Governance of alluvial aquifers and community participation: a social-ecological systems analysis of the Brazilian semi-arid region

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Abstract

Small and shallow alluvial aquifers in arid and semi-arid regions compose an important water system that smallholder farmers rely on 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. Treating a case of alluvial aquifers exploited by smallholder farmers located in the Brazilian semi-arid region as a common pool resource (CPR), this paper analyses the governance of a social-ecological system (SES) for which an alluvial aquifer is an essential source of water. The paper applies the SES Framework to analyse the SES in light of Ostrom's principles for sustainable CPR management to answer the questions: (a) can the governance arrangements support sustainable common pool resource management of the alluvial aquifers? (b) what opportunities are there to make the management of the aquifer more sustainable through community-based governance? (c) 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 the implementation of these policies are identified. Taking into account 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. This work concludes with suggestions that could empower community progress towards more sustainable governance of the aquifer.

Keywords

Groundwater management, Brazil, arid regions, alluvial aquifers, socio-economic aspects

1. Introduction

Water scarcity, which can be defined as the imbalance between the water supply availability and the demands for meeting the needs of ecosystems and people in a given area, is a global concern that affects the livelihoods of people on different spatial and temporal scales (UNDP 2013). It is a problem faced by 4 billion people in the world for at least one month of the year (Mekonnen and Hoekstra 2016) and is exacerbated by population growth and climate change. Climate change is expected to be a "poverty multiplier", with impacts on agriculture being one of the main drivers "to force more than 3 million to 16 million people into extreme poverty" (Hoegh-Guldberg et al. 2018, p. 244) and part of this is due to increased risk of water scarcity. However, recent research has argued 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 the governance of water systems (Tan et al. 2012; Durán-Sánchez et al. 2019 ; OECD 2015).

Groundwater has become an increasingly important source of water over the past century, now representing approximately 1/3 of water consumed in the world (UN Environment 2019) and the imbalance between water extraction and aquifer recharge has been causing aquifer depletion globally (Wada et al. 2010). Systems that are dependent on groundwater face particular governance challenges. The limited knowledge of these groundwater resources and their systems among both the scientific community and stakeholders is a critical barrier for developing an appropriate governance, due to their hidden nature, recent higher exploitation, and costly monitoring and assessment (López-Corona et al. 2013; Bhattacharjee et al. 2019).

In order to overcome these challenges, it has been argued that community participation in groundwater governance 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; Reddy et al. 2014; 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 putting 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 10 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.

Alluvial aquifers, which are formed on the beds and banks of rivers, from the deposition of sediments carried by the action of runoff, are an important source of water in arid and semi-arid regions (Dahlin and Owen 2005; Morin et al. 2009; Andrade et al. 2014; Mvandaba et al. 2018; Walker et al. 2018) . These aquifers, although small and shallow, compose an important water system, which smallholder farmers rely on for irrigation and livestock feeding (Owen et al. 1989; Mackay et al. 2005; Burte et al. 2011; Alves et al. 2018; Rêgo 2012). The small scale of such systems is a complicating aspect for their governance, which causes them to be missed in the broader scale regulation/governance (Benito et al. 2010). While a considerable body of research has investigated strategies for the management of such aquifers (Billib et al. 1991; Burte et al. 2005, 2009; Missimer et al. 2015; Cirilo et al. 2017; Sarma and Xu 2017), analysis of their governance, regulation and of stakeholders' roles is still scarce. Furthermore, a more polycentric approach to integrated water resources management (IWRM) in "minor aquifers of shallow depth and patchy distribution" (Foster and Ait-Kadi 2012, p. 416) requires a deep analysis of the governance of such aquifers.

Treating the case of alluvial aquifers located in the Brazilian semi-arid region (BSA) as a CPR exploited by smallholder farmers, this paper analyses the governance of a SES in which alluvial aquifers are an essential source of water. This analysis seeks to answer the following questions that arise from the above discussion: (a) can the governance arrangements support sustainable common pool resource management of the alluvial aquifers? (b) what opportunities are there to make the management of the aquifer more sustainable through community-based governance? (c) can Ostrom's design principles lead the transition to more sustainable governance of alluvial aquifers?

