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Thesis

A social-ecological systems analysis of the governance of alluvial aquifers in the Brazilian semi-arid region: the case of Sume

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Abstract

Small and shallow alluvial aquifers in arid and semi-arid regions are a strategic source of water that has been largely used for irrigation and livestock feeding. Geological settings and the small scale of these aquifers suggest the need for governance at the local level, but research supporting its development is still scarce. A case of alluvial aquifers exploited by smallholder farmers located in the Brazilian semi-arid region is analysed under the perspective of common pool resources (CPR) and social-ecological systems (SES). The thesis investigated a large database to build knowledge of water table behaviour, groundwater use, and stakeholders' interaction. With this information, the SES Framework was applied to analyse the SES in light of Ostrom's principles for sustainable CPR management to answer the questions: (1) can the governance arrangements support sustainable common pool resource management of the alluvial aquifers? (2) what opportunities are there to make the management of the aquifer more sustainable through community-based governance? (3) can Ostrom's design principles lead the transition to more sustainable governance of alluvial aquifers? Despite a water policy aiming for decentralisation and participatory governance, gaps in its implementation were identified. Considering the challenges imposed by the aquifer characteristics to impact efficient groundwater exploitation, equity in water distribution and conservation of the CPR, the analysis reveals opportunities to improve CPR management by supporting the community to increase participation in the governance of the aquifer in coordination with existing policies. Collective water permits and community monitoring are among the suggestions that could empower community progress towards more sustainable governance of the aquifer. Based on this discussion, a protocol for supporting the implementation of social and technological strategies was synthesised, aiming to provide practical guidance to policymakers.

Keywords: groundwater, common pool resources, protocol

Resumo

Aquíferos aluviais pequenos e rasos em regiões áridas e semiáridas são uma fonte estratégica de água que tem sido amplamente utilizada para irrigação de cultura de subsistência e de forragem. As configurações geológicas e a pequena escala desses aquíferos sugerem a necessidade de governança em nível local, mas as pesquisas que apoiam seu desenvolvimento ainda são escassas. Um caso de aquíferos aluviais explorado por pequenos agricultores localizados na região semiárida brasileira é analisado sob a perspectiva de recursos de uso comum (RUC) e sistemas socioecológicos (SSE). A tese investigou um grande banco de dados para construir conhecimento sobre o comportamento do lençol freático, o uso da água subterrânea e a interação das partes interessadas. Com essas informações, a Estrutura de um SSE foi aplicada para analisar o SES à luz dos princípios de Ostrom para a gestão sustentável de RUC para responder às perguntas: (1) os arranjos de governança podem apoiar a gestão sustentável de recursos comuns dos aquíferos aluviais? (2) quais oportunidades existem para tornar a gestão do aquífero mais sustentável por meio da governança baseada na comunidade? (3) os princípios de Ostrom podem conduzir a transição para uma governança mais sustentável de aquíferos aluviais? Apesar de uma política de recursos hídricos que visa a descentralização e governança participativa, foram identificadas lacunas em sua implementação. Considerando os desafios impostos pelas características do aquífero para impactar a exploração eficiente das águas subterrâneas, equidade na distribuição da água e conservação do RUC, a análise revela oportunidades para melhorar a gestão do RUC, apoiando a comunidade para aumentar a participação na governança do aquífero em coordenação com as políticas existentes. Outorgas coletivas de água e monitoramento comunitário estão entre as sugestões que podem fortalecer o progresso da comunidade em direção a uma governança mais sustentável do aquífero. A partir dessa discussão, foi sintetizado um protocolo de apoio à implementação de estratégias sociais e tecnológicas, com o objetivo de fornecer uma orientação prática aos formuladores de políticas.

Palavras-chave: águas subterrâneas, recursos de uso comum, protocolo

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1. Introduction

The problems and conflicts over groundwater use present a significant challenge to water management, as they are complicated and exacerbated by the complex and hidden nature of groundwater. With this in mind, different approaches have been proposed to improve aquifer yield and support groundwater management. Such strategies involve structural or non-structural measures based on empirical observations, modelling tools or/and governance assessments (Buikstra et al. 2007; Alcon et al. 2019; López-Morales and Rodríguez-Tapia 2019).

This has been no different for alluvial aquifers, which are formed on the riverbed of perennial and intermittent rivers through the deposition of sediments. These aquifers have been studied all over the world, especially in arid and semi-arid regions (Benito et al. 2010; Andrade et al. 2014; Missimer et al. 2015; Sarma and Xu 2017). The conceptual model of the aquifer and the groundwater modelling have been supporting groundwater management in these areas, with information on aquifer potential for different uses, the effectiveness of artificial recharge, stress conditions, among others (Zume and Tarhule 2011; Du et al. 2016; Sarma and Xu 2017; Walker et al. 2018). Moreover, Du et al. (2016) highlight the need for accurate data to develop such models.

River basins comprising small alluvial aquifers of crystalline substrate with ephemeral rivers are a system that is common throughout the Brazilian semi-arid region. Due to the hydrological and hydrogeological conditions of low rainfall, high evapotranspiration and shallow bedrock, the small alluvial aquifers constitute a strategic source of water resources for rural communities (Burte et al. 2005, 2011; Rêgo 2012; Albuquerque et al. 2015).

Recharge of such aquifers depends on the rainfall concentrated in the rainy period of three months between January and June. In areas close to cities, sewage is also an important component of aquifer recharge, although infiltration usually occurs in an unplanned manner, and is not even recognized (Foster and Chilton 2004). The treatment and destination of sewage is a challenge to be overcome in the country. This challenge is accentuated in the semi-arid region due to the intermittency of the rivers (ANA 2017), which has prompted research into the use of this source to increase aquifer yield and the resulting impacts on groundwater quality (Missimer et al. 2012; Izbicki 2014).

They require dynamic and particular management with specific local strategies, since they are generally inefficiently managed- and/or over- exploited, and can collapse before a new recharge occurs (Billib et al. 1991; Montenegro and Montenegro 2012; Rêgo 2012; Cirilo et al. 2017). However, there is limited legislation with few adaptations for these small aquifers, submitting them to the same arrangements that govern more extensive aquifers. This happens because of their small scale, resulting in a lack of attention to them at higher levels of governance. While a considerable body of research has investigated strategies for the management of the alluvial aquifers (Burte et al. 2005, 2009; Montenegro and Montenegro 2012; Rêgo et al. 2014; Alves et al. 2018), governance analysis of their regulation and of the stakeholders' role is still limited (Benito et al. 2010; Taher et al. 2012; Cavalcanti 2015; Braga 2016). These few studies demonstrate the need for integration within greater scales and levels of governance.

In order to overcome the challenges imposed to groundwater governance, it has been argued that community participation has advantages over centralized governance, especially regarding the engagement of users to build and share knowledge and to improve equity in exploitation (FAO 2010; Reddy 2012; Taher et al. 2012; Barthel et al. 2017). Ostrom (1990) provided evidence that common pool resources, such as groundwater resources, can be managed by communities sustainably if eight design principles are followed. A common pool resource (CPR), as described by Ostrom (1990, p. 30), "refers to a natural or man-made resource system that is sufficiently large as to make it costly, but not impossible, to exclude potential beneficiaries from obtaining benefits from its use". Groundwater fits this definition because it does not match administrative boundaries, is very difficult to monitor and assess, and can be extracted by many users via wells located anywhere on the aquifer, hence making it difficult to exclude beneficiaries from accessing it.

The analysis of groundwater governance within this perspective has suggested innovative solutions, as well as placing the groundwater systems into the context of social-ecological systems (SES) — (Molle and Mamanpoush 2012; Foster and Garduño 2013; Giest and Howlett 2014; Seward and Xu 2018). Although there is no single accepted definition of a social-ecological system, it usually refers to a collection of biological and social subsystems that interact and are mutually affected by each other (Colding and Barthel 2019). Given the complexity of the interactions and outcomes, frameworks have been developed and widely applied to support better understanding of CPR challenges, and to improve communication among scientists and society (Basurto et al. 2013; Binder et al. 2013; Partelow 2018; Rica et al. 2018). Binder et al. (2013) compared ten frameworks and highlighted the capability of the social-ecological framework (SESF), also developed by Ostrom (McGinnis and Ostrom 2014), for equally analysing the social and the ecological system, for identifying variables of concern for resource governance and for supporting the construction of a database that could be used in further analyse.

A small alluvial aquifer in the Paraiba river basin has been investigated. It was one of the five study areas of the R&D BRAMAR Project - Strategies and Technologies for Mitigation of the Scarcity of Water Resources in the Northeast of Brazil (Abels et al. 2018), which supported along with its execution (2014-2019), the construction of a large database and development of scientific research. Alves et al. (2018) found it was overexploited, Salgado et al. (2018) identified high influence of wastewater on the water quality, and Silva (2016) applied multicriteria methods to analyse the use of water for irrigation. This aquifer underneath the Sucuru river is, therefore, used as a case of study for this work. In this context, this thesis investigates the governance of a river basin in the BSA with alluvial aquifers impacted by irrigation and wastewater. Our hypothesis is: community-based governance can support a more sustainable management of alluvial aquifers, considering the hydrogeological processes and the interconnection of biophysical and social systems, local arrangements and the water resources policy and management system. We seek to answer the following questions that arise from the preceding discussion: (1) can the existing governance arrangements support sustainable common pool resource management of the alluvial aquifers? (2) what opportunities are there to make the management of the aquifer more sustainable through community-based governance? (3) can appropriate governance principles lead the transition to more sustainable governance of alluvial aquifers?

This thesis comprises seven sections and resulted in a paper published in the Hydrogeology Journal, entitled “Governance of alluvial aquifers in the

Brazilian semi-arid region: a social-ecological systems analysis"[1]. This first section provides the relevance of the topic, the hypothesis, the questions to be investigated, and the thesis structure. In the second section, the objective of this work is indicated. The third section presents the literature review, which contains the main concepts and important information concerning the subject studied in this work. The literature review initiates with a general characterisation of alluvial aquifers in the BSA, followed by the main challenges for groundwater governance and, more specifically, in these small aquifers. With these governance issues in mind, concepts and methods of governance assessment are discussed. Finally, the regulation of water use in the BSA was synthesized, focusing on regulating alluvial aquifer exploitation. In the fourth section, an overview of the study area is presented, allowing for understanding the case representativeness for the hypothesis raised. In the fifth section, the methodology is described, as well as the supporting theory. This section includes the data gathering process, the application of the SES Framework and Ostrom's design principles, the analysis of strategies, and the development of a protocol for supporting water agencies on governing alluvial aquifers. The sixth section presents the results and discussions regarding the groundwater flow and governance analysis, and the aforementioned protocol. Finally, the seventh section brings the conclusions and recommendations.

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[1] The paper is available at: https://doi.org/10.1007/s10040-020-02160-8.

2. Aim and Objectives

The aim of this thesis is to establish protocol for the governance of small alluvial aquifers impacted by irrigation and wastewater in the Brazilian semi-arid region. This is achieved by accomplishing the following specific objectives:

- Develop a conceptual model of groundwater flow and exploitation for a small alluvial aquifer in the region;
- Analyse the alluvial aquifer governance within the perspective of social-ecological systems and common-pool resources;
- Identify challenges and opportunities for improving the governance of the alluvial aquifer;
- Propose a protocol for supporting governance of these aquifers based on such results.

3. Literature Review

3.1 Alluvial aquifers and the Brazilian semi-arid region

The alluvial aquifer is formed through the deposition of sediments that result from the decomposition of rocks and that are carried by the water flow. Therefore, they present a very variable lithology, which is usually mostly sandy. These deposits can result in aquifers of very different dimensions, from large regional aquifers to small ones that are formed along the riverbed of perennial and intermittent rivers.

The small aquifers can be found overlaying regional aquifers (Edmunds et al. 1992; Shentsis and Rosenthal 2003), or bedrocks (Burte et al. 2005; Walker et al. 2018). Under both of these conditions, there is a clear river-aquifer interaction that impacts the recharge of the aquifer. Besides the groundwater supply, the use of these riverbanks of perennial rivers for a process known as margin filtration has become widespread. The riverbank filtration process induces the recharge of the water from the river into the aquifer through the exploitation of wells along the margin of the rivers with the main purpose of improving water quality (Wang et al. 2016; Freitas et al. 2017).

The small alluvial aquifers along riverbed overlaying bedrocks have been mostly exploited for use in irrigation, livestock feeding and domestic supply (Al-Shaibani 2008; Taher et al. 2012; Braga 2016; Alves et al. 2018). The storage volume is limited and, consequently, the recharge is especially significant in terms of groundwater availability. These small aquifers have been mostly studied by the following terms: small alluvial aquifer, wadi, river sand and alluvial strip aquifer.

Frequently, such aquifers are not represented in the geological maps because of their small scale, so their delineation is more common in regional or local surveys. They can have varying dimensions, with some cross-sections as narrow as 30 meters wide, and others with widths that reach a few kilometres. Similarly, the depths found vary from centimetres to hundreds of meters, depending on the geology of the region.

Alluvium investigations are concentrated in arid and semi-arid regions, which demonstrates the need to seek alternative sources of water to coexist with drought and the complexity of water management challenges in these areas.

Motivated by these reasons, some initiatives were developed, such as: Alluvium and Cenozoic sediments; WADE - Floodwater Recharge of Alluvial Aquifers in Dryland Environments; Water of Sands Project - Recovery and shared management of water from alluvium in a dry riverbed in the Pernambuco semi-arid region; and BRAMAR Project - Strategies and Technologies for Mitigation of the Scarcity of Water Resources in the Northeast of Brazil.

The “Alluvium and Cenozoic sediments” Project was developed by the CPRM, Geological Survey of Brazil, within the Groundwater Program for the Northeast Region to carry out a preliminary assessment of the alluviums in the region. The project had the purpose of both obtaining and providing information about the alluvial aquifer yield and the likelihood of its use for domestic supply and small irrigation (CPRM 1998)

The WADE project, which was developed in cooperation with institutions and universities in six countries between 2004 and 2007 and funded by the European Union, carried out an assessment of water resources of ephemeral river basins in semi-arid and arid regions, quantifying water loss and alluvial aquifer recharge during flooding events. Based on four basins located in Spain, Israel, Namibia and South Africa, the improvement of recharge during flooding events was proposed as a sustainable strategy (WADE Project 2004)

The Project Water of Sands – Recovery and shared management of water from alluvium in dry riverbed in the Pernambuco semi-arid region (Braga 2016) was financed by Petrobras and aimed to promote water sustainability for rural communities in the Pernambuco semi-arid region. These aims are sought through environment recovery and management of the alluviums underneath intermittent rivers. The results report good experience in a case with the composition of a network for water sustainability toward the use of alluvial aquifers, with participation of community, non-governmental organizations, educational institutions and rural development municipal councils.

The BRAMAR project is an international cooperation project, involving 15 Brazilian institutions and seven German institutions, which focused on water reuse, managed aquifer recharge and integrated water resources management (Abels et al. 2018). Five representative case studies were identified in the Northeast semi-arid region of Brazil. The Sume case study area is one of them and refers to a river basin that needs appropriate strategies for the management of this source of water (Abels et al. 2018).

Due to the large body of research investigating the valleys of ephemeral rivers in arid regions in the north of Africa and in the Middle East the Arabic term "wadi", which refers to these areas, has become well known (Sorman and Abdulrazzak 1993; Bazuhair and Wood 1996; Al-Shaibani 2008). These investigations already point out the potential of recharge of the underlying alluvial aquifers during flooding events and their relevance as a water source. According to Walker et al. (2018) this type of formation found in the Middle East and South American Southwest is well characterized in the body of research carried out due to the large amount of resources invested and data collected and to the recognized importance of this geological feature. However, research regarding the sand rivers in Africa (the term used by the author, also common in the literature) is still limited in the peer-reviewed literature.

The Brazilian semi-arid region, which experiences low rainfall and high evapotranspiration, has predominantly a shallow bedrock. This region mostly has a lack of groundwater reserves, as it can be observed in Figure 1. As a consequence, the rivers are mostly intermittent, i.e. river flow occurs only seasonally. Considering this scenario, the small alluvial deposits formed over a crystalline substrate, despite their small size, are an important source of water resources. These have been increasingly exploited in the annual dry periods and even during drought occurrences, mainly for irrigation (Mackay et al. 2005; Burte et al. 2011; Rêgo 2012). It should be highlighted that in Brazil research into this aquifer have been mostly conducted in Ceará (Burte et al. 2005, 2009), Paraiba (Rêgo 2012; Alves et al. 2018) and Pernambuco (Mackay et al. 2005; Montenegro and Montenegro 2006; Braga 2016; Coelho et al. 2017). These works were developed with the purpose of proposing management strategies and technologies to better use this source, such as the construction of underground dams, design of a more productive well and managed aquifer recharge (Billib et al. 1991; Costa 1998; Rêgo et al. 2014; Cirilo et al. 2017).

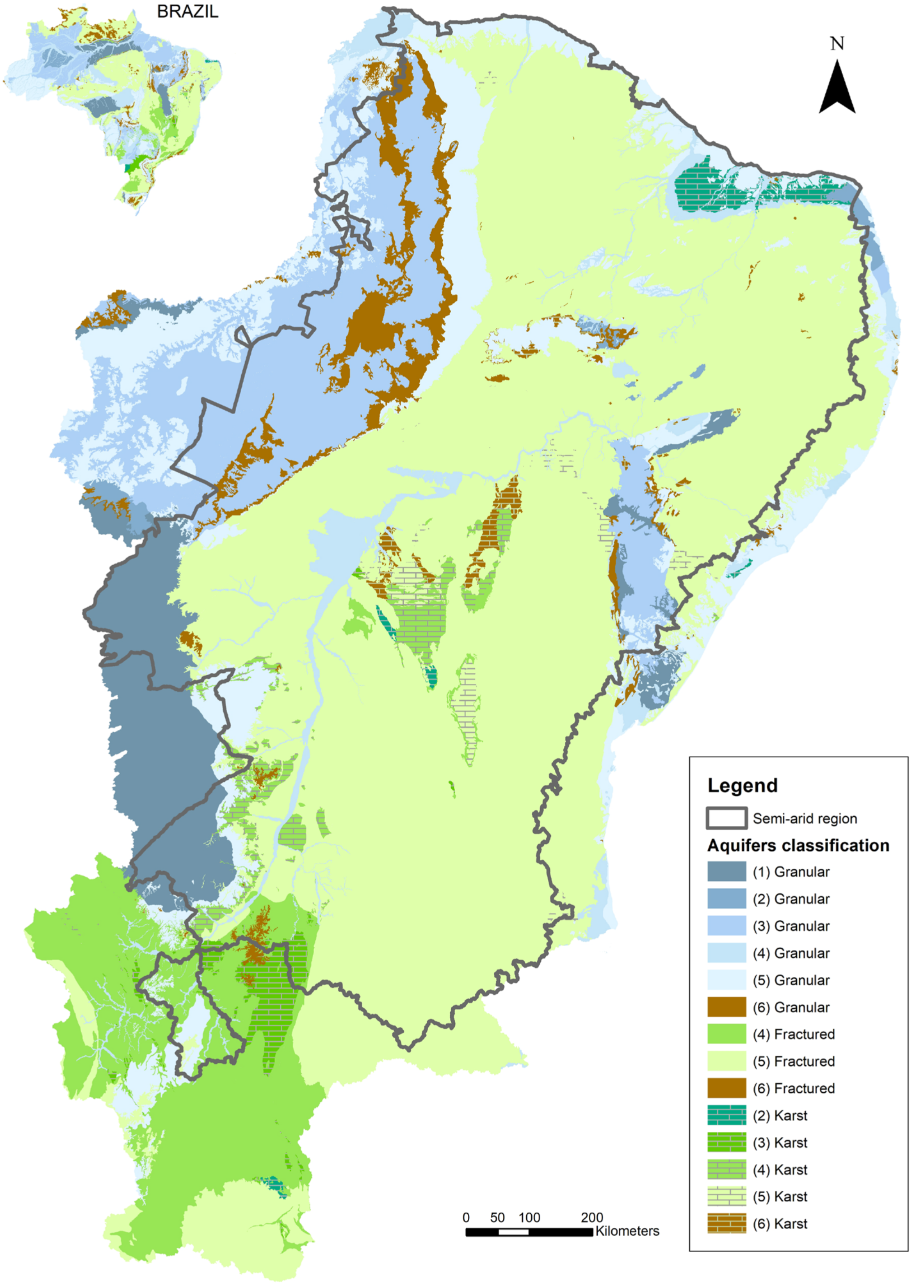


Figure 1: Drainage and hydrogeology of the river basins crossing the Brazilian semi-arid region (the numbers 1 to 6 indicate the productivity of the aquifer from very high to very low/non-aquiferous) - Data source: CPRM (2014)

Underground dams are structures used in alluvial aquifers throughout the BSA (Costa et al. 1998; Cirilo et al. 2017). A ditch is opened along a cross section of the river, the wall is covered with an impermeable material and then the ditch is filled back with the material removed. It is designed to retain groundwater and increase the efficiency of upstream well. Thousands of these dams have been constructed through government programs to support family farm and provide better conditions during drought occurrences, given their recognized efficiency.

The alluvial aquifer that is characteristic of the Brazilian semi-arid region (BSA), here referred to as “aquifer-type”, represents challenges that require field and scientific research, such as: (a) The small size of the aquifer with crystalline substrate, since it requires a more accurate analysis, when compared to the simulations made in regional aquifers, in which inaccuracies can be better compensated throughout their extension; (b) The intermittence of the hydrological regime, which add high complexity to the groundwater flow simulation within these conditions; (c) Anthropic interference, since the recharge is impacted, quantitative and quantitatively, by the infiltration of the sewage and the water used in irrigation; (d) The existence of few measurements in these alluviums, which limits comparative assessment of the data collected.

3.2 The recharge of alluvial aquifers

The aquifer recharge is defined by the volume of water from rainfall or streamflow infiltrating the subsoil, summing up to the water table. It can be classified, according to how it occurs in direct or indirect recharge. The first type results from the infiltration of a portion of the rainfall through the unsaturated zone, and represents the precipitation excess, subtracting the soil moisture deficit and evapotranspiration. The indirect recharge results from the infiltration of part of the streamflow volume over the riverbed, either as perennial or intermittent flow, with the latter occurring mostly in arid and semi-arid regions. The tendency is that the more arid the region, the greater the influence of indirect recharge (Simmers et al. 1997).

In arid and semi-arid regions, river intermittence is common, so streamflow occurs only during the rainy season and the recharge of alluvial aquifers is sporadic. (Sorman and Abdulrazzak 1993; Morin et al. 2009). Due to the size of the alluvial aquifer in the BSA, during these episodes, the aquifer can be almost fully recharged, and then used throughout the year(s).

In addition to natural recharge, the practice of managed aquifer recharge has been investigated by several authors and consists of intentional recharge of surface water in the aquifer for recovery, increase of aquifer yield or for environmental benefits (Dillon et al. 2010; Missimer et al. 2012; Shubo et al. 2020). This recharge can be performed using methods that are mainly classified in three different types; water spreading, well-injection techniques and modification of the channels (Kimrey 1989; Sprenger et al. 2017). Spreading techniques use a structure to create an accumulation of water over an area of unsaturated soil, while injection techniques introduce water directly into the aquifer or into the vadose zone. The modification of channels includes removal of impermeable superficial layers or deposition of sediments along the riverbed. The choice of method depends on both physical and social-economic aspects, and the water recharged can come from different sources, such as harvesting water systems, streamflow retention and treated sewage (Page et al. 2018).

The recharge of treated sewage involves a series of sanitary, technical and regulatory challenges to be analysed and overcome, and has grown due to its significant volume, especially in arid and semi-arid regions, where scarcity conditions are of great concern (Missimer et al. 2012, 2014; De Giglio et al. 2018). Yuan et al. (2017) analysed regulation concerning managed aquifer recharge worldwide and observed secondary treatment as secondary treatment with further requirements such as distance to protection zones and setback distances and hydraulic loading rates. The soil-aquifer treatment (SAT) is a technique that improve water quality through filtration in porous media, due to the retention of impurities on the surface or/and their adherence to the grains of soil (Missimer et al. 2012). Due to a shallow vadose zone in the case of the *aquifer-type*, the potential of this technique is limited and require further investigation to be used (Walter et al. 2018), but Salgado et al., 2018 and Pontes Filho (2018) have provided positive evidence.

The flow of domestic sewage, even from small and medium cities, is especially relevant in ephemeral/ intermittent rivers as they compose a significant portion of aquifer recharge (Foster and Chilton 2004; Mostaza-Colado et al. 2018; Salgado et al. 2018). It guarantees a continuous recharge throughout the year, different from the recharge from rainfall, which is sporadic and temporarily concentrated. However, sewage infiltration, which results in subsequent reuse, usually occurs in an unplanned manner, and is often disregarded (Foster and Chilton 2004). For this reason, it is characterized as an unmanaged artificial recharge. Due to the location and size of alluvial aquifers, they are even more susceptible to contamination by sewage released onto rivers or dry riverbeds without proper treatment, which is common in developing countries.

Likewise, the groundwater quality can be compromised by the land use along the alluvium, causing problems such as the water and soil salinization. Water salinity of groundwater from the aquifer-type have been investigated to recognize the causes and propose alternatives for mitigation (Mackay et al. 2005; Burte et al. 2009, 2011; Fontes Júnior and Montenegro 2017). These works have indicated that the overexploitation of the aquifer and the excessive crop production are the main anthropic factors that influence this salinization.

Mostaza-Colado et al. (2018) recognize the growing impacts of agricultural and urban activities on an alluvial aquifer in the south-eastern region of Madrid. Based on hydrogeochemical analyses, it was observed that influence of rocks weathering, agriculture and wastewater discharge are predominant over rainfall fresh water recharged, as dilution hasn’t been observed. This investigation is pointed out as a baseline, because it allows decision makers to assess the impacts of future changes.

