinity of the water, whose products can feed local herds (Figure 49).

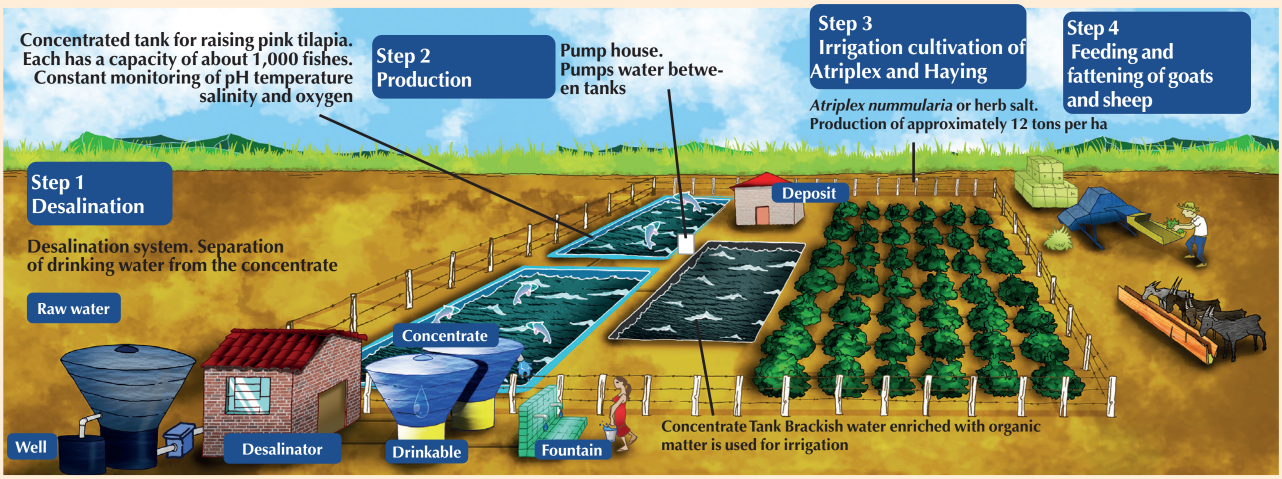

Figure 49 – Illustrative scheme of the system developed by Embrapa
Source: Images from the MDR database

Another differential is the shared management of desalination systems, with the effective participation of communities and representatives of municipalities, states and the federal government. In each community, shared management agreements are built, instruments that define the responsibilities of the parties in the management (Figure 50).

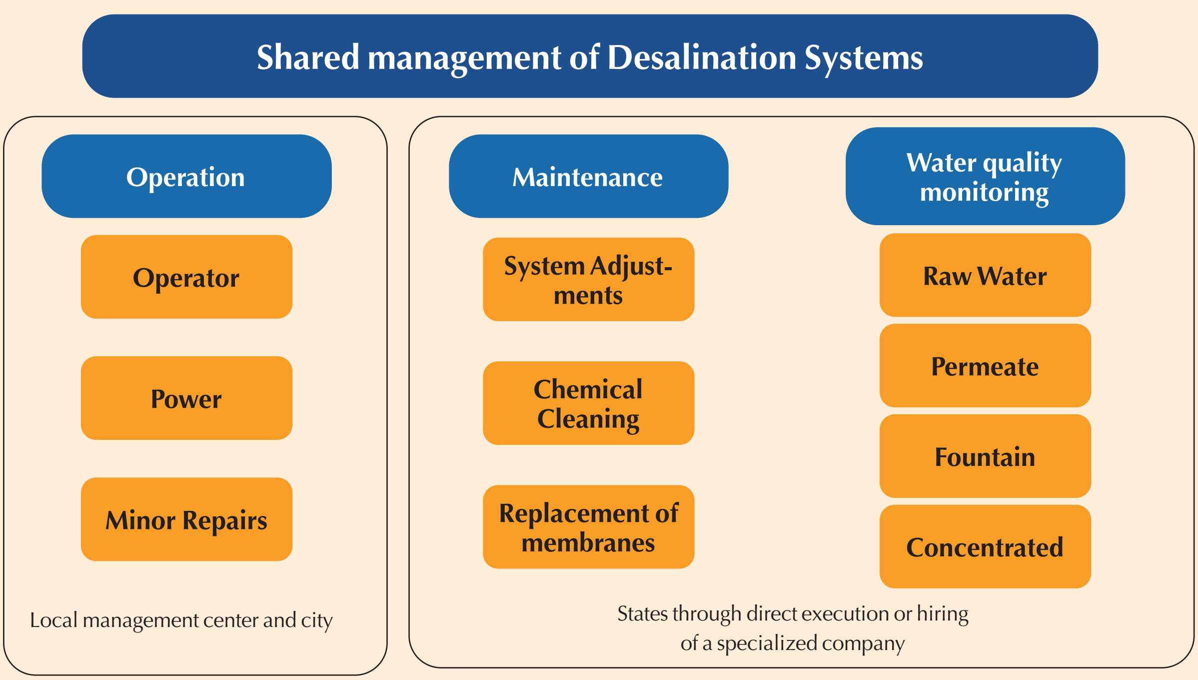

Figure 50 – Shared management of desalination systems
Source: Images from the MDR database

As of 2011, the Água Doce Program entered its scale phase, becoming part of the Água Para Todos Program through Decree No. 7.535, of July 26, 2011, with resources from the Food and Nutrition Security Program. Ever since, the State Plans of the Água Doce Program were implemented, and the program was institutionalized through a decree of the governors, who also instituted the State management and coordination centers.

The Água Doce Program is implemented through partnerships with all the states of the Northeast (Alagoas, Bahia, Ceará, Maranhão, Paraíba, Pernambuco, Piauí, Rio Grande do Norte and Sergipe) and Minas Gerais. Currently, 10 agreements of the Água Doce Program are being implemented, with an investment of approximately R$ 260 million reais, intended to provide quality water to 1,200 rural communities in the Brazilian semiarid region.

As for the execution of the agreements signed under the Água Doce Program, 3,677 communities have been diagnosed so far in 291 most critical municipalities in the Brazilian semiarid region. Around 2,400 operators were also trained to work on the 895 desalination systems in operation. The implementation of the Program in each state is divided into three phases:

1)carrying out diagnoses to define, through technical criteria, flow tests, physical-chemical analysis of water from wells and socio-environmental characterization of communities, to identify those that will be served;

2) implementation of desalination systems; and

3) maintenance and monitoring of systems.

As for the daily operation of the system, the shared management implemented by the PAD suggests that a member of the community assumes the operation of the equipment, with the electricity costs being assumed by the municipality or by the community itself, according to the management agreement. To that end, in each location, the creation of a reserve fund, managed by the community itself, is encouraged to cover operating costs (electricity and operator remuneration) and minor repairs. The monthly amount paid by each family is defined by the community itself.

Considering the minimum reference flow of approximately 1,000 l/h to use a deep well that supplies a PAD system – which represents a large part of the wells located in the Brazilian semiarid region – a PAD system has the potential to produce up to 4,000 liters of desalinated water per day. This allows the provision of 10 liters/day of drinking water per person, and serves up to 400 people/day residing in rural communities. The desalination systems implemented so far have an installed capacity to produce around 3.2 million liters of drinking water per day and benefit approximately 320,000 people.

As a perspective, there is the challenge of advancing in the use of solar energy to feed the desalination systems implemented by the program, such as the photovoltaic solar energy pilot project implemented in the municipality of João Câmara, in Rio Grande do Norte. Finally, there is the possibility of advancing in the use of biosaline agriculture, through demonstrative units of the Água Doce Program combined with the dissemination of crops appropriate to the Brazilian semiarid region that use saline or brackish water in the irrigation process.

The success of the Água Doce Program methodology was recognized with its award by the International Desalination Association (IDA) during the World Desalination Congress, held in October 2017 in São Paulo (SP). Moreover, the PAD's participation in a parallel event to the Economic and Social Council of the United Nations (UN), held in May 2017, in New York, stands out, where the Program was recognized as an initiative that adopts an integrated approach to sustainable development and combating poverty. As a result of the World Desalination Congress held in October 2017, a partnership was established between PAD, IDA and the Latin American Desalination Association (ALADYR).

4.4.3 The need to know the socioeconomic role of groundwater

Brazil lacks studies that analyze the social dimension of groundwater, such as its role in socioeconomic development, especially for vulnerable groups. The governance needs to include in its debates the mass of people who use springs, dug wells or with small flows. Most of the time, these uses are irregular although they can be legalized and classified as exempt or insignificant. Water management needs to create spaces for these social users provided for in Article 12, § 1 of Law No. 9,433/1997, as these users are a completely unknown contingent, whose livelihood depends on groundwater. Unfortunately, the creation of well user organizations is not encouraged by the Government, contrary to what happens in other countries. *Social users* of water are the most threatened by the degradation of the aquifer, given their limited ability to obtain other sources of water, reverse the situation of aquifer degradation, face the damage caused by the decrease or loss of water, and to make themselves heard by the management (VILLAR, 2016).

Groundwater can and should be used as a way of guaranteeing supply, however, its exploitation must be guided by the maximization of social benefits generated and for sustainability, whether by seeking extractions compatible with recharge, drawing up long-term extraction plans, or adopting mechanisms that contribute to promoting recharge. Uncontrolled exploitation can cause damage, even culminating in the depletion of the aquifer. In general, most Brazilian aquifers have adequate exploitation conditions, however, there are already records of worrysome situations, such as the case of Ribeirão Preto (SP), Recife (PETELET-GIRAUD *et al.*, 2017), São José do Rio Preto (HIRATA; FOSTER; OLIVEIRA, 2015) and the Urucuia Aquifer. International literature brings several cases of warning about the economic damage caused by the unsustainable exploitation of the resource. Regional prosperity can be compromised or made unfeasible if the water sources that sustain it are depleted, as in the case of the Ogallala Aquifer in the United States.

> The Ogallala Aquifer is the main hydrogeological unit of the High Plains Aquifer System, which spans eight US states: South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico and Texas. This aquifer is the main source of public and agricultural water supply. For nearly a century, groundwater has sustained economic development through irrigated agricultural crops. However, the unsustainability of use patterns brings the risk of depletion, making supply and agricultural production unfeasible. The main measures proposed to maintain water stocks and reduce losses are: reduction of exploitation, adoption of new irrigation technologies, and replacement of the type of agriculture. Deines *et al*. (2020) state that if the exploitation limits are not modified, 24% of the irrigated area may be forced to adopt crops with low water demand or pastures, whose economic return is lower. Moreover, 13% of the areas would no longer be able to sustain agricultural productivity. The water reality of the aquifer and the containment of this degradation process require a process of adaptation, definition of scales of action and studies on possibilities of substitution of land use to plan the local development strategy (DEINES *et al*., 2020).

The loss of an aquifer means a lower quality of life and livelihood for an entire community; however, the effects caused by the degradation of the resource do not affect all users in the same way. Large users are more resilient as they can drill deeper wells or seek other water sources, while social users are the first to lose their water source. Moreover, their financial capacity to seek alternatives is limited, and may even make it impossible for them to stay there. The effects of overexploitation of aquifers can generate socioeconomic losses that go beyond water users, as in the case of the city of Jakarta, Indonesia (Box 25).

Therefore, groundwater governance must include actions to recognize that: *a)* it is not possible to think about groundwater management without taking into account the management of surface water and soil; *b)* the profile of groundwater users is very varied, since it includes from large economic users to subsistence uses; *c)* social users need to be incorporated into the management process, as they are the first to be harmed by degradation; *d)* groundwater management, especially in critical areas, requires planning that seeks economic alternatives for lower water consumption; *e)* there are no quick solutions to the problems associated with the degradation or depletion of aquifers, and the recovery process can take many decades and demand high costs; and *f)* the prevention of aquifer degradation is always the best alternative.

Box 25 – The overexploitation of the Jakarta Aquifer and its impacts on the city

Dua Kudushana Singgih Yejezkial Klaas

Jakarta, the largest city in Southeast Asia, is an economic growth megacity with around 11 million registered residents. The capital of Indonesia is an administrative area linked to other support zones, which form the metropolitan area of Jabodetabek, whose total population exceeds 30 million. With a modest population growth of 1.35% per year, the city relies heavily on abstraction of groundwater from the upper confined aquifer system of the Jakarta Hydrogeological Basin (JGB). With a total thickness of about 300 m, this system consists of a set of homogeneous, anisotropic, multilayered Pliocene marine aquifers and Quaternary sand and alluvial deposits separated by marine clay as confining layers. The water is collected directly by the inhabitants and by the industries, being self-administered, mostly, without the government's permission, given the absence of inspection and clear regulation for its appropriation.

The continuous pumping of groundwater for domestic and industrial purposes resulted in the rapid decline of hydraulic levels, the shock of soil resistance and its compaction as a way of supporting the overlapping loads. The direct impact of the rapid depletion of groundwater, caused by the overexploitation of the deeper parts of the aquifer system, was the fall of the regional piezometric line to levels below the sea line (SCHMIDT; SOEFNER; SOEKARDI, 1990) and the subsidence of vast portions of land, with average sinking rates between 1-15 cm per year (ABIDIN *et al.*, 2011). This situation has made Jakarta the city that sinks the most in the world. Structures such as buildings have sunk into the ground, causing the abandonment of settlements and the displacement of communities, with their subsequent social impacts such as loss of livelihood and social de-articulation. These direct consequences of land subsidence are particularly visible in the northern part of the city, which is adjacent to the coast. In this area, as the fresh water retreats upstream due to the rapid drop in the water table, and the saline intrusion advances, having invaded more than 14 km in the interior areas (YUWANDARI *et al.*, 2020), thus creating a serious problem for the ecosystem dependent on groundwater and its quality.

The subsurface problems induced by excessive and uncontrolled extraction of groundwater are exacerbated by the annual monsoon floods that, in the rainy season, flood the city, damaging business, education, health and the government sector. The models suggest that the city would sink completely in 2050, which led the current national government to start the evacuation program, determining the transfer of the national capital, including its offices, to the other side of the sea, in the city of Penajam, on the island of Kalimantan, located about 1,200 km from the current capital. That alone would cost the nation $32.7 billion, which is nearly 20% of the state's annual budget.

Moreover, provincial and sectoral egos involved in political fragmentation and conflicting regulations on responsibility for the management of groundwater resources – not only in Jakarta but also in Indonesia in general – have been the main impediment to achieving sustainable management of water in this tropical country. Extreme weather conditions often occur which leave the country vulnerable to the consequences of climate change.

Facing this situation requires a joint effort promoted by different social actors to consider the complex interaction between surface and groundwater in the recharge process in the area (KLAAS *et al.*, 2018). There is, however, no well-defined groundwater recharge program that promotes a constructive effort to naturally or artificially inject water into the aquifer.

4.5 INTEGRATING SOCIETY IN GROUNDWATER MANAGEMENT: THE IMPORTANCE OF SOCIAL PARTICIPATION

Social participation is a central element of water governance and integrated management of water resources. Moreover, besides being a way to increase governance efficiency, social participation can be classified as a fundamental right, provided for in the Brazilian constitutional order (PRETTY, 1995; MELO; SCHIER, 2017). This participation can be defined as a process related to the direct or indirect involvement (representation) of stakeholders in the decision-making process on policies, plans or programs related to the multiple dimensions of water (QUICK; BRYSON, 2016). Stakeholders or social actors are all those people, groups or organizations that can influence or be affected by political decisions involving the protection or use of water (QUICK; BRYSON, 2016).

