# Hydrogeomorphology of Brazilian Springs: Between Diversity and Lack of Knowledge

**Mirella Nazareth de Moura and Miguel Fernandes Felippe**

**Abstract** The springs are understood as complex environmental systems, in which hydrogeomorphological processes are engendered in an inter-scalar manner, under the influence of regional factors (such as climate and geology) and local factors (such as the depth of the alteration mantle and the position of rocky outcrops). The uniqueness of the springs from an ecological, hydrological, and social point of view has drawn the attention of researchers from various fields of knowledge, who are unanimous about the urgency of establishing protection actions for the springs, both globally and associated with the environmental policies of each country. However, a major obstacle on this path is the lack of methodologies for recognition and evaluation of springs that do not obliterate their physiographic and physiological diversity. Based on the continental dimensions and landscape variability of Brazil, this chapter brings to light the problem of classifying the springs, considered one of the first steps toward establishing management and conservation actions for these systems.

## 1 The Springs as Complex Environmental Systems

The academic literature is consistent in defending the importance of springs. These complex systems are noteworthy, since they are configured as unique and heterogeneous environments, endowed with functions and processes not only geomorphological and hydrological but also ecological and social (Valente and Gomes 2005; Springer and Stevens 2009; Felippe and Magalhães 2014; Moura 2020). Felippe and Magalhães (2009) highlight the importance of springs for society since rainwater is ephemeral, consequently, it falls on the perennial springs (fed by baseflow) the task of maintaining the flows of rivers and streams, even in dry seasons.

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However, such relevance has not been manifested in significant advances in the management of springs, so that there is an insufficient regulatory framework for the protection of springs in Brazil (Carmo et al. 2014). Added to this is the fact that, worldwide, research that takes them as objects of study is still scarce (Springer and Stevens 2009), despite being urgent (Stevens et al. 2021; Cantonati et al. 2020). Therefore, several topics for understanding and protecting springs are unclear and unanswered, not only by the complexity of this problem but also by the lack of theoretical and methodological bases. Considering the global threat to spring ecosystems illustrated by Stevens et al. (2021), the reality of Brazilian springs is no exception to the rule.

Brazil is worldwide renowned for its apparent water abundance. The climatic characteristics of most of its territory result in an imposing discharge of freshwater to river systems and, consequently, a robust water production; except in the semi-arid region of the Northeast, which occupies approximately 12% of the country (Sant'anna Neto et al. 2015). These climatic characteristics are consistent with a wide variety of landscapes, from the subtropical hills of the South to the dense equatorial forests of the Amazon, to the forest-covered mountain systems of the Atlantic façade and the semi-humid savannas of Central Brazil. The country is home to some of the largest rivers in the world and aquifers of great continental importance (such as the Guarani and Alter do Chão systems), with a relevant discharge of underground water.

In this context, it is estimated that the density of springs in the territory varies considerably, with works showing from 1.9 springs per km$^2$, in the semi-humid karstic depression, to more than 28 springs per km$^2$ on the Atlantic plateau.

However, little is known about the springs in Brazil. With continental dimensions, much of the territory lacks systematized information, especially in the interior of the country. Furthermore, governmental efforts at cataloging, mapping, and monitoring are incipient and disparate. Of the few studies already published that take the springs as objects of investigation, most deprive themselves of a more robust and sophisticated discussion, dodging the integration of them with the landscape that shelters them. The most recurrent theme is the quality of the springs, usually linked to the conformity of the permanent preservation areas and the contamination of their waters. Almost always, the springs are understood in a limited way, without recognizing the physiographic and physiological diversity of these systems. In the field of geomorphology, the aridity of investigations is even more notorious.

It is at this conjuncture that an international mobilization for the protection of springs has begun. Researchers from different countries have raised an urgent plea to incorporate springs as objects of cross-cutting studies between ecology, geology, and geography in order to build the necessary foundations for the efficient management of these systems. In summary, it can be said that on a global scale, there are major gaps in water exploitation policies, the mapping of springs is inadequate, the assessment protocols are insufficient and inconsistent, leading to fragile inventories on the springs, even in countries with tradition in research on the subject (Gerecke et al. 2011; Cantonati et al. 2020; Stevens et al. 2021). In the Brazilian context, to all these weaknesses can be added the mismatch between public policies on the environment and water resources, the lack of investment in basic research (especially in the socio-environmental area), the great socio-cultural and physical-geographic diversity of the territory, the regional inequality of knowledge about the springs and a shallow and mistaken idea of water abundance (Magalhães and Felippe 2012).

However, in spite of the unfavorable situation, Brazilian researchers are making commendable efforts that are gradually contributing to the advancement of the study of springs. It is already known that the Brazilian springs (Fig. 1) are mostly small discharges and configured hydroecologically as helocrene and reocrene, fed by local


**Fig. 1** Diversity of Brazilian springs: **a** healthy wetland spring—Pantanal; **b** karstic spring used for agriculture and livestock—Semi-humid Central Brazil; **c** limnocrene spring under pressure of livestock—Semi-humid Central Brazil; **d** small helocrene spring—Atlantic Tropical Brazil; **e** pristine piping spring in protected area—Atlantic Tropical Brazil; **f** helocrene spring—Subtropical Brazilian Coastline. Photos: Miguel F. Felippe

underground flows, and vary in their perenniality according to multiple climatic contexts (Felippe and Magalhães 2014; Carvalho et al. 2015). A very strong indication of the importance of the rainfall regime for the hydrological dynamics of the springs is that most Brazilian springs have water between 12 and 60 years of return period, configuring themselves as modern waters (Felippe 2013).