2. Study area

The study area (Fig. 1) is a collection of farms within an irrigated perimeter (IP) on the Sucuru River, Paraiba River Basin, which now rely heavily on groundwater extraction from the alluvial aquifer. The IP was installed in the 1970s and irrigation was supplied by a surface water reservoir. In the 1980s, water supply for irrigation was interrupted in order to assure priority to the supply of the city of Sume and surrounding area (MIN 2007). The interruption of canal-water irrigation led farmers to gradually start exploiting the limited groundwater source to complement the scarce rain-fed irrigation, with some support from state government-funded projects (Mendonça 2010). Farmers have then been forced to dig wells and act individually to secure their water. Only 17 farms – from the initial number of 52 farms at the establishment of the irrigation perimeter – have been able to maintain irrigation activities. The total cultivated area in the IP varies seasonally, currently from 8 ha to 43 ha, compared to an area of 287 ha previously projected to be irrigated. Livestock production has increased, but it remains limited by the water availability and there has been a very low seasonal variation in the total number of animals (mostly sheep) of around 1400. 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.

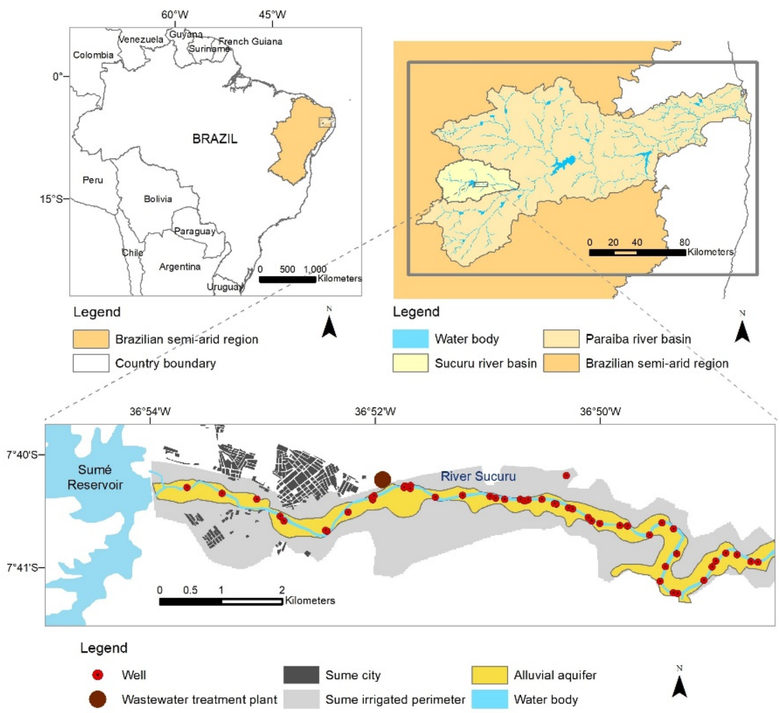

Fig. 1 Study area

The average annual precipitation is about 600 mm, while the average potential evapotranspiration is 2000 mm/year. Climate variability is marked by strong seasonality, with a concentrated 3-month rainy season between January and June, and a dry season that lasts for most of the year (Schimmelpfennig et al. 2018). The Sume Reservoir (capacity of approximately 45 million m^3), just upstream of the study area, controls the intermittent flow of the Sucuru River. Due to the reservoir size and rainfall regime, just a few episodes of overflow were registered, demonstrating that the recharge of the aquifer is limited by the reservoir. The river basin area is characterised by bedrock covered with a thin layer of soil, where the infiltrated water is mostly consumed by the evapotranspiration process, resulting in only a small amount of water recharging the aquifer through the river tributaries. There is also recharge from wastewater from the city that is disposed into the riverbed in the upstream region.

The case is representative of the BSA region (Fig. 1). As the region is mostly underlain by crystalline rocks, 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).

3. Methodology

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* (Fig. 2). Characterisation and analysis of the SES is based on document analysis and data gathered from the study area by an ongoing research collaboration in the study area, summarized in the previous section (Schimmelpfennig et al. 2018). The document analysis includes laws, decrees and plans regulating the water resources in the BSA, the statute governing an existing cooperative of farmers, minutes of collegiate bodies meetings, and reports and research material on both formal and informal governance arrangements, the roles of different organisations and attitudes towards resource use.