The power of participation of social actors is directly related to their ability to interact with government agencies, political leaders and organizations that create or implement public policies, and their engagement in these policies (QUICK; BRYSON, 2016). The universe of social actors related to water is wide. In the case of groundwater, the following stand out: well-drilling companies; deep well users; communities or individuals who are fully dependent on the well or spring for their livelihood; universities and research institutes; Prosecutors' Offices; technical professional associations, mainly those related to Engineering and Geology; and non-governmental organizations related to water resources, especially the Brazilian Association of Underground Waters (ABAS), described in Box 26.

Box 26 – Brazilian Groundwater Association (ABAS)

João Carlos Simanke Souza

The Brazilian Groundwater Association (ABAS) was founded on September 19, 1978 in a historic meeting held in the auditorium of the Environmental Company of the State of São Paulo (CETESB). The hydrogeological community was eager to give groundwater a leading role in government agencies and Brazilian society. São Paulo was the place where the well-drilling activity was stronger and more intense and many companies demanded better legal systems in the sector, fighting the irregularity of the wells.

The drillers' call was also echoed by the university, the government and consumers, which made it possible to set up an organizing committee that led the process of creating ABAS. The Commission itself called a meeting on August 21, 1978, through the publication of the notice in the newspapers Folha de São Paulo, O Estado de São Paulo, Gazeta Mercantil, O Globo, Diário do Comércio e Indústria, and Jornal do Brasil.

The organizing committee was led by engineer Renato João Baptista Della Togna, president of CETESB who, by acclamation, was elected the first president of the Association, together with the Board of Directors and the Deliberative Council, and the vice-president, engineer Euclydes Cavallari, of the Department of Water and Electricity (DAEE). Therefore ABAS, was born from the happy combination of efforts of the business community of driven well drillers, prominent government figures and university technicians and researchers. This plurality of sectors was one of its strengths at the time of its creation, whose characteristic the association still preserves today.

In the following years, under the command of several ABAS leaders, a specific law on groundwater was sought, which was processed, unsuccessfully, for 10 years in the Congress, until Law No. 9,433/11997 (Water Act) was passed, which instituted the National Water Resources Policy (PNRH) and the National Water Resources Management System (SINGREH). In the 1988 Constitution and in the Water Law, it was recognized that the protection of water should be an integral part of the environment. Therefore, the concepts of multiple and sustainable uses of water resources, decentralized management, the participation of all actors, including users, civil society and government in the process of water management and governance were introduced. ABAS participated in the construction of this water resource sector milestone. More recently, it played an important role in the creation of the New Legal Framework for Basic Sanitation and the Ordinance GM-MS 888/2021 on the Potability of Water for Human Consumption, guaranteeing user access to groundwater, with responsibility and environmental care. Currently, ABAS is represented by its centers in all Brazilian states, has members from various sectors, has an international role and is even recognized as the Brazilian chapter of the International Association of Hydrogeologists (IAH).

ABAS is responsible for organizing and promoting the Brazilian Congress on Underground Water, the International Congress on the Underground Environment and the National Meeting of Drillers, in addition to regional symposia, courses and lectures. It also issues the main technical publication in the sector, *Revista Água Subterrânea*. Therefore, it is impossible to think about the history of groundwater in Brazil without ABAS since it was present in the main moments of the country's modern hydrology. ABAS's protagonism brought greater visibility to the groundwater resource, as well as making its use more responsible, equitable and socio-environmentally sustainable.

The literature on water governance highlights the central role of social participation in the success or failure of water policies. Next, the benefits and challenges in the materialization of participatory processes in public water policies are presented (Table 13).

Potential benefits of social participation	Execution problems
It allows for a transparent, better-founded decision-making process with creative solutions.	Centralizing or reluctant government that only receives proposals, but does not respond or follow up, generating disappointment and less acceptance of decisions.
Greater acceptance of decisions, increased trust in the government and reduced implementation problems.	Limited responses and little representation.
Social learning process.	Time and costs.
More open and integrated government practice.	Low quality of social response.
Strengthening democracy.	Inconsistent decision-making processes.
A more comprehensive water management that takes into account economic, social and environmental issues.	Granting privileges to certain groups without a well-articulated rationale.

Table 13 – Benefits and difficulties of Social Participation

Source: Mostert (2003, p. 181).

The overexploitation of aquifers requires the cooperation of non-governmental actors, especially users, drilling companies, class councils and universities (BARTHEL; FOSTER; VILLHOLTH, 2017). In the specific case of groundwater, the following benefits of social participation can be highlighted:

- encourages understanding and stimulates the adoption of good management practices relative to groundwater (for example, adequate techniques to build the well and define its location, adoption of PPPs, etc.) (GARDUNO; STEENBERGEN; FOSTER, 2010);
- contributes to the implementation of management actions, as decisions that do not include the owners of the wells will hardly be implemented, especially with the government's limitations in promoting inspection (GARDUNO; STEENBERGEN; FOSTER, 2010);
- creates the opportunity for users to negotiate with each other and with the government management goals that take into account the socio-environmental impacts of aquifer protection (EMERSON; NABATCHI; BALOGH, 2012);
- allows the construction of cooperative agreements for the execution of activities related to management, such as monitoring, surveillance and inspection (GARDUNO; STEENBERGEN; FOSTER, 2010);
- facilitates the coordination of decisions related to water and territorial planning, even contributing to reduce contradictions between policies (GARDUNO; STEENBERGEN; FOSTER, 2010);

- helps individuals, groups and local communities have a voice in the design of water management, in order to protect their groundwater abstraction, which, in many cases, is the most vulnerable because it deals with springs and excavated wells (QUEVAUVILLER; BATELAAN; HUNT, 2016).

The format and level of participation depend on the institutional, legal and political structure of governments and management bodies (RUIZ-VILLAVERDE; GARCÍA-RUBIO, 2016). Several authors have focused on the way in which these levels of public participation are structured. Among the best known is the example of the Arnstein Ladder scale of citizen participation (ARNSTEIN, 1969). In addition to this system, the Pretty scale (1995) classifies participation according to the involvement in management activities and in the control of the final result, which ranges from manipulative to self-mobilization. Michener (1998) defines participation in two categories: a) the planner-centered approach; and b) the people-centered approach. Ruiz-Villaverde and García-Rubio (2016), based on Mostert (2003), illustrate levels of participation (Figure 51).

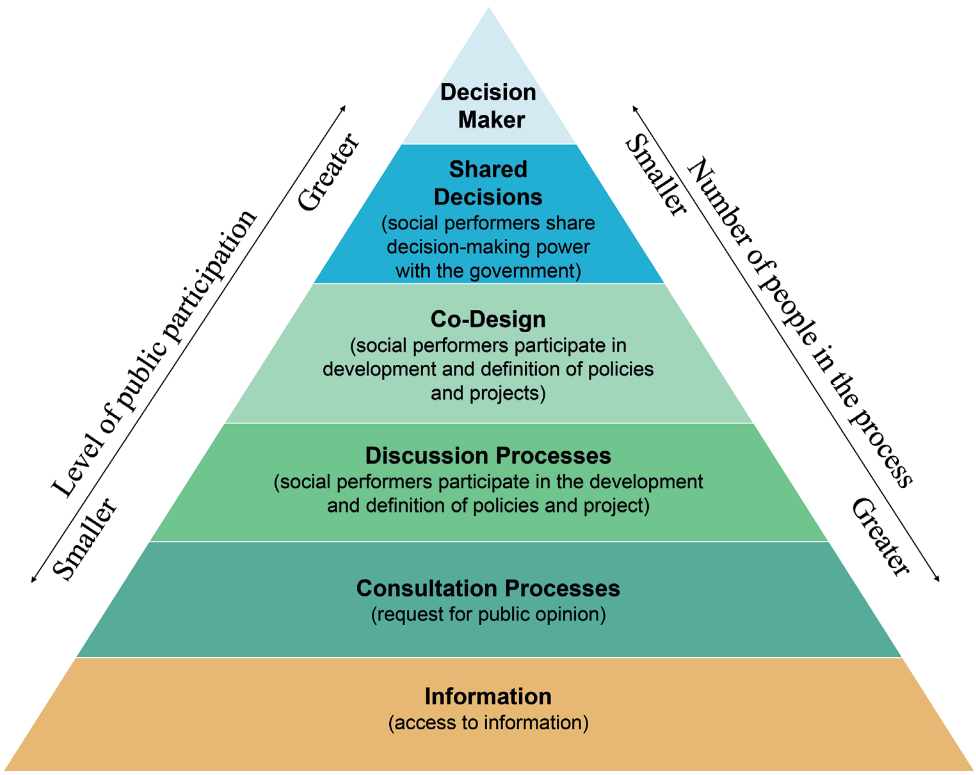

Figure 51 – Different levels of public participation

Source: Ruiz-Villaverde and García-Rubio (2016, p. 5), adapted and translated by Pilar Carolina Villar.

Through public participation, stakeholders can interact with government agencies, political leaders, nonprofits, and business organizations that create or implement public policies and programs. Brazilian legislation incorporates different levels of participation in the exercise of water governance. For example, we can mention the consultation processes in the elaboration of the National Water Resources Plan 2022-2040, the discussions held within the scope of the CBHs or, even, the Shared Management Agreements of the Água Doce Program.

Public Policies face difficulties in promoting the participation of society and users of groundwater, as they cannot motivate them to participate in the process of obtaining information, developing policies and strategies for the management or implementation of these policies (PIYAPONG *et al.*, 2019). In a large part, this is due to the following aspects: a) the lack of information and social knowledge on the subject; b) the extremely technical nature of the groundwater debate; and c) irregularity of use.

Access to information is the first condition of any participatory process (RUIZ-VILLAVERDE; GARCÍA-RUBIO, 2016). If society does not know about aquifers or has only a basic understanding of groundwater resources, it is unlikely that there will be a sense of urgency to include them in public policies, or responsibility to comply with the norms, nor will there be a desire to engage in the development of public policies or contribute to their implementation (JANMAIMAOOL *et al*., 2019). This scenario favors irregular exploitation, which "takes place without regard to the availability of local water, disrespects the right to use of third parties and prevents their impacts on public supply, authorized users and owners of exempt use wells from being arbitrated." (VILLAR, 2016, p. 92).

The execution of environmental education and training programs for groundwater is essential to change this reality. Unfortunately, there is a lack of initiatives that focus on the reality of aquifers and that seek differentiated approaches, according to the target audience: managers, users, drilling companies or society. Box 27 brings an action in this direction, including the Guarani Aquifer in Santa Catarina's High Schools.

The debate on groundwater is marked by a technical discourse, whose complexity, in many cases, removes social participation or relegates it to a passive and submissive posture of this technical knowledge. Technical-scientific knowledge is fundamental to guide management, however, decision-making is a political process (FORSY TH, 2011). If social actors do not understand the reason for this scientific data or the consequences of not guiding their actions by this knowledge, they will hardly adopt behaviors that, in the short term, may seem harmful to their interests, such as, for example, reducing the volume collected, especially when there are flaws in inspection, as is the case in Brazil. Moreover, few managers have the necessary technical knowledge to propose specific actions for groundwater.

Finally, the lack of adherence to public policies, materialized by the prevalence of irregular users, also harms management, as it: a) hides the importance of groundwater in water management; b) empties the debate on the appeal; c) prevents existing interests and conflicts over the use of groundwater from being discussed in a transparent manner among all those who may be affected; d) hinders or prevents the establishment of partnerships in the actions necessary to protect the aquifer; and e) harms the organization of users and the construction of a collective responsibility for the use of the resource.

Unlike countries such as Mexico, Peru and Chile, Brazilian legislation has not established the legal status of well-user organizations. These organizations are groups of groundwater users that can, according to the legislation of each country, function as managing entities (grant water use rights) or as associations or non-governmental organizations that seek to defend their interests in relation to the use or, even, raise funds to carry out works that benefit the group (for example, recharge systems or drilling new wells). The mere legal provision, however, does not guarantee the success of this type of cooperative arrangement, as demonstrated by the case of the Chilean Groundwater Communities, set forth in the gallery of cases. Contrary to what happens with surface water, users of groundwater do not feel motivated to organize themselves. The Chilean and Mexican cases demonstrate that user organizations play an important role in dealing with situations of aquifer degradation.

In Brazil, the managing entities are the state water resources agencies or the basin agencies, however, nothing prevents users from constituting private legal organizations with the objective of promoting complementary actions for managing groundwater. There are even some experiences of irrigation[3] user organizations that can contribute to promoting the sustainable use of the resource, provided that their actions are guided by the sustainable exploration of water and with a focus on long-term objectives.

Social participation in groundwater in Brazil subject of little exploration. Approaches from the social sciences could contribute to fostering the debate on the development and application of methodologies and tools aimed at promoting the dissemination of knowledge, social engagement or mediation and negotiation in the aquifer management process.

3. These initiatives focus on surface water-based irrigation. Some examples are: the Tourão Irrigated Perimeter Users Association (AUPIT) (BA) and the Arroio Duro Irrigation Perimeter Users Association (RS). However, scientific studies on such initiatives are still lacking.

Box 27 – The experience of the Environmental Education Project for Environmental Protection and Sustainable Development of the Guarani Aquifer System, in the Direct Recharge Zone in the State of Santa Catarina/Brazil

Marcio Cardoso
Daniel José da Silva

This project was conducted from May 2005 to February 2007, with the Autopoiésis Brasilis Institute – Public Interest Civil Society Organization – and the Graduate Program in Environmental Engineering at the Federal University of Santa Catarina as the executing team (PPGEA/UFSC). It was carried out in partnership with the Environment Foundation of the State of Santa Catarina (FATMA), the Municipality of Urubici, the Local Support Group in Urubici (GAL) and the Legislative Assembly of the State of Santa Catarina (ALESC). The general coordination was carried out by Marcio Cardoso (Autopoiésis Institute) and Daniel José da Silva (UFSC). The Project developed a model of formal, non-formal and diffuse environmental education to include the theme of environmental protection and sustainable development of the Guarani Aquifer System (SAG) in school curricula and in municipal public policies in the region covered by it in Santa Catarina (Figure 52).