Even though the Brazilian Forest Code mandates a 50 m radius of permanent preservation area for springs throughout the country, this is recurrently ignored. Studies in rural areas show that over 70% of springs are of low environmental quality (Gonzalez and Schiavinato 2019; Rezende and Luca 2017). An example of source degradation is that of Belo Horizonte (Brazil's sixth-largest city), where even urban parks report 35% of springs with moderate or worse integrity, and 24% with the presence of Salmonella sp. in the waters (Magalhães and Felippe 2012). The main pressures on Brazilian springs result from urban expansion, livestock and agricultural use, mining, and deforestation. However, the biggest challenge regarding the protection of springs in Brazil is the awareness of their diversity, functioning, and importance.

Part of these challenges is based on the difficulty of understanding the springs as a systemic whole that goes beyond the water that drains into them. In both technical-scientific and popular circles, the centrality of the "production" of water from the springs means that other elements that are extremely important for their functioning are obliterated. However, the spring is more than the water that flows from it, it is a whole "environmental system in which the upwelling of groundwater naturally occurs temporarily or perennially, and whose hydrological flows in the surface phase are integrated into the drainage network" (Felippe and Magalhães 2013). They thus engender a morphological subsystem and a hydrological subsystem that support the life (ecosystem) of the springs (Fig. 2).

Moreover, the permanent input and output of matter and energy of the spring, promotes new dynamics between the elements of the system, which brings up the debate of complexity in the understanding of the springs (Moura 2020). In the understanding of Morin (2015), any situation within a system can occur, as it may simply not occur, since complex systems are endowed with full autonomy, where the frequent instability creates opportunities for movement in the system, generating new forms of behavior. They are able to create opportunities for actions, interrelationships, and recursions, producing new ways for subjects to relate, subjectivating them, and producing new modes of existence (Alves and Seminotti 2006).

It is assumed here that the unstable and autonomous behavior of the spring system is configured as disorderly, unpredictable, unbalanced, and even chaotic, like any complex system (Moura 2020). For this reason, linear visions based on the balance of matter (water) are fragile and insufficient to understand the springs.

The Brazilian context, of great environmental and social diversity in its territory, only reinforces this assertion. Obviously, the springs in the Pantanal, on the thick Quaternary sedimentary packages in a sub-humid climate, will be different from those on the karstic terrains under the hot semi-humid climate of the São Francisco Depression. Therefore, we advocate the indispensable need to know the physiography and physiology of the springs, contextualize them in their regional environment, and

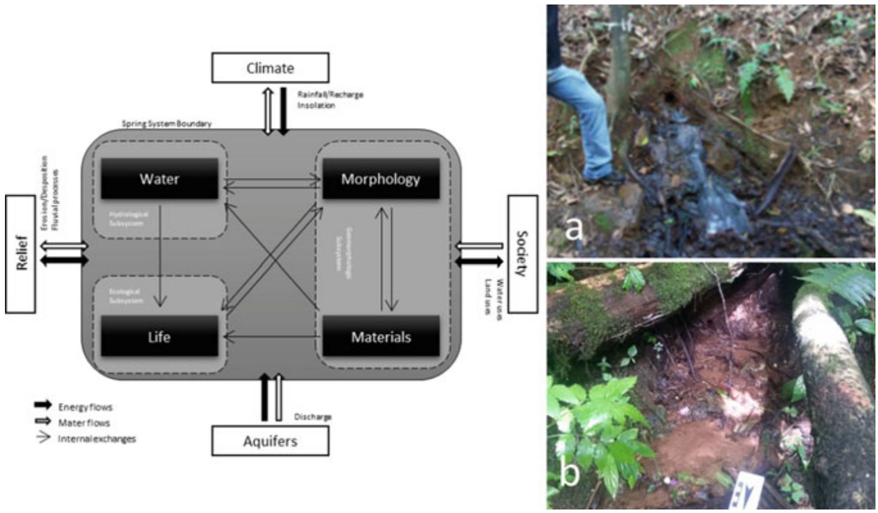


**Fig. 2** Representation of the spring system based on Felippe (2013). **a** Point spring in piping, located in the Quadrilátero Ferrífero Mountains, in Belo Horizonte, MG. **b** Point spring in erosion channel, located in Serra dos Órgãos, Petrópolis, RJ. Photos: Miguel Felipe

understand the dynamics of the inter-scalar processes that constitute them, in order to identify the human pressures, they suffer and thus think about effective protection of these systems. One of the most important scientific artifices used for this is the systematization of heterogeneous elements into groups or classes of similarities.

The international literature traces back to Bryan's efforts (1919) the first broader attempt to systematize springs. For almost a century, this hydrogeological view persisted as the main key to classifying springs in the world, until Springer and Stevens (2009) compiled efforts made for years in springs in the southwestern United States. From this work, a classification based on the hydro-ecology of the springs was disseminated, becoming widely used in the international literature. For the Brazilian context, based on empirical data combined with fuzzy statistics, Felippe (2009) presents a systematization of the hydrogeomorphology of the springs in a new classification.

Thus, we are faced with two major problems: The urgency of systematization of knowledge about springs and the many typologies of springs that already exist. This leads us to a major question: which typology of spring, or rather, which classification key is the most appropriate for studying Brazil's springs?