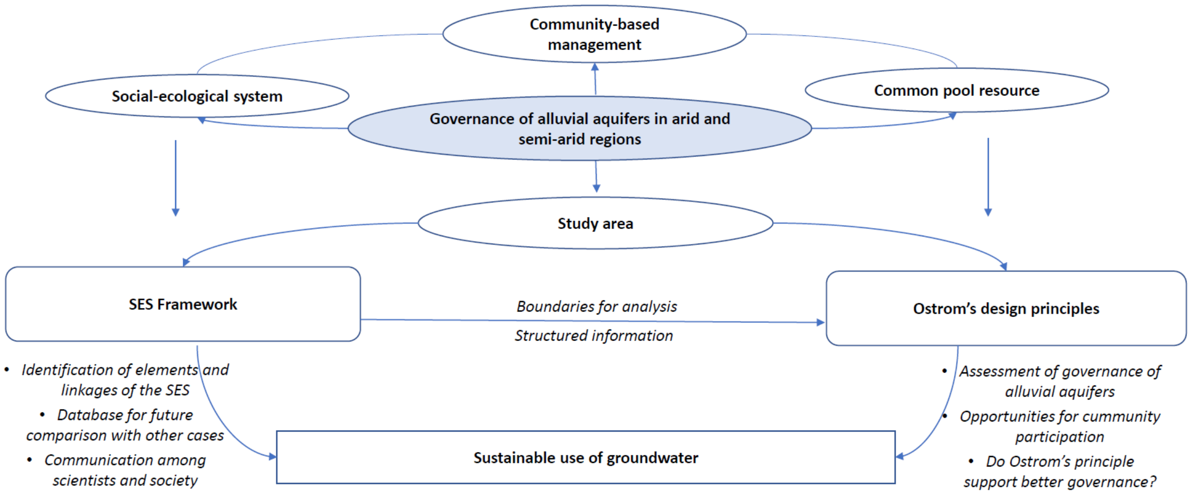

Fig. 2 Summary of research approach for this study

3.1 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 Fig. 3. 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)).

3.2 Governance analysis of SES

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 that were following the path to the "tragedy of the commons" (Gardner et al. 1990). They are briefly described in Table 1. 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 1 Description of Ostrom's design principles adapted from Ostrom (1990)

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*

4. SES Characterisation

The *focal* SES is defined as follows (Fig. 3). 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.

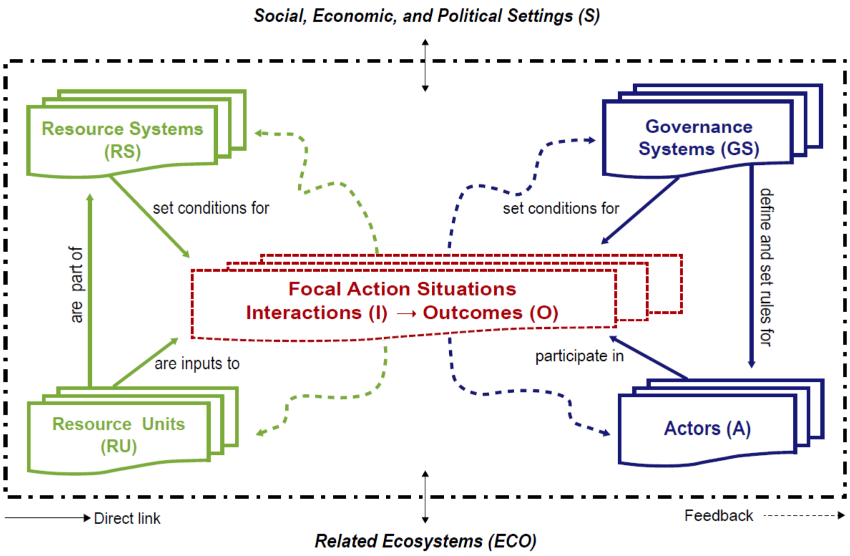

Fig. 3 The core subsystem in the framework for analyzing social-ecological systems (McGinnis and Ostrom, 2014)

The characterisation of the system according to the second tiers of the SESF is presented in Table S1 of the ESM. These characteristics are synthetised into four aspects (Table 2): 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.

Table 2 Characterisation of the focal SES

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)		

4.1 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 hectares, with a width of 50 to 500 meters and a depth of 0.5 to 15 meters (Schimmelpfennig et al. 2018). With a storage capacity estimated at 1,700,000 m^3, 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.

4.2 Governance aspects

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

Table 3 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).

Group	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.
	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 m^3/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.
	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
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 (EMATER), 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 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, EMATER and SEBRAE (state), river basin committee (basin) and rural development councils (municipal).

4.3 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.

4.4 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.

5 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.

5.1 Clearly defined boundaries

Following Cox et al. (2010) this principle is separated into (a) resources boundaries and (b) 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).