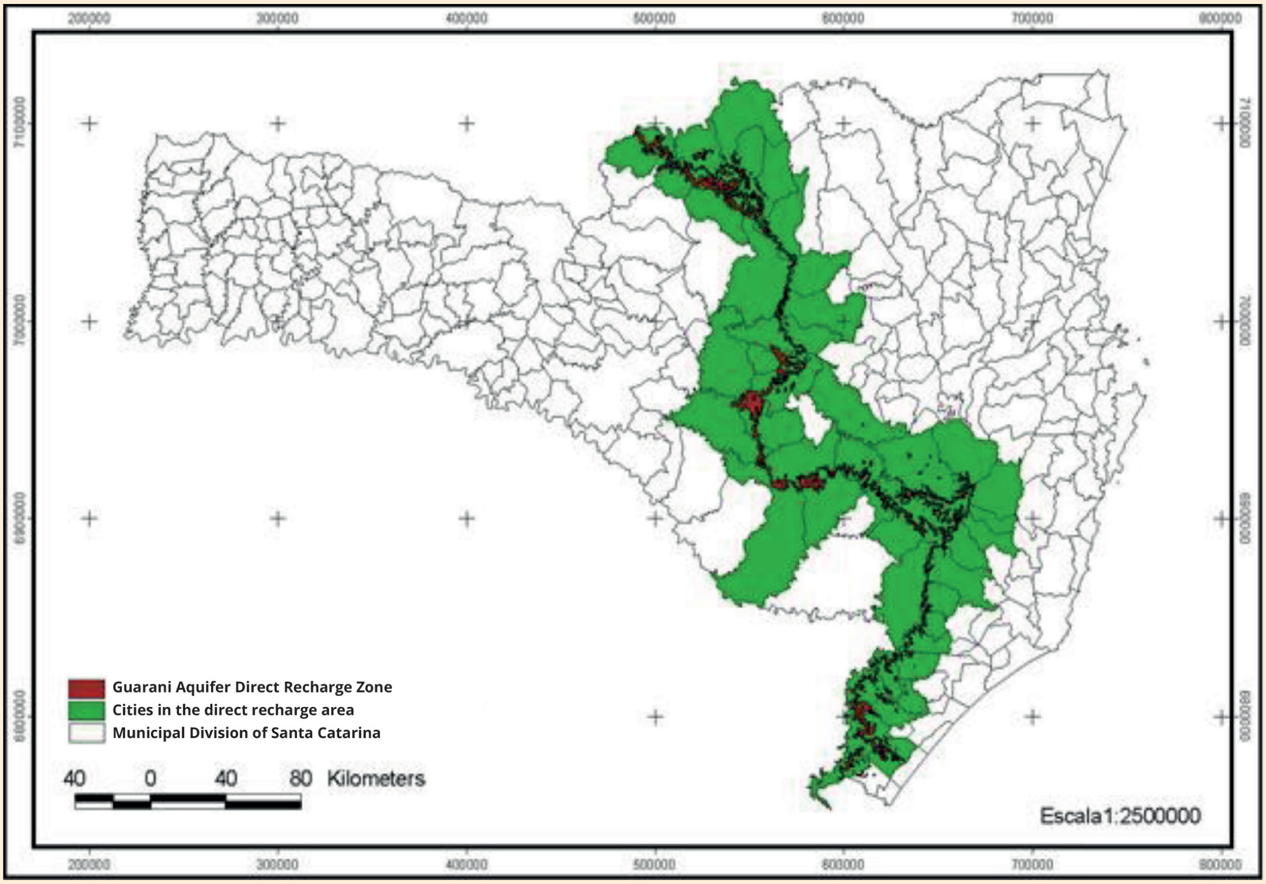

Figure 52 – Recharge area of the Guarani Aquifer System in Santa Catarina

Source: prepared by the authors.

The specific objectives of the project aim to promote: *1)* **Formal Environmental Education** through the inclusion of SAG's environmental protection and sustainable development contents in the Political Pedagogical Project of the Municipality of Urubici; *2)* **Non-Formal Environmental Education** through the social construction of a municipal law project for environmental protection and sustainable development of the SAG, involving councilors, public, social and private managers of the Municipality of Urubici; *3)* **Diffuse Environmental Education** in the 47 municipalities located on the SAG Direct Recharge Zone, in the state of Santa Catarina, through the dissemination of teaching materials and seminars.

The activities were structured in five stages: *1) Research and production of information* – profile and vulnerability report of the 47 municipalities, thematic maps, SAG history, SAG website; *2) Pedagogical and communication materials* – folder, presentation poster, SAG booklet, methodological manual, folder and seminar poster; *3) Training of educators and inclusion of the SAG theme in schools* – training workshop for educators in the Municipality of Urubici, involving schools and NGOs in the Region; *4) Training Workshop for Public and Social Managers and Legislators* – strategies for inserting the SAG theme in schools and municipal policies; *5) Seminar for dissemination and exchange of SAG experiences in SC* – Seminar for 350 participants, dissemination of teaching materials, dissemination and exchange of information between SC, Brazil, Uruguay, Argentina, and Paraguay.

The main recommendations for the next projects in Santa Catarina State involved the preparation of several instruments and the promotion of events, such as: *1)* pedagogical material for formal education in schools; *2)* pedagogical material for non-formal education for young people and adults; *3)* pedagogical material for the inclusion of the SAG Protection and Sustainable Development theme in municipal and state public policies; *4)* informative material to guide rural landowners, farmers, ranchers, industrialists, miners and other entrepreneurs, in the adjustment of conduct for the sustainable use of the SAG; *5)* informative material for the inclusion of the SAG in the municipal master plans, conservation units and hydrographic basins; *6)* social communication material for schools and communities, such as: SAG pedagogical booklet, folder, poster, videos, radio and TV programs; *7)* promotion of Annual State Seminars and National and International Seminars for the exchange of experiences on best practices, pedagogical materials produced and the construction of social networks and partnerships; *8)* expansion of the Education Project for the Protection of the SAG to other municipalities in Santa Catarina and Brazilian states, members of the SAG[4].

4.6 COOPERATION BETWEEN THE VARIOUS ADMINISTRATIVE ENTITIES AND THE FOCUS ON LOCAL MANAGEMENT OF GROUNDWATER

Brazil is a federative country that “institutes the division of responsibilities and autonomy among the federal, state and municipal governments.” (GRANJA; WARNER, 2006, p. 1101). The existence of common and competing competences points to a federalism of cooperation and integration that is reflected in the water policy and in the organization of the National System of Water Resources (SNRH), formed by national, state, regional and local systems. Law No. 9,433/1997 also adopts participatory and decentralized management through the hydrographic basin and operated by the CBHs. Therefore, the water management model in Brazil is guided by federalism and the principle of subsidiarity, which determines that decisions, legislative or administrative, are taken at the lowest possible political level, i.e., by those closest to the of the decisions that are defined, made and executed (GRANJA; WARNER, 2006).

The hydrographic basin as a water management territory is not to be confused with the classic division of administrative entities: the federal government, states, the Federal District and municipalities. The basin transcends the classical administrative limits, for its territoriality is based on physical-natural aspects. Although legal limits are established, subdividing them into smaller portions, as a way of facilitating management, it cannot be ignored that the water system is one. Therefore, a territoriality of decision was created that requires the construction of cooperative and integrative arrangements between all these administrative entities and, in some cases, even with other countries, according to the scale of the basin or aquifer, or due to the correlation between these bodies of water (GRANJA; WARNER, 2006).

Aquifers were included in this management by basins, although their territoriality does not converge with them. Notwithstanding, the basin is still the best territory to manage them, since the main ecosystem services of the aquifers and the impacts of the use of their waters or soil occur, primarily, in the territoriality of the hydrographic basin. As we see in Figure 53, in the same basin there are several overlapping aquifers, which have completely different territorialities, although they may interact with each other and with the basin. Given the scenario of application of Law No. 9,433/1997, thinking about creating a specific territoriality for each aquifer would be an unthinkable management challenge for a country that has not even managed to fully implement the management of hydrographic basins.

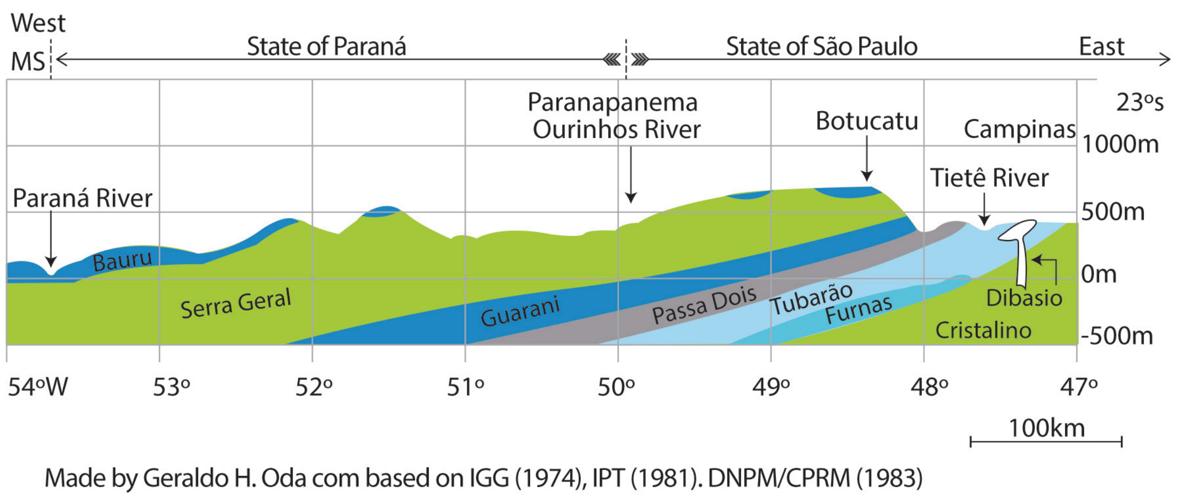

Figure 53 – Schematic geological section of the state of São Paulo and its aquifer systems
Source: São Paulo (2014, p. 29).

Chapter 3 showed that the CNRH set the main guidelines that guide the performance of federative units, municipalities and CBHs in the joint management of basins and aquifers, however, there is a lack of studies that analyze how and if this was done (VILLAR; HIRATA, 2022). Furthermore, it would be important for the CNRH and the State Councils to determine priority areas for the control of aquifer extractions, whose effects could go beyond the basin in which the management takes place. This definition would help to stimulate cooperation between the various administrative entities and the various CBHs involved. These cooperative actions may include: *a)* the idealization of studies and joint monitoring; *b)* the adoption of joint methodologies to determine water availability and control extractions; *c)* the creation of situation rooms for aquifers; or *d)* the devising of inter-basin or international agreements. In this sense, the experience of the Guarani Aquifer System is quite an example of the importance of articulating and coordinating actions at different management levels.

4.6.1 Transboundary and interstate aquifers: the case of the Guarani Aquifer System (SAG)

CNRH Resolution 202/2018, in Article 2, defines transboundary and interstate aquifers as follows:

> III – interstate aquifer: aquifer distributed in the territories of at least two states, or between a state and the Federal District;
>
> IV – transboundary aquifer: aquifer shared by Brazil with at least one neighboring border country; [...].

Several Brazilian aquifers are interstate. Unfortunately, a unique map has not yet been produced to demonstrate these aquifers, which would help states and CBHs to form joint actions. Brazil has 11 transboundary aquifers (Figure 54): Amazonas, Aquidauana, Boa Vista, Bauru-Caiuá, Roraima, Pantanal, Permo-Carbonifero, Costeiro, Litorâneo, Serra Geral and Guarani.

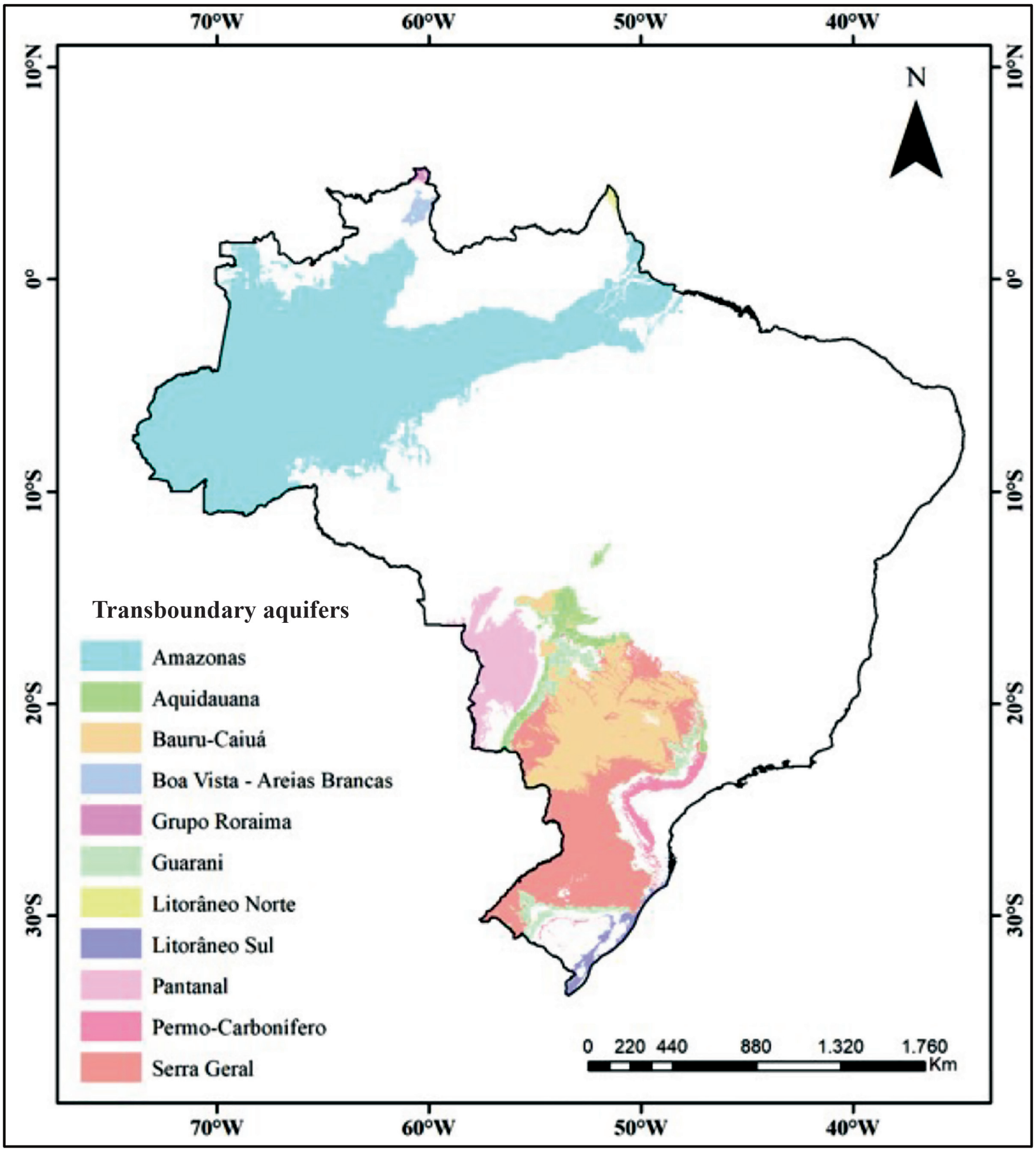

Figure 54 – Transboundary aquifers in the Brazilian territory
Source: ANA (2017, p. 1), adapted and provided by Felipe Nincao.

The Guarani Aquifer System (SAG) is undoubtedly the best known and the only one that has an International Agreement (Box 28). As shown in Figure 54, this transboundary aquifer is overlapped by two other aquifers that are also transboundary: Serra Geral and Bauru-Caiuá, so that Figure only shows their outcrop areas.

Its area occupies 1,087,879 km^2, encompassing the territory of Argentina (225,500km^2), Brazil (735,918 km^2), Paraguay (71,700 km^2) and Uruguay (45,000 km^2) (OAS, 2009, p. 62) (Figure 55). Brazil holds the largest portion of the aquifer (61.65%) which, in Brazilian territory, is classified as an interstate aquifer as it extends over eight states: Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Paraná, Rio Grande do Sul, Santa Catarina and São Paulo, representing 80% of Brazilian use (OAS, 2009). It is a sedimentary aquifer and confined to 90% of the territory, and the outcrop zones correspond to only 124,650 km2 (LEBAC/UNESP, 2008).