Therefore, in this work, it was seen as very appropriate to make a comparison between the three types of springs, since, in the technical field, knowing well the springs, their characteristics, and classifications, are important tools for better management and environmental planning. From an academic perspective, this comparison allows the understanding of the different ways of systematizing knowledge about the springs, giving the researcher the opportunity to learn about the different theoretical and methodological spheres covered by the spring system.

However, it should be noted that for any classification proposals, knowledge of a spring comes first from its physiographic description. Subsequently, the application of a typology of springs allows them to be grouped according to their similarities. Such an artifice is essential for the protection of springs because with an efficient classification, management strategies can be drawn up to ensure their environmental protection.

## 2 Recognizing Brazilian Springs

The main contribution that geomorphological science can make to the study of springs in Brazil is to show that not all springs are the same. The inter-scalar relations between the elements of the vertical and horizontal structure of the landscape promote distinct hydrogeomorphological processes in space and time. Thus, it is to be expected that the set of springs in the South Amazonian crystalline depression, for example, is different (in hydrogeological and hydrogeomorphological terms, but also in ecological, economic, and socio-cultural terms) from the springs in the sedimentary plateaus of Central Brazil (as shown in Fig. 1).

However, within the same landscape unit, springs can occur under different physiographies due to local factors. For this reason, it is relatively common in a field reconnaissance to identify springs with completely different hydrogeomorphological and ecological aspects, even if they are spatially close. Added to this is the lack of understanding of the natural evolution of the springs (from the development of the drainage network, for example), which can cause two "neighboring" springs to be in different temporal stages of evolution (under the logic of homeostasis of the environmental system).

As seen in Fig. 2, the influences of the external elements on the spring system provide matter and energy to be worked on in the internal subsystems. Furthermore, regional factors are determinants in understanding the springs, although the local scale cannot be ignored. Thus, free and granular aquifers have a different influence from fissured and deep aquifers. More or less friable rocks tend to produce more or less thick alteration mantles, which is another extremely relevant factor. In addition, climate, together with baseflow, will be determinant for the flow of springs, not only due to the occurrence of specific precipitation events but especially due to the seasonality of the rainy season and its relevance in the recharge of aquifers. Finally, relief and society come together to direct water flows and control the distribution of water within the hydrological cycle (Felippe and Magalhães 2014).

In Brazil, the climatic factor is preponderant not only in feeding the springs but also in acting together with the geology to shape the alteration layers. Most of the springs are partially or totally supplied by the water contained in the soil. In less wavy reliefs this becomes evident since the surface coverings are over 100 m deep. On the other hand, environments with shallow soils tend to shelter temporary springs, the perennial ones being conditioned to the outcropping of fractured rocks. Surface excavation associated with overland flow is another relevant element, causing springs to occur in erosive gullies and ravines, especially on more undulating slopes (Felippe and Magalhães 2014). All this alternates regionally in dialogue with the vertical structure of the Brazilian landscapes.

This complexity associated with the physiographic diversity of the springs only reinforces the need for systematization studies to advance knowledge about these systems in Brazil. However, before characterizing and classifying the springs according to the three typologies chosen for this study, it is quite appropriate to present a brief description of the classification keys to be worked on, as well as where they were applied.

## *2.1 Classification Keys*

As previously stated, three proposals for classification of springs are put in dialogue: Bryan (1919), Springer and Stevens (2009), and Felippe (2009).

In general terms, it should be taken into account that the construction of Bryan's (1919) typology of springs is based on two factors: the origin of the water and the structure of the rock that brings it to the surface, and one can notice strongly present and defined hydrogeological highlights throughout its characterization.

For Springer and Stevens (2009) the criteria used include geomorphic considerations, forces that emerge the water to the surface, flow properties, habitats, spring biota, management, and use of springs. That is, the authors focus on the ecology and manifestation of water, fostering, with a high degree of subjectivity, its typology.

Felippe (2009), on the other hand, based on qualitative empirical data, developed a typology of springs that would enable the use of the groupings created in different environmental dynamics, clearly emphasizing in its classification, a hydrogeomorphological nature. For him, the sample universe will define the groupings of springs (inductive reasoning), and the same spring can fit into more than one class (fuzzy logic).

## *2.2 Bryan's Classification (1919)*

Bryan's (1919) typology of springs are divided into two types: *deepwater springs* and *shallowwater springs*. Deepwater springs are subdivided into *volcanic springs* and *fracture springs*.

The volcanic springs are associated with current or past volcanism and originate from water expelled from the action of the underlying magma or surface water in contact with very heated rocks. The fracture springs, on the other hand, generally have a strong and constant flow, without annual oscillations, high temperature, and are often well mineralized.

As for shallow water springs, Bryan (1919) subdivides them into more categories. The first is that of the *springs in depression* (or porous rocks), formed where the saturation zone reaches the soil surface. They have a smooth flow, being slowly and continuously replenished, normally in the form of swamps. The depressed springs are divided into four categories, according to their topographic position: *dimple springs,; valley; channels; on the edge* (slope breaks).

The *contact springs*, on the other hand, are those whose porous rocks overlap the impermeable material, directing the water to the surface through the stratigraphic contact. The shape and altitude of the surfaces adjacent to this impermeable material determine the subtypes when the contact will be more *regular and horizontal*, *inclined regular* or *irregular*.

*Artesian* water has water contained in the pore spaces of a permeable bed, situated between impermeable strata. Within this category are listed *Plunging springs*, in bedded rocks, inclined and eroded in such a way that the porous bed receives water from the rain or from channels in its upper end (the lower end remains exposed on the surface); *siphoned springs*, originating from folds, where a porous stratum constitutes itself as an inverted siphon for the transport of water; *springs without an impermeable layer*, which occur in unconsolidated deposits, where the porous material is exposed, so as to receive water at a high level and discharge this water at a lower level; *fracture springs,* which do not depend on the outcrop of the saturated porous bed in its lower portion for the exfiltration of water, but rather on fractures, openings that carry the water to the surface.