5.2 Congruence between appropriation and provision rules and local conditions

At the local level, there are 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. 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.

5.3 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, because the water permits are provided individually by AESA, even though they are directly affected. However, 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. 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.

5.4 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.

5.5 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.

5.6 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.

5.7 Minimal recognition of rights to organise

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, suggesting that there is some 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.

5.8 Nested enterprises

The SES characterisation demonstrated that the studied water system sits within interconnected biophyscial 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 is a route for farmers to influence the governance of their water resources in cooperation with the interconnected systems, but they will always have a limited voice in wider governance, due to their small numbers. 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. Discussion

The characterization based on the SESF established an effective framework to answer the research questions. The 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. 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).

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 (Fig. 4). 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.

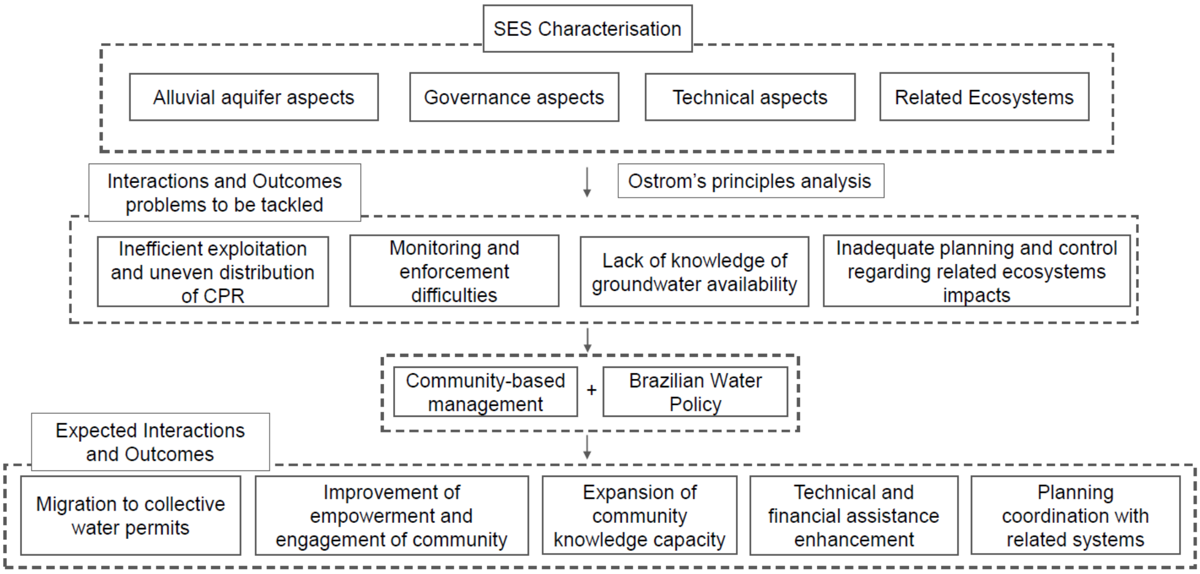

Fig. 4 Identification of key problems and opportunities for better governance of the aquifer

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 (Fig. 4): 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.

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; 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 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: a) ensuring their installation based on the geological settings and hydrodynamic parameters of the aquifer, producing better results in terms of efficiency; b) avoiding benefitting one person to the detriment of others thus producing greater benefits to the whole; and c) 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. 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 (Jadeja et al. 2018; FAO 2010). 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.

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). Long-term planning of water allocations, considering Managed Aquifer Recharge (Billib et al. 1991) and securing allocation from the dam, all require coordination with other agencies. 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). 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.

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 don't 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. 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.

7. Conclusions

This paper 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. 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 semi-arid regions, and the method and findings are likely to be applicable to similar groundwater systems. Further research could add more detail to the SES characterisation, including social performance measures which might reveal further opportunities for improving sustainability.

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.

Acknowledgements

The authors would like to thank the editors and anonymous reviewers for their valuable comments and suggestions that helped to improve the paper. The research reported in this paper was funded by the Brazilian Agencies CAPES (Finance Code 001), CNPq (grants 550059/2014-8 and 310789/2016-8), FINEP (grant 01.13.0340.00) and FAPESQ/PB, through 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".

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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).

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.
GS	GS1	Government organizations	ANA AESA DNOCS EMATER 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.
First tiers	**Symbol**	**Second-tiers**	**Case study**
GS	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.
	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.

First tiers	**Symbol**	**Second-tiers**	**Case study**

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).
	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.