3.3 Groundwater governance

Water scarcity, which can be defined as the imbalance between the water supply capacity and the demands for meeting ecosystems’ and peoples’ needs in a given area, is a global concern affecting environment/livelihood/development conditions on different spatial and temporal scales (Rijsberman 2006; UNDP 2013). It is a problem faced by 4 billion people in the world at least one month of the year (Mekonnen and Hoekstra 2016), and is exacerbated by population growth and climate change. Climate change impacts have been projected (Howard 2015; Huang et al. 2016; Spinoni et al. 2018) and are expected to be a “poverty multiplier”, with impacts on agriculture being one of the main “drivers to force millions of people into extreme poverty” (Hoegh-Guldberg et al. 2018). Still, recent research has highlighted that water scarcity in many areas is much more a water governance issue, than a biophysical one (Pahl-Wostl and Kranz 2010; OECD 2011; Silva et al. 2015), focusing the attention of the scientific community and decision makers on analysing how to improve governance of water systems (Baldwin et al. 2012; Tan et al. 2012; Durán-Sánchez et al. 2019).

The Integrated Management of Water Resources aims to match demand and supply of water in a river basin, promote sustainability and avoid conflicts among users. Bottom-up approaches have been widely recommended in the management of water resources, by involving stakeholders in the discussions and decisions (UNESCO 2005). This is important due to the need of strategies and legislation adapted to local aspects in order to improve the efficiency and effectivity of projects/water schemes (Loucks et al. 2005; van Koppen et al. 2012). According to Rogers et al. (2003), governance is an even broader concept: it "encompasses laws, regulations, and institutions but it also relates to government policies and actions, to domestic activities, and to networks of influence". Assessing water governance is essential for its effective implementation, as it may indicate the need of changes and the achievement of the goals established in the plans (UNDP 2013).

Effective governance is the key to assure sustainability of natural resources and management institutions (Dietz et al. 2003). The term sustainability has been used in very different contexts, and one of the most known definitions was provided in the report of the World Commission on Environment and Development, associating the concept of sustainable development as means to meet the “needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). Following this discussion, the 2030 Agenda for Sustainable Development came up with 17 goals which encompass 169 targets to protect the planet and guarantee peace and prosperity for all people (UN OWG 2014). According to Rêgo et al. (2021), appropriate governance of the alluvial aquifer significantly contributes to meet six goals: End hunger, achieve food security and improved nutrition and promote sustainable agriculture (Goal 2); Ensure availability and sustainable management of water and sanitation for all (Goal 6); Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (Goal 9); Ensure sustainable consumption and production patterns (Goal 12); Take urgent action to combat climate change and its impacts (Goal 13); Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (Goal 15).

Systems that are dependent on groundwater face particular governance challenges (López-Corona et al. 2013; Kumar et al. 2018; Bhattacharjee et al. 2019). There is limited knowledge of these groundwater resources and their systems among both the scientific community and stakeholders due to their hidden nature, recent higher exploration and costly monitoring/assessment. This has created a critical barrier for developing their proper management. With increasing use, groundwater has become a main source of water in this past century, representing approximately 1/3 of water consumed in the world (UNEP 2019) and the imbalance between water extraction and aquifer recharge has been causing aquifer depletion (Wada et al. 2010).

Kulkarni et al. (2015) highlight the complexity of groundwater management, as there is a significant difference among the processes of groundwater accumulation and movement according to the geological settings. The authors claim that rather than infrastructure solutions, a groundwater governance framework established based on interdisciplinary science, participatory processes and regulation development is preferable.

The small scale of the *aquifer-type* is a complicating aspect for the management of this resource, which results in lack of its regulation/governance at higher governance levels. While a considerable body of research has investigated strategies for the management of such aquifers (Burte et al. 2005, 2009; Montenegro and Montenegro 2012; Rêgo et al. 2014; Alves et al. 2018), the governance analysis of their regulation and of stakeholders' role/interaction is still scarce.

The limits for sustainable groundwater exploitation have been investigated through the analysis of hydrological simulations under different scenarios, considering aspects such as the rates of natural recharge of the aquifer, the possibility of induced recharge, and climate changes (Zhou 2009). Özerol et al. (2018) performed a comparative analysis of water governance studies, and concluded that "addressing the issues of justice, equity, and power" is one of the four main areas to be investigated in future research.

It should be highlighted, however, that the concept of sustainable exploitation of the *aquifer-type* has differences from the regional aquifers, as it can be almost fully depleted and recharged annually. For these aquifers, concerns regarding equitability, efficiency and optimization of its exploitation and recharge, as well as regarding water quality issues, have been raised and require attention (Burte et al. 2005, 2009; Rêgo 2012; Andrade et al. 2014; Cavalcanti 2015; Cirilo et al. 2017; Alves et al. 2018).

Rêgo (2012) applied groundwater modeling to propose scenarios for exploiting an alluvial aquifer in the Piranhas-Açu river basin in Paraiba state. Based on that, the author demonstrated that the location of wells and pumping management (considering closing some of the wells temporarily) directly affects the groundwater availability over the dry season.

Burte (2008) characterized an alluvial aquifer of the Brazilian semi-arid region (BSA) and analyzed different strategies to better harness the aquifer resource using groundwater modelling. The construction of underground dams and the release of water from a surface reservoir to recharge the aquifer were some of the strategies simulated. Analysing the management aspects of the case study in the context of family farming and public policies, the author emphasized the lack of interaction at the local level.

Cavalcanti (2015) indicated the importance of exploiting alluvial aquifers to the rural communities given the climate variability in the Brazilian semiarid region, using a case study in the Capibaribe river basin in Pernambuco state. She registered the community’s observation of a reduction in groundwater availability after the 1970s, associated with an increase in exploitation, vegetation removal, sand extraction, and changes in flood events. Braga (2016) highlight the need for community participation in the management of the alluvial aquifers in the semi-arid region of Pernambuco, and the importance of the local municipal councils.

3.4 Governance analysis: common pool resources and social-ecological systems

In order to deal with the variety of challenges of governance and to promote the systems resilience, institutions and arrangements should be designed to allow changes for adaptation to better face the impacts (Dietz et al. 2003). These authors are known for introducing the term “adaptive governance” in science. This has been broadly arisen over attempt to reach a more desirable state of systems governance and/or as response to disturbances that the systems are subjected to (Chaffin et al. 2014; Huntjens 2012).

A concept that has been commonly connected to the adaptive capacity is "polycentric governance". Ostrom (2001) defines polycentric systems as "the organization of small-, medium-, and large-scale democratic units that each may exercise considerable independence to make and enforce rules within a circumscribed scope of authority for a specified geographical area". Scholars have been argued that polycentric governance improve the likelihood of institutions and stakeholders adapting to new circumstances, as communities can have a voice within decision jointly with institutions at different levels and scales of governance (Folke et al. 2005; Pahl-Wostl et al. 2012).

Linking the concepts of scale and governance is necessary to deal with the impacts on social-ecological systems, as they are nested throughout different spatial and temporal scales (Kok and Veldkamp 2011). This need is illustrated by the observation that framing a phenomenon in different scales can influence decision making and provide insights for improving governance of natural resources (Newig and Moss 2017).

In this context, frameworks and principles for governance of natural resources have been developed in order to improve assessment and address innovative solutions and participatory process. As an example, we have the OECD principles for water governance. The Organization for Economic Cooperation and Development (OECD), which is composed of 36 countries to coordinate policies and solve common problems, has analysed governance failures. Aiming to identify what aspects are hindering the formulation and implementation of water policies, OECD suggested a set of responses and best practices to overcome them. Based on this, 12 OECD principles for water governance have been developed to support the assessment of governance systems functioning and indicate areas for improvement (UNDP 2013). Similarly, Lockwood et al. (2010) proposed eight governance principles for natural resources management that can support the design of institutions and governance monitoring and evaluation.

Analyses of natural resources under the perspective of common pool resources are intensively developed. The common pool resource (CPR) is described by Gardner et al. (1990) as a "resource system, whose size or characteristics makes it costly, but not impossible, to exclude potential beneficiaries from obtaining benefits from its use". The definition of groundwater as a common pool resource is well established (Nibbering 1997; Ostrom 2008; López-Corona et al. 2013; Langridge and Ansell 2018). Groundwater fits this definition because it does not match administrative boundaries, is very difficult to monitor, and can be extracted from many different points, hence making it difficult to exclude beneficiaries from accessing it. Different approaches have been applied in the analysis of the commons, such as game theory, statistical analysis and modelling (Esteban and Dinar 2013).

Ostrom developed eight core design principles for governing the common pool resources (Ostrom 1990). The principles were derived from empirical evidence, by observing diverse cases of sustainable and unsustainable common pool resources exploration. She evaluated what characteristics were present in successful cases of governance and lacking in cases that were following the path of the resource depletion (Gardner et al. 1990). Previously, Hardin (1968) had foreseen the tragedy of the commons (i.e. the depletion of the resource as a result of a selfish behaviour of users). Then, government interference, on one extreme, or privatization, on the other, have been pointed out as ways to avoid depletion. However, Basurto et al. (2013) emphasize that no panacea would solve this, neither we should treat each case without looking to others' experiences. Thus, Ostrom applied the IAD framework to evaluate several cases and presented a set of factors that can influence positively communities' behaviour in favour of mutual cooperation, and of the resources sustainability (Ostrom 1990). The principles, which describe these factors, are the following:

1. Clearly defined boundaries;
2. Congruence between appropriation and provision rules and local conditions;
3. Collective-choice arrangements;
4. Monitoring;
5. Graduated sanctions;
6. Conflict-resolution mechanisms;
7. Minimal recognition of rights to organize;
8. Nested enterprises.

Molle and Closas (2019) listed among the main issues for groundwater state regulation the scarce information concerning water availability, lack of political will, corruption, and difficulties at monitoring and enforcement. The authors identified stories from different countries where the state succeeded in governing groundwater at some aspects. They call attention to the fact that frequently the state power over groundwater use is overstated, while the establishment of strict official rules is far from being the solution to guarantee control.

Seward and Xu (2018) analysed groundwater governance in South Africa using Ostrom’s design principles and compared the use of these principles with other approach – the 20 benchamarking criteria defined by Foster et al. (2009) - for such assessment. The authors found the approaches to be compatible and complementary. Moreover, they provided support to understand the principles in the context of groundwater and encouraged the adoption of principles to improve governance in the country. Molle and Closas (2019b) investigated whether groundwater's comanagement (involving users and state) might be the solution to deal with all the challenges imposed. The authors point out Ostrom's work as a pioneer in the literature that subsidies the concepts of collective action and collaborative governance. Despite the low number of successful cases to support identifying influencing factors, they indicated the importance of the state legitimacy, the users’ authority to make decisions, and the balance of state rewarding/punishing users’ actions.

In Yemen, where groundwater depletion has occurred, local initiatives have arisen on groundwater management, including in wadis, and measures such as wells spacing and limiting aquifer depth were part of the decisions and commitments settled within communities (Taher et al. 2012). Steenbergen (2006) analysed a number of cases where local initiatives had significant results on restricting groundwater use in India, Pakistan, Egypt, and Yemen. The author registered the success of programs for promoting local groundwater management and how some communities followed the rules collectively defined concerning the number and depth of wells, crop choices, and water distribution.

Cavalcanti (2015) analyzed an experience of sharing a well that supplies a group of users for domestic use and livestock feeding, whereby they shared tasks and costs of maintenance. She observed benefits to all of them through collective action (e.g., improvement in access to water, multiple water uses awareness, accomplishment of tasks) and fragilities in the agreements set (e.g. different impressions regarding water rights).

Thereafter, in a later work, Ostrom also proposed a framework, so called SES framework (SESF), which has been further developed, with the aim of going beyond panaceas and of finding out arrangements capable of solving complex governance problems to avoid the resource extinction due to its overuse (Ostrom 2007, 2009; Ostrom and Cox 2010; McGinnis and Ostrom 2014). The SESF is "a multi-tiered approach" that allows proper examination of the social-ecological systems. Basurto et al. (2013) summarizes the primary components of the SES Framework (Figure 2):

> "The point of entry to the SES framework begins with the first tier variables that a researcher would need to define to determine the particular focal CPR system of interest (table 2): The Resource Units (RU) are part of the Resource Systems (RS), the Governance Systems (GS) define and set rules for Actors (A). All of them influence the resultant Interactions (I) and Outcomes (O) and create feedbacks. These variables (also conceptualized as processes) make up the focal CPR system that links to exogenous factors like other Related Ecosystems (ECO) and Social, Economic, and Political Settings (S)."

Each first-tier variable is characterized by second-tier variables (Table 1). The list has been defined, improved and exemplified, as the framework has been intensively applied (Ostrom 2009; Hinkel et al. 2014; McGinnis and Ostrom 2014; Partelow 2018; Hudson et al. 2019). Ostrom (2007; 2009) demonstrates de influence of several of these factors to the sustainability of the systems and the likelihood of self-organization of the regimes. It is important to highlight that depending on the SES assessed, some of these variables are not relevant and only some are considered in the analysis. Water management is one of the main research areas that has been applying and adapting the SES Framework for the SES characterisation at different levels (Delgado-Serrano and Ramos 2015; Silva et al. 2015; Falk et al. 2016; Taggart-Hodge and Schoon 2016; Colding and Barthel 2019).

Partelow (2018) reviewed 92 papers applying the SES Framework in different areas of research. According to various criteria, these works were disentangled, such as the type of analysis, area of research, and studied variables. An extended table containing indicators of the second-tier variables was presented. Thus, he discussed the SESF development and adaption to suit distinct purposes, allow comparison, and build theory.

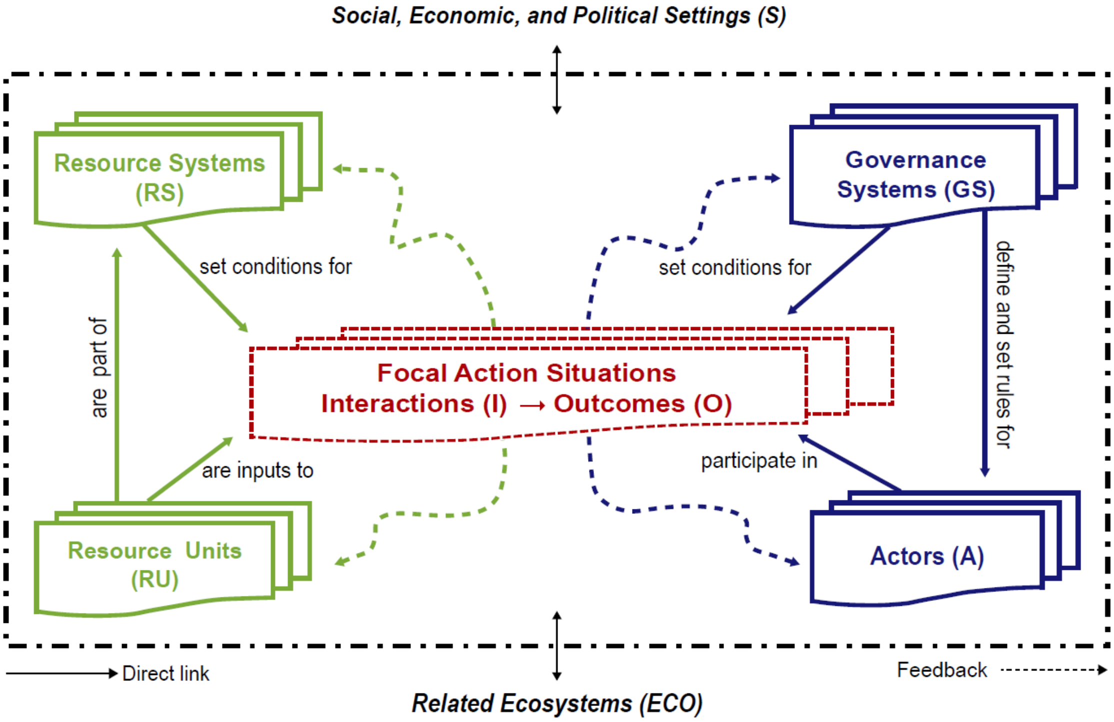


Figure 2: The core subsystems in a framework for analysing social-ecological systems (McGinnis and Ostrom 2014)

Table 1: The first- and second-tier variables of the Social-ecological system framework (McGinnis and Ostrom, 2014)

The first-tier variables	The second-tier variables
Social, economic and political settings (S)	S1 Economic Development
	S2 Demographic trends
	S3 Political stability
	S4 Other governance systems
	S5 Markets
	S6 Media organizations
	S7 Technology
The first-tier variables	The second-tier variables
Resource Systems (RS)	RS1 Sector
	RS2 Clarity of system boundaries
	RS3 Size of resource system
	RS4 Human constructed facilities
	RS5 Productivity of system dynamics
	RS6 Equilibrium properties
	RS7 Predictability of system dynamics
	RS8 Storage characteristics
	RS9 Location

The first-tier variables	The second-tier variables
Governance systems (GS)	GS1 Government organizations GS2 Nongovernment organizations GS3 Network structure GS4 Property-rights systems GS5 Operational-choice rules GS6 Collective-choice rules GS7 Constitutional-choice rules GS8 Monitoring and sanctioning rules
Resource units (RU)	RU1 Resource unit mobility RU2 Growth or replacement rate RU3 Interaction among resource units RU4 Economic value RU5 Number of units RU6 Distinctive characteristics RU7 Spatial and temporal distribution
Actors (A)	A1 Number of relevant actors A2 Socioeconomic attributes A3 History or past experiences A4 Location A5 Leadership/entrepreneurship A6 Norms (trust-reciprocity)/social capital A7 Knowledge of SES/mental models A8 Importance of resource (dependence) A9 Technologies available
Action situations: Interactions (I)	I1 Harvesting I2 Information sharing I3 Deliberation processes I4 Conflicts I5 Investment activities I6 Lobbying activities I7 Self-organizing activities I8 Networking activities I9 Monitoring activities I10 Evaluative activities
Action situations: Outcomes (O)	O1 Social performance measures O2 Ecological performance measures O3 Externalities to other SESs
Related Ecosystems (ECO)	ECO1 Climate patterns ECO2 Pollution patterns ECO3 Flows into and out of focal SES

3.5 Water use regulation in the BSA

3.5.1 Brazilian water resources management framework

The governance context of water is defined at the national level by the principles and instruments in the Brazilian Water Law 9433/1997 (Brasil 1997), a turning point for water resources management in the country. This Law establishes the National Water Resources Policy (PNRH) and creates the National Water Resources Management System (SINGREH). The principles, in synthesis, establish that water is a public good with economic value, the priority of use is human consumption and water management should promote multiple uses through a participatory process.

A proper governance should be accomplished by applying 5 instruments: water plans, which address the main programs and actions over water use in three different scales (National, State and River basin); water permits, to provide users with the right for using a defined amount of water for limited period of time, assuring control of water use, the exercise of water rights and the multiple use; a classification system of water bodies according to their water quality to assure compatibility with their kinds of use and prevent pollution; bulk water fees to charge for the water use recognizing its value, promoting rational use and gathering resources to finance plans execution; and water information system to gather, treat and disseminate data and information about Brazilian water resources, water availability and demands, and provide support for the water resources plan.

The Brazilian Constitution (Brasil 1988) treats water as a public good, and as a result, divides the surface water dominion between State and Federal Government according to the basin they are affluent and the territory the basin crosses. If the basin is fully located in only one State, its rivers are under State's dominion, otherwise, they are under Federal's. One exception occurs for surface reservoir constructed by the federal government that, regardless of which basin it is part of, is federal's dominion. In the case of groundwater, it is always under the State's domain, regardless. The dominions settings define in which sphere of the governing institutions the decisions are going to be made.

The National Water Resource Management System, which is presented in the Figure 3, is composed of collegiate bodies, responsible for policy formulation in conjunction with Secretariats for Water Resources (Executive Power), and water agencies that work on the implementation of management Instruments, acting on National, State and/or River basin levels. The National and State Water Resources Councils and the River Basin Committees are the collegiate organisations, with the latter being the main arena for Water Resources Management discussion between stakeholders, having representation from Government, users and civil society. The national executive power for policy formulation was previously located at the Ministry of Environment, but from December 2018, it is at the Ministry of Regional Development.

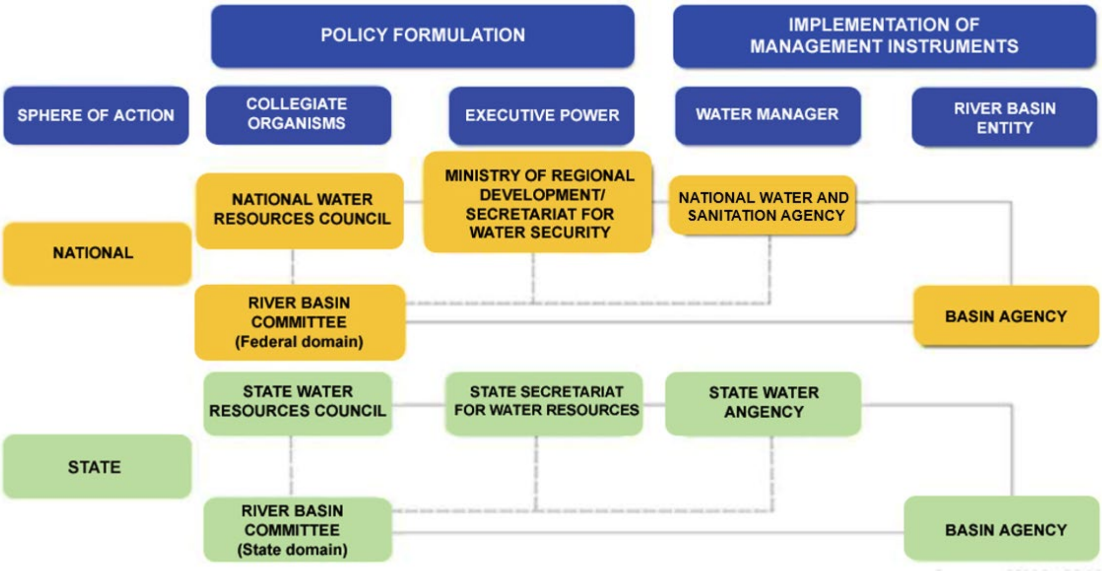


Figure 3: Brazilian Water Resource Management System in Brazil (Adapted from Ribeiro 2017)

There is a legislation body regulating the instruments of the PNRH defined by water agencies, water resources councils, environmental council, among other organizations. We can highlight some documents defining guidelines concerning groundwater, such as: Resolution CNRH 22/2002 for inclusion of groundwater in the water plans; Resolution CONAMA 396/2008 for classification of groundwater bodies; Resolution CNRH 107/2010 for groundwater network monitoring; and Resolution CNRH 202/2018 for integrated management of surface water and groundwater.

The classification is a goal for water quality of water bodies and the classes/criteria are specified in the resolutions CONAMA 357/2005 and 396/2008, for surface water and groundwater, respectively. The guidelines for such classification are described in resolution CNRH 91/2008. Concerning surface water, freshwater water is divided into five classes: class 1 encompasses the most restrictive uses, and class 5 the least restrictive ones. Groundwater is similarly divided into 6 classes.

After two decades of the SINGREH model, difficulties on decentralization of power have resulted in frequent lack of response attitude from water institutions and aggravated water crisis scenarios (Libanio 2018; Neto et al. 2018). According to Ribeiro (2017), financial issues hindering better water governance at the state level and difficulties on the coordination across scales are factors that limit the implementation of the Brazilian water resource policy. Regarding the BSA, all the nine states that are part of the region, have their Water Resources Plans, as in the Maranhão state the water resources council has recently approved the plan (ANA 2018; SEMA 2020). Furthermore, 51 State river basins committees and 4 national river basin committees were created in the BSA. These numbers may indicate an awareness regarding the need of water management, but they are not enough to draw conclusions of its implementation, as problems and challenges have been identified by research developed in the region (Araújo et al. 2012; Ribeiro et al. 2012; Silva 2014; Silva et al. 2017) .

3.5.2 Water resources management in the Paraiba state

The institutional water system in the Paraiba state is presented in Figure 4. AESA is the state water manager and works under the State Secretariat for Infrastructure, environment and water resources. There are four committees in the state, including the committee for the Paraiba River Basin, where the study area is located. As there is no river basin agency for the state river basin committees, AESA has been the only responsible state entity for the implementation of the instruments.

The Paraiba state water policy defines instruments for its execution and management (Paraiba 1996). The execution instruments are the water resources management and planning Integrated system, the water resources state plan, and the intergovernmental plans and programs. The management instruments are the water permits and the bulk water charge.

The Paraiba state water resource plan dates from 2006 and has been under revision process. Several meetings open to public participation have been occurring to inform the citizens and conduct public consultation. The water resources plan of the Paraiba river basin plan dates from 2001.

Concerning the water permits in the state, AESA registry accounts for approximately 5,300 licenses for different water sources (rivers, lakes, reservoirs and wells) and purposes (such as urban and rural water supply, irrigation, aquiculture, wastewater disposal, mining). Despite efforts on capacitation of water agencies and campaigns for regulation of water use, it is known that a large number of users has no license for water use.

The collective water permit is a different approach for performing concession of water rights, other than the regular individual water permits. Although there is no specification concerning its concept and use in the legislation that regulates water permits, it has been spread out as a form to improve water management (ANA 2011, 2013; Secretaria dos Recursos Hídricos do Estado do Ceará 2017). According to these documents, the term covers the following forms of water rights concession to a group of users, among others, if appropriate:

- The water act defining several individual water permits, as result of a campaign for water use regularization, such as during drought events;
- The water act defining a maximum extraction for a group of users, as result of water allocation negotiations, with percentages for each user;
- The concession of water rights provided to an users' association to supply them.

The bulk water charge is implemented in the state and is regulated by the Decree 33613/2012 (Paraíba 2012). This defines the criteria that AESA is responsible for collecting the taxes, which are the source for the State Water Resources Fund (Paraíba 2007). Such financial resource should be applied according to the river basin where it is collected.

There is no definition of the classification of water bodies according to water quality as an instrument of the state policy. However, this classification is mentioned in the policy: its approval as part of the water council duties, its proposal to be part of the water resources plan and an information to be evaluated for bulk water charge. The classes of water bodies under state dominion in Paraiba were defined in 1988 (SUDEMA 1988), with rivers classified into classes 1, 2 and 3, but mostly 2. Furthermore, there is no classification for groundwater in the state.

