Hydrogeoethics and Inclusion in Projects with Traditional Communities: The Case of the Baía Formosa Quilombo, Armação Dos Búzios, Brazil

Dandara RODRIGUES, Gerson CARDOSO, Katia MANSUR and Emilia BOCANEGRA Brazil

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Sumary

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1. INTRODUCTION

The central objective of this work is to propose water and energy autonomy solutions for the Baía Formosa quilombo, linking the socio-environmental reality of the Região dos Lagos to social technologies tailored to family farming and afrotourism. This objective is based on the diagnosis that the region's public supply relies on large, centralized systems, which fail to ensure regular service for traditional communities.

The project seeks to assess and strengthen the hydrogeological and energy autonomy of quilombola and rural communities that historically have remained on the margins of public infrastructure networks, structuring water supply and decentralized renewable energy solutions as levers for local development and territorial rights.

In the energy field, the specific objective is to link water planning to decentralized renewable solutions, such as photovoltaic systems and, where technically feasible, the use of local head differences for small-scale generation, reducing pumping operating costs and dependence on external grids. The aim is integrate water-and-energy systems that are robust in the face of regional climatic variability.

Finally, the work aims to strengthen quilombola territorial management by turning maps, well inventories, hydrogeochemical analyses and salinity indicators into participatory planning tools, helping the community define use zones and strategies for monitoring water quality. By integrating hydrogeological science and community-based tourism projects, the intention is to contribute to a development model that reinforces the political, economic and cultural autonomy of the Baía Formosa quilombo, taking water and energy as structuring axes of permanence in the territory.

Recent research, particularly from Brazilian academic journals and local histories, has consolidated this complex narrative using documentary, archaeological, and anthropological approaches (Silva, 1994; Pereira, 2024; Halac, 2023). These studies emphasize the ongoing importance of recovering indigenous and African contributions, as well as the environmental impacts of colonial economic cycles.

1.1 The Concept of Quilombo

A "quilombo" is a socio-political community historically formed by escaped African slaves and their descendants in Brazil, functioning as autonomous territories that resisted colonial

domination and the institution of slavery. These communities provided spaces for freedom, cultural preservation, and the creation of alternative social and economic relations, emphasizing collective ownership and self-determination (Pereira Junior, 2023). Quilombos were also places of resistance where marginalized groups, including Indigenous people, could assert their identities and fight against oppression (Nascimento, 2023).

Figure 1 - Members of the Baia Formosa quilombo at a local event.

In contemporary terms, quilombos represent not only a historical memory but also living communities recognized by Brazilian law, which affirm Black cultural identity and territorial rights. These communities continue to demand the recognition and respect of their collective land ownership and cultural heritage amidst ongoing social and political challenges (Comissão Pró-Índio, 2025). Their persistent presence highlights the importance of quilombos as symbols of resilience and the fight for social justice in Brazil today.

The Quilombo of Baía Formosa, located in the municipality of Armação dos Búzios, Rio de Janeiro State, represents a traditional Afro-descendant community whose history is intrinsically linked to the processes of territorial resistance and water autonomy along Brazil's southeastern coastal zone. The community's territorial occupation reflects centuries of adaptation to the geomorphological and hydrogeological characteristics of the region, where access to groundwater resources plays a crucial role in sustaining livelihoods, cultural identity, and environmental resilience. Recent studies highlight that quilombola communities in Brazil, including Baía Formosa, face systemic inequalities in water access, aggravated by urban expansion and institutional neglect (Furtado et al., 2021; Santos & Tavares, 2020). Within this context, the development of hydrogeoethical frameworks—integrating local knowledge, participatory water management, and ethical responsibility—has been proposed as an effective approach to promote water justice and community-based sustainability (Peppoloni & Di Capua, 2017; Mansur et al., 2022). Thus, Baía Formosa stands as a relevant case study for examining

how hydrogeological science can intersect with social inclusion and traditional rights in coastal aquifer systems.

2 MATERIALS AND METHODS

Armação dos Búzios is located within the Cabo Frio Tectonic Domain (DTCF), a major structural unit of the Ribeira Belt in southeastern Brazil. The DTCF is characterized by a juxtaposition of Paleoproterozoic orthogneisses (Região dos Lagos Complex) and Cambrian paragneisses (Búzios Succession), intruded by Mesozoic mafic dykes related to the opening of the South Atlantic Ocean (Schmitt et al., 2008; Rebelo, 2013; Carvalho, 2023).