## *2.3 Springer and Stevens' Classification (2009)*

Springer and Stevens (2009) list 12 types of springs based on hydroecological aspects. *Cave springs* are characterized by the exfiltration of water in underground cavities of a well-developed karstic system. Also associated with karstic systems, *exposed springs* correspond to where the water can seep out of caves, rock shelter fractures, or drains, where unconfined aquifers are exposed close to the ground surface.

The *fountain springs*, on the other hand, are configured as artesian springs with pressurized $CO_2$ in a confined aquifer. *Geyser springs* show an explosive flow of hot water of aquifer confinement. The *jet springs* are also punctual but show a discrete flow, which gushes from a cliff wall, originating from an unconfined and overlying aquifer.

*Hanging garden springs*, have drip flow generally horizontally along with a geologic contact in a cliff wall of an unconfined, perched aquifer. *Helocrene springs* emerge from low gradient wetlands, often indistinct or multiple springs, exfiltrating from shallow unconfined aquifers. The *hillside springs come* from confined or unconfined aquifers on a slope (30–60º), often showing indistinct or multiple exfiltrations. The *hipocrene ones* are found buried where the flow does not reach the surface, usually due to very low discharge and high evaporation or transpiration. *Limnocrene* springs, on the other hand, are marked by the exfiltration of water from confined or unconfined aquifers into lakes or wells. The penultimate type of spring, the hill springs, are those where the water emerges from a *mineralized hill,* often in magmatic or fault systems. Finally, the *reocrens*, encompass fluid springs, originating from one or more transmission channels.

### 2.4 Felippe's Classification (2009)

According to Felippe's (2009) proposal, six fundamental types of springs are contemplated, from the relationship of exfiltration with the local morphology and the hydrological feeding system.

The *phreatic springs* have diffuse exfiltration, with considerable variation of the water table and granular aquifer overlaid on a fissure aquifer, resulting in a low average annual flow. The *dynamic* ones have high energy in all their processes involved, being perennial and usually with high flow. They exfiltrate in a punctual or multiple ways, in outcrops or ducts. The *floating springs*, on the other hand, are defined by the fluctuation of the phreatic level throughout the year, promoting the longitudinal movement of the spring on the slope, normally with diffuse exfiltration resulting from contacts of the rock with the mantle. Like the phreatic springs, they are morphologically characterized by concavities and low flow.

Two classes of seasonal springs (with considerable hydrological variation between dry and wet periods) are placed. The *seasonal erosive* type is characterized by seasonal interception of the water table by erosive features, (gully slopes or drainage channel slopes). They are intermittent, punctual, and of low flow. The *seasonal hillside* springs occur on slopes with deep layers of weathering and are intermittent. Its morphology is usually in vertical or horizontal ducts, the flow is low, and the type of exfiltration is punctual.

The last type of spring is related to the *anthropogenic* ones, i.e., originated by human intervention. Identifying a spring as anthropogenic can be complex, due to the absence of information prior to the intervention carried out in that space. Thus, anthropogenic springs may possess any of the characteristics of the other types, but present anomalies in their dynamics, which would not be verified in a "natural" spring.

The main difference between Felippe's (2009) proposal is that, despite the possibility of fitting into these six standard types, it is assumed that a spring can possess characteristics of several types. With this, hybrid profiles can be created contemplated (e.g., dynamic-floating; phreatic-erosive, etc.).

### 2.5 The Application of the Classification Keys

For the comparison of classification keys, 13 springs were chosen as illustrative cases. All had already been duly characterized by Oliveira et al. (2013), Dias et al. (2014), Moura et al. (2016) and Moura (2020), with the survey of the following basic parameters: depth of the soil and surface coverings; types of land use and occupation in the PPA of the spring and in the contribution basin; lithology of the contribution basin of the springs; lithology of the aquifer of the spring; flow rate of the spring; slope of the first-order channel; water uses of the spring; morphology of the spring; type of exfiltration; mobility and seasonality of the springs.

The classification was based on primary data obtained in the aforementioned studies, organized and corrected according to the same system. Another essential tool for the characterization and classification of the springs was the use of geoprocessing and remote sensing, which allowed the observation of characteristics of the springs that were not always clear in the field. After this compilation, from the physiographic and physiological elements described for each spring, we observed the fundamental descriptive elements for the classification of the springs in the classification keys of Bryan (1919), Springer and Stevens (2009), and Felippe (2009).

The springs are located on the campus of the Federal University of Juiz de Fora, under Cwb climate with an average annual rainfall index of 1,572.8 mm (Machado 2010). The local relief is configured as a set of high slopes predominantly convex, configuring successive headwaters that drain to the same base level, formed by Manacás Lake. The mamelonization of the surface over thick and evolved alteration mantles is regionally common in the context of the Ribeira Belt, in the orogenic system called Mantiqueira Province (western terrain, in the limits of the Minas Gerais central-south plateau system), developed during the Brazilian-Pan African Neoproterozoic Orogeny (Heilbron et al. 2004).

The rocks that underlie the study area date back to the Neoproterozoic, in the Andrelândia Megassequence, in which banded biotite gneiss with intercalations of quartzite and sillimanite-granada-biotite gneiss stand out; sillimanite-granate-biotite gneiss with intercalations of orthopyroxene-granate-biotite gneiss; banded biotite gneiss; quartzite and calcisilic rocks (Duarte et al. 2003).