Since 2015, water allocation meetings have been organized by the National Water and Sanitation Agency for cases in which the water systems have faced problems with water availability. The meetings were performed by reservoir, and aims to define short-term and long-term plans for allocation of water based on participatory process. In the Paraiba state, they have been developed for nine reservoirs located in the Paraiba river basin and in the Piranhas-Açu river basin. In 2019 and 2020, meetings to negotiate water allocation for the Sume reservoir have been developed. In these meetings the allocation of water for irrigation has been one of the main concerns, considering the current exploitation of the alluvial aquifer (ANA 2020a)

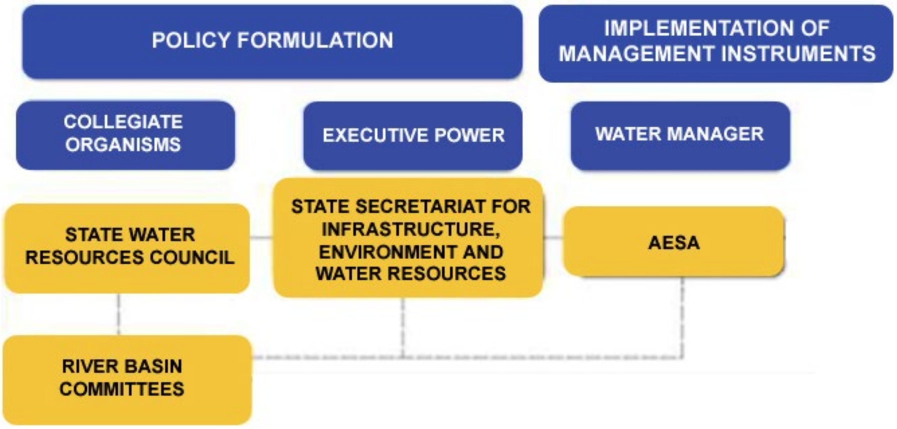


Figure 4: Institutional water system of the Paraiba state

3.5.3 Regulation concerning alluvial aquifer exploitation in the BSA

The concession of rights to groundwater is the responsibility of the states (Brasil 1988), and the investigation of this instrument among water resources legislation in the BSA shows that some States have established criteria for groundwater permits. In general, these criteria refer to the production test of the wells or recharge capacity of the aquifer. The criteria adopted in the Alagoas State law (Alagoas 2016), which defines aquifer exploitable rates, interference in neighboring wells and aquifer recharge capacity, consider important aspects for the *aquifer-type*, due to its emptying/recharging in a short period of time and high interference of wells extraction on other ones. Some states have general criteria, as the definition of insignificant uses, for which water permits are exempted. It should be highlighted, however, that regardless of the exemption of water permits, all wells should be part of the water users' registry, in order to keep control of the extractions. In the most part of the states of the semi-arid region, as the case of the Paraiba State, the insignificant uses are established as around 2m^3/h, which can sum up a high extraction for alluvial aquifers in a day (48 m^3/d), especially with the proximity of wells.

In Pernambuco, the extraction of sand from the riverbanks raised concerns, as it has been threatening the water reserve of the alluviums. This led the State agency (APAC) responsible for water permits to determine through a resolution the procedures to regulate and control such extraction (APAC 2013). Also, in the Paraiba River Basin, the irregular extraction of sand has been discussed in meetings of the river basin committees, as it was observed throughout its low region. As a result, responsible agencies (state environment and water agency) have been required to take action.

Regarding planning aspects on the river basin scale, water plans should present the water budget considering water demands and availability, as also priorities for water rights. The Paraiba River basin plan has no specific guideline or program for management of alluvial aquifers. Some state water plans in the semi-arid contain information regarding alluvial aquifers (water availability and uses) and/or guidelines for water permits limits, as the cases of Paraiba and Pernambuco states (Pernambuco 1998; Paraíba 2006). The Paraiba state water resources plan (PERH) has taken into consideration alluvial aquifer characteristics in the definition of exploitable reserves.

For groundwater management purpose, the Paraiba PERH divides the groundwater into “water potential” and “water reserve”, adopting the following concepts: the groundwater potential is the average annual base flow, or the volume of water that the aquifer retrieve to the rivers, and the other part that under natural condition is permanent, is so called water reserve. For the regional aquifer, the plan defines the maximum groundwater exploitable volume as 60% of the aquifer potential. But for the specific case of the alluvial aquifer, due to its hydrogeological characteristics that make it easier to be recharged, it is allowed to explore the entire potential as also the reserve volume. While the Paraiba state water plan determines the exploitation limit as 1/3 of the reserve volume (Paraíba 2006), some authors consider using the whole reserve or the discharge exploitation that still allows flow to downstream (Vieira 2002; Alves et al. 2018). These limits can vary according to the management choice, and the more adequate solution can be different according to the existent specific conditions, considering the watershed and local analysis.

According to the water law, the wastewater release into the rivers should be controlled through the water permits and through the classification system of water bodies according to water quality. Oliveira et al. (2010) discussed the influence of intermittency, salinity and local aspects over the selection of parameters for monitoring river water quality and defining water bodies classes in the Brazilian semi-arid region. Moreover, the river intermittency is a complicating aspect of wastewater dilution in the BSA, which increases alluvial aquifers vulnerability and require specific solutions, such as a more efficient wastewater treatment or water reuse (ANA 2017). For instance, Pessoa et al. (2015) analysed the effects of centralized and decentralized actions to reduce inflowing pollutant loads in an intermittent river in the state of Bahia. The water reuse is, therefore, even more important in this context. The National Water and Sanitation Agency (ANA) and the national water resources council (CNRH) elaborated specific resolutions for addressing wastewater disposal onto ephemeral riverbeds, in which minimum treatment requirements are specified (CNRH 2012; ANA 2016).

4. Case study area

The case study area is located in the Sucuru River Basin, in the semi-arid region of the Alto Paraiba River Basin (Figure 5). The average annual rainfall is about 600 mm, and is characterized by two distinct seasons: the rainy season, lasting 3 to 4 months, which occurs in the first half of the year, and the dry season for most of the year. The average potential evapotranspiration of the region is 2000 mm / year (Vieira 2002). As the BSA region is mostly underlain by crystalline rocks, the small and shallow alluvial aquifers, that are common throughout the region, are a strategic source of water, especially for smallholder farmers' use in irrigation and livestock feeding (Burte et al. 2009; Alves et al. 2018).

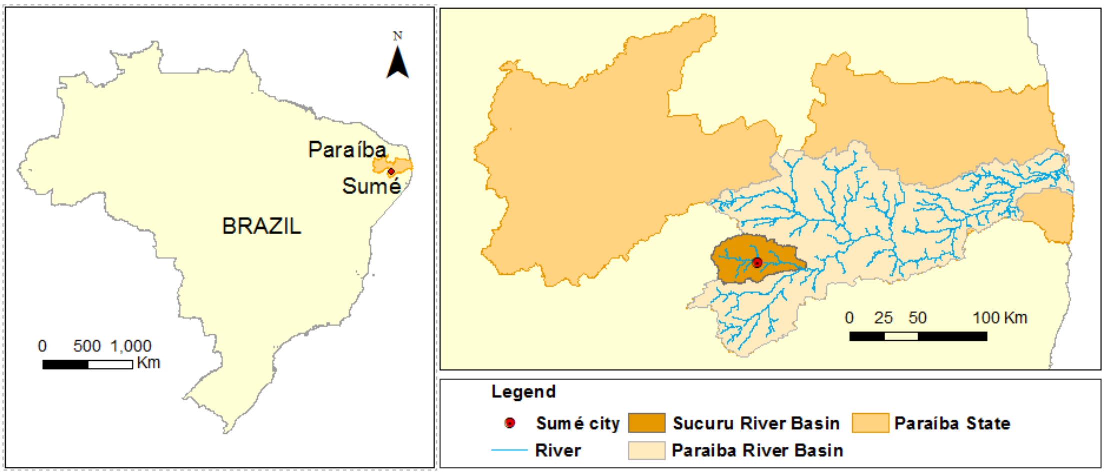


Figure 5: Location map of the study area

For research purposes, the Sucuru river basin was divided in three regions (Figure 6): i) region 1, in which the flow is controlled by the Sume reservoir outlet; ii) region 2, which effectively contributes to recharge the portion of the alluvium exploited by farmers of an "Irrigated Perimeter"; iii) region 3, which is subject to a lower anthropic impact. In this thesis, analysis focus mainly in the second region of the basin, for which a robust database has been constructed through the BRAMAR Project.

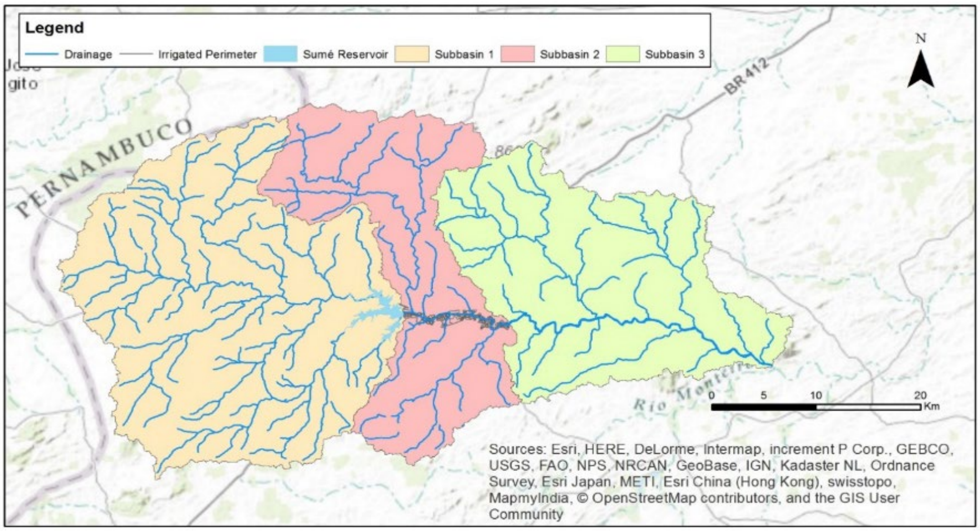


Figure 6: Sucuru River Basin and its sub-basins delimited for research purpose

The Sume case study is analysed as representative of a water system in a semiarid region comprising an alluvial aquifer located downstream of a surface reservoir and a city that empties its sewage into the riverbed, recharging the alluvium. The area has been the focus of a research collaboration at the R&D Project BRAMAR - Strategies and Technologies for Water Scarcity Mitigation in Northeast of Brazil: Water Reuse, Managed Aquifer Recharge and Integrated Water Resources Management", as one of the four representative case studies (Abels et al. 2018). The aim of the research is to help create better management of the groundwater system to support coexistence with the semi-arid climate. Understanding the current governance system and investigating alternative governance arrangement is an important aspect of this.

We focus in the the area of the Irrigated Perimeter of Sume (IP), which is a collection of farms on the Sucuru River, Paraiba River Basin and now rely heavily on groundwater extraction from the alluvial aquifer underneath (Figure 7). The irrigated perimeter (IP) was installed in the 1970s as part of Brazilian policy for the semi-arid region with the purpose of providing improved conditions for the rural population.

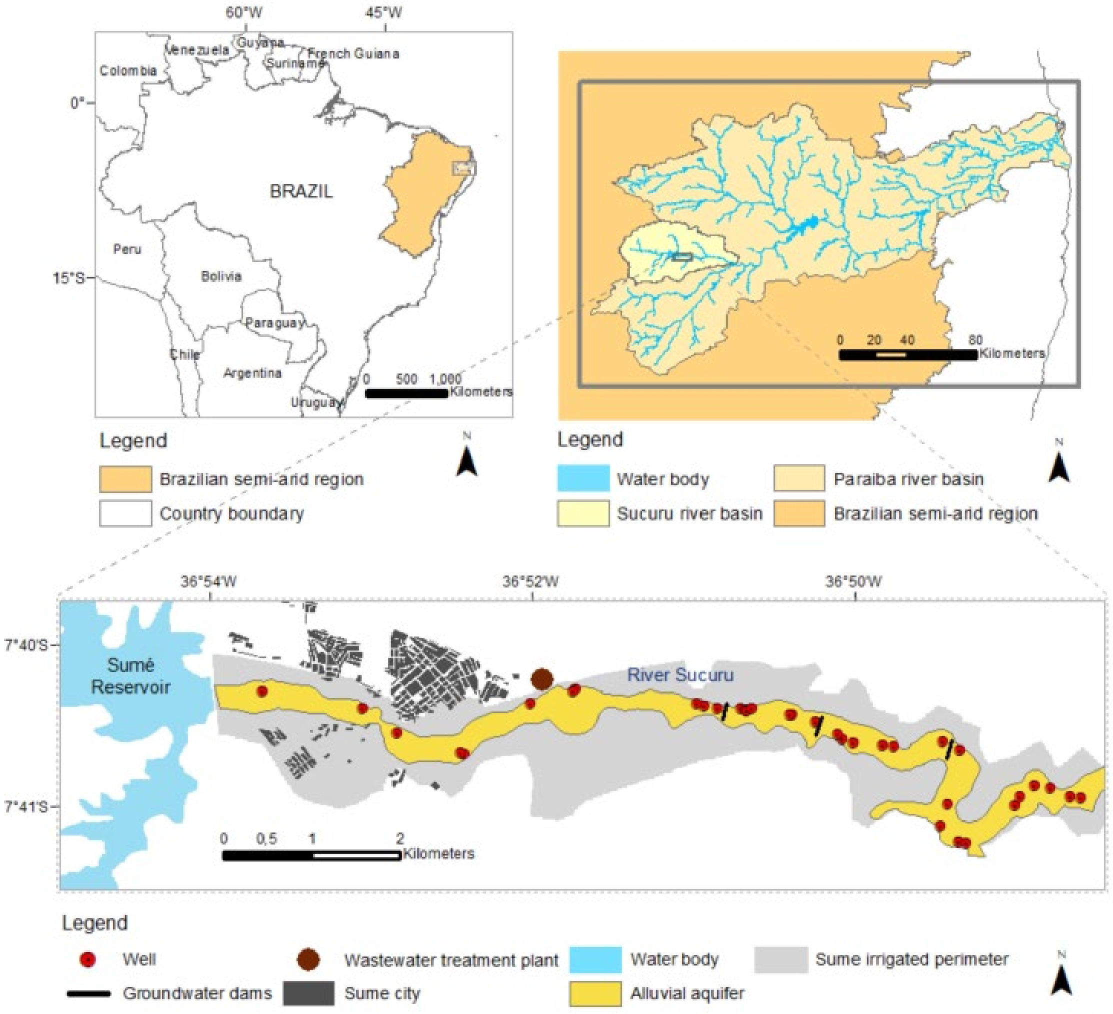


Figure 7: Study area (Adapted from Tsuyuguchi et al. 2020)

Initially, irrigation was supplied by a surface water reservoir through two constructed channels (MIN 2007). The farmers jointly operated through a cooperative, with support from the National Department Against Drought, reaching a production of 745 tons of tomatoes in one year. In the 1980s, water supply for irrigation was interrupted in order to assure priority to the water supply of the city of Sume and surrounding area. Since then, agricultural production has drastically reduced and has been maintained through alluvial aquifer exploitation (Figure 8).

Consequently, the farmers within the case study area have faced a change in water supply from reliance on a reservoir to reliance on groundwater. The interruption of canal-water irrigation led farmers to gradually start exploiting the limited groundwater source to complement the scarce rainfall water supply, with support of government projects. Farmers have been forced to drill wells and act individually to secure their water, resulting in increased groundwater extraction. At the same time, there have been recent long-term drought conditions, which have further increased pressure on the groundwater from the aquifer. As a result, farmers are facing increased vulnerability and threats to their livelihood. While some of them began to exploit the aquifer, some abandoned their farms. This situation precisely illustrates the tragedy of the commons, as described by Hardin (1968).

Figure 8: Photos of the case study area: dry riverbed of the Sucuru River and well in the IP Area

Under a reformed water management framework and relying only on limited alluvial aquifers as a source of water for more than 30 years, only 17 lots (from the initial number of 52 lots defined at the establishment of the irrigation perimeter) were able to keep irrigation activities. Recent long-term drought conditions (2012–2018) have further increased pressure on the groundwater exploitation and, as a result, farmers are facing increased vulnerability and threats to their livelihood.

Some strategies have been used in the region to augment the exploitation efficiency, such as specific design of wells and underground dams. Due to the dimension of the aquifer, the construction of wells with impermeable material allows only low exploitation rates for short periods of time. The well dries up quickly because it is only able to fill from the base and not through the well walls. Therefore, a specific well design, the “duckbill well”, was proposed considering the characteristics of the aquifer and a type of brick available in the region to improve the exploitation rate (Rêgo et al. 2014). Also, three underground dams were constructed in the area.

The wastewater, which is untreated or treated with low technology, has not been diluted by intermittent rivers and pollutes the underlying alluvial aquifers. However, wastewater also becomes a source of continuous aquifer recharge that is crucial in a region of low rainfall concentrated in a short period of the year. The Sume sewage treatment plant was designed for a discharge of 1,460 m³/day, which represents a significant amount considering the water flows in the region. Water quality issues were recognized, especially due to the wastewater disposal onto the Sucuru riverbed (Pontes Filho 2018; Salgado et al. 2018; Walter et al. 2018). Salgado et al. (2018) observed groundwater contamination caused by the sewage, agriculture and livestock. These authors identified a high impact over groundwater quality near the urban area, and a gradual improvement along the alluvial aquifer, indicating its capacity to filter and disperse pollutants.

Preliminary estimates point out that the aquifer is capable of supplying 1/3 of the irrigation demands of the IP project (Atecel 1999), which is significative to the region, but it has been exploited intensively, disregarding its limitations and hydrogeological setting (Alves et al. 2018).

5. Methodology

This research is based on the observations of a case study area that is representative of alluvial aquifers in the BSA, as similar water systems are distributed throughout the region. The area has been the focus of a research collaboration at the R&D Project BRAMAR - Strategies and Technologies for Water Scarcity Mitigation in Northeast of Brazil: Water Reuse, Managed Aquifer Recharge and Integrated Water Resources Management" (Abels et al. 2018), as one of the four case studies. The aim of the project was to help create better management of the groundwater system to support coexistence with the semi-arid climate conditions. The methodology is associated with the tasks of this research in the diagram below (Figure 9).

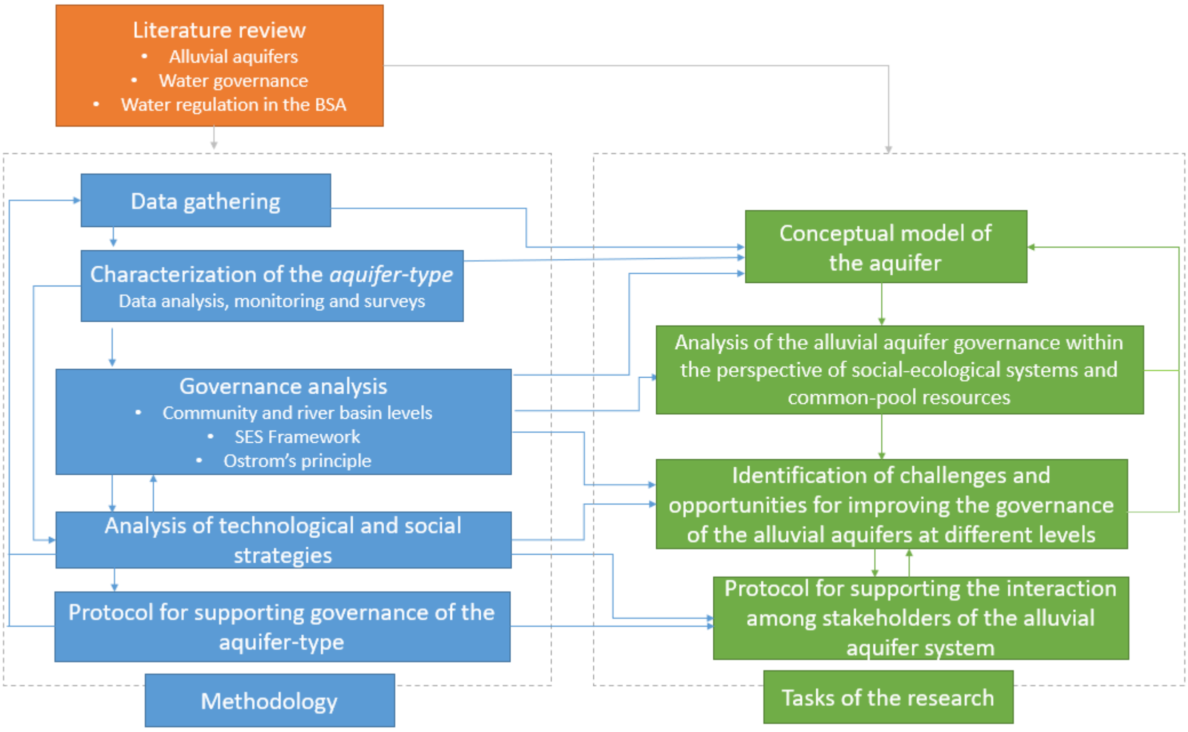


Figure 9: Framework of the research

5.1 Characterisation of the aquifer-type: monitoring and surveys

The database has been constructed with support of the BRAMAR Project through: (a) information gathering from the literature and data/documents provided by government and non-government organizations; and (b) hydro(geo)logical and water quality monitoring and physical and social surveys performed since April 2015 until May 2019 (UFCG 2019). This database permitted the development of a conceptual model of the *aquifer-type* that characterizes the hydrogeological characteristics, processes and other aspects that influence the groundwater use.

In order to develop the following steps of this work, the physical characterisation of the aquifer, the monitoring of water balance components and the understanding of groundwater quality are important steps. This field work was developed with support of the BRAMAR Project. Data gathering with government agencies and previous research projects was performed and followed by surveys to complement existing information (Atecel 1999; Vieira 2002; Abels et al. 2018).

The topography was defined by DNOCS elevation curves (MIN 2007) and 46 points collected with geodesic GPS to better adjust the digital elevation model and accuracy of the data collected through the water table monitoring network. Geological profiles of 112 boreholes, obtained by percussion drilling (during BRAMAR Project and from previous surveys), were analysed to determine the geology settings and the aquifer dimensions. The hydrodynamic parameters of the aquifer have been defined based on a pumping test performed by Vieira (2002), tests using the Guelph Permeameter, slug tests, and simulations that were carried out since the beginning of the project (Tsuyuguchi et al. 2017; Arruda and Rêgo 2018; Arruda et al. 2020)

The BRAMAR Project monitoring work developed between April 2015 and May 2019 is described below, and summarized in Table 2:

Table 2: Periods of monitoring and physical surveys

Monitoring/ Physical Survey	Period
Groundwater level	April 2015 - May 2019
Rainfall	December 2016 - May 2019
Wastewater discharge	February 2019
Land use	October 2017, April 2018, December 2018
Groundwater quality	May 2015 -August 2018

Rainfall monitoring: Five rainfall gauges were distributed in the Sucuru river basin (Figure 10) in addition to the existing meteorological station of the

State Agency of Water Management (AESA), to identify the rainfall spatial and temporal variability and to better estimate the recharge.

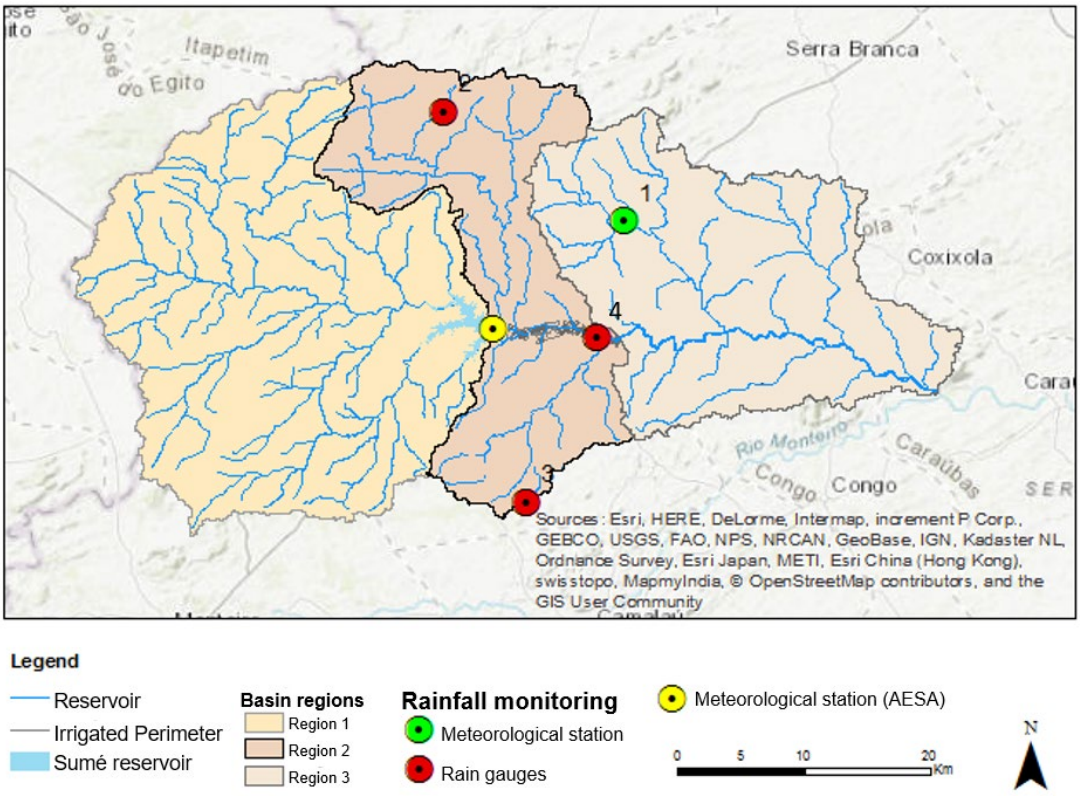


Figure 10: Rainfall gages monitored in the Sucuru River Basin

Water table monitoring: The water table has been monitored through around 35 wells and 16 piezometers since April 2015 (Figure 11) until May 2019. The levels were measured monthly or fortnightly. This network is dynamic, as some wells were obstructed while others were built over the last few years.