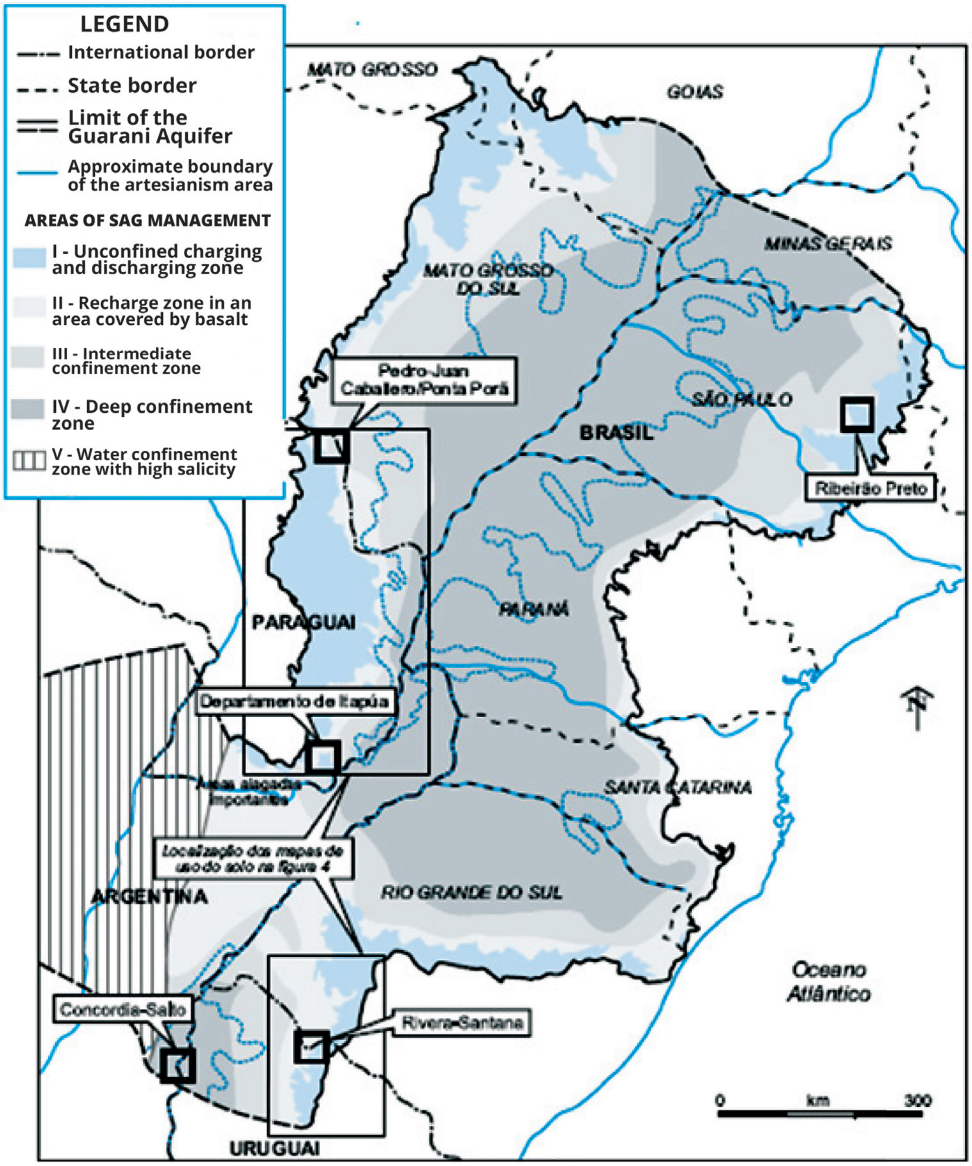

Figure 55 – The Guarani Aquifer System and its management zones
Source: Foster *et al*. (2009, p. 11).

Contrary to descriptions commonly disseminated in non-technical media, the SAG is not a uniform structure, like a sponge or an underground lake/river. On the contrary, the aquifer is quite heterogeneous, either in relation to the rock formation that composes it, or to the characteristics of its waters. It has outcrop areas and regions covered by basalt of different thicknesses, which can exceed more than 1,500 m in depth (OAS, 2009; BORGHETTI; BORGHETTI; ROSA FILHO, 2011). This characteristic influences the water permanence time, which can be months or more than hundreds of thousands of years, which indicates extremely low recharge rates, in addition to conditioning the geochemical characteristics of the water. These geochemical characteristics display portions of excellent quality and others with high salinity or natural anomalies related to high fluoride and salinity concentrations (OAS, 2009, p. 66; BORGHETTI; BORGHETTI; ROSA FILHO, 2011). Thus, Figure 55 illustrates this heterogeneity, proposing five Management Zones that demonstrate the need for different planning approaches (FOSTER *et al*., 2009):

I. **unconfined recharge and discharge zone:** the aquifer rises to the surface, so the waters are continually replenished, contributing to surface water resources. On the other hand, it is vulnerable to contamination;

II. **recharge zone in an area covered by basalts:** recharge occurs through basalt fractures, being considerably lower than in the outcrop zone. The connection with surface resources needs to be further studied;

III. **intermediate confinement zone:** the area is covered by the basalts of the Serra Geral formation, therefore, there is no significant recharge. The waters have a permanence time of over 10,000 years and their extraction would be equivalent to mining the aquifer. Very low risk of human contamination. Possibility of water quality problems arising from permanence time and lack of renewal. In some areas, the content of dissolved salts including fluorine and arsenic can compromise its potability;

IV. **deep confinement zone**: similar to Zone III, however, the basalt layer that confines the aquifer exceeds 400 m. The cost of extraction makes exploitation unfeasible, except for hydrogeothermal use;

V. **confinement zone with high salinity:** in addition to the confinement, in this region the waters have high salinity, and can be used for hydrogeothermal purposes or after treatments if economically viable.

Although this division suggests a certain homogeneity, there are still heterogeneities that can only be assessed at the local level. For example, in the municipality of Ribeirão Preto (SP), it is possible to find Zones I, II and III with distances that vary from a few kilometers. Moreover, considering the water permanence time, most impacts end up having local effects. The overexploitation of the SAG in Ribeirão Preto may compromise the aquifer in neighboring cities, but does not influence the exploitation of another country or Brazilian state.

The Ribeirão Preto region, in addition to being a pilot area of the Guarani Aquifer System Project, was the object of a Technical Cooperation Agreement between the state of São Paulo and Bavaria (Germany), called "Pilot Information System for Environmental Management of Underground Water Resources in the Outcrop Area of the Guarani Aquifer System in the State of São Paulo." The recommendations of this study contributed to the creation of the Groundwater Use Restriction and Control Area in the city of Ribeirão Preto (SP) (VILLAR; RIBEIRO, 2011).

Although geological formations extend beyond national boundaries, water flow has local characteristics, so "the current and potential transboundary effects of SAG are restricted to a narrow range of no more than a few tens of kilometers, depending on hydrodynamic conditions, both local and specific." (OAS, 2009, p. 18). Transboundary problems in the SAG can occur if extensive areas with intense exploitation are located close to the border, This situation could result in significant reductions in the potentiometric level of the aquifer and cause damage to these areas and, consequently, to neighboring countries.

The logic of local flows is maintained in the Brazilian States. Therefore, from the point of view of interstate cooperation, it is important to delimit areas with extensive and intense exploitation close to interstate boundaries. In the logic of state management, states must define such areas in which underground flows are shared precisely to promote cooperation between basins and propose joint actions. The National Water Resources Plan (PNRH) and the State Water Resources Plans (PERH) play a prominent role in promoting this coordination.

Brazil is responsible for most of the exploitation of the SAG, but the problems of overexploitation are still localized and their occurrence is restricted to the state of São Paulo. Although there are no significant transboundary problems (VILLAR; RIBEIRO, 2011; VILLAR, 2015; HIRATA; FOSTER, 2020; HIRATA; KIRCHHEIM; MANGANELLI, 2020), this aquifer achieved the remarkable feat of making itself known to society and encouraging actions aimed at groundwater. To a large extent, this is justified by the implementation of the Project Environmental Protection and Sustainable Development of the Guarani Aquifer System (also known as the Guarani Aquifer System Project – PSAG), between 2003 and 2009. This international project had the participation of all the countries in the aquifer and the support of several organizations, notably the World Bank, the Organization of American States (OAS) and the Global Environment Fund (GEF). Its execution was only possible thanks to a previous history of cooperation encouraged by the universities of the countries that realized the possibility of having a hydrogeological connection between geological formations shared by the countries (VILLAR, 2015). From there, it was possible to mobilize international organizations and states (VILLAR, 2015; SÍNDICO; HIRATA; MANGANELLI, 2018),[4] culminating in the creation of a Regional Center for Groundwater Management in Latin America and the Caribbean (CeReGAS), described in Box 29. The SAG will be the target of a new medium-sized international project called the "Strategic Action Program for the Guarani Aquifer: Rendering Regional Actions Feasible" [5], organized by the states, the GEF and the Latin America Development Bank (CAF).

Box 28 – The Agreement on the Guarani Aquifer

Pilar Carolina Villar

The agreement on the Guarani Aquifer was signed by the concerned countries on August 2, 2010, in the city of San Juan (Argentina), and is highly celebrated by the water community, as it: a) characterizes a specific agreement for a transboundary aquifer, which is rare in the global context; b) mentions, in its preamble, the United Nations General Assembly Resolution No. 63/124 (2008), reinforcing the importance of this document; c) includes the principles of International Freshwater Law, showing its applicability to aquifers; d) it is the first specific agreement for an aquifer in Latin America, and may encourage the conclusion of other agreements; e) represents the continuity of the cooperation process established between the countries within the scope of the Guarani Aquifer System Project6; and f) is an example of preventive diplomacy, as there were no conflicts over the use of groundwater (VILLAR; RIBEIRO, 2011).

The long ratification process dampened the initial optimism. In October 2020, Paraguay deposited the last instrument of ratification, which allows the agreement to enter into force. Its object is "the transboundary water resources of the Guarani Aquifer System" (Article 1), and represents a flexible cooperation tool that obliges states to manage groundwater, in accordance with the International Law standards (VILLAR, 2016).

The entry into force of the Agreement allows the States to deepen the cooperation process. However, the following actions are required to that end: a) creation of a commission for the Guarani Aquifer; b) implementation of cooperation programs for groundwater; c) identification of critical areas, especially in border areas, which effectively share a flow between states; and d) definition of the arbitration procedure for resolving disputes through the publication of an Additional Protocol (Article 19). Among these actions, the most urgent, without a doubt, is the creation of the Commission, responsible for coordinating cooperation in fulfilling the principles and objectives of the Agreement. Without the regulation of its statute, defining its structure and powers, the Agreement will have limited effectiveness in the regional context (VILLAR, 2020).

4. For more information, see: https://www.thegef.org/project/implementation-guarani-aquifer-strategic-action-program-enabling-regional-actions.

5. See: http://www.oas.org/DSD/WaterResources/projects/Guarani/SAP-Guarani.pdf.

Box 29 – Regional Center for Management of Groundwater in Latin America and in the Caribbean (CeReGAS): practical example of the importance of international cooperation

Alberto Manganelli

As a result of the boost provided by the Guarani Aquifer System Project (2003-2009) and in light of the need to have a regional articulation office to promote cooperation between the countries of the region in relation to the management of groundwater resources, particularly transboundary, presented In 2011, the proposal for the creation of the Regional Center for Groundwater Management in Latin America and the Caribbean (CeReGAS) was proposed before the Unesco Intergovernmental Hydrological Program (IHP-LAC). After a long approval process, in March 2014, the Agreement was signed between the Government of the Oriental Republic of Uruguay and UNESCO for the creation of CeReGAS as a Category II Center. The purpose of CeReGAS is to generate scientific and technical capacities that contribute to the sustainable development, management and governance of groundwater, as well as to the environmental protection of aquifers from an integrated perspective. Its strategic objectives include:

- to boost cooperation among the countries of the region in relation to the management of groundwater resources, particularly in the case of transboundary water resources;
- to promote the creation and/or strengthening of regional and international thematic research networks on the topic;
- to develop and/or promote the creation of management tools and train professionals and researchers to use them;
- to disseminate the knowledge generated on the subject and promote public awareness actions on the sustainable use of groundwater resources.

Regarding the structure, its highest body is represented by the Board of Directors which, according to the Uruguay and Unesco Agreement, is composed of a representative of the Uruguayan government, one of UNESCO, in addition to representatives from the following countries: Argentina, Bolivia, Brazil, Mexico and Paraguay. CeReGAS promotes, participates and articulates projects at regional and national levels, such as the Guarani Aquifer System II Project (Argentina, Brazil, Paraguay and Uruguay) and the Lagoa Mirim Project (Brazil and Uruguay). Moreover, it teaches courses of its own or in association with different regional institutions, the most notable being: Integrated Groundwater Management in Latin America and Transboundary Aquifer Governance, both with regional reach in Latin America and the Caribbean. CeReGAS also coordinates the work group of UNESCO's International Shared Aquifer Resources Management (ISARM) Americas Program, which is developed as a collective effort by the countries of the continent, with the objective of identifying and evaluating transboundary aquifer systems in the Americas.

4.7 MONITORING OF GROUNDWATER RESOURCES

Groundwater monitoring is carried out by monitoring hydraulic and/or biophysical-chemical parameters in time and space, with different objectives that range from the initial characterization of an aquifer to as part of a groundwater protection or remediation strategy.

Therefore, different objectives will impose different monitoring programs, which must consider: i) location of the point to be monitored; ii) densities of monitored points and constructive profile of wells or hydrogeological characteristics of the water point; iii) measurement frequency; iv) analysis parameters; v) data to be collected and vi) definition regarding its form of organization and verification, among others.

Groundwater monitoring used to characterize aspects of quantity (availability of the resource) or quality (natural and anthropogenic pollution) but has an intrinsic constraint: the low capacity of monitoring wells or water production wells (used for monitoring) characterize the phenomena that occur in the aquifer.

These phenomena, such as pollution, generate specific plumes that hardly reach more than 1-2 km away from the causing source. On the other hand, wells exclusively for static monitoring (as opposed to pumping wells) can only identify the plume that reaches them, i.e., if the boundary of a plume is located a few meters from the well, it will not be identified. Therefore, studies of contaminated areas have a high density of wells (between tens to hundreds of wells per hectare). Another characteristic of polluting plumes is that they are three-dimensional entities, i.e., there is almost certain to be stratification of the aquifer water quality, i.e., if the well filter is not located in front of the plume, it will not be detected.

Monitoring associated with the characterization of point source contamination events is well developed in the country. And, despite requiring a large number of wells in determining the limits of contaminant plumes, there are several standardized procedures. The main actions suggested by hydrogeologists to monitor contamination and remediate point sources are the adoption of well drilling technologies, the installation of multilevel wells and the use of adequate equipment to collect representative water samples.