The springs on campus are fed by granular and fissure aquifer systems, with dynamic communication between the shallow granular cover, associated with interaction mantles and colluvial deposits, and the underlying fissural aquifer.

Therefore, having in question a free aquifer system (due to the water pressure on the bordering surface) and a granular-fissural system (due to the water transmission capacity), it is common to observe a water table formed by the permeability rupture between the higher hydraulic conductivity of the granular aquifer and the lower hydraulic conductivity of the fissural aquifer (Costa 2008). Thus, it is possible to observe throughflow, oscillating seasonally (a condition often observed in the UFJF springs), and baseflow associated with deeper waters of the fissural aquifer.

The occupation of the site by the university accompanied by landfills, cuts, and earthworks has promoted a typically technogenic relief, with consequent changes in the dynamics of hydrological flows, which directly influence the physiographic and physiological characteristics of the springs (Fig. 3).

In order to present the studied springs and the respective typologies in which they were classified, it is necessary to first specialize all 28 springs on campus within the perimeter, 13 of which were studied, as shown in Fig. 3, and then briefly describe these 13 studied springs.

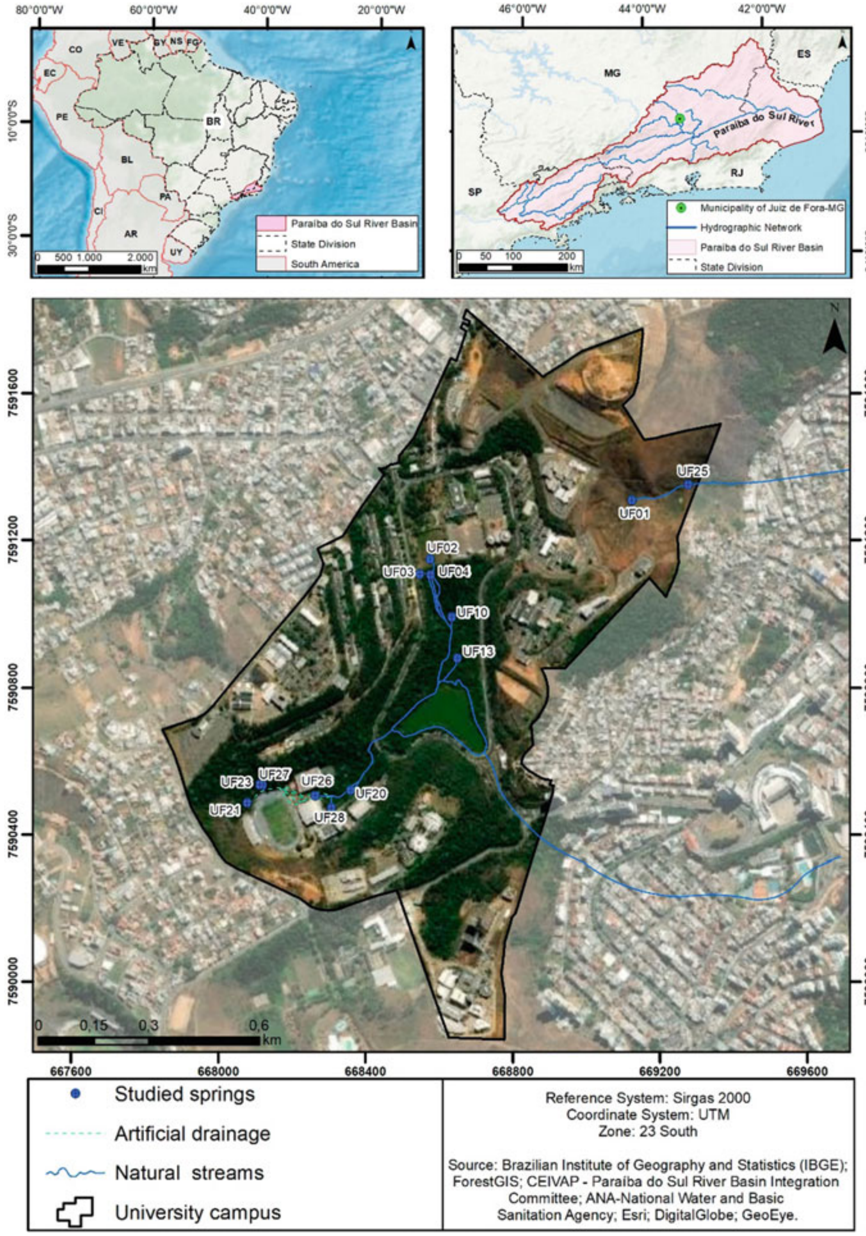


**Fig. 3** Location of the springs studied on the UFJF campus. *Source* Elaborated by the authors

The UF01 spring is located in a drainage headwater on the northwest edge of the campus. It is a spring that has been heavily altered by the population for domestic supply of the residents of the neighborhood. Thus, part of its flow was channeled and dammed in a water tank. Moreover, this spring comes from the abrupt change of slope between the headwater slope and its hollow. Its exfiltration is diffuse and comes from a humid area of low gradient (a markedly swampy environment poorly defined and with a very thick mantle of weathering). It is greatly influenced by the fluctuation of the water table, which corroborates its marked mobility on the slope and low annual flows.