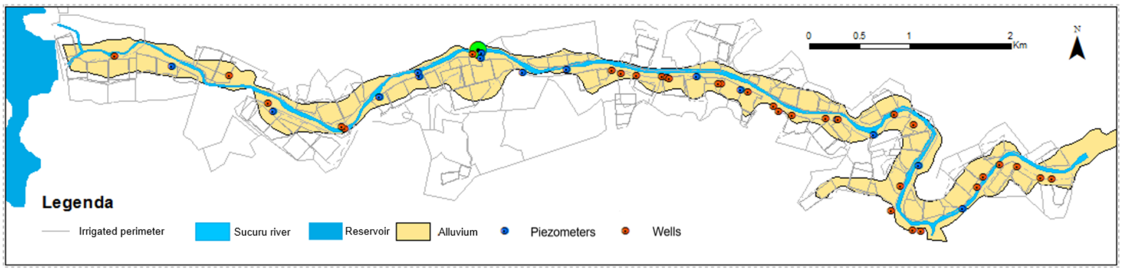


Figure 11: Water table monitoring

Wastewater production: The sewage discharge from the wastewater treatment plant of Sume was observed in February 2019. The values observed had no significative variations, and were considered representative for the 4 years-period. The wastewater discharge measured was a part of the total wastewater produced in the city, as the sewerage system was not concluded and, consequently, only a part of the wastewater is treated in fact. The total wastewater was estimated based on information from the National Sanitation Information System, considering the percentage covered by the sewerage system (SNIS 2019).

Groundwater quality monitoring: nine wells along the longitudinal section composed the monitoring network of physical-chemical and microbiological analyses performed on a monthly basis (Figure 12). The water quality analyses included physicochemical and microbiological parameters, and have been performed and examined by Pontes Filho (2018) and Salgado et al. (2018) . These studies aimed to verify the water quality dynamic of the alluvial groundwater caused by seasonal variations regarding recharge and runoff (dry and rainy period) and anthropic impacts (sewage and agriculture), and were be used in this work.

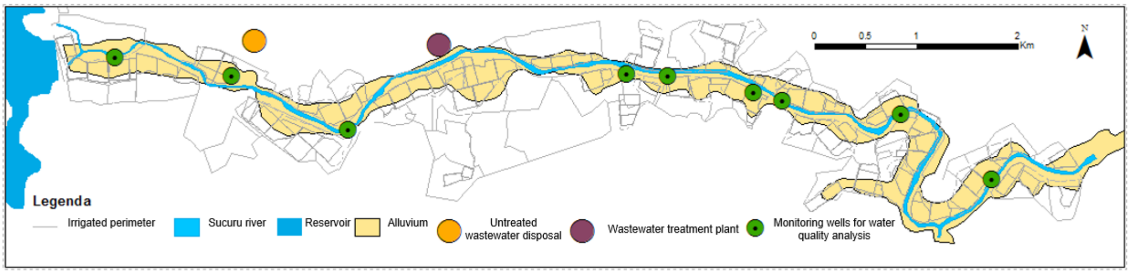


Figure 12: Water quality monitoring network

Land Use: Land use surveys were developed with the aim of identifying irrigated and rain-fed crop areas and livestock activities along the aquifer. This survey was conducted in three different periods in order to observe seasonal variations. These data associated with the information of whether the wells were pumped were used to estimate the groundwater exploitation.

The lack of data regarding alluvial aquifers hinders their management, so that the surveys and the monitoring network described represent an important contribution for the research body that investigates the *aquifer-type*.

5.2 Governance analysis

The governance analysis was performed considering the water management at the levels of the community and of the river basin. Considering the need of a bottom-up approach, it was initiated with a deeper analysis at a small scale with the aim of recognizing opportunities to improve the groundwater governance through community-based management. This approach facilitates the understanding of how the decisions at higher levels of water management can produce impacts on the aquifer (positive or not) and of key elements to move forward a sustainable groundwater governance.

The main elements integrating and affecting the studied system were identified. From this definition and characterisation, main stakeholders were identified and their relationships and the norms regulating the dynamic of the system were analysed. The governance analysis was based on the document analysis, the database constructed as described in the previous section and the arrangements established. The referred documentation includes laws, decrees and plans regulating the water resources in the BSA, farmers' association statute, minutes of collegiate bodies meetings, and reports and research material on the case study area. Complementing this, notes have been taken during the field work based on the observation of formal and informal governance arrangements, of the roles of different organization and of attitudes towards resource use.

This allows to gather farmers' input, as there was continuous contact with the group, adding to our understanding the farmers' concerns, perceptions and behaviour, which include:

- Level of knowledge of groundwater flow and recharge.
- Impressions of the farmers/hostility regarding exploitation in the group.
- Level of participation and involvement of the members in the CAMIS (Association partially functioning).
- Information on support from state projects and programs.
- Access of the farmers to technical and financial assistance (EMPAER, DNOCS, SEBRAE, PRONAF).
- Level of knowledge from farmers regarding the possibility of improving efficiency of aquifer exploitation.

- Impressions of CAMIS regarding the Paraiba River Basin Committee meetings

The aim is to create a robust assessment of the governance system. This analysis can support the evolution of the institutions' roles and arrangements for a better governance of the aquifer and the river basin. Demographic information about farmers, infrastructure and water consumption habits could not be collected and was not available at secondary sources. If available, they would have allowed a deeper analysis of these actors' behavior.

The analysis of the alluvial aquifer's SES was performed in two steps. Firstly, the SES framework proposed by McGinnis and Ostrom (2014) was applied to synthesise the information on the study area in a structured way to characterize the SES appropriately. Then, the governance of the SES system was analysed against Ostrom's design principles (Figure 13). Characterisation and analysis of the SES were based on document analysis and data gathered from the study area by a research collaboration in the study area, summarized in the previous section (Schimmelpfennig et al. 2018).

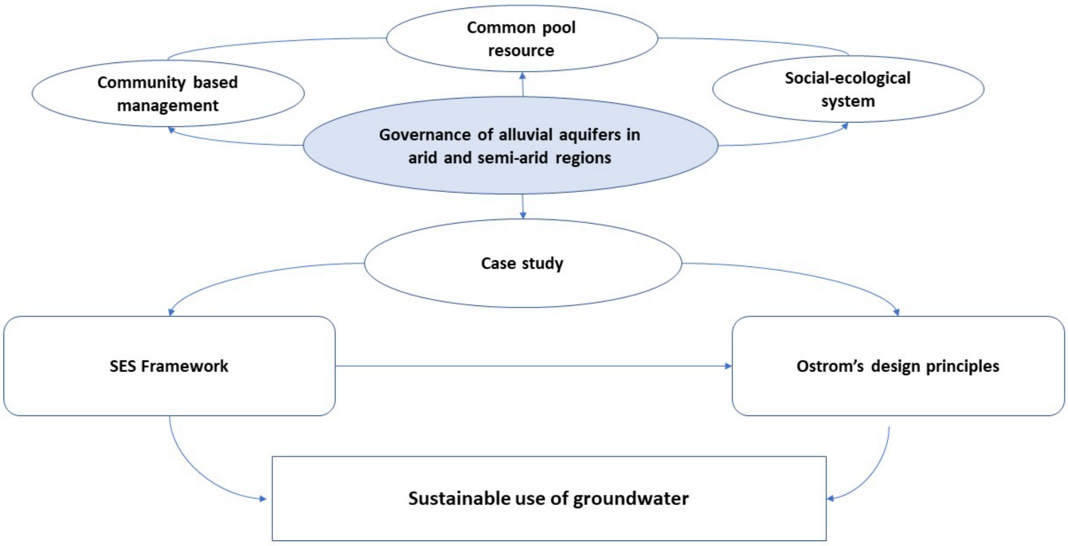


Figure 13: Summary of research approach for this study (Tsuyuguchi et al. 2020)

5.2.1 SES framework

The "SES framework" (SESF) concept, developed by McGinnis and Ostrom (2014), was used to characterise the SES for analysis. The SESF is a multi-tiered approach that supports the diagnosis of an SES based on the framework shown in Figure 14. The characterisation of the SESF starts with the definition of the first tiers: resource systems, resource units, governance systems and actors. The actors participate in action situations for which the resource units are inputs, while the resource systems and governance systems set conditions for the 'interactions' and the resulting 'outcomes'. These tiers compose the SES of concern ('focal SES'), which is linked to influential exogenous factors ('related ecosystems' and the 'social, economic and political settings'). Each first-tier is described by second-tier variables, which provide a checklist for a complete characterisation and allow for efficient application of the framework and comparison of different cases —Table S1 in the electronic supplementary material (ESM).

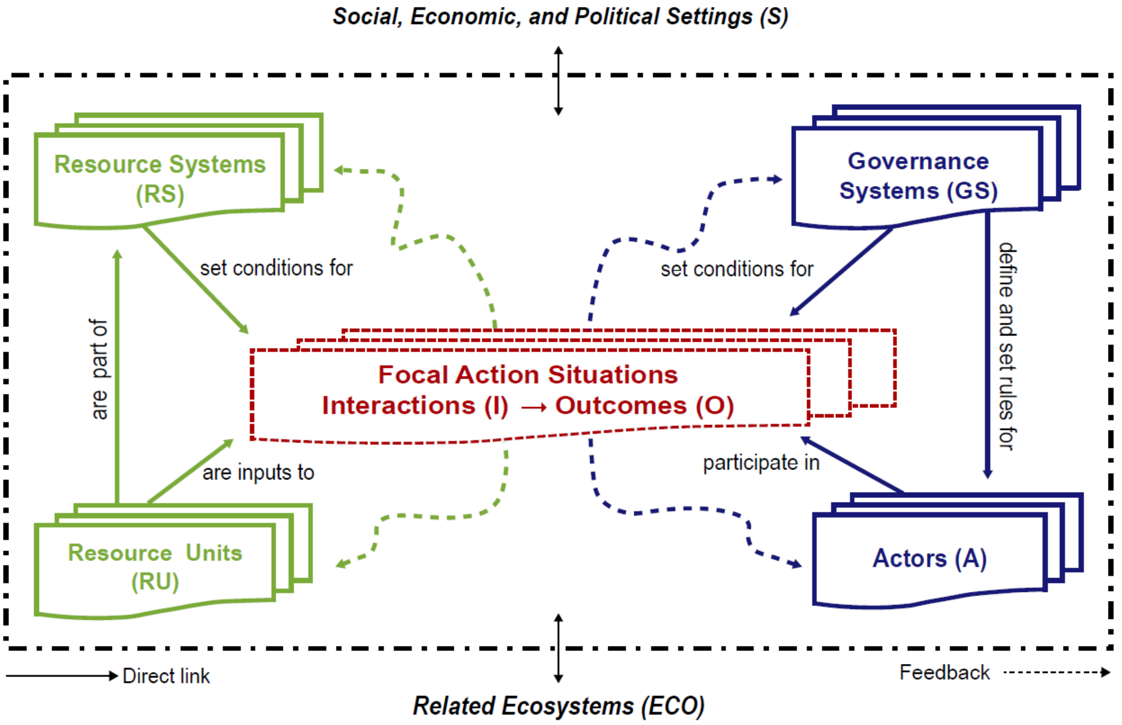


Figure 14: The core subsystem in the framework for analyzing social-ecological systems (McGinnis and Ostrom 2014)

5.2.2 Governance analysis of SES through Ostrom's principles

Ostrom's design principles (Ostrom 1990) were proposed as necessary for the sustainable management of CPR and have provided the basis of governance analyses elsewhere (Foster and Garduno 2013; Seward and Xu 2018; Silva 2015). The principles were derived from empirical evidence, by observing diverse cases of sustainable and unsustainable CPR exploration and examining what characteristics were present in successful cases of governance and lacking in cases in which there was depletion of resources as predicted in the theory of the “tragedy of the commons” (Gardner et al. 1990). They are briefly described in Table 3. The analysis investigates whether the current governance of the SES aligns with the principles and enable the identification of opportunities to enhance CPR sustainability. This work supports previous studies and augments the large body of empirical investigation of these principles to achieve better governance.

Table 3: Description of Ostrom’s design principles, from Ostrom (1990) (Tsuyuguchi et al. 2020)

Ostrom’s Common Pool Resource Principles	
1. Clearly defined boundaries	*Defined boundaries of resources and over withdrawal rights of users*
2. Congruence between appropriation and provision rules and local conditions	*Match rules governing use of common goods to local needs and conditions*
3. Collective-choice arrangements	*Ensure that those affected by the rules can participate in modifying the rules*
4. Monitoring	*Develop a system, carried out by community members, for monitoring members’ behaviour*
5. Graduated sanctions	*Use graduated sanctions for rule violators*
6. Conflict-resolution mechanisms	*Provide accessible, low-cost means for dispute resolution*
7. Minimal recognition of rights to organize	*Make sure the rule-making rights of community members are respected by outside authorities*
8. Nested enterprises	*Build responsibility for governing the common resource in nested tiers from the lowest level up to the entire interconnected system*

5.3 Analysis of social and technological strategies

Based on the analysis of the SES, social and technological strategies were proposed. Technological strategies correspond to the strategies that involve physical structures, while social strategies refer to arrangements and rules that affect the groundwater use, whether they are formal or informal.

Focusing on the aspects framing the governance of the alluvial aquifer raised in the previous section, we identified key interactions and outcomes that need to be tackled. For each of them we indicated strategies that can create opportunity for such improvement, based on the literature and data gathered. The implementation was briefly discussed considering different scales and levels of governance, particularities concerning the aquifer-type and Brazilian and state water policies.

5.4 Protocol for supporting governance of the alluvial aquifer

The protocol was developed to translate the discussion of this work into a more pragmatic guidance to the institutions and other agents responsible for governing the alluvial aquifer's exploitation. At first instance, this will support the state water agency (AESA) to address important issues of this type of aquifer. We initiate with instructions to investigate and collect data that are necessary to build knowledge on groundwater flow and use, followed by the identification of stakeholders, the suggestion of strategies concerning groundwater availability and use, and directions about assistance.

6. Results

This chapter presents the aquifer conceptual model, which comprises information on hydrogeology and groundwater availability and use, followed by the governance analysis. The conceptual model presents the aquifer particularities based on understanding the water system and monitoring data. The governance analysis was performed considering such peculiarities and identified challenges and strategies to turn aquifer governance sustainable.

6.1 Conceptual model of the aquifer

The Sucuru River basin is characterized from a hydrogeological point of view by shallow impermeable crystalline bedrocks cut by small alluvial aquifers which are sedimentary layers forming riverbeds and banks of intermittent rivers. The upper region of the Sucuru River basin comprises several reservoirs, from which the biggest one is the Sume Reservoir (maximum capacity of approximately 45 million m³), just upstream of the study area, controlling the intermittent flow over the Sucuru River. The disconnection of the studied aquifer reach with the upstream region imposed by the construction of the reservoir was also observed through the aquifer water level just downstream of the Sume reservoir during the last four years, which indicates that no or very low leaking occurs from the dam to the aquifer. Due to the reservoir size and rainfall regime, just a few episodes of overflow were registered in a way that the reservoir then limits the recharge of the aquifer most of the time.

The recharge area is so the subbasin region 2 of the Sucuru River Basin (Figure10). It is characterized by bedrock mostly covered with a thin layer of soil. This thin layer is also discontinuous and of low permeability, and therefore does not constitute an aquifer. The infiltrated water does not flow underground, and for this reason the water evaporates and just a small amount reaches the alluvial aquifer to recharge it. The recharge occurs mainly due to streamflow over the riverbed and lateral water contributions from affluent intermittent creeks. Schimmelpfennig et al. (2018) estimated the potential for groundwater recharge (infiltration) in the region of the Sucuru River Basin downstream of the reservoir as about 60 mm/year average, which is quite high. However, the authors call attention to the fact that it mostly gets lost in a re-evaporation process, as previously explained. Besides the natural recharge mentioned above, there are contributions from sewage disposal of Sume city (estimated in approximately 400,000 m³ per year) and return flow from agriculture developed in the area.

Regarding the groundwater flow, due to the elongated and narrow shape of the aquifer, the predominant direction is along its length (from west to east), which is the direction of the streamflow. In the case of the groundwater flow, however, it can be inverted locally and temporarily under specific conditions, (Alves et al. 2018). The upstream boundary, due to the reservoir constructed, has a very limited occurrence of flow. There is no occurrence of flow along the boundaries defined by the contact of the crystalline rocks with the alluvium, laterally along the aquifer. The downstream boundary, however, is permeable and allows flow. This flow, which is expected to occur from west to east under natural conditions, might be inverted due to a more intense exploitation at the studied region.

It has been observed that the evapotranspiration in the alluvium can be relevant, especially during and just after the rainfall period, due to the water table that can be very close to the surface, groundwater-fed pools and pools that are formed in areas with low permeability of the upper layer. This observation is in agreement with other investigations of alluvial aquifers that highlight the riparian vegetation and low permeability layers beneath the river sediments (WADE Project 2004; Shanafield and Cook 2014). It is recognized that the preservation of alluvial aquifer has the potential of reducing evaporation of water that infiltrates, instead of flowing over the river channel. In a similar aquifer, Araújo Filho et al. (2014), in the preliminary results of an experimental analysis with buried tanks, investigated the minimum thickness over the water table to avoid evaporation considering two types of sand and found that the thickness should be greater than 32 cm and 42 cm.

In the diagram (Figure 15), an initial conceptual model of the aquifer-type developed by the BRAMAR Project (Walter et al. 2018) summarizes the components that interfere with the water balance and the main processes of recharge. The quantification of such components and groundwater availability is expanded and discussed below.

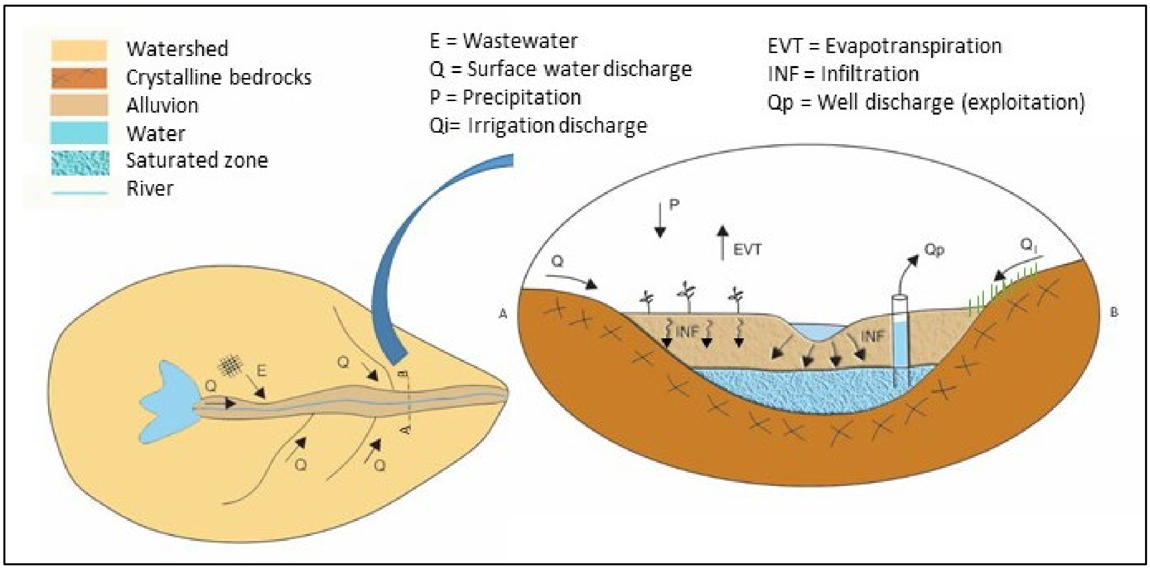


Figure 15: Initial conceptual model of the aquifer (Walter et al. 2018)

6.1.1 Hydro(geo)logical aspects

From the surveys, it was possible to verify an alluvial aquifer with a width varying between 50 meters (where a bridge was built) and 500 meters, including some areas known as terraces, which are shallow layers where water can accumulate. The terrain elevation in the alluvium area varies from 496 to 524 meters, with higher altitudes in the surrounding area, especially just downstream of the reservoir (Figure 16). The bedrock-surface topography presents variation along the aquifer resulting from different geological and hydrological processes, affecting the aquifer depth that varies from 0.5 to 15 meters. The geological surveys indicated that the alluvial aquifer layer has a high variability of lithology, mostly sandy (around 59%). A geological profile can be observed in Figure 17. The data available (information of grain sizes present in the geological profile boreholes each 1 m) allowed an approximation of the presence of the different grain sizes, presented in the Table 4. The storage capacity of the aquifer was estimated in 1,700,000 m³, based on a geological model of the aquifer built in the software FEFLOW, using information of topography, aquifer depth, lithology, and effective porosity.

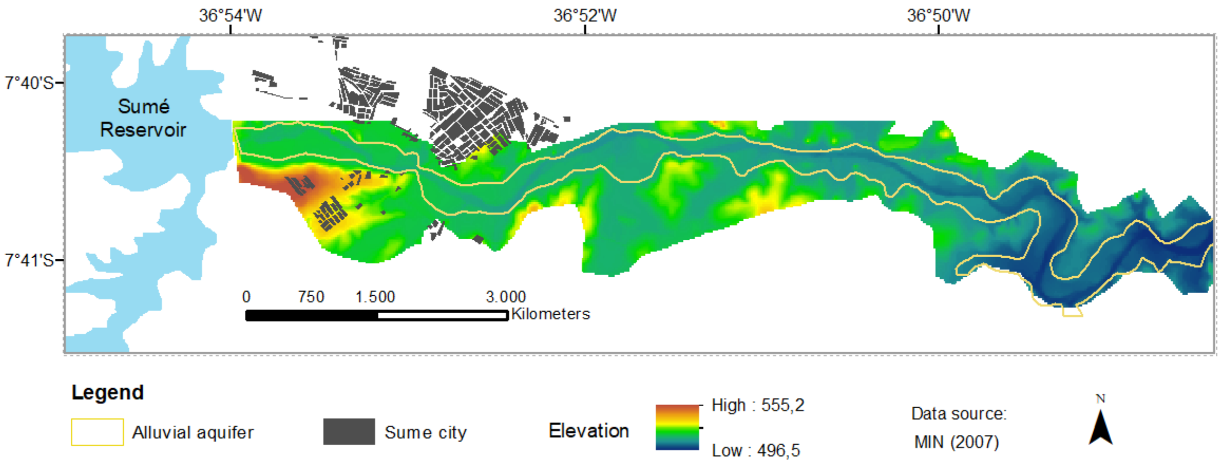


Figure 16: Elevation map of the studied aquifer reach

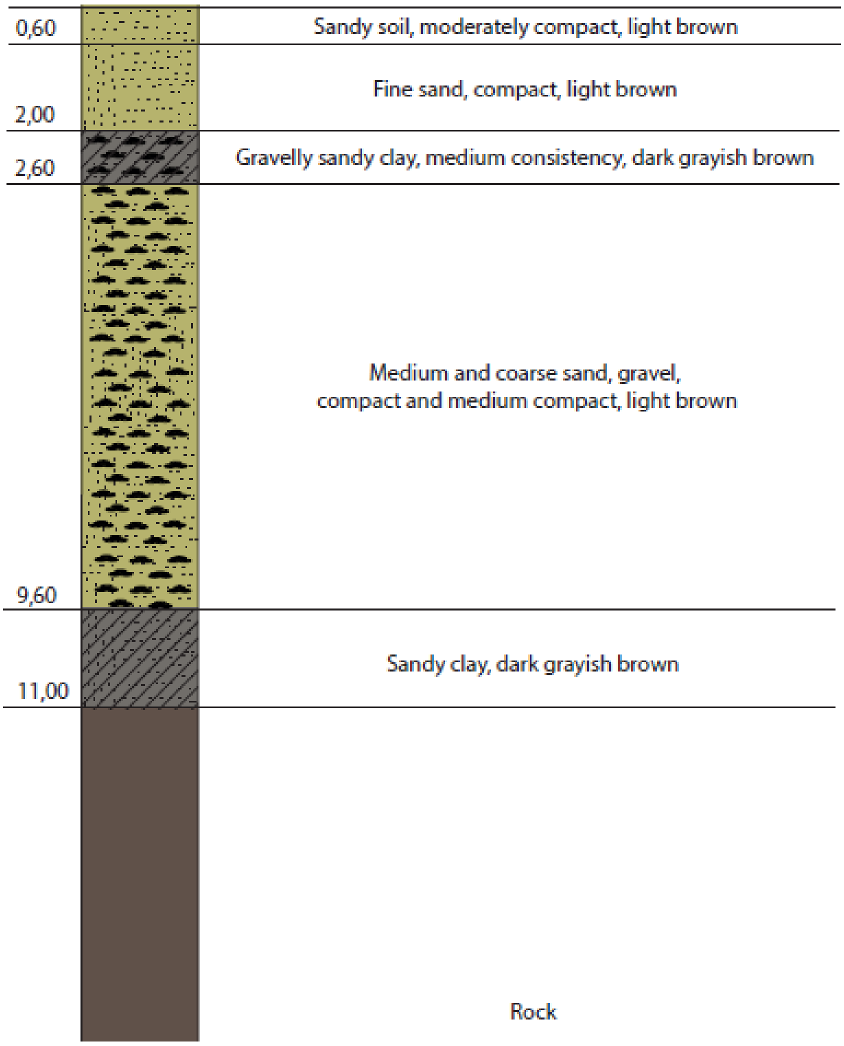
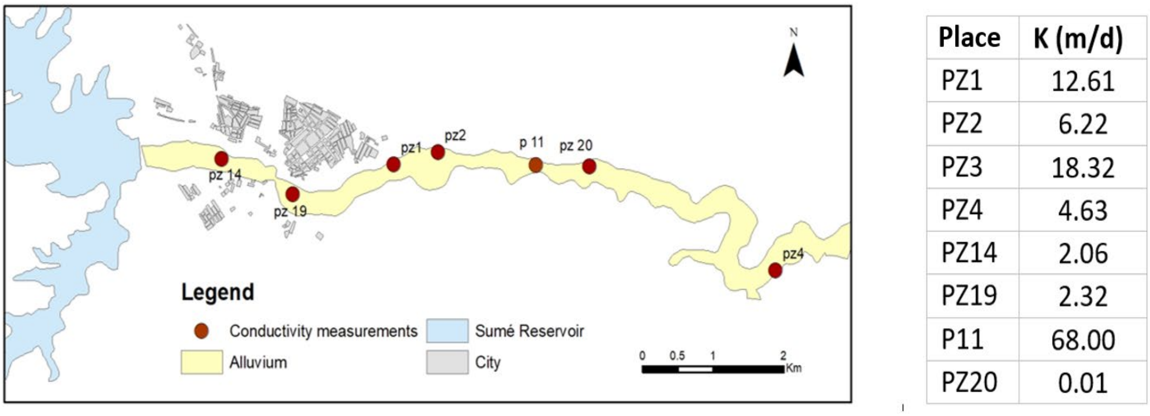


Figure 17: Geological profile of a borehole in the study area (Adapted from Atecel 2015)

Table 4: Percentage of presence of the different grain sizes in the geological profiles' boreholes per meter – in parenthesis, the number of boreholes that reached the referred depth (consolidated from data available at Vieira 2002 and UFCG 2019)

Grain size	0-1 m (112)	1-2 m (110)	2-3 m (96)	3-4 m (66)	4-5 m (47)	5-6 m (35)	6-7 m (19)	7-8 m (10)	8-9 m (06)	9-10 m (03)	10-11 m (01)	Total (112)
Clay	12%	15%	21%	18%	24%	21%	15%	15%	17%	44%	50%	17%
Silt	16%	7%	7%	7%	6%	6%	15%	0%	0%	0%	0%	9%
fine sands	31%	17%	12%	8%	9%	13%	10%	5%	0%	0%	0%	16%
medium sands	21%	29%	21%	21%	13%	11%	6%	20%	25%	33%	50%	21%
coarse sands	13%	20%	23%	28%	27%	27%	22%	30%	25%	11%	0%	22%
Gravel	6%	12%	16%	18%	20%	22%	32%	30%	33%	11%	0%	15%

The field experiments have shown values of hydraulic conductivity varying between 0.01 (with Guelph permeameter in a clay layer) and 68 m/d (through pumping test), indicating relatively high permeability (Arruda and Rêgo 2019; Arruda et al. 2020; Vieira 2002). The location of the wells used for the tests and respective values found for hydraulic conductivity are presented in Figure 18. The value obtained in the PZ20 is significantly lower and refers to a layer of silt and clay.