In turn, when water quality monitoring involves dispersed and multipoint sources, a high density of wells is required to recognize the extent of damage to the aquifer, which, in practice, makes monitoring ineffective or very costly. Generally, contaminations of this type generate extensive plumes and are very heterogeneous in terms of concentration, a fact which makes data interpretation even more complex.

In many regional studies, the characterization of aquifer contamination is carried out by tubular water production wells, i.e., those where the placement of filters takes into account only the aquifer production. Driven wells are vertical structures that connect different levels of water in the same aquifer, mixing waters of different ages and chemical quality inside. Often, this mixture of water ends up masking the more superficial contamination of the aquifer, leaving important plumes undetectable.

Quantity monitoring has the same issues. Therefore, it would be important to monitor the potentiometric level over time, which would require periodic and systematic measurements to assess long-term variations, such as changes in recharge due to climate change, or to identify overexploitation problems. In the latter case, monitoring wells should be installed where the water extraction wells are located. Data interpretation, in turn, needs to isolate those arising from hydraulic interference from a nearby catchment or from regional drawdown, which must be quantified. To that effect, monthly or even half-yearly measurements are necessary, common to regional monitoring programs, as well as hourly or at least daily piezometric monitoring, requiring the installation of pressure transducers and several wells in a region.

Therefore, the greatest limitation of monitoring is in the regional characterization, when the objective is to identify overexploitation or contamination of a dispersed nature arising from agricultural and urban activity. Some states have implemented regional quality monitoring networks with biannual monitoring of their waters. The São Paulo network monitors the geochemistry of 316 active groundwater quality monitoring points (CETESB, 2020). Considering that each point can monitor what happens within a 200m radius, the area each well monitors is 0.13 km^2. Therefore, the network is only monitoring 0.02% of the State's area (~41 km^2). These numbers give the dimension of the low representation of regional water quality networks and the need to resize regional networks of this type and with this approach. It was found that there is a relationship between the concentrations of nitrate in groundwater and the occupation of land within one km of the well, indicating that the well network, instead of monitoring the state of São Paulo, analyzes the situation close to the 316 wells located in different urbanization contexts (PILEGGI *et al.*, 2021). These numbers give the dimension of the low assertiveness of regional water quality networks and the need to rethink regional networks of this type with this this approach.

To overcome the limitations in regional monitoring, it is necessary to have clarity of the intended objectives. The São Paulo network is efficient in the sense of showing how cities modify water quality over time, in long historical series, but limited in verifying the impacts on aquifer units as a whole.

As for RIMAS, from the Geological Survey of Brazil, shown in Box 30, it is more regional and broader. In this case, the objective is to follow the evolution of groundwater levels in natural areas far from human occupation, together with meteorological stations. This method tries to trace the evolution of potentiometric levels over time, indicating, for example, the variations expected by global climate change. Therefore, even with a lower number of wells, the characterization of the background and its long-term evolution of the potentiometric levels determine the suitability of such a scale and technique for the intended objective.

Overcoming the low representation of monitoring wells in regional networks is a challenge, especially when investments are low. There are alternatives that use different strategies. One of them is to complement data from the Regional Quality Network with the results of the Sanitary Surveillance Network in cities supplied by groundwater. The legislation requires that the points of the water network of a city be periodically monitored and the information forwarded to the Health agencies. If the parameters indicating regional contamination (including electrical conductivity, chloride, ammonium and nitrate) were systematically analyzed and the sampling points associated with the producing wells identified, there would be an extensive network of thousands of points, whose concentration variations of the elements in time could indicate the degradation of the aquifer or part thereof.

One way to assess the problems of overexploitation of aquifers would be to use the data contained in the reports on the construction of driven wells. Well-drilling companies should be required to provide compulsory delivery of this information, as well as the date of drilling, the elevation of the land, the static and dynamic level, and the flow rate of the well, as well as its full depth.

In areas with evidence of intense extraction (due to the density of wells or reports of conflicts), a monitoring strategy would be to establish the grid of points, divide it into 500 m x 500 m or 250 m x 250 m squares and in each of them evaluate, systematically, the decays of potentiometric levels over time (every five years, for example) (MetQ method). In the squares where there is a significant drop in levels, the person responsible for monitoring could select a well or even install another well dedicated to the installation of pressure transducers, and periodically monitor the potentiometric level over time. The main objective is to optimize data that is not generally used by the environmental agency and allow the extension of conventional monitoring networks.

Box 30 – Integrated Groundwater Monitoring Network (Rimas)

Daniele Tokunaga Genaro
Frederico Cláudio Peixinho
Maria Antonieta A. Mourão
João Alberto Oliveira Diniz

The Integrated Groundwater Monitoring Network (RIMAS) emerged from the need to expand knowledge of the main aquifers in Brazil and from the requirement, present in various legal instruments of state management bodies, of an action tool to subsidize the management of groundwater resources. Its purpose is to record the natural variations of the water level to estimate the recharge, hydraulic parameters and calculation of the water balance, in addition to monitoring the variation of the water level in conditions influenced by the intense exploitation and occupation of land (MOURÃO; PEIXINHO, 2012). RIMAS also assists in the identification of variations in the quality of monitored groundwater, as it performs complete chemical and physical-chemical analyzes at the installation of the well and during network operation, based on the in loco determination of parameters considered indicators (pH, electrical conductivity and temperature). Secondly, it monitors climatological parameters (rainfall, relative humidity and air temperature) in the places where the observation wells are installed.

Monitoring is carried out throughout the national territory, meeting the following prioritization criteria:

- wells/piezometers dedicated (exclusively) to the monitoring activity;
- free sedimentary aquifers (recharge area);
- socio-economic importance of water;
- use of water for public supply;
- aspects of natural vulnerability and risks; and
- spatial representation of the aquifer.

RIMAS is an automatic network for recording hourly water levels. Its operation and maintenance is divided between the eight Superintendencies and three Regional Residences of the Geological Service of Brazil (SGB-CPRM), which are responsible for three to five operation and maintenance itineraries, frequently reassessed according to financial conditions, operational framework (employees) and inclusion of new monitoring points. Also depending on the particularity of each route, the visits alternate between two to four times per well/route.

After the visits in which the water level data extraction (from the dataloggers) are carried out, the teams return to the offices, carry out the data consistency and its synthesis (daily median). Subsequently, the data is made available on RIMAS website (http://rimasweb.cprm.gov.br/layout/) through which the evolution of the water level can be seen in analytical and temporal charts, allowing download according to the relevant period of interest.

The monitoring network has more than 400 wells located in 24 aquifers, in its free portion, in addition to some confined and semi-confined units, undifferentiated sedimentary covers and crystalline aquifers. Furthermore, it has approximately 100 platforms for the automatic collection of data on rainfall, temperature and relative air humidity, specific to the project, and is present in 21 Brazilian States.

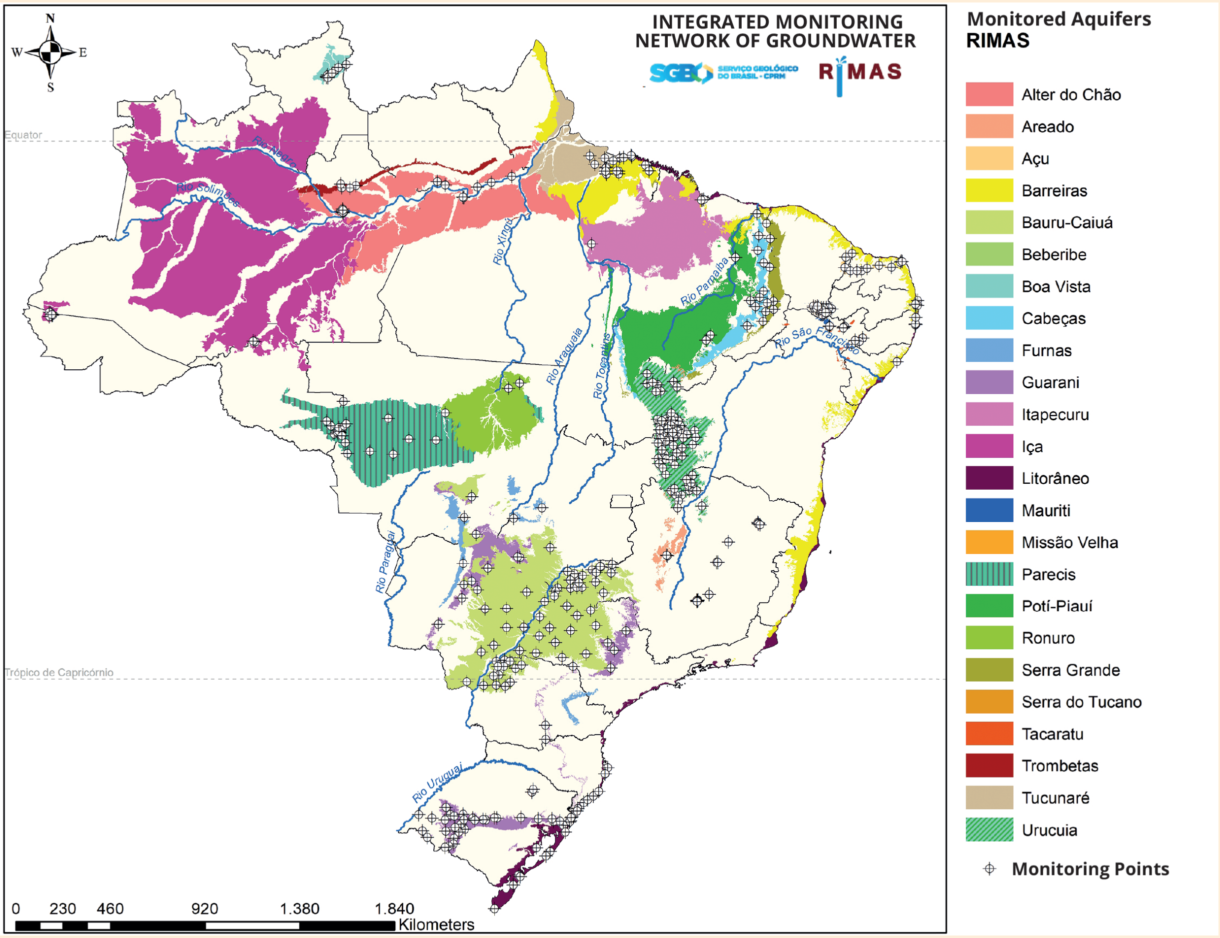

Figure 56 – Integrated Groundwater Monitoring Network (RIMAS)

Source: SGB-CPRM (2021).

Part of RIMAS is operated in an integrated manner with the National Hydrometeorological Network (RHN), in partnership with the National Water and Sanitation Agency (ANA), in the Urucuia Aquifer area (western Bahia) and in the Verde Grande and Carinhanha (the state line between Bahia and Minas Gerais). Among its specific objectives, the following can be highlighted:

• to promote a reliable assessment of the quantitative condition of groundwater bodies, including assessment of water resource availability;

• to establish long-term trend assessments, both as a result of changes in natural conditions and as a result of anthropogenic activities;

• to define the qualitative state of bodies of water;

• to identify significant growth trends in the concentration of pollutants and in the increase of the lowering of the water level;

• to assess the reversal of trends in qualitative and/or quantitative conditions after the implementation of mitigating measures;

• to establish the degree of interaction between groundwater and surface water.

The continuity and expansion of groundwater monitoring is essential to expand knowledge about aquifers and to assess the influence exerted by different factors, such as population growth, intensive exploitation and climate change. This information provides fundamental subsidies for planning, implementing and evaluating the effectiveness of management procedures.

4.8 CASE GALLERY

4.8.1 The management of complex contaminated areas by multiple sources: the case of the Industrial District of Jurubatuba, São Paulo

Marcos B. Barbosa
Reginaldo A. Bertolo

The former Industrial District of Jurubatuba, located in the city of São Paulo, has several properties that contain sources of contamination by organochlorine compounds. The geographic distribution of these sources characterizes the region as an extensive complex contaminated area (ITRC, 2017). This term refers to areas where environmental recovery is uncertain and the achievement of environmental goals is expected to occur within considerable time frames, i.e., on the order of several decades. Complex areas present numerous technical and non-technical challenges that contribute to the existence of uncertainties in their environmental recovery.

In the Jurubatuba region, the technical challenges of managing contaminated areas are numerous: occurrence of fractured aquifers; contamination of deep aquifer levels (up to 300 m); variation in groundwater levels due to pumping from irregular tube wells; existence of dense contaminants in non-aqueous liquid phase; complex conditions of degradation of these contaminants; existence of multiple sources of contamination and extensive and combined contamination plumes; in addition to the existence of receptors to contamination.

The non-technical challenges in Jurubatuba are also numerous and cause great uncertainty as to the success of its environmental management. Among the main challenges, the following stand out: *a)* multiple legal jurisdictions in dispute; *b)* difficulties in carrying out the identification of other persons responsible; *c)* existence of orphan contaminated areas; *d)* conflicts of understanding between public authorities on the environmental management of the area; *e)* litigation of conflicts between public bodies and polluters; *f)* environmental management carried out individually (without coordinated actions to understand the technical challenges at the appropriate scale); and *g)* lack of financial resources and a policy that facilitates access to financing funds for the recovery of environmental impacts.

Parallel to the problems of environmental management, the existence of these contaminated areas also caused conflicts between users and owners of driven wells, constituted by manufacturers themselves, by commercial enterprises and by condominiums. The contamination of aquifer water by organochlorine compounds led to the interdiction of dozens of private tube wells in 2005, and the establishment, by organs management bodies, of a large area of restriction of groundwater use (Figure 57). This deliberation is undergoing a general review process coordinated by the Technical Chamber of Groundwater (CTAS) of CBH do Alto Tietê (CBH-AT), and the main proposal is to make the use of groundwater for non-potable purposes more flexible after treatment, even if it shows some sign of contamination of industrial origin. It is expected that such a measure will help minimize the effects of the high demand for water resources in the region.

The management of environmental problems of this nature in places of strong demand for water resources is among the biggest challenges for public management bodies in Brazil and worldwide. The advancement of digital technologies and the internet represents a step towards practicality in the management of these problems, as the handling of information can be done in an easier, more agile and comprehensive way. However, the lack of an integrated data system and trained personnel is a challenge that persists in the environmental management of these complex areas. The entire efficient approach to deal with these cases makes use of a Geographic Information System (GIS), since the information is invariably associated with a location in physical space (LONGLEY *et al.*, 2005).