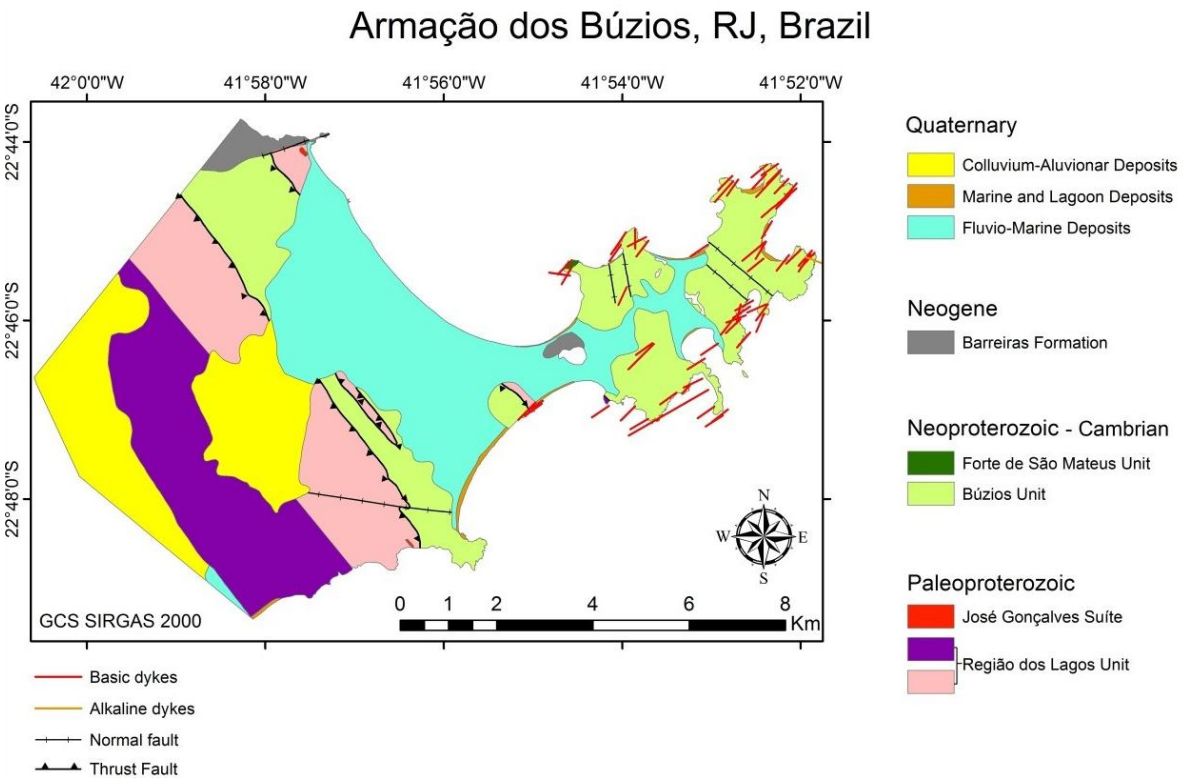

Figure 2 – Geological map of Armação dos Búzios

Detailed mapping identifies fault breccias, cataclasites, and striated surfaces indicative of recurrent reactivation. These fault-related features have a large impact on fluid flow regimes and local geomorphology by compartmentalizing aquifers and forming structural traps that influence hydrogeological behavior (Rebelo, 2013).

The Barreiras Formation in Armação dos Búzios predominantly comprises arkosic sandstones, conglomerates, and siltstones deposited in alluvial fan and fluvial channel settings. Petrographic studies highlight the immature nature of these sediments, rich in lithic fragments derived

primarily from the nearby crystalline basement rocks, reflecting a proximal sediment source and rapid deposition (Carvalho, 2023).

Sedimentary structures such as cross-bedding, graded bedding, and imbricated clasts point to high-energy depositional processes controlled by fault-generated topography and active tectonics, supporting the interpretation of syntectonic sedimentation (Carvalho, 2023; Rebelo, 2013).

2.1 Socioeconomic survey and community engagement

A socioeconomic survey was conducted as a central component of the methodology, aiming to understand the demographic profile, living conditions, territorial ties, and water-related challenges faced by the community. Data were collected through semi-structured interviews with community members, allowing both quantitative and qualitative information to be gathered.