Place	K (m/d)
PZ1	12.61
PZ2	6.22
PZ3	18.32
PZ4	4.63
PZ14	2.06
PZ19	2.32
P11	68.00
PZ20	0.01

Figure 18: Field estimates of hydraulic conductivity (Adapted from Arruda and Rêgo 2019; Arruda et al. 2020; Vieira 2002)

The average monthly potential evapotranspiration in the area of Sume calculated based on the tank class A can be observed in the Figure 19 (MIN 2007).

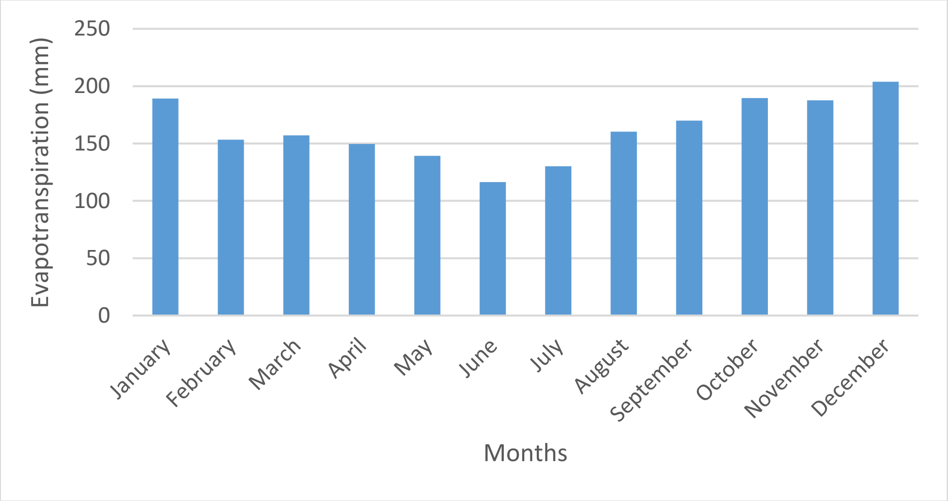


Figure 19: Average monthly potential evapotranspiration (MIN, 2007)

A water crisis has been observed in recent years, after a drought that lasted from 2012 to 2018 (Marengo et al. 2017), causing a lowering of the level of surface reservoirs, even collapsing in some cases. During this period, only in 2014 the Sume rainfall gauge still registered a relevant rainfall, although the reservoir storage was still lower than 40 % of its capacity. More specifically, during the monitoring period 2015-2019, the period 2015-2017 presented very low rainfall with an increase observed in 2018-2019 (Figure 20). More detailed daily rainfall data the period of 2017-2019 can be observed in Figure 21. They were collected in five rainfall gauges located in the Sucuru river basin, along both sides of the river.

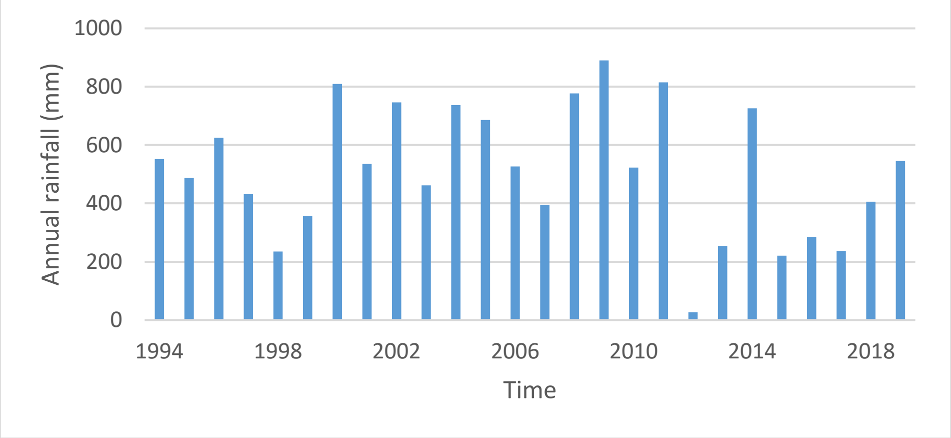


Figure 20: Annual rainfall registered in the Sume rainfall gauge (AESA 2019)

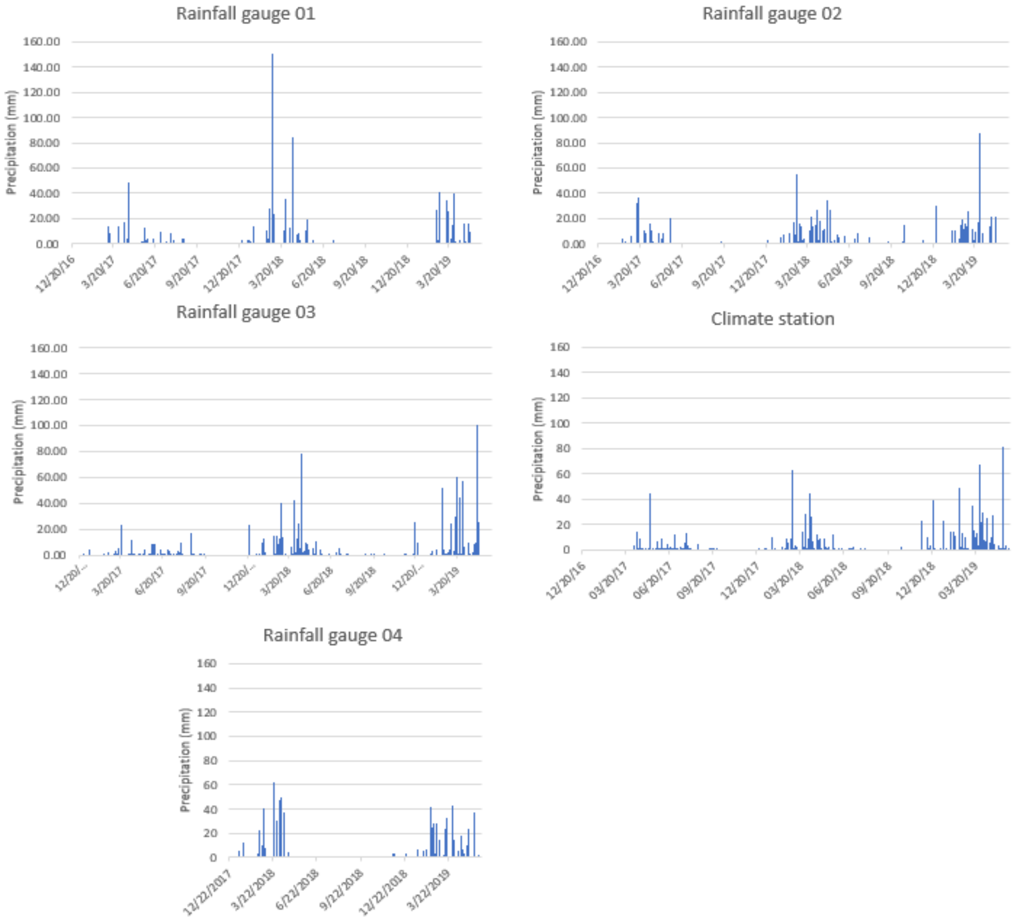


Figure 21: Daily rainfall registered in the rainfall gauges installed by the BRAMAR Project

Water table behaviour

Water table data from 25 of 48 monitoring wells are presented in Figure 23 (a, b, c). They make the most consistent and longest data series and allows an overview of the water table fluctuation in the whole aquifer. It was possible to identify data gaps due to water pumping, monitoring reading errors and problems of access. The data was manually corrected/completed through comparison with neighboring monitoring wells and with a linear function, based on the recession curve analysis. When surrounding area of the well was flooded, the water level was filled with the topographic level, while when the well was dry, the water level was equal to the bottom of the well. The data tables are presented in the Appendix B. To facilitate the data observation, they were divided into three groups, ordered upstream to downstream, as observed in Figure 22.

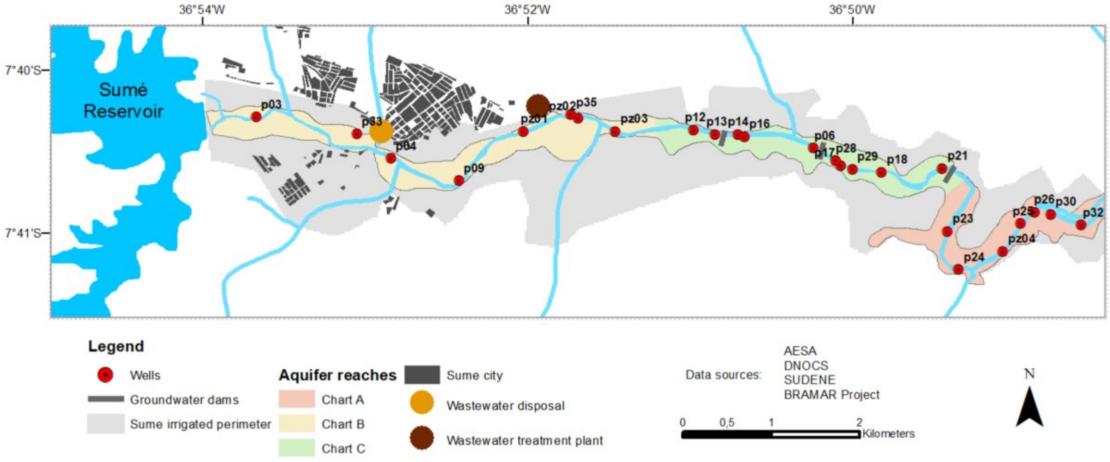


Figure 22: Location of the selected monitoring wells and the division on upstream, middle and downstream reach.

The first chart of Figure 23 contains the first eight monitoring wells, which are located in the upstream region. This region is mostly marked by the city and by the contribution of its wastewater to recharge. On the other hand, a smaller area of drainage is contributing to the aquifer recharge, as reservoir overflow barely occurs (with no overflow occurring in the monitoring period). The second chart contains ten monitoring wells in the aquifer's middle region, where three underground dams were built and previous modelling studies were developed (Alves et al., 2018; Vieira 2002). The third chart presents the last seven wells, in the aquifer's downstream region, where there is an accentuated curve.

Although in the year 2016 low rainfall occurred in the region, a relatively significant recharge of the aquifer occurred. In 2017, the rainfall was even lower and distributed along the year, resulting in a very low recharge of the aquifer. The year 2018 ended this cycle of drought, with rainfall that in the rainy period amounted to 432 mm, resulting in a high recharge of the aquifer. The variations in the level of the water table (Figure 23) indicated a fast recharge, capable of modifying in a short time the conditions of water availability of the aquifer. During the dry periods, especially in 2017, due to the water table's drawdown and the geological setting, some regions of the aquifer have become empty.

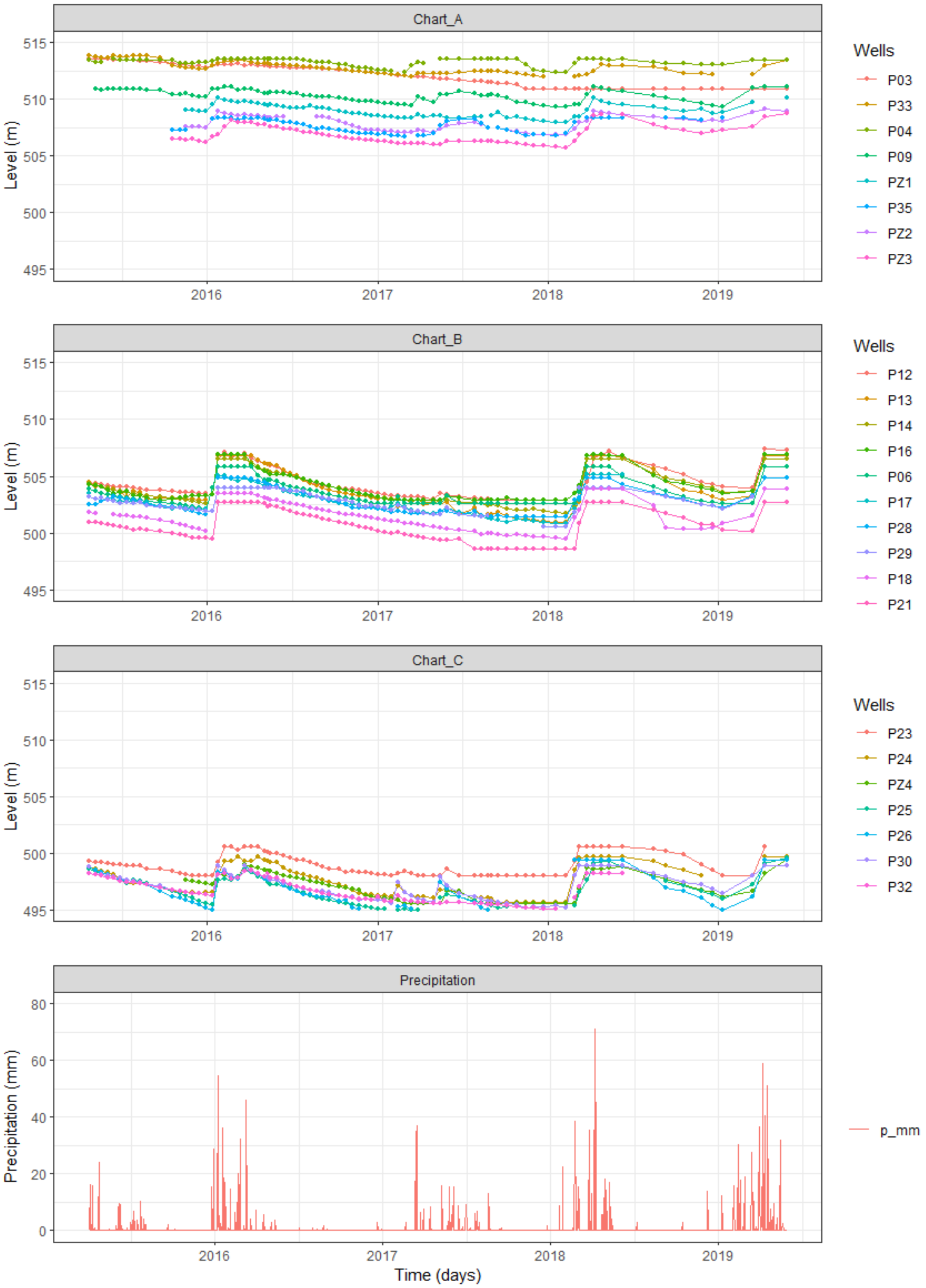


Figure 23: Water table data of selected monitoring wells in the: A) upstream area; B) middle area; C) downstream area, in meters.

Although the total annual rainfall in 2016 and 2017 observed in the Sume station are similar (Figure 20), a very different aquifer recharge occurred as a response. This behaviour can be explained by the fact that the recharge in the aquifer-type is mainly related to the occurrence of streamflow, which depends not only on total rainfall but also on events duration and intensity, and infiltration capacity at the beginning of the rainfall events. We can observe in Figure 23 that in 2017 the maximum daily amount was lower, and rainfall was more sparsely distributed over the year. Moreover, the rainfall over the drainage basins, which may have different conditions for infiltration, can present high variation, affecting the streamflow amount. This variation can be verified in the Figure 21.

Analysing the groundwater level in the well P03 over the monitored period, we can observe that different from all the other wells, it presented a minimal recharge in the rainy season in 2015, and after that, it had been lowered and remained dry since then. The higher level in 2015 can be explained by more significant rainfall in 2014 and artificial recharge. Farmers reported that before beginning the monitoring work, there had been a water release from the dam to recharge the aquifer, although there was no precision in when it occurred. However, as P03 is located just after the Sume dam, before the contribution from the first effluent river, it has a small drainage area contributing to recharge, restricting the recharge amount. There is unexpected water table behaviour in the P04 at the end of 2017. The hypothesis of a more intense exploitation can explain this, and pumping may have affected the values. Some level records in the charts may be of dynamic groundwater levels, such as in areas with higher exploitation rates. Their identification is hindered by the aquifer's specific conditions of flow and exploitation.

Figure 24 presents the boxplot of water table levels measured during the monitoring period, ordered upstream to downstream. Anthropic and natural factors highly influence the water table fluctuation in the alluvium. As natural factors, we can mention the variation in topography, geology and lithology, as well as the dry spells and droughts throughout the years. The aquifer's base and the relevant presence of clay result in natural barriers to groundwater flow both transversally and longitudinally to the river. In terms of urban activities, we call attention to the recharge of sewage from the city. Moreover, agricultural activities affect groundwater behavior due to the groundwater pumping, the evapotranspiration of the cultivated crops, and the return flow from irrigation. These aspects can explain the occurrence of more accentuated variations in the water level of some wells during a short period. Given the small dimensions of the aquifer, the water level responds very quickly to such changes. This can be observed, for instance, in most of the wells of the middle and downstream area in the year of 2017 (when rainfall was very reduced) and in the well P18 in the middle of the year 2018. The volumes of return flow are probably very low, due to the irrigation methods (mostly sprinkler and drip irrigation) and the water scarcity conditions. Moreover, the estimation of this value was not viable as it would require a controlled experiment, given the lack of information on irrigation volumes and other components.

The boxplot of the measurements of groundwater level allows having an overview of the aquifer longitudinally. We should pay attention to the well P04, located just downstream of the Pedra Comprida river. This river is affluent of the Sucuru River, receiving expressive wastewater of the city. Such disposal may explain that this well has the highest groundwater level values and the lowest variation.

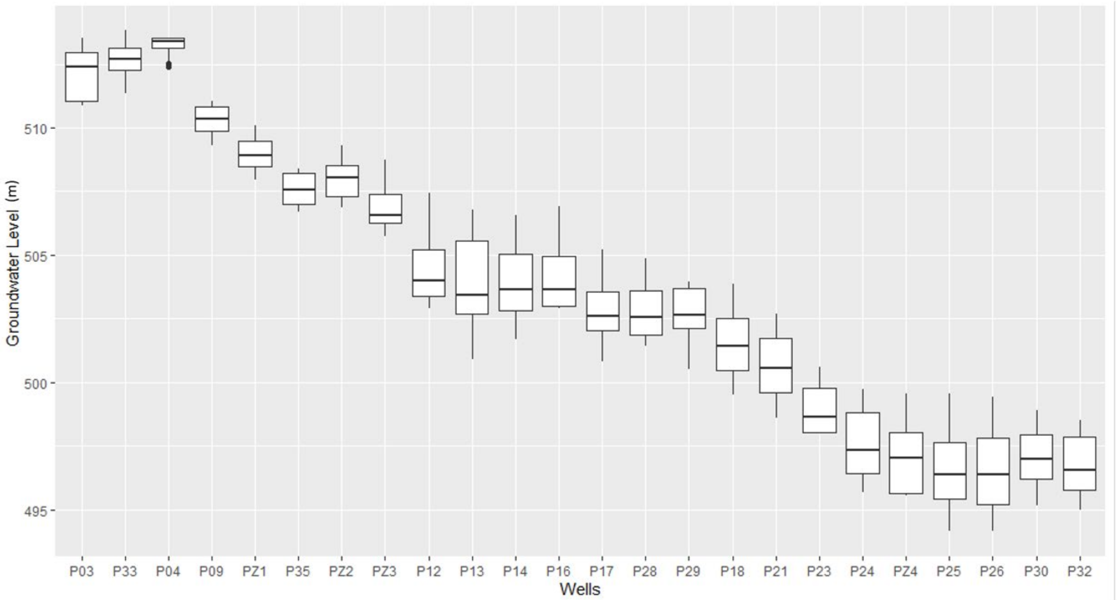


Figure 24: Boxplot of water table data over the monitoring period (2015-2019), in meters

Another data that can support the understanding of the water table behavior is the saturated depth. Table 5 presents the depth and maximum and minimum values of saturated depth (Max. S.D. and Min. S.D.) for each monitoring well over the monitored period. The information can also be observed in Figure 25. This chart allows an overview of the variation of aquifer depth along the aquifer and water table fluctuation at each well over the monitoring time. Most of wells have dried up at some point for a period.

Table 5: Data n of depth, and maximum and minimum values of saturated depth (Max. S.D. and Min. S.D., respectively) for the monitoring wells

Well	P03	PZ16	P33	P04	PZ15	P10	P09	PZ11	PZ13	PZ1	PZ5	P35	PZ2	PZ6	PZ3	PZ12
Depth	3.44	4.25	4.4	3	4.4	3.02	5.7	8.8	6.7	3.35	6.2	1.65	11	6.35	9.8	5.95
Mín. S.D.	0	1.46	0	1.85	1.49	0	3.94	1.45	0.64	1.24	2.04	0	6.63	4.32	6.04	1.97
Máx. S.D.	2.67	3.83	2.46	3.01	3.78	2.54	5.7	8.17	4.36	3.35	4.18	1.68	9.06	6.35	9.04	5.95

Well	P12	P11	P13	P14	P15	P16	P37	PZ10	P08	P07	P27	PZ9	P06	P28	P17	P29	P18
Depth	4.9	9.5	5.9	5.1	4.42	4.4	5	4.3	6.7	8.2	6.1	6.3	3.8	3.45	4.4	3.4	4.47
Mín. S.D.	0	0.63	0	0.24	0	0.45	0.23	0	0.7	1.8	0	0.84	0	0	0	0	0
Máx. S.D.	4.5	7.85	5.9	5.1	4.42	4.4	5.1	4.3	5.3	8.2	5.51	6.18	3.8	3.45	4.4	3.4	4.47

Well	P19	PZ14	PZ8	P21	P20	PZ7	P23	P22	P24	P34	PZ4	P36	P25	P26	P30	P31	P32
Depth	2.6	4.65	3.4	4.1	5.5	7	2.6	3.48	4.07	5.7	6.05	7.6	8.4	5.3	4.4	4.2	4.2
Min. S.D.	0	0.73	0	0	1.67	0.56	0	0	0	0	0	0	0	0	0.69	0	0.91
Máx. S.D.	2.61	4.02	3.37	4.1	5.45	5.39	2.6	3.48	4.07	5.7	3.99	7.3	5.39	5.3	4.4	4.2	4.2

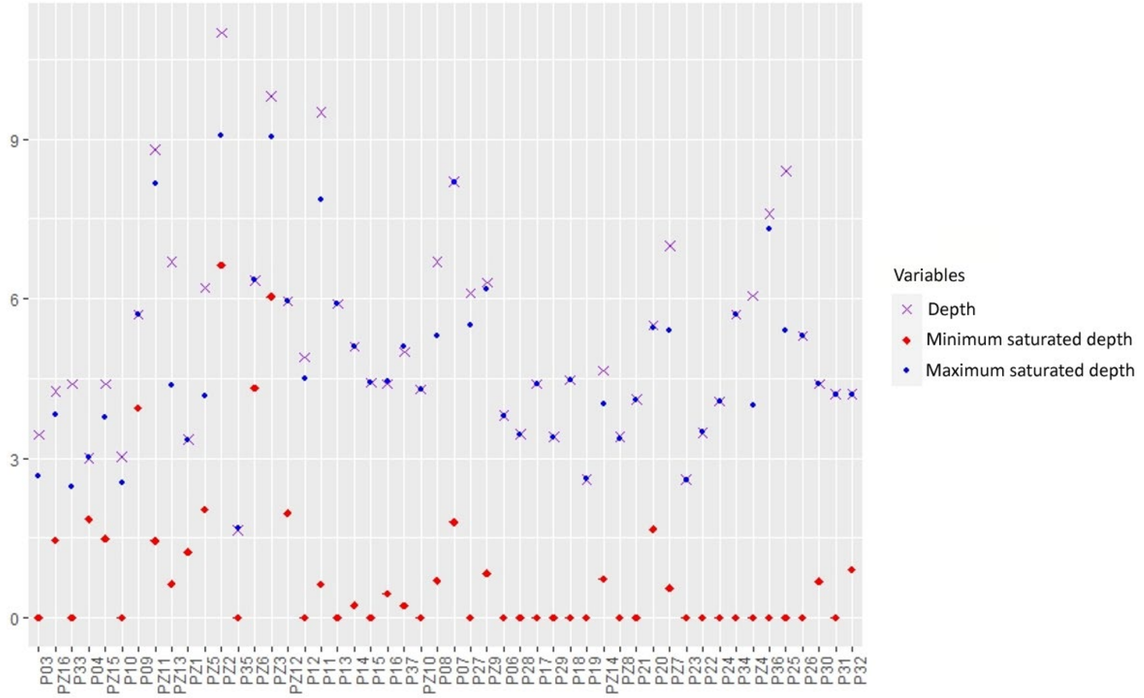


Figure 25: Chart with information of depth, minimum saturated depth and maximum saturated depth for each well, in meters

6.1.2 Groundwater availability and use

Aquifers are frequently seen and treated as reservoirs, due to their high storage capacity and the very slow groundwater flow. In fact, they partially work as such, but differently from simple reservoirs, and especially considering the alluvium settings, the alluvial aquifers are mainly conductors. By that, we mean that the higher velocity of groundwater flow and relative variation of volume storage call attention to a more unsteady regime in the alluvial aquifer compared to regional aquifers. This fact, allied to the variability on topography of aquifer top (ground surface) and base (crystalline bedrocks), adds complexity to the analysis of limits for exploitable volumes, and warning levels for groundwater exploitation, demonstrating the need for groundwater flow modelling. The peculiarities of the studied alluvial aquifer should be carefully observed to estimate groundwater availability, as we can notice by the following observations initially pictured in the previous topics: i) due the aquifer settings, groundwater availability varies fast and significantly over the time and along the aquifer; ii) while one year of very low rainfall can result in the impossibility of exploitation in several reaches of the aquifer, the recharge resulting from a single rainfall event completely changes the groundwater availability in the aquifer; iii) the continuous recharge of sewage from the city of Sume, estimated in approximately 0.4 M m³ per year, contributes to the water table level, especially in the upstream region of the aquifer; iv) there is an intrinsic relationship between the groundwater availability and the groundwater management in the small alluvial aquifer.