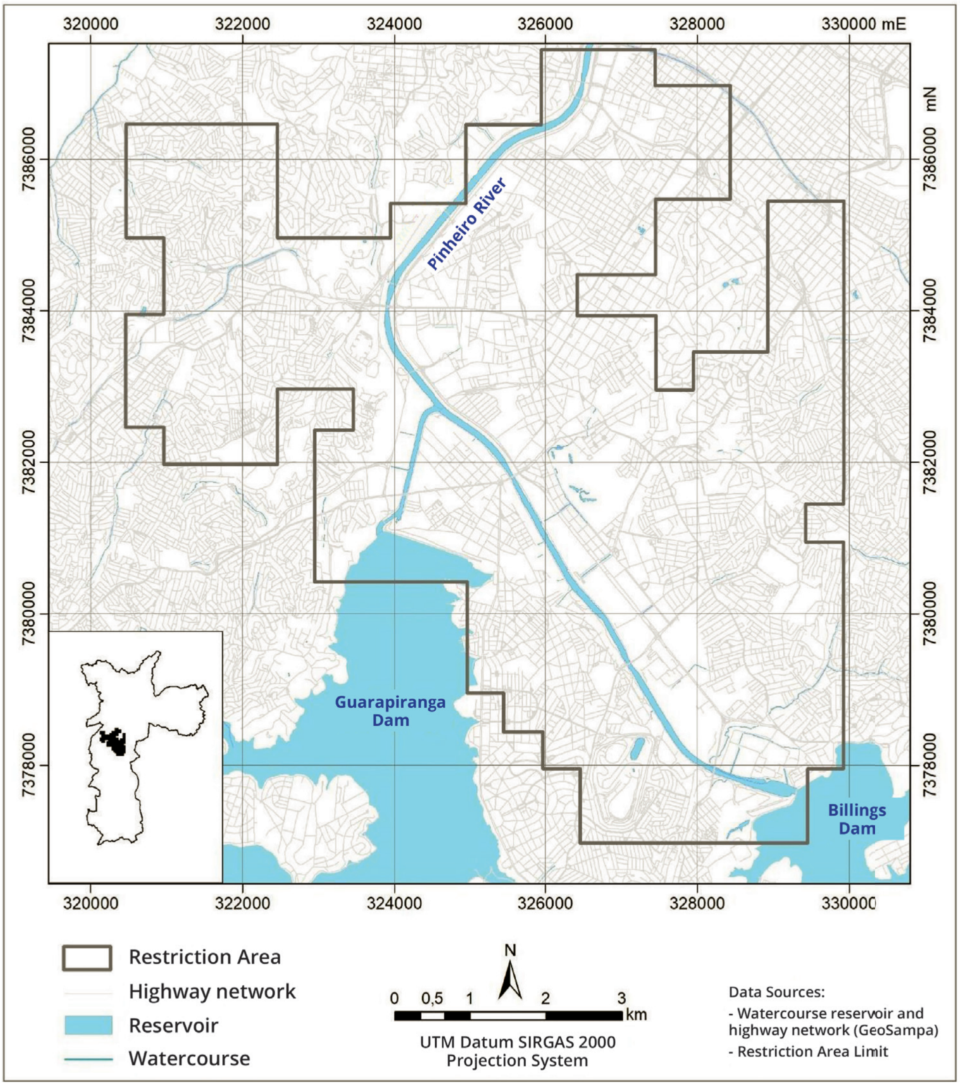

Figure 57 – Limits of Restriction and Control Area (ARC) for catchment and use of groundwater in the Region of Jurubatuba

Source: CBH-AT (2021).

In the case of the ARC of Jurubatuba, a spatial database was organized to systematize all available and relevant information regarding contaminated areas and driven wells (BARBOSA; BERTOLO; HIRATA, 2017). This integration made it possible to manage a large amount of data that was previously disconnected, which provided new interpretations from the existing information, in addition to allowing a broader understanding of the contamination of the area (Figure 58).

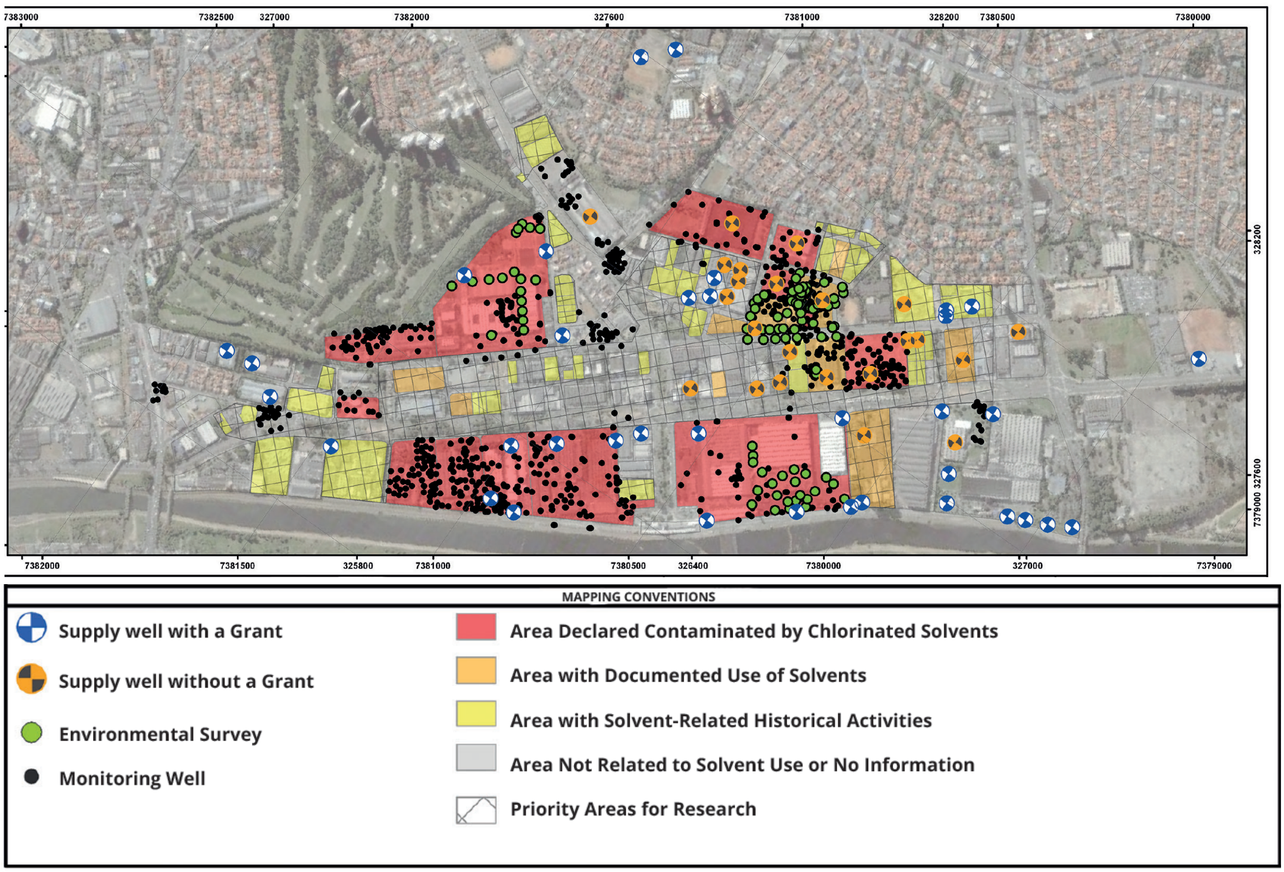

Figure 58 – Data analysis and processing based on the crossing of information available in the IMS of Project Jurubatuba, integrating data from contaminated areas, CETESB environmental management, registration of driven wells and field data collection

Source: Barbosa, Bertolo and Hirata (2017, p. 329).

The main results obtained in this work were:

1) to highlight critical aspects of the data, such as: spatial and temporal distribution; format and quantity; and reliability;

2) to indicate priority areas to be investigated;

3) to minimize data inconsistency from more than a thousand monitoring and drilling wells, as well as to reliably delimit the main lithological units that occur in the study area;

4) to understand the groundwater flow dynamics at the Project scale, indicating that the Pinheiros River is indeed a shallow aquifer discharge zone, and suggesting that crystalline aquifer recharge may be under the influence of the Billings and Guarapiranga reservoirs;

5) to delimit five sites where concentrations of organochlorine compounds were present, both in the sedimentary aquifer and in the fractured aquifer (by the deep driven wells);

6) to identify the places with high concentrations of organochlorine compounds in the fractured aquifer (in driven wells), close to areas that manipulated these compounds in the past, without the occurrence of investigations so far.

The absence of a water quality monitoring network with spatial and temporal coverage makes it difficult to establish an investigation strategy compatible with the scale of the problem in Jurubatuba ARC. In this case, a semi-regional or semi-local and integrated strategy could result in a smaller number of wells, located at strategic points, composing a monitoring network that is more representative of the different aquifers, with greater efficiency and lower cost.

The work approach adopted at ARC Jurubatuba although structured for cases of contamination from multiple sources can be applied in the management of contaminated areas for the entire state of São Paulo, facilitating the process of identifying new complex areas and the adoption of more efficient strategies in environmental management.

The systematization and importation of data are complex and laborious activities, whose responsibility lies with the entity that produces or contracts the data collection service. The management of information after integration into the database should be the responsibility of the system administrator (for example, the environmental agency itself). The data can be entered directly into the GIS, validated by a manager and evaluated by a technician from the environmental agency. When structuring the GIS, it is possible to create validation rules with the objective of minimizing the mistakes associated with this process. Figure 59 presents an information management model that can be developed and applied to the process of managing contaminated areas.

One of the most laborious steps, which could be incorporated into the GIS, would be the entry of data from drilling and chemical analyses. In the case of laboratories, they already have a database system in Structured Query Language (SQL), and its importation could be done directly, thus greatly reducing the printed and digital volumes sent for analysis by the environmental agency.

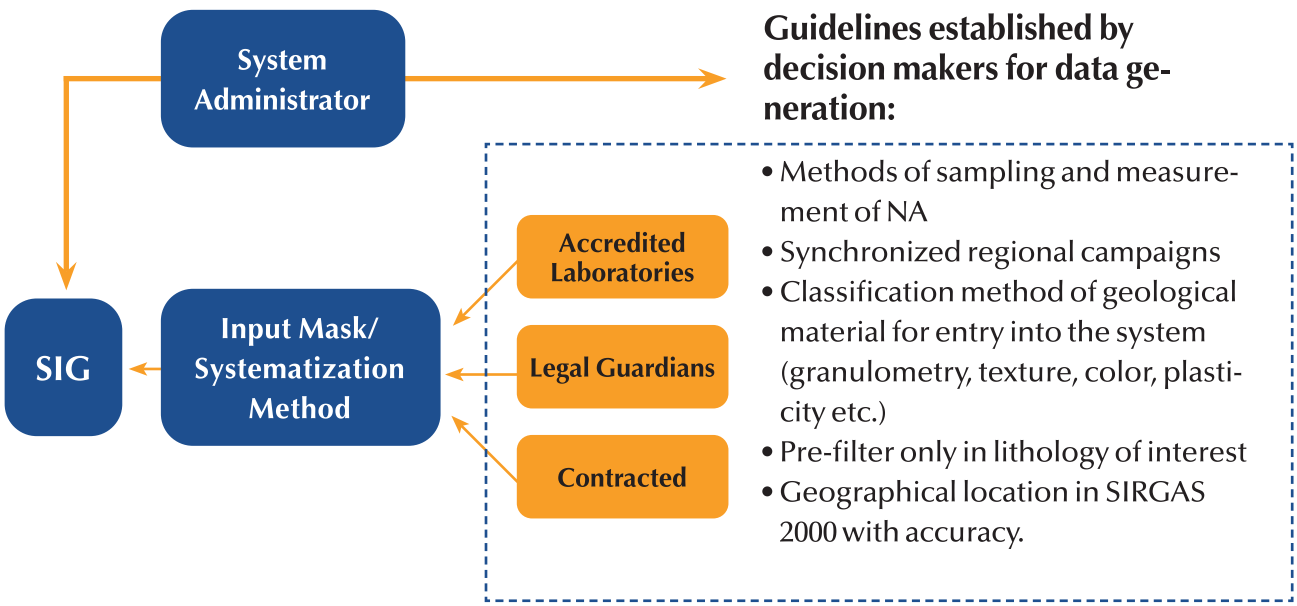

Figure 59 – Information management model applied to the management of critical areas
Source: Barbosa, Bertolo and Hirata (2017, p. 335).

The adoption and implementation of a GIS represents an important step in the integrated management of the environmental problem and the use of groundwater resources in the region, whose environmental recovery will only be achieved in future generations due to the complexity of the challenges. The GIS also helps in decision-making with a view to a more effective approach to the technical challenges identified, as well as the rational use of available resources. It also contributes to the resolution of non-technical challenges, bringing greater clarity to communication between the different parties involved in conflicts, responsible for solving environmental problems.

4.8.2 Water management and recovery of the Santo Domingo Aquifer, Comondú, Baja California Sur, Mexico

Zulema Guadalupe Lazos Ramírez

In the Santo Domingo Valley, in Baja California Sur, Mexico, the low average annual rainfall of 170 mm/m2 reduces the possibility of taking advantage of rain and surface water. The main source of supply of the different uses of water (mainly agricultural) is the Santo Domingo aquifer (Figures 60 and 61). Historically, the local situation imposes great challenges for the management and management of water, in order to guarantee the development of this basin and the strengthening of its economy, considering population growth (Table 1).

Municipality	Location	1990	2000	2010	2020
Comondú	Cidade de Constitución	34.692	35.589	40.935	43.805
	Cidade de Insurgentes	8.463	7.654	8.741	9.133

Table 1 – Population of the main locations in Vale de Santo Domingo
Source: INEGI (1990, 2000, 2010 e 2020).

Figure 60 – Location of the Santo Domingo Aquifer, Baja California Sur, Mexico
Source: Conagua (2020).

On July 2, 1954, the National Irrigation District of Baja California Sul was created by Presidential Decree, consisting of a delimited area in which the irrigation zone is located supplied by water extracted from the Santo Domingo Aquifer. The action contributed to agricultural development, resulting in economic and population growth in the community. Over time, however, problems arose due to poor management and lack of control over the use of groundwater. Water extraction exceeded aquifer recharge, whose water levels resulted in a drop of three to 15 meters per year.

Considering that the Santo Domingo Aquifer is of the coastal type, saline wedge migration occurred, which significantly increased the salinity of the groundwater. Some wells have reached mineralization levels of 3,000 ppm, making the water quality unsuitable for human consumption and agricultural use. The consequence of this exacerbated extraction, therefore, was an imbalance of the ecosystem, reflected in the increase in salinity. This increase affected the quantity and quality of the aquifer water for its use in agricultural activities which are the basis of the economy of Vale de Santo Domingo.