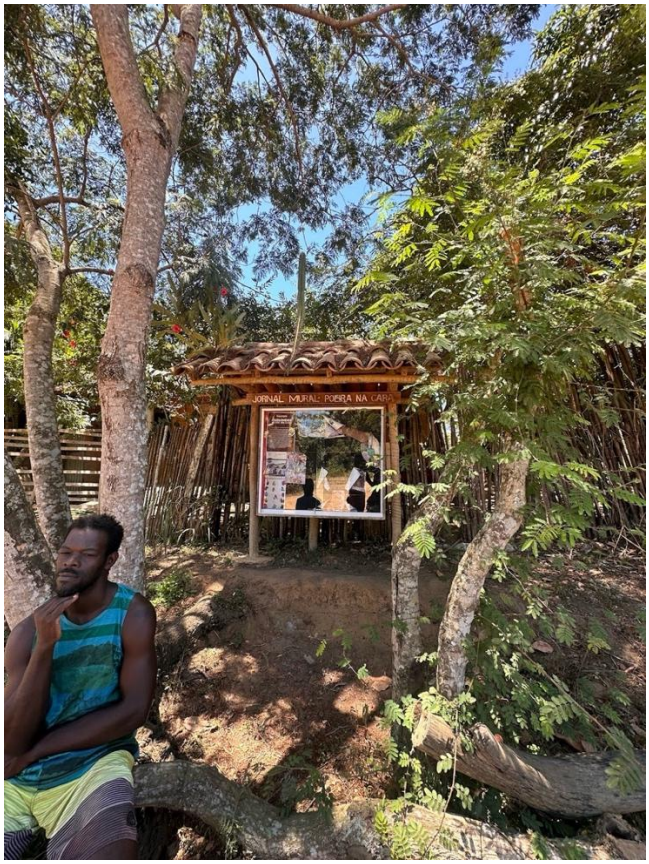

Figure 2 - Interviews with the community

The survey was carried out with the direct support of local community leaders, whose involvement was essential for facilitating access to respondents, ensuring trust, and respecting cultural protocols. Participation was voluntary, and ethical considerations guided all stages of data collection.

A total of 23 individuals participated in the survey, representing different age groups, family nuclei, and residential situations, including residents currently living outside the quilombola territory due to historical processes of land expropriation.

The questionnaire addressed key variables related to: Place of residence and territorial linkage; Age distribution; Occupational activities and economic conditions; Access to basic services, including education, water supply, and electricity; Perceptions of water availability and daily water use.

Survey responses were systematized in a digital spreadsheet and analyzed using a descriptive and interpretative approach. The analysis focused on identifying patterns of vulnerability, territorial displacement, and dependence on groundwater resources, providing essential contextual information for the technical design of water abstraction systems.

2.2 Ethical framework

The methodological design of this research is explicitly grounded in the principles of hydrogeoethics, which emphasize responsibility, equity, participation, and respect for traditional knowledge in groundwater studies. Rather than treating the community as a passive recipient of technical solutions, the methodology positioned quilombola residents as active agents in the diagnosis, decision-making, and implementation processes.

This ethical framework guided interactions with the community, data interpretation, and the formulation of technical recommendations, ensuring alignment with the human right to water, environmental justice, and intergenerational equity. The approach adopted in this study seeks to contribute not only to hydrogeological knowledge, but also to the development of ethical protocols for technical interventions in traditional and marginalized territories.

2.3 Methodological limitations

As with any applied research in vulnerable territories, certain limitations were encountered, including financial constraints, restricted access to advanced monitoring equipment, and logistical challenges inherent to the study area. Nevertheless, these limitations were partially mitigated through the use of accessible methods, community collaboration, and adaptive field strategies, reinforcing the feasibility of replicating this methodological model in similar contexts.

3 Hydrogeological Context of Armação dos Búzios, Rio de Janeiro (RJ)

The hydrological and geological framework of Armação dos Búzios is defined by a combination of semi-arid climatic conditions, complex basement lithology, coastal sedimentary

deposits, and a shallow unconfined aquifer system sustained by meteoric recharge, controlled by Neoproterozoic fractured basement rocks, localized alluvial deposits, and coastal dynamics. The following synthesis integrates field and petrographic data from Rebelo (2013), Benfeita (2017), and Carvalho (2023), complemented by contextual information from Almeida & Lima (1999) and CPRM – Brazilian Geological Service (2001).

The hydrochemical characterization of coastal aquifers along the eastern Rio de Janeiro littoral, extending from the municipality of Niterói to Rio das Ostras (including Armação dos Búzios), reveals significant spatial variability in groundwater salinity and geochemical composition controlled by marine influence (Silva Junior, G. C.; Menezes, J. M., 2010).