In this context, the storage capacity of the aquifer, that was estimated in 1.7 M m³, does provide a basis concerning the potential for the aquifer to supply irrigation. Recalling the definition for exploitable volume in the Paraiba State Water Plan, described in section 3.5.2, the recommended exploitation limit is given by 1/3 of the reserve, besides the entire aquifer potential. The concept for “aquifer potential” in the plan refers to the mean annual baseflow or the volume of water that the aquifer retrieves to the river, while the remaining volume, which under natural condition (with no exploitation) is permanent, is the “reserve”. Given the river-aquifer interaction and other settings mentioned above, groundwater flow is more dynamic in these aquifers, and these definitions need further discussion. Furthermore, estimating these values would require the observation of long data series that are not available. If groundwater is not exploited in this case, it will be mostly retrieved to the rivers in the studied reach or later downstream, except the volumes retained in the natural barriers formed by the variation on aquifer basement or localized occurrences of low permeable lithology. Due to the same reasons, exploiting such retained volumes, is physically impossible. On the other hand, based on the easiness of the aquifer recharge (that can be observed, for instance, in the water table data of 2018), some authors consider using the whole reserve (Vieira 2002) or the discharge exploitation that still allows the flow to downstream (Alves et al. 2018).

This flexibility for the exploitation volume limit is also supported by the information of relevant sewage recharge. Moreover, groundwater management enable to access the potential of the aquifer that would flow to downstream and be retrieved to the rivers. For example, in a reach of 2 km length of this aquifer, during a year of regular rainfall, it is possible to improve exploitation from 126,300 m³ to 166,500, managing the construction of an underground dam and the irrigation period (Vieira 2002). The appropriate selection of wells' and underground dams' location can optimize the use of the stored (in fact, flowing) volume, enabling even to duplicate the volume exploited and still control the impact over upstream and downstream areas (Alves et al. 2018). Results of a water balance in an aquifer reach of 600 meters length, performed applying groundwater modeling for two scenarios with modifications in the wells and dam arrangements, demonstrated such variations (Table 6).

Table 6: Results of the water balance in the modeled area to the final 15 days of the quarterly exploitation period simulated for the same scenario but with modifications in well and dam arrangements in scenario 3 (Adapted from Alves et al. 2018)

Volumes (m³)	**Scenario 2**	**Scenario 3**
Affluent volume across the borders (upstream or downstream)	1188.00	224.00
Effluent volume across the downstream border	569.25	113.25
Volume pumped out of the wells	624.00	1399.95
Variation in the stored or withdrawn volume	4.80	1289.00

As described previously, several aspects also influence the variation of groundwater availability along the aquifer, such as its small size, the variation of its basement elevations, lithology and topography, and anthropic activities. Therefore, depending on theses aspects and on the groundwater use, the alluvial aquifer can be overexploited at one reach and underused in the reach a couple of kilometers downstream.

As for groundwater use, the total cultivated area in the IP varies seasonally, currently from 8 – 43 ha, compared to 287 ha previously projected to be irrigated with water from Sume reservoir. Livestock production has increased, but it remains limited by water availability. There has been a very low seasonal variation in the total number of animals (mostly sheep and goat), around 1,400 (Figure 26). In the Figure 27, it is possible to see an aerial image of an area in the irrigated perimeter.

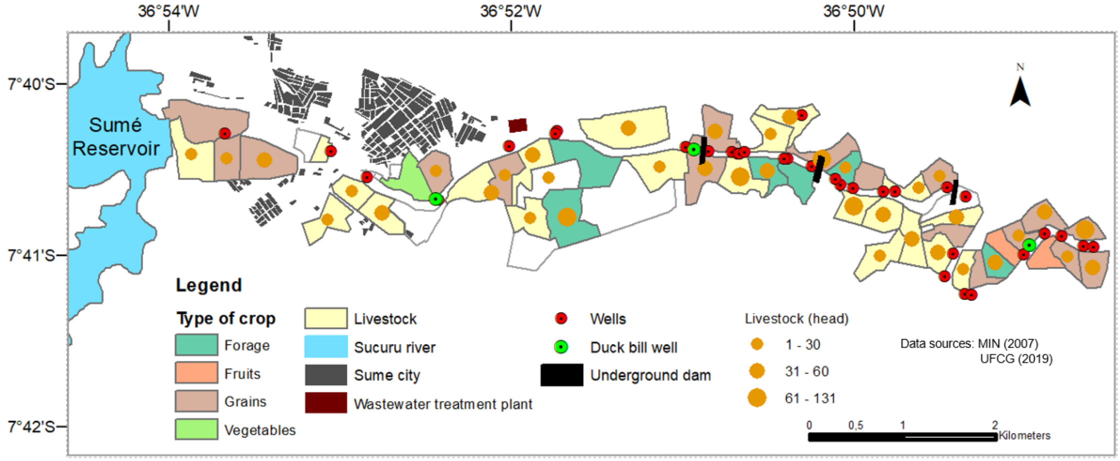


Figure 26: Land use in the Irrigated Perimeter (Rêgo et al. 2021)

Figure 27: Aerial photograph of a portion of the study area in January 2020 (AESA 2020)

Based on data of energy consumption of the state government program “tarifa verde”, which promotes energy efficiency and assistance for the rural area, groundwater withdrawal in the area downstream of the Sume reservoir was estimated at 12 l/s in 2018-2019, i.e. at 378,300 m³/year (ANA 2020a). This value might be overestimated, considering the uncertainties of the method and the area evaluated.

Based on the areas cultivated throughout the year and the information of the wells, the average exploitation rates, in m³ per day, were estimated (Tables 7 and 8), for the rainy and dry seasons. The total exploitation over a year reached a total of 224,000 m³, what is coherent with the estimation based on energy consumption. This estimation was performed based on the surveys of 2018 and considered the water demands according to the crop culture associated with the wells exploited to supply its irrigation. These rates are affected by different factors besides groundwater availability, such as the decision of farmers considering the risks, and constructive aspects of wells and underground dams. However, they can provide an idea of the groundwater distribution and influence of anthropic activities.

Table 7: Exploitation rates, in m³ per day (rainy period)

Well	p04	P40	P35	p11	p14	P08	P06	P28	P17	P29	P21
Q (m³/day)	14	65	11	51	12	13	21	18	13	51	15

Well	P20	P39	P23	P34	P36	P25	P26	P30	P31	P32
Q (m³/day)	17.3	45	9.5	20.6	64	29.7	48.2	60.5	9.5	38.2

Table 8: Exploitation rates, in m³ per day (dry period)

Well	P04	P05	p40	p35	p11	p14	p08	p28	p20	p39	p34	p36	p25	p26	p30	p32
Q (m³/day)	23	38	140	34	43	2	32	6	9	49	7	39	57	100	14	5

From 22 lots, 17 keep irrigating throughout the year and the cultivated areas are drastically reduced in the dry period. This can be explained by the water table lowering, but also by the need for increasing irrigation (and consequently pumping energy). We call attention to the differences of values among the wells, especially during the dry period, with values from 2 to 140 m³/day. The well P40 is benefitted by the sewage recharge and present relevant exploitation rates in the entire year. The effect of underground dams can also be noticed. P11 is a duckbill well with a underground dam downstream and present exploitation rates from 43 to 51 m³/day. The owner of P06, that is located upstream of the second underground dam, in previous years was one of the farmers with the greatest production. The current reduction in exploitation is due to personal reasons, as revealed in our fieldwork. In the meanwhile, the well accumulated sediments and have been mostly dry. The owner of P28 reported a relevant reduction of pumping capacity after dam's construction upstream of the well, but he was able to keep irrigating even during the dry period. The owner of P20, that is also located downstream of another underground dam, also keeps irrigation throughout the year, but excavated a temporary hole upstream of the dam after its construction to supplement irrigation volume.

It is possible to observe that there is a competitive use of groundwater. On the other hand, comparing the values concerning groundwater availability and use, in the year of 2018, when water table raised, there is the need for improving exploitation efficiency. Concerning regulation, according to data from the registry of AESA, there are 10 dug wells for which water permits were conceded for irrigation purpose, with pumping rates varying from 3 to 10 m³/h (annual withdrawals varying from 4,200 to 29,200 m³), summing up to a total volume exploited in the year of 101,810 m³. According to Decree 33613/2012, the bulk water charges in the Paraiba river basin are applied if the extraction for irrigation purposes sums up over a year a value equal to or higher than 350.000 m³ by each farmer. Therefore, farmers are not charged.

Recently, a short-term plan for allocating water from the Sume reservoir was defined with public participation (ANA 2020b). The plan included water release to recharge the aquifer and can increase groundwater availability (a volume of 2,100,000 m³ per year). A limit of 1 ha to be cultivated by each farm was agreed. This recharge definitely multiplies the volume of groundwater available, duplicating at least. The water table levels should be monitored previously and after the water release events to understand the impacts. By the way, Pontes Filho (2018) proposed strategies to improve groundwater availability through recharge techniques using rainwater, surface and reclaimed water.

The observations in this section agree with the above-mentioned aspects of groundwater flow in the alluvial aquifer and indicate the potential for conflicts caused by groundwater scarcity, which are aggravated by the variable groundwater availability depending on the management of the exploitation and on the management decisions adopted.

6.2 Governance analysis[2]

6.2.1 SES characterisation

The focal SES is defined as follows (Fig. 2). The resource system refers to a region of the alluvial aquifer exploited by the group of farmers. The resource unit is the groundwater. The governance system is set by the water resources policy and management system, by the governance structure of the IP and by policies framed for rural communities in the BSA. The actors are the farmers of the IP and the stakeholders who are connected to the governance system and who directly interact with the farmers. The interactions, outcomes and exogenous factors are described further in this article.

The characterisation of the system according to the second tiers of the SESF is presented in Appendix A. These characteristics are synthetised into four aspects (Table 9): alluvial aquifer aspects, technical aspects, governance aspects and related ecosystems. The alluvial aquifers aspects combine the SESF tiers resource systems and resource units, as the groundwater is not only part of the alluvial aquifer, but also is entirely conditioned to the aquifer setting. The governance aspects combine the SESF tiers governance systems and actors. The technical aspects could be included within the previous tiers, but they are separated to call attention to their importance and impact on the exploitation efficiency and the water distribution equity from the aquifer. The related ecosystems directly align with the same SESF tier and present exogenous factors relevant to the focal SES.

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[2] This part of the thesis has been published in the Hydrogeology Journal (https://doi.org/10.1007/s10040-020-02160-8)

Table 9: Characterisation of the focal SES (Tsuyuguchi et al. 2020)

Alluvial aquifer aspects	Governance aspects	Technical aspects	Related ecosystems
Shallow and narrow aquifers	Water resource policy aiming participatory governance	Wells location	Annual long dry spells and droughts
High lithological variability	Alluvial aquifers considered in State water plan	Technologies response (Underground dams, artificial recharge, wells design)	Surface reservoir
Water availability variation along the aquifer	Program for rational exploration of alluvial aquifers at the State water plan	Limited technical knowledge and technical assistance regarding aquifer exploitation	Wastewater disposal
Water availability variation during the year	Individual water permits		
Aquifer easily recharged	Existence of a farmers' cooperative		
Exploitation easiness	Farmers' cooperative as member of river basin committee		
Local and regional relevance	Farmers are the only users and compose a small group		
	Unique available resource for farming (high dependence)		

Alluvial aquifer aspects

These aspects refer to a set of biophysical and social characteristics that are particular to the alluvial aquifer system typical of the BSA region. The aquifer, underlain by crystalline rocks, has small dimensions: along the 12 km length portion studied, the alluvial sediment package occupies an area of 351 ha, with a width of 50–500 m and a depth of 0.5–15 m (Schimmelpfennig et al. 2018). With a storage capacity estimated at 1,700,000 m³, it presents relatively high variability regarding lithology and aquifer depth, causing very different conditions of groundwater availability along the aquifer. There is also a relatively great variation in water table and storage volume during the year as a result of an excellent recharge during the short rainfall period combined with high permeability and abstractions through exploitation and evapotranspiration. The aquifer recharge occurs through infiltration of part of the rainfall directly onto the narrow aquifer surface and through part of the streamflow over the riverbed. This recharge resultant of the intermittent streamflow, which is formed by the runoff that reaches the aquifer laterally and through the river tributaries, is more significant. As the phreatic level is shallow, the water exploitation is easy, as wells can be drilled with simple methods and low cost. Finally, while the storage capacity refers to a small reserve, it is locally and regionally significant given the context of the case. Variation of water availability along the aquifer causes uneven water distribution among the farmers because they use wells individually in the vicinity of their own farms.

Governance aspects

The governance system can be hierarchically arranged in three main groups: (1) overarching rules set by the water resources policy (PNRH) and the water resources management system (SINGREH); (2) the governance structure of the IP; and (3) public policies related to technical and financial assistance for family farming. Their scope, necessary for understanding the SES characterisation, is summarised in Table 10, which also provides a glossary for the governance analysis.

Table 10: Main aspects of the governance system of the focal SES related to groups I (water resources policy and the SINGREH), II (irrigated perimeter structures) and III (policies for rural communities) (Tsuyuguchi et al. 2020)

	Aspect of governance
I	National water resources policy (PNRH): a turning point of the water resources policy in Brazil, establishes decentralised and participatory governance, a management system (SINGREH) and instruments for policy implementation.
	SINGREH (national, state and river basin levels): - Collegiate bodies for policy formulation (national and state water councils and river basin committees) - Executive bodies for policy implementation (federal and state organisations and water agencies)
	Groundwater: State domain
	River basin committee: Collegiate organism that functions as arenas at the river basin level of management in which members (from government, water users and civil society) debate water issues, arbitrate conflicts in the first instance and approve and follow the execution of water plans.
	Water plans (national, state, river basin): should present the water budget considering water demands and availability, the priorities of water use and the programs to meet the water policy goals in the region/basin: - Executive bodies should elaborate the plan and collegiate bodies should approve it and follow its execution - The National and Paraiba State Water Resources Plans consider the important role of alluvial aquifers for improving conditions in rural areas. The State's Plan designed a program for rational exploration of groundwater in alluvium and sedimentary deposits and establishes a criterion for defining an exploitable reserve that considers characteristics of this type of aquifer.

	Aspect of governance
	Water permits: instrument to regulate the concession of water, through which the state provides the user with the right to use a defined amount of water for certain periods: - Issued and enforced by the executive bodies - Water permit types: - Individual: single entitlement for a single user (current situation in the study area) - Collective: single entitlement for a group of users - Water demands below a certain magnitude (2 m³/h for groundwater) are exempted from water permits but need registration
	Bulk water charges: The users subject to water permits must pay for resource extraction. The bulk water charges are the source of the State Water Resources Fund, which is the main financial resource for the water management system.
	Classification of water bodies according to water quality: set progressive goals of water quality based on current condition and most restrictive use purposes of the water body, for both surface water and groundwater.
	The state water management agency (AESA) is the executive body and among other responsibilities should, for water bodies under the states' dominion: - Keep the state water users' registry updated - Issue and enforce water permits and charges - Monitor water usage - Execute water plans
	Water allocation meetings by reservoir: participative meetings organized by the National Water and Sanitation Agency (ANA) for cases in which the water systems have faced problems with water availability.
II	National Department Against Drought (DNOCS): federal institution responsible for the administration and development of the IP Project
	Agricultural farmers' cooperative of Sume (CAMIS) - Democratic values - Statute establishes rights and duties of the members and governs the dynamics of the cooperative
	Previous high investment: - Project development, land reclamation, technical and social assistance - Infrastructure for administrative work, storage of products and water conveyance
III	Rural credits are provided, i.e. loans and funding for improving rural production from public and/or private enterprises and development banks.
	Technical assistance for rural communities is provided by organizations such as Technical Assistance and Rural Extension Enterprise of Paraiba State (EMPAER), Brazilian Micro and Small Business Support Service (SEBRAE) and DNOCS.
	National Family Farming Strengthening Program (PRONAF) has been supporting family farming with credit and technical assistance. PRONAF's Rural Development Councils facilitate the formulation and implementation of policies to attend farmers' needs and support governance at the local level.
	Government projects and programs support farmers (such as providing well-drilling and irrigation kits)

The Brazilian water resources governance arrangements (group I) do encourage interaction among the different components of the management system (SINGREH), either at national, state or river basin levels. The interactions between SINGREH and institutions of group III, however, is less clear, especially at the local level. They interact through their participation as members of the collegiate bodies of the SINGREH (River Basin Committee and State Water Resources Council) and through cooperation in governmental programs developed throughout the BSA, to support agricultural planning and technical assistance.

At the IP level (group II), the farmers are organised in a cooperative (CAMIS), which was created during the implementation of the IP Project, but has been largely missing participation and involvement of the members. They are the key actors within the SES, comprise a small group and are the only users of the aquifer, which is the only source of water for irrigation. CAMIS has a broader purpose than water management but is a member of the river basin committee (as civil society). As the farmers are the only water users and their decisions about crop and areas to be irrigated highly affect water use, it is the group with the greatest interest in the CPR and has the highest potential to make use of the aquifer sustainably. CAMIS and farmers have a close relationship with DNOCS, responsible for the administration of the IP. National, state, basin and municipal institutions and organisations closely interact with farmers and CAMIS: DNOCS, PRONAF and development banks (national), AESA, EMPAER and SEBRAE (state), river basin committee (basin) and rural development councils (municipal).

Technical aspects

The technical aspects directly and indirectly impact the water exploitation efficiency and equitable distribution. The location of the wells and choice of technologies has a direct/physical influence on the amount of water extracted and, consequently, on the distribution of the resource among the farmers. The efficiency of wells and response of technological strategies can vary largely according to physical characteristics of the aquifer. The term “technological strategies” here is used to name the strategies that involve physical structures, which are well design and underground dams.

Well design refers to the choice of material and structure for construction of the well and affects its production capacity. The use of impermeable material, for example, allows only low exploitation rates for short periods of time before the well dries up because it is only able to fill from the base and not through the well walls. In order to improve exploitation rates, a new well design was developed in the study area (the “duck bill” well) considering the characteristics of the aquifer and a type of brick available in the region (Rêgo et al. 2014); however, only two wells were constructed applying the developed design. Underground dams are structures used throughout the BSA designed to retain groundwater and increase the efficiency of upstream wells but, on the other hand, may reduce the production of downstream wells. There are three underground dams along the aquifer portion. The appropriate location and use of wells and appropriate technologies relies on knowledge of the aquifer and groundwater flow that, consequently, affects the groundwater exploitation efficiency. As a resource that flows underground, the CPR is not visible, making it difficult to acquire knowledge of the ecological system. Knowledge of the aquifer has been built through community experience, government programs (Atecel 1999) and R&D projects (Rêgo et al. 2014; Schimmelpfennig et al. 2018); however, it is restricted by the lack of sharing of such knowledge, due to limited interaction and technical assistance regarding the exploitation of water.

Related ecosystems

This tier refers to exogenous factors affecting the focal SES that can be characterised through the following, as defined by the SESF: climate patterns, flows into and out the focal SES, and pollution patterns. Regarding climate patterns, annual long dry spells and recurrent droughts have a major impact on water availability. The other two ecosystems are highly influenced by human actions: (1) the surface reservoir draws an important boundary of the resource system, disconnecting the groundwater system of the river flow system upstream of the reservoir, and (2) the wastewater disposal is a relevant flow into the focal SES, in terms of source of recharge and pollution.

6.2.2 Ostrom’s principles analysis

This section uses Ostrom’s eight principles to analyse the alluvial aquifer SES to identify to what extent the system aligns with the principles and what opportunities there are to make management of the CPR more sustainable.

Clearly defined boundaries

Following Cox et al. (2010), this principle is separated into (1) resources boundaries and (2) group boundaries, which generally correspond to biophysical and socio-economic boundaries, respectively, and that can either align or not, and in general are defined by natural and social/economic aspects, respectively.

Given the focal SES, the resource boundaries consist of the geological limits of the alluvial aquifer (Schimmelpfennig et al. 2018) and the group boundaries delineate the small group of farmers with similar interests. However, as the alluvial aquifer aspects in the SES characterisation show, the occurrence of the resource unit (groundwater) inside the defined boundaries varies temporally, as seasonally the aquifer can be almost fully recharged and discharged. Hence, although both social and biophysical boundaries are defined, the alignment with this principle is hindered by the fact that the resource availability (spatially and temporally) is strongly influenced by factors outside of the defined boundaries (related ecosystems).

Congruence between appropriation and provision rules and local conditions

At the local level, there have been no rules for sharing the alluvial aquifer as a CPR. Farmers use wells individually in the vicinity of their own farms, and the technological strategies available, although compatible with the local economy (relatively low cost) and aquifer settings (Rêgo et al. 2014; Cirilo et al. 2017), are limited and not properly implemented (see section ‘Technical aspects’). As a result, farm location is the defining factor of access to groundwater and there is an uneven water distribution among the farmers. Recently, a water allocation plan limited the area to be irrigated by each farmer, but the compliance should be monitored for further analysis (ANA 2020b). The characteristics of the aquifer, especially its small dimensions and the high temporal and spatial water availability, make the process of matching rules to local conditions in a fair and equitable way more difficult than in the case of regional aquifers.

Regarding the concession of water permits, there are national and state-level principles, rules, instruments and a management system to control the water extraction in the aquifer (governance aspects). However, on the ground extraction mainly depends on water availability, which usually limits exploitation rates, duration and frequency. This indicates that the policies and/or implementation are failing to manage the aquifer effectively. Also, as evidence that the water-permit criteria do not fit alluvial aquifer characteristics, Alves et al. (2018) identified overexploitation in the aquifer, even though most wells had exploitation rates in accordance with the permits; thus, better knowledge of the aquifer yield and well yield could help improve the definition of water-permit criteria, as well as decisions of strategies to optimize the exploitation. The lack of such knowledge restrains the opportunities for governing in congruence with local conditions. The congruence between appropriation and provision rules are influenced by the variation of groundwater availability, which depends on geological and topographic conditions along the aquifer. The analysis of such aspect of this principle is limited in this work and can be further observed in future research.

Collective-choice arrangements

In this case, the collective choice principle can be analysed through two perspectives: (1) rules inside the community, i.e. whether there are mechanisms to guarantee farmers' equity of access and evolution of rules; and (2) rules established outside the community, i.e. whether there are opportunities for community to be able to modify rules governing water resources established at different levels of governance. The governance aspects of the SES demonstrate that, regarding the first perspective, farmers have no say on the use of the resource by other farmers, even though the statute the statute of the cooperative, CAMIS, affirms that "the cooperatives are based on values of mutual help, responsibility, democracy, equality, equity and solidarity", and establishes deliberation mechanisms of voting. This occurs due to the fact that water permits are provided individually by AESA. It is important to highlight that there is no evidence of power asymmetry among farmers influencing such concession of rights, given according to pumping capacity. On the other hand, this arrangement might be hindering the farmers from finding solutions collectively.

Regarding the second perspective, the meetings of the river basin committee are opportunities for the members to participate in the modification of the rules at the river basin level. The representative of the CAMIS is one of the most assiduous members of this committee, but makes few comments, as observed in the minutes; therefore, there is the opportunity for discussing the groundwater use internal arrangements in the CAMIS and the external arrangements through the river basin committee. The fact that farmers do not appear to appreciate or significantly make use of how these cooperative arrangements can improve their access to water and the current water permits scheme suggests that they need more information regarding the opportunities to bring them into discussion both inside and outside the community and thus improve the efficiency of aquifer exploitation.