The UF02 spring emerges from a low gradient wetland area with a thick layer of weathering. Furthermore, it is possible to verify a seasonal interception of the water table by ravines. It is also characterized as a spring of cavity morphology, diffuse exfiltration, low flow, mobile and perennial. It is noteworthy the strong human pressure on this spring, which is located in the main recreational area on campus.

The UF03 spring is manifested on a slope by a PVC pipe after being drained upstream. Although its morphology was severely modified, thus being considered a channeled spring, its exfiltration is punctual and perennial.

The UF04 spring is located in a break in the slope, very close to the base level. Its exfiltration is diffuse and in concavity, it has low flow and is located in a humid area of low gradient and deep mantle of weathering.

The UF10 spring, on the other hand, is a point, occurring in an erosive furrow in one of the lowest points of the slope. It is intermittent and has very low flow, with notable oscillation of the water table throughout the year.

The UF13 has a channel morphology, punctual and fixed exfiltration, and as for its seasonality, it is perennial. It is a very fluid spring, originating from two or three transmission channels (depending on precipitation events). It is noteworthy that the morphology of this spring is in a channel today because it is the result of anthropic intervention.

The UF20 and UF21 springs are used for public supply. They are formed in a channel, excavated by anthropic intervention. Both are formed by water erosion, especially due to cavitation in breaks in the channel slope. The exfiltration of the UF20 is diffuse while the UF21 is punctual. Both are fixed, perennial, and of low flow.

UF23 is formed by water erosion, as well as excavation processes in the area, and channelization of the spring itself. Its exfiltration area is configured as a humid area with thick mantle and low flow. The spring is channeled; however, its channel has hydraulic contact with groundwater indistinctly.

The UF25 spring has suffered interference to facilitate water collection by the population, being artificially drained. It has high energy of hydrological processes, where it is clearly noticeable the erosion of the water downstream. Thus, its morphology can be considered a channel, with punctual, fixed, and perennial exfiltration, with high flow for the standards of the sample universe.

Finally, the UF26, UF27, and UF28 springs are located in breaks in the slope of their respective slopes. They were originated from previous excavations, linked to the installation of urban infrastructure. However, the UF27 and UF28 springs are multiple, fluid, and have a concavity morphology, while the UF26 spring is punctual, with a channel morphology, perennial, and fixed.

Table 1 shows the framework of the 13 studied springs in the respective classification keys; the relative frequency of each type is shown in Fig. 4.

Firstly, it should be noted that in none of the classification keys all types were verified. Based on Bryan's (1919) classification, the springs on campus are divided into valley and dimple springs. It is emphasized that both types are part of the shallow water springs group and the subgroup of springs in depressed areas. This homogeneity is explained by the fact that the study area is not very large, where the springs are fed by the same type of aquifer system and also over the same geological-geomorphological domain. Since the UFJF context is a large concavity, surrounded by an interfluve, the water coming from the recharge zones of the campus is already very close to the discharge area, where the base level controls not only the geomorphological base level but the phreatic level itself, which is already shallow. In this way, all the water has the same path, engendering a very specific geomorphological configuration.

However, considering the initial motivation to carry out a systematization of the springs, it does not seem very fortuitous to have as a result a grouping in so few classes. In practice, this would result in little or no difference in terms of conservation and environmental recovery strategies. Notably, for large areas and of vast

**Table 1** Framework of the studied springs, according to the typologies of Bryan (1919), Springer and Stevens (2009), and Felippe (2009)

| Types of Springs | | | |
|---|---|---|---|
| Springs | Bryan (1919) | Stevens and Springer (2009) | Felippe (2009) |
| UF01 | Valley Spring | Helocrene | Floating |
| UF02 | [a] | Helocrene | Erosive seasonal |
| UF03 | Dimple spring | Hillslope | Dynamic |
| UF04 | Valley Spring | Helocrene | Hillslope seasonal |
| UF10 | Valley Spring | Rheocrene | Erosive seasonal |
| UF13 | Dimple spring | Rheocrene | Phreatic |
| UF20 | Dimple spring | Rheocrene | Phreatic |
| UF21 | Dimple spring | Hypocrene | Anthropogenic |
| UF23 | Dimple spring | Hypocrene | Phreatic |
| UF25 | Dimple spring | Gushet | Dynamic |
| UF26 | Valley Spring | Hillslope | Anthropogenic |
| UF27 | Valley Spring | Rheocrene | Anthropogenic |
| UF28 | Valley Spring | Rheocrene | Anthropogenic |

[a] Due to the drainage of the spring to a location different from the original one, it is not feasible to perform its classification by Bryan's key (1919), since there are no safe records of the previous conditions