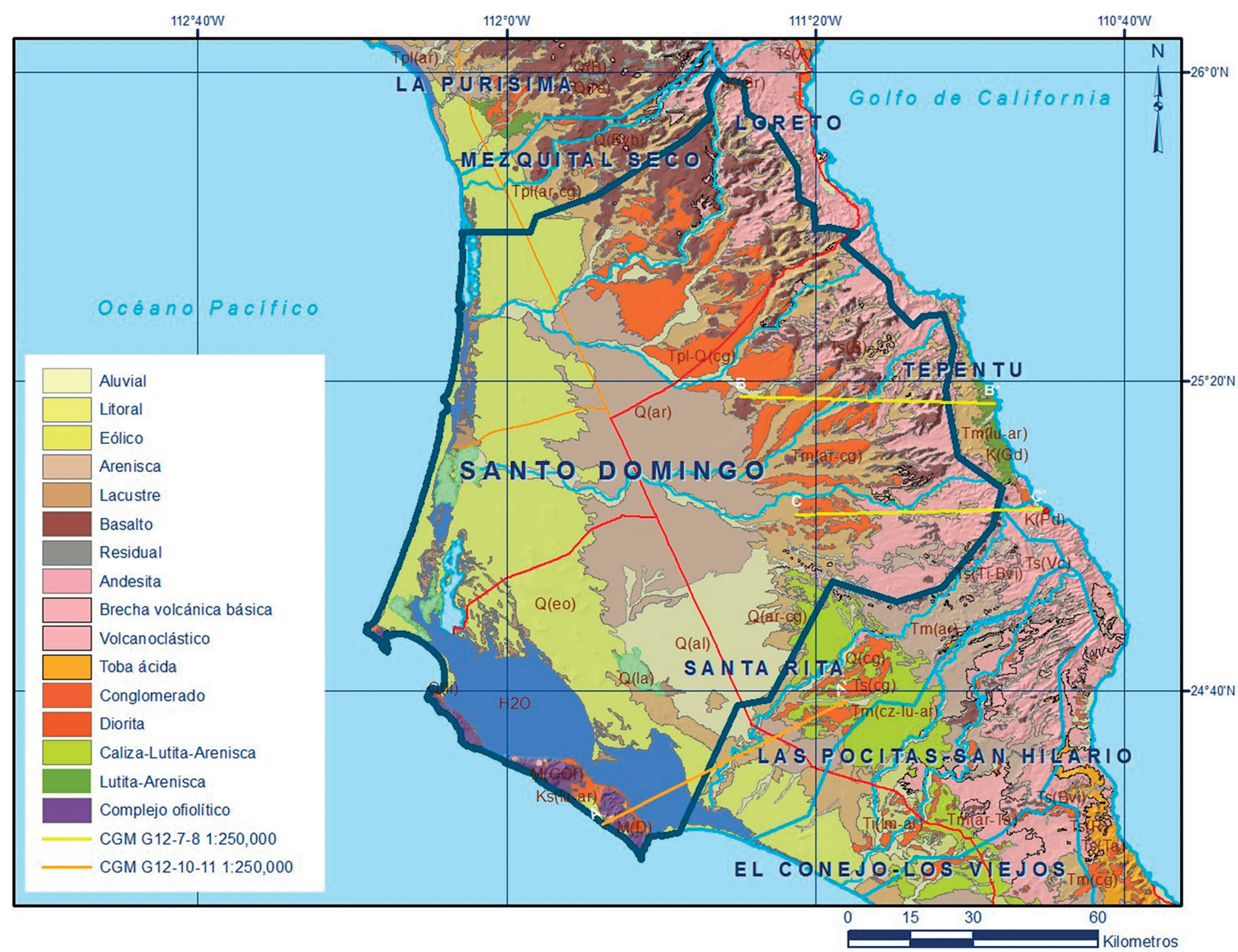

Figure 61 – Geology of the Santo Domingo Aquifer
Source: Conagua (2020).

Due to this situation, on August 14, 1992 the Federal Government's Official Press published the "*Due to this situation, on August 14, 1992, the "Regulation for the use, exploration and exploitation of underground waters in the area known as Vale de Santo Domingo, municipality of Comondú, in the state of Baja California Sur, and establishing the respective potable water reserve.*"[6] As of that year, the Water Authority in Mexico included the participation of Aquifer User Organizations and Associations, so that they could propose solutions related to the water problem, as well as commit to promoting efficient water management and aquifer protection.

Santo Domingo was the first aquifer to be regulated in the country, allowing the reduction of extracted volumes, however, it only reached the necessary volume for the stabilization of the ecosystem in 2004, when the extractions stabilized. The reduction in the potentiometric level of the aquifer, however, continued to deepen in the central part. Based on these findings, in 2010, as a result of the impacts observed on the aquifer, the water dependence and the community's responsibility in water management, the Valle Santo Domingo Aquifer Recovery Project was carried out with the participation of society, with the objective of reducing the levels of drawdown through actions of monitoring and measuring the quantity and quality of water (CONAGUA, 2010).

With the participation of different institutions from the three levels of government (federal, state and municipal) and, mainly, the users of national waters, mostly belonging to the agricultural sector, the National Water Commission (CONAGUA) organized work tables with the objective of defining a program that would integrate both the actors responsible for the decision-making process and those who carry out actions for the benefit of the aquifer to give visibility to the water situation and, from there, establish solutions.

The organization of the work tables allowed the development of an operative planning matrix, as well as the construction, in a participatory way, of a project execution structure, with actors committed to continue the execution, monitoring and inspection of the agreements signed for the aquifer recovery. The result of these actions was formalized in a document (CONAGUA, 2010).

The most representative data of the positive effects of citizen participation are revealed in the maintenance of annual volumes of water extraction from the aquifer, of which about 94% refer to agricultural use, which consumes the equivalent of 165.12 million m3 of water. Figure 62 demonstrates the stabilization of annual extractions of water volumes for agriculture. The recovery of the aquifer has not yet been achieved, however, it is already moving towards this, thanks to the support of different actions that must be implemented, such as: preparation of studies and projects, promotion of the qualification of producers for the knowledge of norms and culture of water, expansion of macro and micro measurements of water extractions, management of water resources etc.

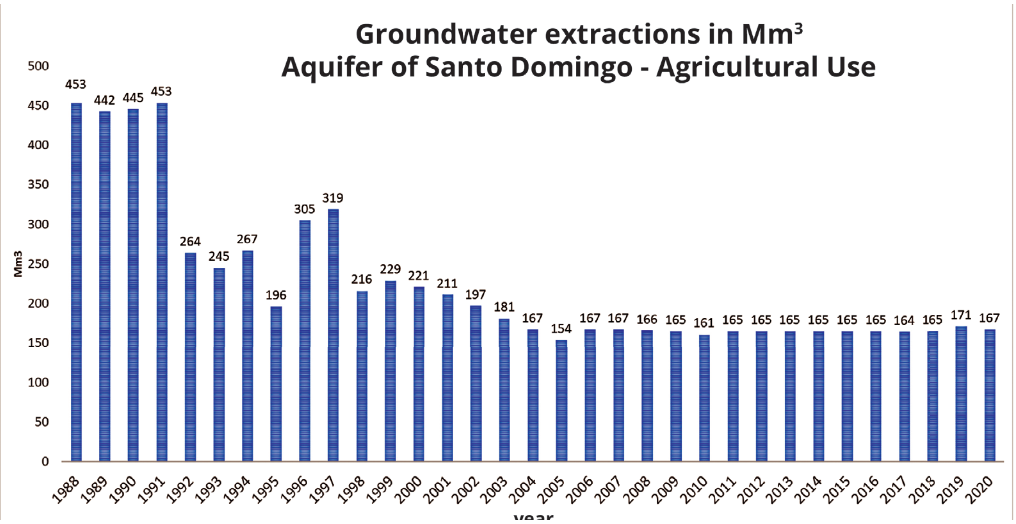

Figure 62 – Extractions of groundwater in Mm^3 in the Santo Domingo Aquifer (agricultural use)

Source: Conagua (2020).

6. Available at: http://dof.gob.mx/nota_detalle.php?codigo=4682007&-fecha=14/08/1992.

In the "*Emblematic Project for the Recovery of the Aquifer of the Vale de Santo Domingo, City of Constituición, Baja California Sur*", the population of Valle de Santo Domingo is an example of commitment and participation in the promotion of economic, environmental and social development, as the community participates, engages, decides, verifies compliance with the proposed objectives and commits to programs aimed at efficient water use, whether for agricultural purposes or for domestic activities.

On September 17, 2020, Conagua published, via the Official Gazette of the Federation, the Agreement in which it updates the average annual availability of groundwater for the 653 aquifers in the United Mexican States. In this scenario, the Santo Domingo Aquifer presents a groundwater extraction volume of 176,771 m^3 a year, whereas the aquifer recharge is 146,4 Mm^3 a year. It is therefore necessary to follow the recovery actions and integrate new measures to achieve the proposed objectives more effectively and quickly.

The recovery of the Santo Domingo Aquifer is a complex process and, due to the participation of the community, it knows and understands that this work will take many years to be achieved, mainly due to the geological conditions of the aquifer, its recharge capacity, the atmospheric conditions and human activities in the Santo Domingo Valley. However, although the recovery process takes time and the continued development of actions, community engagement contributes to the care and efficient use of water in the region. The success of this experience is directly related to the participation of the community, which is committed to the actions necessary to achieve sustainability in the use of water resources.

4.8.3 The Groundwater Communities (CAS) in Chile

Ovídio Alejandro Melo Jara

Jose Luis Arumi

The Chilean model

Chile has a special model for managing its water resources, characterized by granting Water Usage Rights (DAA) to individuals free of charge, in perpetuity and without expiration or revocation instruments that protect the public interest. The only mention, however, that the Political Constitution makes in relation to inland waters is to guarantee private title of these rights.

The State, consequently, does not see itself in the obligation to protect for the common asset. On the contrary, it offers the market freedom and flexibility to deal with the conflicts generated by the maintenance of a system, which can be unequal and ecologically irresponsible. The purpose of this policy is to achieve the economic optimization resulting from this freedom of transaction and the legal certainty generated by the model.

Once these DAAs are granted, the powers attributed to the State in relation to the management of water resources are considerably reduced, leaving the main functions related to the management of uses to the market (the transfer) and to individuals. Thus, the people who hold DAA constitute the so-called Water User Organizations (OUA), which are entities regulated by the Water Code, endowed with legal personality, whose objective is to capture the waters of the matrix flow, divide it among the holders rights, build, explore, conserve and improve the extraction work, aqueducts and others that are necessary for their use. In the case of natural water courses, the OUA are configured as a surveillance board, while in artificial channels water communities and channel associations are organized.

In the case of groundwater, through an act of public authority, based on and materialized through a Resolution of the General Water Board (DGA), a certain Hydrological Sector of Common Use (SHAC) is declared as a restriction area or zone of prohibition of extraction, which gives rise to the formation of a Groundwater Community (CAS) for the SHAC in question.

This model is based on the assumption that there are functional and empowered OAUs in the fulfillment of their function, and that these constitute valid interlocutors before the relevant institutions and social actors in each of the territories under their jurisdiction. The very existence of these organizations, however, is not guaranteed, as only 40% of the country's hydrographic basins have a surveillance board for the management of their waters. Moreover, less than 10% of SHACs declared as restricted areas or prohibited zones were organized as CAS (SCHNEIDER; RIBERA, 2021).

It is in this context that, during the last decades, the State, through the National Irrigation Commission, has developed programs to strengthen the OUAs in a large part of the national territory, increasing the number of these organizations, reinforcing their structure and organizational dynamics, improving their participation and, therefore, contributing to water management. Likewise, the DGA created the Department of User Organizations, which has contributed considerably to this strengthening. However, the existing gaps in this model are the main challenge in relation to water governance in the country.

Lack of user interest in being part of a CAS

According to the University of Concepción (2019), it is common to observe that in surface water courses there are always those interested in constituting the respective OAU. In the case of groundwater, however, there is a considerable lack of interest on the part of the parties to carry out this action, which can be explained by the absence of incentives. In the case of surface water, there are always users who need the organization, especially those located downstream of the water courses, who notice a negative impact produced by those positioned upstream. Moreover, the simple fact of sharing a watercourse generates numerous organizational needs, such as: cleaning, infrastructure maintenance, improvement of common works, water distribution and financing of actions, among many others.

A CAS arises from the legal obligation to protect the common good and relevant ecosystems for future generations, not from the need of individuals. Notwithstanding, it is not easy to find the catalytic elements that motivate the creation of these organizations – as is the case with surface waters – therefore, the interest in creating them practically does not exist.

It is not surprising, therefore, that of the more than 170 SHACs declared as Restricted Areas or No-Extraction Zones on a national scale, only 14 have organized themselves as CAS. Only after the beginning of the legal procedures for the constitution of a CAS and when its conformation becomes inevitable, is the interest of some users aroused with a higher level of information that intend, mainly, to occupy the spaces of power (management) and approve the relevant statutes. The legislation in force seeks to circumvent this lack of interest in organizing itself, as it is enough for a person to ask the empowered judge to set up an organization and it is then materialized. Moreover, in the event of absence of applicants, the DGA may make such a request.

Consequently, given the public interest that presupposes the organization of a CAS, it seems logical that the state should continue to provide the necessary instruments to materialize its organization in the SHAC declared as a Restriction Area or Extraction Prohibition Zone, despite the lack of interest of users. Moreover, the state should promote changes in the legislation that generate incentives for the organization of CAS, such as, for example, some type of requirement for the performance of procedures of interest, such as the transfer of collection points by users.

Finally, as only the DAA members participate in the decision-making process at the OAU, the challenge arises of including other relevant social actors in the territory that represent different interests, such as those of future generations, ecosystems and society as a whole.

The joint management of surface and groundwater

According to Melo (2019), in 2005, the 1981 Water Code was modified to include the management of aquifers in the administration of the OAU. First, Article 186 established that the origin of an OAU can also be the aquifer. Furthermore, Article 263 defined that the surveillance boards (JV) are formed by those who take advantage of the surface or underground waters of the same hydrographic basin. In turn, Article 266 of the Code establishes that the purpose of the JV is to manage the waters to which their members are entitled, from natural sources. Art. 22 determined that to constitute the DAA, the authority must consider the "existing relationship between surface and groundwater."

This new legislation allowed the arising of a management model in which the JVs not only manage surface water, but also, jointly, groundwater. The way, however, to materialize this integration was not regulated in any of the fundamental aspects of the management carried out by the OAU. For example, the incorporation of groundwater into the JV is carried out individually or through organized CAS, through the regulation of corporate participation or equivalence of underground rights in relation to surface rights or what the essential aspects for decision-making are, and how funding is provided within the organization.

As a result, it was only more than 10 years after the Regulation was promulgated that the first actions aimed at materializing a joint management of surface and groundwater emerged, all of which are very incipient experiences, which allow a small advance, but without reaching a minimum organizational development.

4.8.4 The Geneva Aquifer (Switzerland-France): a success story in cross-border cooperation on the local level

Gabriel de los Cobos

Lake Leman and the Geneva Aquifer (Switzerland-France) provide drinking water to a population of almost 700,000 of the Franco-Genoese region, shared by the Canton of Geneva (Switzerland) and the Department of Haute-Savoie (France), and jointly exploited by 10 wells in Switzerland and four in France (situation in 2017). The Geneva Aquifer extends for 19 km in length between Lake Geneva and the western end of the Canton and part of the French territory of Haute Savoie (Figure 63). Its width varies between 1 and 3.5 km, and the thickness of the saturated gravel reaches 50 m (Figures 64 and 65). The average water level is between 15 and 80 meters deep, depending on topographic conditions.

Figure 63 – Location of the Geneva Aquifer

Source: Service de géologie, sols et déchets (s.d.).