Monitoring

Continuous monitoring of groundwater level (measurements of the water table) and exploitation (measuring the pumping and/or the irrigated area) has a significant impact on groundwater governance. At the local level, farmers have an idea of who benefits more from water exploitation due to the crop area irrigated, but there is no monitoring of the resource or other farmers' behaviour. This can be partly explained by the lack of knowledge regarding how to use monitoring information and by the fact that the right of using the water is an arrangement between each farmer and AESA. In terms of institutional monitoring, despite the existing regulation, only a small number of wells drilled in the alluvial aquifer are part of the AESA wells registry and there is almost no monitoring of resources or users by the agency. However, the SES characterisation supports the possibility that community responsibility for monitoring is a viable strategy due to the small depth of wells and due to the fact that farmers are in the field on a daily basis. This could support better aquifer management, and it could help farmers understand water flow and develop more reliable information about the aquifer dynamics.

Graduated sanctions

The current governance of the SES means that at the community level, as no internal rules are set, there is no foundation for graduated sanctions. Regulation set by the water policy defines procedures/sanctions to be applied in cases of violation of water permits, such as warnings, suspension of water rights and fines; however, there is a lack of effective implementation, due to the absence of monitoring and enforcement capacity. Improving monitoring of the resource and knowledge of the aquifer yield and groundwater flow, could allow farmers to better regulate the resource use and identify violations. This might support decentralised enforcement; however, applying sanctions would require the farmers to sign up to a formal or informal set of agreements, and for other governance stakeholders (e.g. AESA) to support this more decentralised approach.

Conflict-resolution mechanisms

This principle refers to the importance of providing ways to resolve the conflicts in a short-term period and with low costs, in order to maintain a good relationship among the members of the group, avoid power asymmetry and find fair solutions for sharing the CPR. At the community level, the statute of CAMIS establishes a mechanism for resolution of conflicts between the members. Conflicts have been observed, created by the discontent of some farmers with the actual situation and some hostility among them regarding the differences of water availability/well yield along the aquifer. The river basin committee is supposed to arbitrate conflicts over water use but, considering the scale of the SES studied and of the Paraiba River basin, the committee meetings provide limited means for accessible dispute resolution among the IP farmers. Hence, the mismatch of biophysical and governance scale uncovered by the SES characterisation limits effective conflict resolution.

Minimal recognition of rights to organise

The rights of the community to organize are recognized, as water users and as a cooperative of farmers. However, this principle demands a trust building exercise in both directions: upper-level organisations trusting the community to build good rules, and the community trusting such organisations to not impose rules on them no matter what they do.

Seward and Xu (2018, p. 2) explain that “rules in this case would mean rules about the management of a groundwater resource, rather than (just) the internal institutional operating rules of a groundwater water user association”. The community does not have internal rules to be followed by its members regarding the exploitation of water; however, the CAMIS representative in the Paraiba River Basin Committee has the positive perception that their opinion and concerns are considered, demonstrating that there is recognition of the rights of the farmers to organise. Similarly, the collective water permits are an existing instrument that can provide the community with the opportunity to set the rules for water use within a limit for the total abstraction set by the water policy.

Nested enterprises

The SES characterisation demonstrated that the studied water system sits within interconnected biophysical and governance systems operating at different scales; therefore, there is the need for coordination between the different governance stakeholders across different scales. The river basin limits comprise of an important set of boundaries (e.g. Benito et al. 2010), which is the management unit established in the Water Act but is significantly larger than the scale of aquifer resource use. As described in the governance aspects, institutions from the different levels of governance (national, state, basin and municipal) do affect at the local level (aquifer unit), but there are relevant failures onto addressing these interactions through different institutions over sustainable groundwater. This includes management of the impacts of the related ecosystems (whether positive or negative) on the aquifer, as they influence the system and how the other principles can be applied.

The participation of the cooperative (CAMIS) in the river basin committee could be a route for farmers to influence the governance of their water resources in cooperation with the interconnected systems. However, although CAMIS has voice and vote in the committee as all other members, their demands are frequently dismissed due to the priority of use and relatively low social and economic impact considering their small number. As a result, getting the community to engage in the governance of the CPR is difficult because of decisions that are out of their control affect them in such ways that can make their efforts seem pointless.

6.3 Analysis of social and technological strategies

In analysing whether the governance matches Ostrom' principles, negative interactions and outcomes were identified as a result of biophysical and governance settings of the SES and the interconnected systems (Figure 28). The problems concerning the location of wells and technological strategies, presented in the analysis of the second principle—matching rules governing the CPR to local needs and conditions—reveals that, due to the aquifer characteristics, individual exploitation connected to land location and determined through individual water permits, should be critically examined. Water permits do not seem to be working properly in achieving their purpose in the way that they have been managed. Due to territory dimensions and financial issues, monitoring and sanctioning violations of water use have become a hard task for AESA to manage. The lack of monitoring also reflects the lack of knowledge of the aquifer yield and of the effects of technological strategies in the groundwater flow. Without this information, farmers are not able to visualise the advantages of investing in group organisation, and self preservation leads farmers to act individually to improve personal benefits.

Hence, the analysis suggests that more sustainable use of the alluvial aquifer might be possible if it was governed cooperatively by the community at the local level and was also recognised at the higher levels of government. The analysis highlighted the gaps and opportunities for the implementation of the principles through enhancement of community-based governance. Based on this, the development of five interconnected pillars are suggested as a way to encourage the transition to a more sustainable governance of the alluvial aquifers in this study area and in similar arid and semi-arid regions (Figure 28): the migration to collective water permits, the expansion of community knowledge capacity, the engagement and empowerment of community, an organisation/systematization of technical and financial assistance and the coordination of plans with related systems.

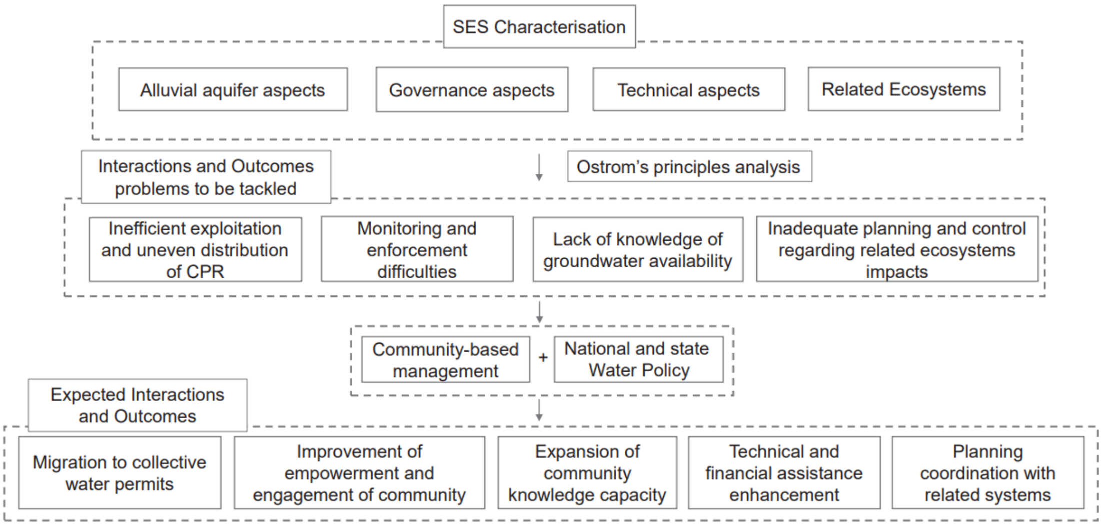

Figure 28: Identification of key problems and opportunities for better governance of the Aquifer (Adapted from Tsuyuguchi et al. 2020)

Collective water permits: The individual water permit establishes an arrangement between the farmers, who are numerous, and the state water agency. In contrast, the collective water permit reduces the number of compliance points to be monitored by AESA and provides the farmers with an opportunity for implementation of their own arrangements (OECD 2015). Reddy (2012) highlights the need for delinking the concepts of groundwater right and land property. With this in mind, the collective water permits could encourage farmers to change their perception of groundwater rights linked to land property and to recognise aquifers as a management unit, providing the farmers with the opportunity for collaboration through community-based governance and acknowledging community's rights to organise, in accordance with the water resources regulations framed by the water policy. The decisions regarding groundwater exploitation at community level can also involve negotiations related to farming activities that affect the aquifer and the group, thus guiding the management of water resources and land use as highlighted in studies on similar systems (Burte et al. 2005; Burte, 2008; Mackay et al. 2005; Walker et al. 2018). The relationship between upstream groundwater inflows and the flow to downstream, suggested by Alves et al. (2018), could be a reasonable criterion for allocating water permits in the aquifer, instead of using the usual measure of pumping capacity. The challenge of getting acceptance of shared permits in the community will require good demonstration of their benefits. Monitoring groundwater flow to the downstream section and modelling tools can support this implementation of water permits. Different arrangements for sharing groundwater can be designed through groundwater flow modelling (e.g. RÊGO 2012) and integration of participatory models approaches as developed by Reddy et al. (2014).

Community empowerment: Although the power of the farmers' cooperative CAMIS has been weakened, the cooperative can provide the basis for community involvement in governance, as described through the principles 1, 3, 6 and 7. There is evidence elsewhere of the benefits of cooperatives. Herrera et al. (2018) analysed a large database regarding Brazilian family farming and found that being part of a cooperative or association was one of the variables that impacted the most the farmers' income. The community empowerment is necessary to help farmers think collectively and manage resources based on cooperation to benefit the whole group. The farmer's high dependence on the water resource causes them to value the cooperative, but their engagement in the governance of the CPR depends also on their understanding of their responsibility as the only users and of the likelihood of reaching more sustainable and efficient exploitation with different arrangements. Sharing of wells can be proposed as an alternative way to increase the role of the community in the governance and management of the aquifer in order to achieve a more efficient exploitation and fairer distribution of the resource (RÊGO 2012). This type of arrangement is a management strategy that can address some issues related to the technological strategies such as underground dams and 'duck bill' wells by: (1) ensuring their installation based on the geological settings and hydrodynamic parameters of the aquifer, producing better results in terms of efficiency; (2) avoiding benefitting one person to the detriment of others thus producing greater benefits to the whole; and (3) facilitating the financing of joint implementation of these structures.

Knowledge capacity**:** There is evidence that the farmers have developed some knowledge regarding the aquifer and groundwater flow during the last decades. This knowledge led some farmers to build underground dams, to construct wells, to demonstrate interest in the monitoring data and to request aquifer recharge with water from the surface reservoir from the water agency; however, improving this knowledge is still needed for both developing strategies and monitoring/controlling the resource. Farmers' participation in the water allocation meetings of the Sume reservoir water system in 2020 indicates that they are aware of the possibility of artificial recharge but that they do need support to increase efficiency at aquifer exploitation and avoid water losses. The literature has shown that good outcomes can be achieved by building the capacity of local leaders to improve shared knowledge, through the combination of knowledge obtained both in the field (with life experience) and with specialists, and through a good relationship developed within the community (FAO 2010; Jadeja et al. 2018). This approach can support the process of building trust inside the community, which is, according to Giest and Howlett (2014), the basis for commons governance, and the engagement of community in the governance of the CPR. Community responsible for water table monitoring supports the process of knowledge building on groundwater availability, and consequently on decision making concerning production and infrastructure investments. Also, such monitoring allows the application of gradual sanctions.

Planning and coordination: Understanding the connections with the broader water system and how decisions at higher levels of governance may impact the resource system, and vice versa, is important for both mitigating external disturbances in the SES and building external support for decisions and strategies (Molle and Mamanpoush 2012; Seward and Xu 2018). Interaction of stakeholders through the river basin committee, long-term planning of water allocations, considering Managed Aquifer Recharge (Billib et al. 1991; Burte et al. 2009; Shubo et al. 2020) and securing allocation from the dam, all require coordination with other agencies. Long-term planning should establish overall guidelines, but as decisions of water allocation depends on the hydrological conditions, which present high variability seasonally and interannually, the decisions should be revisited and re-evaluated in short-term. This pillar applies across different management scales (local, river basin and regional) and sectors (such as water resources, sanitation and land use), and this integration is encouraged, but not appropriately addressed, in the Water Act (Ribeiro 2017).

Technical and financial assistance*:* Technical and financial assistance is necessary in every interaction. The main challenge to providing this assistance is the lack of consideration of the aquifer as a management unit and, in turn, limited coordination of among the responsible organizations. Assistance more focused on sharing knowledge and expanding community capacity can have a significant impact on community empowerment and CPR conservation (Barthel et al. 2017). This requires continuous communication based on training farmers to develop some activities more efficiently, such as irrigation management and monitoring of water table and groundwater use. Importantly, the demand for this support will be reduced as the knowledge and involvement of community increase and as equity and efficiency are improved, hence such assistance can be an investment rather than simply a cost. Moreover, there is need for improving capacity building of institutions responsible for governance and technical support concerning the social and technological strategies that are compatible with local conditions.

Implementing community governance and management is not straightforward, however. A concern raised by Seward and Xu (2018) is the risk of a water user association focusing on the interests of the community while neglecting the sustainability of the interconnected system, but in the case study, the benefits and damages generated are mainly restricted to the community, and the downstream users rights would be protected by the enforcement of collective water permits. Community initiatives regarding the governance of alluvial aquifers are often opportunistic and do not always have concern for sustainable management of the aquifer (Shah 2012), technical assistance is needed support the farmers to understand that this concern is actually essential to protect their interests.

Nonetheless, this research supports the assertion of Reddy (2012) that progress in groundwater management depends on integration of policies and on involvement of local community. For instance, the results align and contribute to water security considering the four dimensions approached in the national water security plan - human, economic, ecosystem, and resilience dimensions (ANA 2019). More sustainable governance arrangements involving greater participation of the community could be put in place through existing rules and guidelines that are in the current policies, but that are not properly explored or implemented. The barriers for this implementation are the need for a shift in the current forms of providing assistance, performing monitoring and providing concessions of water rights. However, addressing these changes are facilitated by the principle of participatory processes enshrined in the water law, the aquifer characteristics that make community participation more favourable, and there is at least a partial network structure capable of supporting these changes. Adopting collective water permits, if they are acceptable to farmers, requires the same technical knowledge from AESA and lower resources with monitoring in comparison with the provision of individual water permits, but higher costs in the initial stage for building community capacity and supporting integration of the community. Furthermore, the State Water Resources Fund provides financial resources for supporting the participatory governance process.

6.4 Protocol for analysis of alluvial aquifers

The characterisation based on the SESF established an effective framework to answer the research questions. A large amount of literature applying this framework over diverse sectors and scales (Partelow 2018; Rica et al. 2018; Basurto et al. 2013) allowed for a good understanding of the second-tier variables and, consequently, for a detailed analysis of Ostrom's principles in the study area. The table S1 presents overall aspects observed for this aquifer, but that also characterizes the aquifer-type. Further information should be included for the second-tiers, according to peculiarities already identified and to new investigations. Application of the SESF identified the key relevant characteristics of the SES to be used in the analysis of the design principles. The challenges found in this analysis should not discourage its use as an approach to achieve better governance of groundwater, but instead emphasize the need for, and guide, efforts fostering appropriate management of the resource, as observed by Ross and Martinez-Santos (2010) and Seward and Xu (2018).

Based on the procedures and analysis developed in this thesis, we propose a protocol for identifying important aspects of the alluvial aquifer and supporting the development of policies and institutional evolution for its governance. Therefore, this protocol result from the analysis developed of both the aquifer conceptual model and the governance, and can support the transition to a more sustainable governance of this aquifer. A system comprising an alluvial aquifer must be analysed to gather all available information and address new investigations. We synthesize below the protocol guidelines concerning the investigation and implementation of governance strategies for these small alluvial aquifers.

I) Hydro(geo)logical characteristics

Perform surveys for gathering information: dimensions of the sediment package (surface area and average depth); hydrodynamic parameters; lithology; natural barriers formed by the presence of clay or variation in the aquifer base; the occurrence of rainfall over the year and how it affects the processes of recharge, groundwater flow and discharge since there is a fast response due to small size of these aquifers. Based on this, groundwater availability can be estimated.

Previous works can provide great information. For the delineation of the aquifer surface area, observation of topography and images can support this work, as well as remote sensing products. They should be analysed jointly with geological surveys for further information of aquifer base and lithology. Field experiments should be performed for building knowledge of the hydrodynamic parameters and groundwater flow, such as pumping tests, slug tests and Guelph permeameter. The information of aquifer depth and lithology obtained during wells' drilling add valuable information and, therefore, must be part of the database constructed by the water agencies. For water table fluctuation a monitoring plan is necessary, considering the possibility of users' participation.

II) Groundwater use

Small alluvial aquifers are mainly used for irrigation and livestock feeding, but can also be a water supply source. The use for human supply can impose tighter restrictions on contamination of water and to the exploitation due to priority of water use. Therefore, it should be carefully observed through agencies registries and field surveys. The exploitation behaviour should be analysed in order to picture the current conditions of use, i.e. volumes of withdrawals and what has been limiting this extraction. This is the base for further definition of measures concerning the control of use and wastewater disposal.

III) Organization of water users

Observe the existence of associations(s) where the users of groundwater from alluvial aquifers and the users of water in the water system in analysis can solve conflicts, such as water users' associations. In the analysis of these aspects, the water system at different scales should be observed (aquifer, river basin or other relevant ones).

The agricultural practices and groundwater exploitation performed by one farmer can affect the amount of groundwater available to the other ones in a very short-term period. Therefore, we call attention to the potential of farmers' cooperative to be this place of discussion in the case of small alluvial aquifers, where negotiations can integrate the management of agriculture and water. Due to the aquifer-type dimensions, and local/regional relevance, these associations or cooperatives are likely to encompass the users of a river reach. The sectioning of the aquifer into reaches along the aquifer can be defined according to the social-ecological aspects, such as the geological settings, the water uses purposes, the water availability and the existing arrangements.

These aspects should be observed in the discussions of the river basin committee meetings, meetings for water allocation by water system (supply reservoir), or other opportunities to discuss water use and set arrangements.

IV) Organizations integration

It is important to list all the organizations that participate in water management and their roles. The summary of organizations interacting should encompass the following: a) the components of the water management system, b) the associations of water users, c) municipal, state and national environment organizations and councils, d) the organizations that provide technical assistance for decisions concerning the use and control of water resources (e.g. irrigation). The consensus concerning the need to look at the alluvial aquifers as a strategic source in the semi-arid region can be built through the water plans, defining specific programs and guidelines for them. There should be also guidelines to regulate the exploitation of the alluvial aquifer considering the permanent preservation areas according to the Brazilian forest code (Law 12651/2012).

V) Development of technological and social strategies

We highlight as potential strategies to be applied for governance of alluvial aquifers: a) the use of underground dams the construction of wells designed considering the hydrogeological and social aspects (such as the duck bill well); b) artificial aquifer recharge using reservoir water and/or rainwater harvesting; c) water table monitoring by farmers; d) sharing wells; e) plans for locating wells and dams; f) collective water permits (i.e. the concession of water rights can define limits of exploitation per reach of the river, instead of individually). It should be observed what strategies are already in place, and what can be done to improve their performance.

VI) Provision of appropriate technical and financial assistance

Technical assistance is supposed not only to provide information concerning the technologies and rational use of water but also to facilitate the development of communication and trust. The database of water table fluctuation and the use of groundwater modelling are essential to define the best strategies. There are several uncertainties in predicting groundwater flow. Modelling is an important tool with uncertainties inherent in the method that can be reduced using better monitoring data series.

Based on the exchange of knowledge between farmers and technical bodies and on the provision of courses and guidance both to farmers and to organizations' staff (such as AESA and EMPAER), these social and technological strategies should be implemented according to the decisions discussed by the stakeholders. This interaction allows to connect different sources of investments and assistance for the rural community and avoid wasting resources. Cooperatively, they can define measures to be compatible and establish preconditions (concerning groundwater interference) to authorize hydraulic structures and provide financial assistance.

Different scenarios should be designed and evaluated, considering location and pumping of underground dams and wells, the occurrence of recharge, irrigation plans, among others. Instead of making rules and control if they are followed, the water agencies can encourage the users to negotiate, given the appropriate support. The state water fund can be applied for this purpose. The meetings for negotiating water allocation by water system/reservoir that ANA has coordinated are an example for this support to be implemented but bringing the alluvial aquifer to attention. Another opportunity for this kind of action is the water control campaigns when the water agency can provide technical support and promote negotiations among the farmers to define groundwater use through collective water permits. In order to maintain the trainings, monitoring works and evolution of institutions and arrangements, several aspects should be considered, such as special technical chambers for alluvial aquifers, support from graduate programs (e.g. ProfÁgua), support from programs (e.g. Progestão), specific legislation for alluvial aquifers, among others.

7. Conclusions

This thesis presents an analysis of a local Brazilian small alluvial aquifer using an SES framework to compare the system’s governance against Ostrom’s principles for common pool resources. Groundwater availability is limited and varies significantly along the aquifer due to the semi-arid features and to the variation in aquifer depth and lithology. Moreover, because of the particular dimensions and low rainfall concentrated in three or four months, the water table behaviour can be very different over the year, presenting a fast response to natural and anthropic factors. The water approximates the surface for a short time in the rainy season, but the aquifer may dry up in some regions during the dry season. These characteristics demand even more action within local management to promote appropriate governance.

Appropriate governance principles provide the basis for improving interactions that are making resource use unsustainable. However, it should be highlighted that the design principles are not rules to follow blindly, but guidelines revealing how a set of factors may affect the outcomes in different ways according to the peculiarities of the focal social-ecological system. It was found that to a large extent the laws, policies and principles seem to be in accordance with Ostrom’s principles, but that implementation is failing, rendering management of the alluvial aquifer unsustainable. The analysis suggests that increasing the level of community participation in governance can contribute to increased sustainability of the resource, improve its extraction and distribution, and raise awareness of alluvial aquifer systems in water resources policy more broadly. This demonstrates the application of the SES framework and the analysis of Ostrom’s principles to a case that is typical of arid and semiarid regions, and the method and findings are likely to be applicable to similar groundwater systems. Thus, based on these approaches, it is possible to develop a protocol and provide a more pragmatic guidance to the institutions and other agents responsible for governing the alluvial aquifer's exploitation.

Farmers are the main interest group in conserving the alluvial aquifer and using it efficiently. Greater cooperation among the farmers can facilitate arrangements for shared wells, which would help to overcome the blueprint thinking of exploitation defined by land location and move toward integrated governance that considers water system boundaries. These arrangements would also help ensure technological strategies for managing the groundwater were more suitable and appropriate. Collective water permits are an important instrument in this process, as they can connect community-based governance to the existing water resource framework. They can be used to shift from a centralised governance, led by institutions without staff capacity to deal with such monitoring and enforcement work, towards a polycentric governance, sharing the responsibility with communities for whom the CPR is more meaningful. However, it will be important to secure agreement of the farmers, and their views on collective permits are not clear. As noted in the discussion, creating more participatory and collaborative governance, even using existing tools, will require awareness raising, resources and capacity building among farmers.

Importantly, there is a role for research and technical assistance from specialised institutions to improve and share knowledge regarding the aquifer, to support the plans and decisions made by the community, considering the water permits, and to make use of modelling tools to reduce uncertainties and increase reliability of management strategies. The fact that the modelling requires data, field knowledge and support of modellers is a clear barrier that could be managed through community engagement, shared knowledge and coordination of governmental and nongovernmental organizations, including Universities. More information on alluvial aquifers throughout the BSA would provide a better understanding of this resource on a regional scale and support development of alternative governance arrangements for more sustainable management of the water resources. Therefore, further research could advance both in groundwater modelling and in the SES characterisation, including other environmental and social performance measures which might reveal further opportunities for improving sustainability.

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8. Appendix A

Table S1 Characterization of the case study by the second-tier variables of the SES Framework (Ostrom, 2009; McGinnis and Ostrom, 2014) linked to the first-tier variables: Resource Systems (RS), Resource Units (RU), Governance systems (GS), Actors (A), Social, economic and political settings (S) and Related Ecosystems (ECO), Interactions (I) and Outcomes (O). (Tsuyuguchi et. al., 2020)

First tiers	Symbol	Second-tiers	Case study
S	S1	Economic Development	Policies for mitigation of water scarcity impacts in the BSA region.
	S2	Demographic trends	Decreasing rural population in municipality.
	S3	Political stability	Relatively stable political situation with some level of democracy and reasonably strong government institutions.
	S4	Other governance systems	Some related governance systems, e.g. sanitation and health governance.
	S5	Markets	Water markets not allowed in the country. Crop production commercialised in the local markets.
	S6	Media organizations	Local, regional and national media accessible in the case study. There is freedom of speech.
	S7	Technology	Water extraction and irrigation technology available, although some are expensive. Internet, telephone and other communication technologies available in the region.
RS	RS1	Sector	Water
	RS2	Clarity of system boundaries	Boundaries are difficult to be defined as the resource is mobile. Boundaries of the aquifer have been well investigated. The boundaries vary according to the water table level.
	RS3	Size of resource system	Small area and volume, as the aquifer is very narrow and shallow. Comparing to the river basin, it is significantly smaller.
	RS4	Human constructed facilities	Exploitation wells and underground dams.
	RS5	Productivity of system dynamics	Low exploitation rates, can be improved considering hydrogeological conditions.
	RS6	Equilibrium properties	High water availability variation over time and along the aquifer.
	RS7	Predictability of system dynamics	Very subjected to the occurrence of rainfall: long dry spells annually and droughts characterize the climate.
	RS8	Storage characteristics	Small, as the aquifer is narrow and shallow, but significant considering the water scarcity conditions.
	RS9	Location	Recharge limited due to the reservoir just upstream. Higher exploitation when comparing to other alluvial aquifers due to the IP created in the 80s

First tiers	Symbol	Second-tiers	Case study
GS	GS1	Government organizations	ANA AESA DNOCS EMPAER SEBRAE Paraiba river basin committee State water resources council Sustainable rural development municipal councils
	GS2	Nongovernment organizations	CAMIS
	GS3	Network structure	National water management system. DNOCS/Irrigated Perimeter. Rural technical assistance.
	GS4	Property-rights systems	Groundwater is under State dominion. Water permit instrument (controlled by AESA) defines the concession of water (how much and for how long).
	GS5	Operational-choice rules	Water permits define limits of exploitation rates.
	GS6	Collective-choice rules	CAMIS, as a cooperative with democratic values, has procedures to be followed for decision making by the members, but there are no rules regarding the aquifer
	GS7	Constitutional-choice rules	Water resources legislation.
	GS8	Monitoring and sanctioning rules	AESA is responsible for monitoring and sanction. There are no rules among farmers.
RU	RU1	Resource unit mobility	The resource is highly mobile and depends on hydrogeological characteristics and extractions.
	RU2	Growth or replacement rate	Easily recharged, but subject to the occurrence of rainfall.
	RU3	Interaction among resource units	Groundwater is the resource unit analysed.
	RU4	Economic value	Economic value of water is low, as no charge is applied for its use by the farmers. However, crop production highly depends on the groundwater, which is an important source of income for the farmers.
	RU5	Number of units	Only one (groundwater).
	RU6	Distinctive characteristics	Distinct hydrogeological conditions along the aquifer result in distinct water availability.
	RU7	Spatial and temporal distribution	Relatively high temporal and spatial distribution.
A	A1	Number of relevant actors	Farmers that exploit the aquifer compose a small group. Number of people working on the mentioned institutions that interact with the farmers is small.
	A2	Socioeconomic attributes	Family farming. Farmers have currently low income from crop and livestock.