*Source* Prepared by the authors

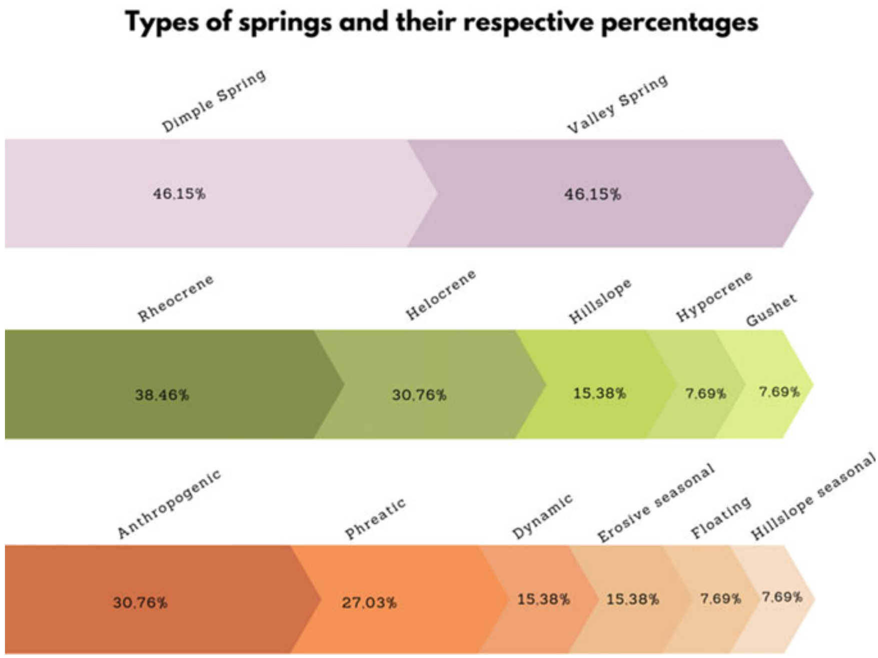


**Fig. 4** Graph referring to the three classifications studied and the percentages referring to the typologies identified. *Source* Prepared by the authors

hydrogeological diversity, Bryan's (1919) classification seems useful, which does not apply to localized contexts.

Observing the classification keys of Springer and Stevens (2009) and Felipe (2009), it was possible to see a greater heterogeneity of types (Fig. 5). However, even in the face of a certain heterogeneity, when taking into account the typology of Springer and Stevens (2009), it can be observed that the Reocrena type springs (38.46%) are more recurrent while taking into account the typology of Felippe (2009), the anthropogenic springs appear more frequently (30.76%).

The recurrence of anthropogenic springs is associated with the action of topographic modification by clippings and earthworks in a context of shallow water tables. The concavity in which the campus is inserted facilitates the triggering of fast and short flows, which converge toward the Manacás Lake, causing the campus to have a water table very close to the surface. Not coincidentally, the phreatic springs were also very frequent in Felippe's classification key (2009). Precisely because they are associated with the shallow aquifer, their occurrence will be conditioned by the surface morphology. The concave segments of the slopes are coherent shelters for this type of spring. However, if there is interception by erosive channels, the tendency is for a seasonal erosive or floating spring to form, depending on the severity of the oscillation of the water table.


**Fig. 5** Types of springs found for the classification keys of Bryan (1919), Springer and Steves (2009) and Felippe (2009), respectively: **a** UF01—Valley Spring/Helocrene/Floating; **b** UF03—Dimple spring/Hillslope/Dynamic; **c** UF27 Valley Spring/Rheocrene /Anthropogenic; **d** UF13 Dimple spring/Rheocrene/Phreatic. *Source* Mirella Moura

For Springer and Stevens (2009), Reocrena springs were the most common on campus. Due to the local morphology (sequence of headwaters) and the cuttings in the terrain for civil construction, the linear erosive processes are intense, engendering unrestricted furrows. As already mentioned, with the water table close to the surface, only a few centimeters of vertical incision are sufficient for water exfiltration to occur. The helocrens were also very present, having been described in situations where the topographic gradient is not conducive to the formation of channels, thus promoting diffuse exfiltration in small marshes.

It should be noted that these classifications have different parameters, so they emphasize different traits, which means that there is no correspondence and pairing between them. They are just different ways, with different attributes, to characterize a spring. Thus, much before opposing each other, the classification keys presented complement each other. The exercise carried out in a limited sample universe shows that Bryan's classification (1919) is the most limited of the three. On the other hand, both Springer and Stevens (2009) and Felippe's (2009) classification proved effective in highlighting the diversity of springs. The former, however, highlights aspects related to groundwater manifestation and may be useful for ecological studies.

The latter seems more suitable for understanding human pressures since it has the hydrogeomorphological processes as its main focus.

## 3 Reflections and Recommendations for Studies on the Brazilian Headwaters

The studied springs illustrate a reality far beyond that of their own spatial cutout (Fig. 6). This is because the springs are located in the context of Tropical Atlantic Brazil, with an elevated relief, a thick mantle of alteration, and a humid climate, regional conditions that are repeated over much of the territory. Another element that reinforces this aspect is the direct and indirect human influences on hydrological processes that generate disturbances in the dynamics of the springs, something recurrent in the Brazilian urban and periurban context.

The intention here is in no way to construct arguments from an irresponsible and generalist induction. However, the recurrence of the aforementioned aspects is undeniable, which can be easily recognized in the literature produced on springs in different regions of Brazil, as in Felippe and Magalhães (2014), Carmo et al. (2014), Marques and Felippe (2017), Silva et al. (2017), Gonzales and Schiavinato (2019), Pieroni et al. (2019), Schiavinato and Gonzales (2020). Thus, the types found in this study reflect the reality of springs in Tropical Atlantic Brazil. Considering the preponderance of factors related to local morphology, climatic seasonality, and the characteristics of the surface coverings, and adding the literature reports in case studies scattered throughout the country, the correspondence of the sample universe of this research with cases recognized in the Atlantic facade of southern Brazil, in the crystalline domain of Central Brazil, in the semi-humid context of the Sertanejo Residual Plateaus, among others, is notorious.

An important reflection is the demystification of the point source, perennial and of great flow, mistakenly reported by the media. Nor are the artesian and volcanic springs recurrently reported in foreign literature. Brazilian research is unanimous in agreeing that the country's springs are mostly of small magnitude, often diffuse, fed by shallow flows, and depending on the climatic context, intermittent.