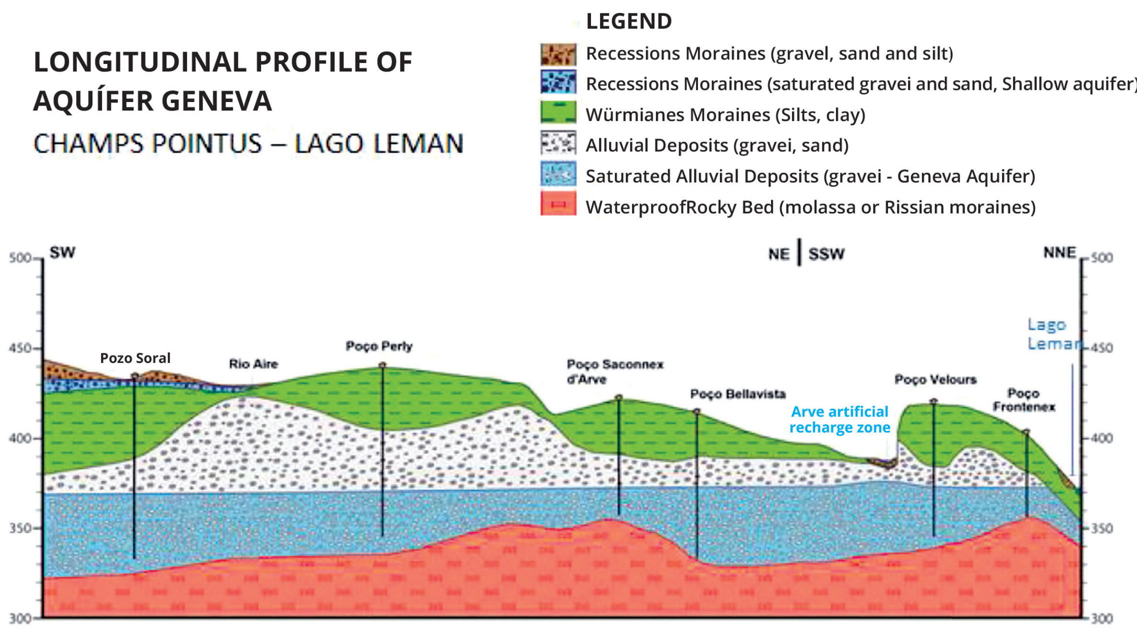

Figure 64 – Longitudinal profile of the Geneva Aquifer
Source: Service de géologie, sols et déchets (s.d.).

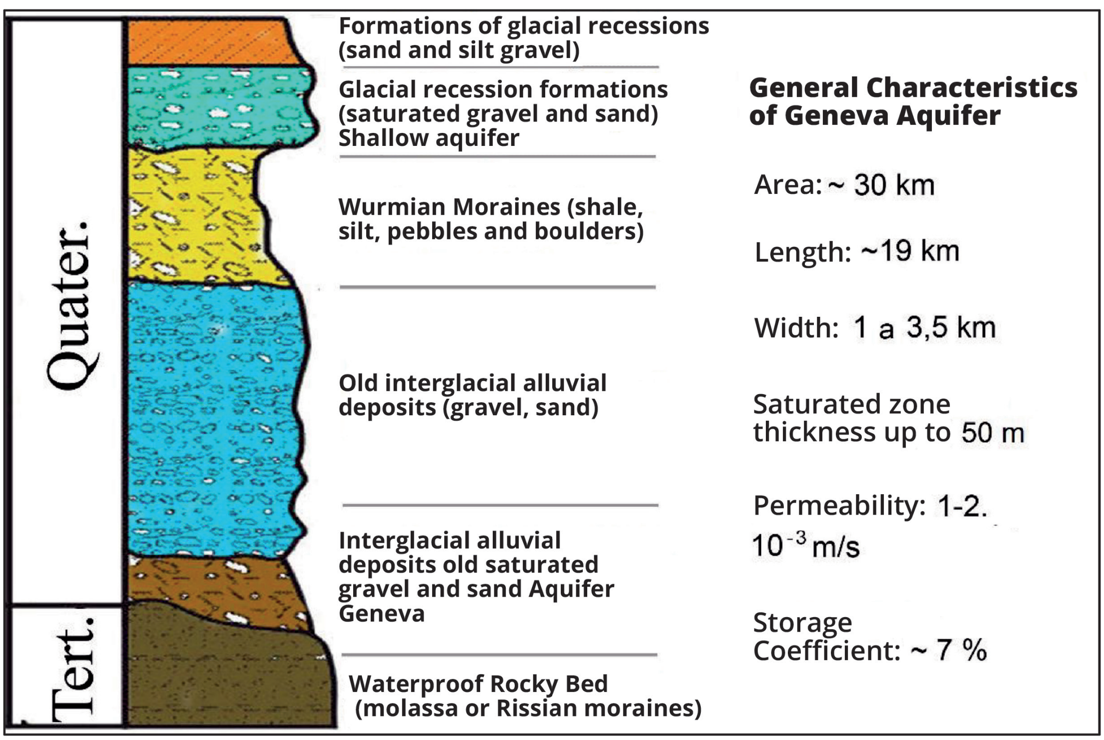

Figure 65 – Lithostratigraphic section of the Geneva Aquifer's component units
Source: Service de géologie, sols et déchets (s.d.).

Between 1940 and 1960, groundwater abstraction from the Geneva Aquifer was very close to the average exploitable flow (7.5 Mm^3/year). There was a slow trend of lowering of the groundwater level, without any indication of serious threat. Between 1960 and 1980, however, the aquifer was overexploited, with withdrawals that reached 14 Mm^3 per year in 1971, almost double the amounts available. The average water level of the aquifer has dropped from 6 to 7 m in 20 years, with the use of about a third of the total reserves.

Hydraulic management proved to be urgent, with two options: *a)* reducing the withdrawal, exploring another resource, which would require the construction of a new filtration and water treatment station in the lake; or *b)* enhancing the natural capacity of the aquifer through artificial recharge. The choice was not easy: on the one hand, there was a well-known technique (filtration station in the lake); on the other, artificial recharge, surrounded by uncertainties in the balance equation. Artificial recharge was chosen based on two criteria: *a)* supply security criterion (diversification of resources); and *b)* economic criterion (the high cost of building and implementing a new filtration station).

In parallel with the preparation of studies and tests at the experimental station, there was a political will to develop the project jointly across borders, despite the fact that approximately 90% of the aquifer surface is located in the territory of the Canton of Geneva, and only 10 remaining % are on French territory. Several meetings and discussions were held within the scope of the technical studies and the preparation of a draft, in order to obtain:

- restrictions on exploration while the aquifer, which was to be depleted, was not artificially recharged;
- equitable distribution of the costs of the work which, once completed and operational, would benefit operators located on both sides of the border.

Since the first Franco-Swiss meetings in 1972, the depletion of groundwater in the Geneva Aquifer was evident, as the water level dropped regularly. The problem affected not only the Geneva region, but also the French side. Between 1973 and 1974, activities focused on the inventory of drinking water resources in the region, as well as on hydrogeological aspects such as losses, natural recharge, future pumping (and application of corresponding fees). The entire set of issues that should be considered at that time were addressed in order to lay the foundations for a possible Franco-Swiss Agreement.

In the course of 1975, the French side declared its intention to abandon the exploitation of underground water resources and use other water resources located on French territory. However, France expressed the desire to maintain the possibility of a subsequent participation in the recharge and related benefits. In 1977, the benefits of artificial recharging were assessed for all users. Finally, an Agreement between the Canton of Geneva (Switzerland) and the Haute-Savoie Region (France) was signed on June 19, 1978, valid for a period of 30 years.

The 1978 agreement between the State of Geneva and the Haute-Savoie Region

The agreement concluded between the Council of State of the Republic of the Canton of Geneva and the Mayor of Haute-Savoie was motivated mainly by "the need to establish a coordinated exploration of the Geneva Aquifer in order to safeguard this natural resource and to preserve the quality of its waters". This agreement covered the following aspects:

- the annual aquifer management program, i.e., the flows reserved for each user, according to the availability and reserves of the aquifer, and the needs of each one, taking into account the provisions issued;
- a list of facilities for artificial recharging;
- each user's water rights;
- the price of water (calculated on the basis of station construction costs).

It was expected that the cost of recharge (depreciation, interest, renewal and equipment operating costs) would be attributed to all abstractions, regardless of the water source (natural or artificial recharge). The French part obtained a maximum pumping of 5 million m^3, however, with an annual concession of 2 million m^3. Above this quota, the price per m^3 would be calculated according to an equation established as a function of several parameters, such as pumping and operating costs.

A Franco-Swiss commission was created in charge of the exploitation of groundwater, which would regularly review the situation of the resource, according to pumping and artificial recharge. This commission would be composed of representatives appointed by the

Council of State in Switzerland and by the sub-district (*sous-préfet*) on the French side. Moreover concerning aspects related to the annual program of artificial recharge, budget, repair and maintenance projects, the commission should give prior notice on all matters submitted to it in the context of the management and protection of the Geneva Aquifer.

The renewal of the 1978 Agreement: the 2008 Convention

Between 2007 and 2008, the Commission responsible for the exploration of groundwater in the Geneva Aquifer created a French-Swiss working group to develop a framework document for the management of groundwater resources over the next 30 years. Legal support was included as a way of ensuring that the technical characteristics accepted by the parties fit into a politically and administratively recognized global context.

The first steps were to put in place the cross-border legal framework on which the new agreement was to be based. In fact, the 1978 Agreement had no basis in legal instruments for cross-border cooperation for the simple reason that these did not exist at the time. Many instruments have emerged since 1980 and have been ratified by both Switzerland and France. Figure 66 comprises the main legal instruments related to the promotion of international cooperation, which supported the 2008 Convention.

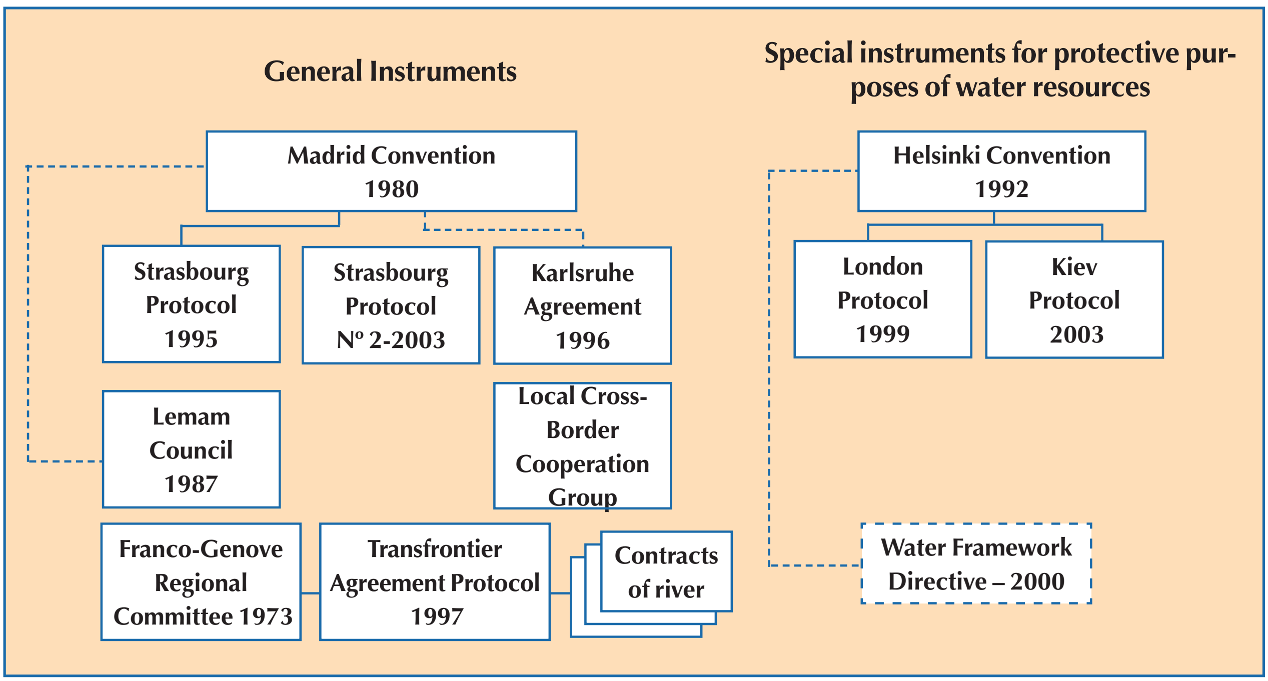

Figure 66 – Legal instruments related to promoting international cooperation for the Geneva Aquifer
Source: prepared by Gabriel de los Cobos.

Based on the Karlsruhe Agreement, specifically regarding the possibility provided for in its Article 5, which allows the delegation of a mission to one of the local authorities, it was possible to reach an agreement between the Canton of Geneva and the three French authorities involved (*Annemasse Agglo*, *Community of Communes du Genevois* e *Commune de Viry*).

As in the 1978 Convention, this Convention was established with the common objective of ensuring the sustainability of the Geneva Aquifer and thus guaranteeing, as far as possible, the water abstraction capacity necessary to ensure the supply of drinking water for the populations. The administrative, legal, technical and financial provisions necessary for the proper execution of this task were defined. This Agreement replaced the 1978 Agreement and entered into force on January 1, 2008, for a period of 30 years.

Review of 40 years of shared management

The Geneva Aquifer Management Agreement is one of the few existing examples of a legal instrument dedicated to a transboundary aquifer at the local level, i.e., between communities belonging to both France and the Swiss Canton. It is, therefore, the result of what can be considered the legal validation of a pragmatic approach. From a transboundary policy perspective, the successful management of the Geneva Aquifer forms the basis for the establishment of a transboundary aquifer community, formalized by the signing of a Memorandum of Understanding for Transboundary Cooperation in Water Ownership on 12 December 2012.

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FINAL CONSIDERATIONS

After more than two decades since its implementation, the National Water Resources Policy (PNRH) is yet to become fully operational from an institutional point of view or from the standpoint of application of management instruments in several basins in the Brazilian territory. This scenario impacts the management of water. Groundwater assumed a supporting role in said management, despite its importance in maintaining surface water and ecosystems, and despite its strategic nature in public and private supply, including water security for vulnerable social groups.

Gradually, Singreh agencies are seeking to encourage the inclusion of aquifers and to provide guidelines for the management of water. However, there is still not sufficient data and monitoring as to the way the states - who have jurisdiction over this resource - have promoted said management. The application of water management instruments at the state level faces serious difficulties in the inclusion of groundwater. In many cases, the approach to aquifers in basin plans is superficial, without defining priority management areas. Wells granted under concession are the exception, since the majority of users is irregular and see no benefit from legalizing them. On the other hand, there is tolerance by the Government relative to this situation, in light of the difficulty faced by management agencies in carrying out inspection. In many cases, concessions have been granted without the necessary hydrogeological assessments to determine the exploitable flow of aquifers, for the purposes of protecting them from overexploitation. The classification of groundwater bodies has not left the drawing board, especially given the lack of state regulations for the applicability thereof. Enforcement, in turn, if any, is immaterial in light of the scenario of irregular appropriation of water.

Overall, Brazil has a legal-institutional structure capable of promoting integrated management of water resources; however, it is necessary to improve the environment of water governance, so as to improve: *i)* coordination between the different government entities and sector-based management (environmental, sanitation, economic development, territory governance etc.); *ii)* the involvement and support from social actors, especially well owners and drilling companies; *iii)* the qualifications of technicians working on the management; *iv)* promotion of technical and social knowledge on the theme; and *v)* effective inclusion of this water in management instruments. Based on the foregoing governance, it will be possible to encourage strategic planning of groundwater taking into account the relations between society vs. aquifer, as well as aquifer vs. river vs. ecosystem.

Baby playing in the recharge area of Guarani Aquifer in Ribeirão Preto (SP)
Photo: Pilar Carolina Villar / ANA Image Database

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ISBN 978-658810138-4