First tiers	Symbol	Second-tiers	Case study
A	A3	History or past experiences	Irrigated Perimeter history: high production in the past, due to a greater water availability (reservoir water was used), but current very low production. DNOCS paternalism harmed farmers' interaction among themselves.
	A4	Location	Farmers and their lands are located along the aquifer, which facilitates groundwater use and a clear definition of group boundaries.
	A5	Leadership/entrepreneurship	CAMIS president. River basin representative.
	A6	Norms (trust-reciprocity)/social capital	Limited evidence of trust-reciprocity in resource management but some social capital among farmers and between farmers and government agencies.
	A7	Knowledge of SES/mental models	Limited due to the hidden nature of the resource and high hydrogeological variability hinder the knowledge building on the aquifer. Farmers have developed some knowledge regarding the aquifer and groundwater recharge and flow during the last decades. University has increasing knowledge of the aquifer. Government organizations have knowledge over general processes but lack specific knowledge on resource.
	A8	Importance of resource (dependence)	High dependence of the groundwater for irrigation, as it is the only resource available, besides rainwater harvesting.
	A9	Technologies available	Underground dams and specific well design. Only a few farmers are benefited by these technologies.
I and O	I1	Harvesting	Overexploitation has been identified through modelling.
	I2	Information sharing	Limited knowledge sharing (limited technical assistance and limited interaction between AESA and farmers).
	I3	Deliberation processes	Limited evidence of deliberation in resource management.
	I4	Conflicts	Dissatisfaction of some farmers and some hostility among them regarding differences on water availability/well yield.
	I5	Investment activities	Some limited investment from government and farmers.
	I6	Lobbying activities	Farmers have requested water allocations from the government in the past, but have not been successful.
	I7	Self-organizing activities	CAMIS cooperative partially functioning but with limited support and capacity.
	I8	Networking activities	Meetings of CAMIS cooperative occur (low-frequency, with specific demands).

First tiers	Symbol	Second-tiers	Case study
I and O	I9	Monitoring activities	Monitoring of the water table have been performed by the Federal University of Campina Grande. No monitoring by farmers. Lack of monitoring by AESA due to absence of monitoring and enforcement capacity.
	I10	Evaluative activities	Groundwater modelling results have shown inequality of water exploitation among farmers. Dry wells and very low exploitation rates in some wells indicate inefficient exploitation.
	O1	Social performance measures	Low interaction among farmers, but CAMIS is still functioning in a limited way. Limited shared knowledge among institutions and between institutions and farmers.
	O2	Ecological performance measures	Some measurements have been performed by university.
	O3	Externalities to other SESs	Downstream farmers (lower exploitation, as farmers are more sparsely located).
ECO	ECO1	Climate patterns	Semiarid climate.
	ECO2	Pollution patterns	Wastewater disposal from nearby urban areas affects resource system.
	ECO3	Flows into and out of focal SES	Wastewater recharge. The reservoir disconnects the groundwater system from the river flow system upstream of the reservoir.

8. Appendix B

Water table data of monitoring wells (* means that data was treated, and ND means that no value was informed to complete the charts of Figure 23), in meters (consolidated from data available at UFCG 2019) (cont.).

	Ground surface	Well's base	04/22/15	05/07/15	05/05/15	06/03/15	06/15/15	06/29/15	07/13/15	07/27/15	08/10/15	08/24/15	23/09/15	10/19/15	11/04/15	11/16/15	11/30/15
P03	514.30	510.86	513.51	513.53	513.53	513.49	513.47	513.43	513.42	513.39	513.36	513.31	513.21	513.11	513.06	513	512.89
P33	515.75	511.35	513.78	513.71	513.67	513.64	513.81	513.69	*	513.79	513.81	513.78	513.68	512.92	512.85	512.78	512.75
P04	513.54	510.54	513.44	513.21	513.21	ND	513.49	513.44	513.48	513.44	513.44	513.39	513.44	513.39	513.15	513.11	513.14
P09	511.04	505.34	ND	510.89	510.81	510.92	510.89	*	510.87	510.86	510.89	510.81	510.78	510.41	510.44	510.47	510.31
PZ1	510.08	506.73	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	509.05	508.99
P35	508.35	506.75	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	507.3	507.27	507.3	ND
PZ2	511.24	500.24	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	507.6	507.58
PZ3	509.50	499.70	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	506.52	506.44	506.42	506.51
P12	507.81	502.91	504.46	504.33	504.26	*	504.12	504.07	504.09	503.99	503.92	503.82	503.75	503.67	503.61	503.58	*
P13	506.77	500.87	504.47	504.09	ND	ND	503.87	503.56	503.22	503.64	503.58	503.04	*	503.08	*	503	*
P14	506.56	501.46	504.38	ND	ND	ND	503.83	503.69	503.59	503.48	503.37	503.27	*	*	*	*	*
P16	506.85	502.45	504.3	504.18	504.06	*	503.49	503.63	503.67	503.3	503.3	*	502.92	502.99	503.12	503.17	503.26
P06	505.84	502.59	503.87	503.69	503.49	*	503.28	503.2	*	*	*	*	502.74	*	*	502.4	502.29
P17	505.20	500.80	503.5	ND	503.07	ND	502.9	502.84	502.79	502.8	502.75	502.66	502.34	*	502.27	502.24	*
P28	504.87	501.42	502.47	502.54	502.82	*	503.24	*	*	502.9	502.79	502.54	502.43	*	502.18	*	501.88
P29	503.93	500.53	503.23	502.97	503.05	*	502.81	502.65	502.72	502.61	502.66	502.4	502.29	*	502.18	*	502.03
P18	503.88	499.41	501.83	501.75	ND	ND	501.6	501.55	501.53	501.45	501.43	501.29	*	*	500.79	500.69	500.59
P21	502.70	498.60	500.98	500.91	500.84	*	500.69	500.59	500.49	500.3	500.39	*	*	*	*	*	499.6
P23	500.61	498.01	499.33	499.23	499.17	499.11	499.07	499.01	498.97	498.91	498.89	498.65	498.61	*	498.19	*	*
P24	499.73	495.66	498.79	498.63	498.47	*	498.13	*	497.33	*	497.38	497.22	496.96	*	496.6	496.56	*
PZ4	501.60	495.55	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	497.69	497.58
P25	502.57	494.17	498.67	498.43	498.14	*	497.94	497.83	497.38	497.61	497.53	497.39	*	496.71	*	496.26	496.03
P26	499.44	494.14	498.82	*	*	*	497.86	497.69	497.64	497.58	497.44	497.25	*	496.2	496.11	*	*
P30	498.88	494.48	498.78	ND	498.18	498	497.9	497.8	497.63	*	497.43	497.28	497.16	496.73	*	496.57	*
P32	498.28	494.08	498.28	498.16	498.02	497.88	497.8	497.53	497.46	497.46	497.33	497.22	497	496.77	*	496.61	*

Water table data of monitoring wells (* means that data was treated, and ND means that no value was informed to complete the graphics of Figure 23), in meters (consolidated from data available at UFCG 2019) (cont.)

	12/14/15	12/28/15	01/11/16	01/25/16	02/08/16	02/22/16	03/07/16	03/21/16	04/04/16	04/18/16	05/02/16	05/11/16	05/16/16	05/30/16	06/13/16	06/27/16	07/11/16
P03	512.9	512.73	512.9	513.06	513.08	513.03	513.15	512.97	513.01	512.95	512.97	512.96	512.83	512.83	512.83	512.78	512.76
P33	512.68	512.66	512.9	513.18	513.36	513.29	513.39	513.41	513.28	513.19	513.15	513.18	513.08	513.08	513.01	512.96	512.91
P04	ND	513.16	513.34	513.54	513.54	513.54	513.54	513.54	513.54	513.54	513.54	*	513.54	513.54	513.54	513.54	513.54
P09	510.21	510.16	510.9	510.94	*	511.04	510.82	*	510.9	510.74	510.54	*	510.64	510.64	510.64	510.54	510.47
PZ1	508.93	508.93	509.57	510.08	509.96	509.85	509.76	509.81	509.75	509.63	509.53	509.46	509.49	509.38	509.31	509.26	509.26
P35	ND	ND	508.21	508.35	508.35	508.35	508.15	508.3	508.29	508.33	508.22	*	508.11	508.11	507.92	507.96	507.9
PZ2	507.54	507.5	508.21	508.97	508.72	508.65	508.51	508.61	508.57	508.53	508.42	508.37	508.33	508.43	508.41	ND	ND
PZ3	506.34	506.2	506.67	506.87	507.53	508.15	508	507.95	507.98	507.79	507.74	ND	507.57	507.56	507.36	507.33	507.28
P12	*	*	ND	506.5	507.09	506.74	506.77	507.04	506.65	506.34	506.11	506	505.89	505.88	505.41	505.25	504.96
P13	*	*	ND	506.77	506.77	506.77	506.77	506.77	506.77	506.4	506.17	*	505.99	505.97	505.54	505.29	505.06
P14	502.7	*	ND	506.56	506.56	506.56	506.56	506.56	506.24	505.88	505.59	505.49	505.39	505.37	*	*	504.94
P16	503.26	503.27	503.4	506.85	506.85	506.85	506.85	506.85	506.08	505.7	505.43	*	505.2	505.2	505.13	505.08	504.88
P06	502.19	502.09	504.01	505.84	505.84	505.84	505.84	505.84	505.84	505.02	504.65	504.69	504.62	504.6	504.29	504.09	503.98
P17	*	*	ND	505.05	505.05	504.75	504.57	504.89	504.59	504.44	504.15	*	504.15	504.14	503.7	503.61	503.43
P28	*	*	ND	504.82	504.82	504.87	*	504.87	*	*	*	*	504.16	504.16	503.88	*	*
P29	501.98	*	502.33	503.93	503.93	503.93	503.93	503.93	503.93	503.93	503.93	*	503.93	503.93	503.83	503.69	*
P18	500.49	500.39	ND	503.53	503.53	503.53	503.47	503.53	503.5	503.3	503.08	*	502.95	502.95	502.68	502.56	502.49
P21	499.62	499.55	499.52	502.7	502.7	502.7	502.7	502.7	502.7	502.7	502.6	502.3	502.37	502.36	*	501.89	501.75
P23	ND	ND	ND	499.22	500.61	500.61	500.26	*	500.61	500.61	500.23	*	500.01	500.01	*	499.65	499.39
P24	*	496.59	496.61	498.15	499.33	499.33	499.71	499.33	499.33	499.73	499.43	*	499.21	499.19	498.7	498.4	498.23
PZ4	497.48	497.32	497.23	498.21	498.04	497.97	497.92	498.98	498.84	498.72	498.58	498.44	498.39	498.23	498.08	497.95	497.83
P25	495.9	*	495.72	497.64	497.74	497.65	497.9	498.63	498.31	497.93	*	*	497.28	497.27	*	497.06	496.67
P26	*	*	495.02	498.32	498.35	497.99	497.78	498.94	498.51	498.12	497.79	*	497.62	497.62	497.16	496.91	496.66
P30	*	*	496.29	498.88	498.58	498.08	497.86	498.88	498.48	498.14	*	*	497.62	497.61	497.4	497.26	497.08
P32	*	*	496.27	498.13	498.21	497.79	497.88	*	*	498.23	497.93	*	497.87	497.87	497.51	497.29	497.07

Water table data of monitoring wells (* means that data was treated, and ND means that no value was informed to complete the graphics of Figure 23), in meters (consolidated from data available at UFCG 2019) (cont.)

	07/25/16	08/08/16	08/22/16	09/05/16	09/19/16	10/10/16	10/24/16	11/07/16	11/21/16	12/05/16	12/19/16	01/02/17	01/16/17	01/30/17	02/02/17	02/27/17	03/13/17
P03	512.77	512.74	512.78	512.66	512.62	512.57	512.52	512.47	512.43	512.37	512.32	512.28	512.22	512.17	512.1	512.05	511.99
P33	512.87	512.83	512.76	512.71	512.67	512.62	512.54	512.47	512.42	512.37	512.32	512.28	512.22	512.16	512.12	512.05	512
P04	513.39	513.34	513.25	513.25	513.22	513.09	513.01	512.89	512.78	512.74	512.66	512.6	*	512.5	ND	512.38	512.94
P09	510.32	510.26	510.24	510.22	510.18	510.09	510.04	509.94	509.86	509.79	509.77	509.7	509.66	509.61	509.53	509.49	509.42
PZ1	509.18	509.46	509.26	509.2	509.11	508.92	508.82	508.77	508.71	*	508.57	508.53	508.48	508.43	508.35	508.35	508.35
P35	507.74	507.56	507.41	507.42	507.41	507.26	507.15	507.09	506.98	506.94	506.94	506.92	506.98	506.82	506.75	506.75	ND
PZ2	ND	ND	508.48	508.49	*	*	*	*	*	507.3	507.26	507.24	507.2	507.15	507.1	507.06	507.07
PZ3	507.1	507.03	506.94	506.86	506.78	506.67	506.6	506.52	506.46	506.4	506.35	506.29	506.25	506.19	506.14	506.09	506.05
P12	504.69	504.47	504.31	504.21	504.12	503.97	503.89	503.84	503.78	503.67	503.56	503.47	503.37	503.31	503.25	503.23	503.19
P13	*	504.33	504.18	503.95	503.74	503.63	*	*	503.32	503.26	503.14	503.03	ND	ND	502.33	ND	ND
P14	504.73	*	*	504.27	*	*	*	ND	503.52	*	503.22	*	*	502.98	502.98	*	502.81
P16	504.72	504.6	504.44	504.3	504.16	503.92	503.77	503.64	503.51	503.4	503.28	503.16	503.02	502.9	502.9	502.9	502.9
P06	503.87	503.76	503.64	*	503.41	503.24	503.12	502.98	502.88	502.77	502.59	502.59	502.59	502.59	503.21	502.59	502.59
P17	503.28	*	503.19	503.08	502.84	502.65	*	*	502.47	502.3	502.31	*	502.05	*	502.58	502.3	502.04
P28	503.51	*	*	*	*	502.72	502.52	502.25	502.23	*	502.18	*	502.04	501.85	501.91	501.81	*
P29	503.68	503.36	*	503.1	503	502.86	502.95	502.66	502.42	502.33	502.4	502.29	502.21	502.02	502.44	*	501.97
P18	502.37	*	502.14	502.04	501.94	501.77	501.67	501.59	501.51	501.43	501.32	501.21	501.13	501.06	501.08	500.88	500.83
P21	501.67	501.51	501.39	501.28	501.17	500.98	500.83	500.7	500.58	500.46	500.34	500.21	500.1	499.97	500.1	499.91	499.78
P23	499.4	*	*	*	498.62	498.65	498.29	498.45	498.31	498.3	498.26	498.17	498.11	498.03	*	498.45	498.19
P24	498.14	497.98	497.82	*	497.45	497.24	497.06	496.78	496.47	*	496.37	496.24	496.26	496.2	497.17	496.59	496.28
PZ4	497.71	497.58	497.45	497.32	497.19	497.07	496.95	496.87	496.77	496.32	496.23	496.14	496.05	495.96	495.88	495.55	495.55
P25	496.53	496.31	496.13	496.03	495.86	495.67	495.6	495.46	*	495.27	495.18	495.12	495.07	494.96	495.05	495.1	495.05
P26	496.39	496.39	496.22	496.19	496.15	495.77	495.93	495.2	495.1	494.93	494.81	494.77	494.72	*	495.26	495.41	495.14
P30	496.91	496.73	496.66	496.63	496.54	496.31	496.19	496.2	495.87	495.99	495.86	495.92	495.86	495.55	497.43	496.6	496.26
P32	496.93	496.81	496.71	496.51	496.41	496.29	496.16	496.11	496.03	495.96	495.88	*	495.82	495.75	496.29	495.9	495.8

Water table data of monitoring wells (* means that data was treated, and ND means that no value was informed to complete the graphics of Figure 23), in meters (consolidated from data available at UFCG 2019) (cont.)

	03/27/17	04/10/17	05/01/17	05/15/17	05/30/17	06/23/17	07/28/17	08/11/17	08/25/17	09/01/17	09/15/17	10/04/17	10/27/17	11/15/17	12/01/17	12/22/17	01/18/18
P03	511.98	511.93	511.83	511.77	511.73	511.63	511.56	511.53	511.52	511.48	511.42	511.36	511.26	510.86	510.86	510.86	510.86
P33	512.23	512.28	512.24	512.28	512.3	512.34	512.42	512.43	512.42	512.48	512.41	512.38	512.23	512.12	512.05	511.96	ND
P04	513.21	513.17	ND	513.54	513.54	513.54	513.54	513.54	513.54	513.54	513.54	*	513.54	*	512.51	*	512.39
P09	510.24	510.01	509.74	510.36	510.39	510.7	510.54	510.35	510.3	510.38	510.32	510.14	509.74	509.68	509.57	509.45	509.28
PZ1	508.64	508.49	*	508.5	508.38	508.35	508.41	508.41	*	508.57	508.8	508.35	508.41	508.24	508.17	508.08	508
P35	506.8	506.75	506.98	507.66	508.02	508.24	508.28	507.84	507.42	507.54	507.43	507.23	ND	506.8	506.89	506.86	506.75
PZ2	507.28	507.22	507.06	507.38	507.62	507.83	507.93	507.78	ND	ND	ND	507.29	507.14	506.96	506.92	506.9	506.87
PZ3	506.11	506.06	506.01	506.01	506.34	506.27	506.29	506.29	ND	506.25	506.22	506.17	506.09	506.01	505.95	505.89	505.79
P12	503.17	503.11	503.02	503.45	503.41	503.17	503.1	503.02	*	502.91	502.91	502.91	502.91	502.91	502.91	502.91	502.91
P13	502.57	502.52	*	*	502.7	501.6	502.17	501.44	501.6	501.61	501.79	501.57	501.27	501.19	501.13	501.06	500.99
P14	502.93	502.67	*	502.77	502.92	502.71	502.68	502.59	502.46	502.48	502.41	502.11	502.04	501.99	502.12	501.88	501.84
P16	502.9	502.9	502.9	502.9	503.34	503.1	502.9	502.9	502.9	502.9	502.9	503.08	502.9	502.9	502.9	502.9	502.9
P06	502.59	502.59	502.59	502.59	503.26	502.59	502.59	502.59	502.59	502.59	502.59	502.59	502.59	502.59	502.59	502.59	502.59
P17	501.77	501.82	501.77	501.91	502.25	501.87	*	501.4	*	501.25	*	500.97	501.23	501.13	501.02	500.91	500.8
P28	501.71	501.7	501.62	501.94	501.93	501.65	501.96	501.52	*	501.47	501.52	501.42	501.42	501.42	501.42	501.42	501.42
P29	501.88	501.75	501.66	501.59	502.23	501.59	501.56	501.47	501.5	ND	ND	ND	ND	ND	ND	500.53	500.53
P18	*	*	*	500.41	*	*	500.15	499.82	499.93	500	*	499.81	499.83	499.76	499.7	499.64	499.59
P21	499.68	499.57	499.44	499.37	499.38	*	498.6	498.6	498.6	498.6	498.6	498.6	498.6	498.6	498.6	498.6	498.6
P23	498.01	*	498.01	498.01	498.61	498.01	498.01	498.01	*	498.01	498.01	498.01	498.01	498.01	498.01	498.01	498.01
P24	*	*	496.11	496.75	496.9	496.46	496.19	496.11	496.08	495.99	495.66	495.66	495.66	495.66	495.66	495.66	495.66
PZ4	495.55	495.55	495.55	495.55	496.66	496.65	495.88	495.55	495.55	495.55	495.55	495.55	495.55	495.55	495.55	495.55	495.55
P25	495	*	494.82	496.08	496.37	496.18	495.83	495.67	*	495.4	495.21	495.27	494.17	494.17	494.17	494.17	494.17
P26	494.94	494.65	494.51	497.48	*	496.21	*	495.22	*	*	494.7	494.49	494.44	494.34	*	*	494.14
P30	495.98	495.91	495.73	497.91	497.19	496.46	496.18	496.03	495.84	495.82	*	495.61	495.46	495.21	495.33	495.33	495.37
P32	495.73	495.68	495.62	495.58	495.73	495.67	495.61	495.57	495.53	495.49	495.45	495.41	495.33	495.25	495.2	495.12	495.09

Water table data of monitoring wells (* means that data was treated, and ND means that no value was informed to complete the graphics of Figure 23), in meters (consolidated from data available at UFCG 2019)

	02/09/18	02/26/18	03/09/18	03/26/18	04/09/18	4/26/18	5/11/18	6/9/18	8/16/18	9/11/18	10/18/18	11/26/18	12/20/18	1/11/19	3/15/19	4/11/19	5/28/19
P03	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86	510.86
P33	ND	511.98	512.03	512.14	512.47	513	512.91	512.96	512.82	512.63	512.23	512.25	512.12	ND	512.13	512.99	513.47
P04	512.38	513.19	513.54	513.52	513.54	513.54	513.44	513.49	513.24	513.19	513.14	513.08	513.09	ND	513.39	513.04	513.39
P09	509.37	509.48	509.48	510.44	511.04	*	510.8	510.69	510.28	510.09	509.87	509.59	509.46	509.31	510.99	511.04	511.04
PZ1	507.97	508.44	508.47	509.02	510.08	*	509.63	509.49	509.32	509.14	508.93	509.16	508.76	508.86	509.74	ND	510.08
P35	506.93	507.95	ND	508.35	508.35	ND	508.35	508.35	ND	508.38	508.35	508.18	ND	508.3	ND	ND	ND
PZ2	506.9	507.36	507.95	508.08	508.9	508.8	508.74	508.63	508.43	508.33	508.22	508.03	508.17	508.07	508.88	509.15	508.92
PZ3	505.74	506.31	506.84	507.41	508.58	508.67	ND	508.61	507.8	507.42	507.23	507.02	ND	507.27	507.53	508.46	508.74
P12	502.91	503.53	503.98	504.51	506.66	506.89	507.18	506.64	505.96	505.66	505.16	504.49	504.31	504.03	504.01	507.41	507.3
P13	*	502.21	502.73	506.77	506.77	506.77	506.77	506.67	*	504.57	503.79	503.59	503.2	502.87	503.34	506.77	506.77
P14	501.7	502.32	503.58	506.56	506.56	506.56	506.56	506.56	505.24	504.86	504.54	504.14	503.94	503.63	503.69	506.56	506.56
P16	502.9	503.45	504.16	506.85	*	*	506.85	506.85	505.06	504.6	504.4	504.02	503.82	503.5	503.64	506.9	506.9
P06	502.59	502.59	ND	505.84	505.84	505.84	505.84	504.98	504.05	503.69	503.23	502.82	502.7	502.59	502.59	505.84	505.84
P17	500.8	502.16	502.94	505.2	505.2	505.2	505.2	505.2	ND	ND	ND	ND	ND	ND	ND	ND	ND
P28	501.42	502.87	503.05	504.87	504.87	504.87	504.87	504.23	503.6	503.32	503	502.5	502.45	502.2	503.26	504.87	504.87
P29	500.53	501.8	503.93	503.93	503.93	503.93	503.93	503.93	503.45	503.24	502.91	502.54	502.39	502.12	503.16	ND	ND
P18	499.49	501.3	ND	503.88	503.88	503.88	503.88	503.88	502.37	500.46	500.31	500.31	500.43	500.8	501.54	503.88	503.88
P21	498.6	498.6	500.83	502.7	502.7	*	502.7	502.7	502.04	501.73	501.33	500.7	500.7	500.3	500.18	502.7	502.7
P23	498.01	499.31	500.61	500.61	500.61	500.61	500.61	500.61	500.41	*	499.89	499.02	498.51	498.01	498.01	500.61	ND
P24	495.66	498.56	*	499.73	499.73	499.73	499.73	499.73	499.29	498.93	498.53	498.02	ND	ND	ND	499.73	499.73
PZ4	495.55	495.55	496.9	498.76	498.59	498.63	498.77	498.81	498.08	497.74	497.28	496.8	496.56	496.2	496.72	498.26	499.54
P25	494.17	495.42	*	497.66	499.08	499.35	499.27	498.83	ND	497.53	497.12	496.67	496.41	496.01	497.25	499.13	499.56
P26	494.34	499.44	499.44	499.44	499.44	499.44	499.44	499.44	*	496.94	496.72	496.05	495.44	495	496.21	499.44	499.44
P30	495.17	498.05	498.88	498.88	498.88	498.88	498.88	498.88	498.28	497.93	497.48	497.28	496.9	496.48	498.08	498.88	498.88
P32	494.99	496.09	497.08	498.28	498.28	498.28	498.28	498.28	ND	ND	ND	ND	ND	ND	ND	ND	ND