In view of this, it does not seem useful for the Brazilian case to focus exacerbatedly on the hydrogeological aspects of the springs, as recommended by Bryan (1919), under the penalty of making a systematization that will reflect few classes. On the other hand, the typology of Springer and Stevens (2009) and that of Felippe (2009) present a good resolution for the commonplace of springs in Brazil. Therefore, depending on the objective of the studies one or the other (or even both) can be used.

The approach of Springer and Stevens (2009) seems to be more effective with regard to environmental restoration practices. With more precise description of the aquatic and terrestrial ecosystems that border the springs, this classification key subsidizes the choice of appropriate specimens for plant recomposition, for example.

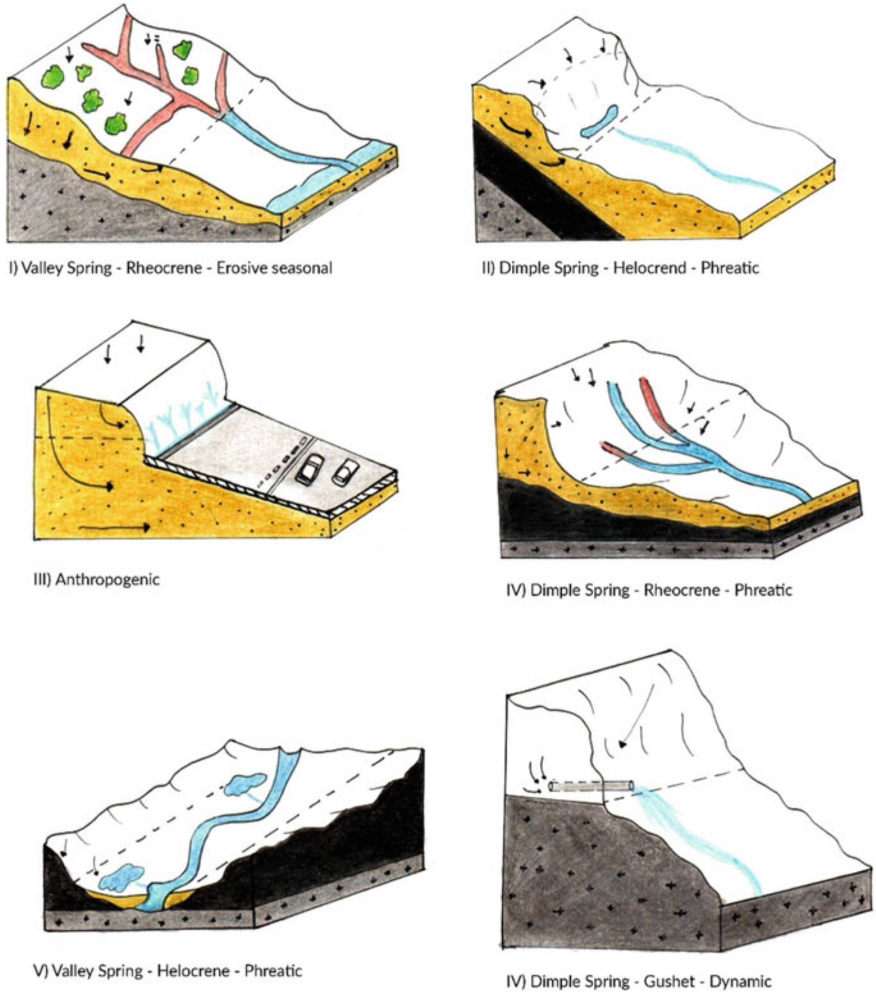


**Fig. 6** Types of springs most recurrent in the Brazilian reality. *Valley spring—Rheocrene—Erosive seasonal* (springs formed by vertical incision promoted by rainfall runoff in climates of double seasonality). *Dimple spring—Helocrene—Phreatic* (springs located on predominantly concave terrain, with the formation of swamps and humid areas, from which the springs originate). *Anthropogenic* (springs whose exfiltration is promoted by anthropic action, normally as a consequence of cuts or severe changes in the terrain. *Dimple spring—Rheocrene—Phreatic* (preferably springs in concave morphologies with channels in the form of erosive furrows, normally dry, until reaching the phreatic level, where exfiltration occurs). *Valley spring—Helocrene—Phreatic* (springs located in the valley bottoms, originating from marshes and humid areas that feed the main channel). *Dimple spring—Gushet—Dynamic* (*springs* in concave relief, normally with steep slopes, promoting punctual exfiltration of concentrated subsurface flows)

On the other hand, it contributes little to the prevention of damage to the springs, since the processes are in the background, overshadowed by the biocenoses habitat.

Meanwhile, the typology of Felippe (2009) stands out. Besides being the classification key that showed the best resolution within the sample universe, with the largest number of classes, it advocates the processes associated with the springs, focusing not only on the structure of the system but also on its functionality. Therefore, it seems the most appropriate for the protection of the springs, in the sense of defining strategies to avoid their degradation. Moreover, presenting more classes has the advantage of enabling greater detailing of management actions, which require a close approach to the idiosyncrasies of each spring.

Finally, we defend the idea that beyond the choice of a classification key, it is necessary to understand that the springs are diverse systems and that, therefore, no single technical solution will be efficient in all of them. This is particularly important in view of the Brazilian political-environmental context, in which legal regulations on a national level govern the management of springs in the most diverse physical-geographic and socio-cultural contexts. The classification keys should therefore be understood as tools to better understand the springs. Based on this knowledge, any initiatives will have a greater chance of success.

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