The Paleoproterozoic basement of the DTCF (Cabo Frio Tectonic Domain), associated with the Região dos Lagos Complex, is composed predominantly of orthorhyolitic granitic gneisses with crystallization ages ranging from 2.03 to 1.96 Ga (Schmitt et al., 2016). These rocks represent continental crust formed during the Orosirían period through calc-alkaline magmatic series. The most ancient recorded lithologies include amphibolite groups, biotite-quartz dioritic rocks, and tonalitic orthogneisses (Carvalho, 2023).

The Barreiras Formation is the primary sedimentary unit hosting groundwater resources in Armação dos Búzios. This formation extends discontinuously along Brazil's eastern coastal region from Amapá State to Rio de Janeiro, representing one of the most extensive Neogene deposits in South America. The formation's age is constrained to the Miocene-Pliocene interval (approximately 20-2 Ma), with stratigraphic and sequence analysis indicating two major depositional cycles controlled by eustatic fluctuations (Arai, 2006).

In the Búzios region specifically, Morais et al. (2006) documented a facies association comprising matrix-supported conglomerates described as very massive, occasionally displaying normal grading, facies of very coarse, massive arenites with argillaceous matrix, and intensely ferruginized pelitic facies. These deposits are interpreted as representing gravitational sediment flows in association with braided fluvial environments, with depositional control exerted by the Pai Vitório Fault. The alluvial fan deposits adjacent to the fault scarp indicate that fault reactivation during the Cenozoic directly controlled the geometrical configuration and sedimentological characteristics of these deposits (Morais, 2001; Carvalho, 2023).

3.1. Climate and Hydrogeological Balance

The Armação dos Búzios region exhibits a distinctive semi-arid hot climate (BSh classification according to Köppen-Geiger system), an unusual condition for southeastern Brazil that results from the upwelling of cold Malvinas Current water near the Cabo Frio promontory (Rebelo, 2013). This oceanographic phenomenon creates a climatic anomaly characterized by:

- Annual precipitation: 800-905 mm
- Annual evaporation: approximately 1,575 mm
- Annual water deficit: approximately 670 mm
- Predominant wind direction: NE-SW (consistent throughout the year regardless of season)

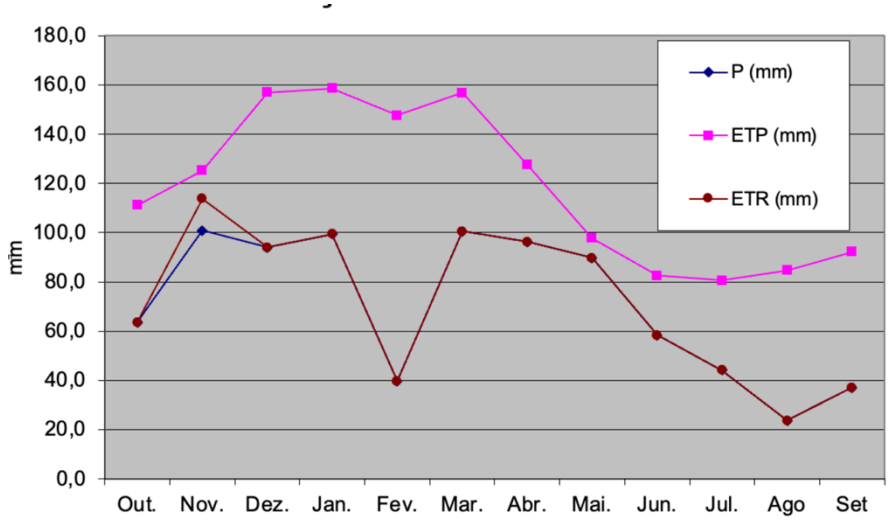

Figure 3 - Hydrometeorological Water Balance of the Municipality of Armação dos Búzios - RJ

The substantial water deficit creates critical groundwater dependency, particularly in rural areas where surface water resources are largely absent or intermittent. The permanent influence of marine aerosol, driven by persistent NE-SW winds, elevates salinity levels in shallow groundwaters, particularly in areas proximal to Cabo Frio and São Pedro da Aldeia. This climatic regime, combined with rapid urban development and population fluctuations (particularly during peak tourist seasons), places intense pressure on already limited water resources (Raposo de Almeida and Lima, 2000).

Monitoring conducted by Carvalho (2023) over 14 months (December 2021 through February 2023) documented significant seasonal fluctuations in water levels, with dramatic declines during dry periods followed by rapid recovery during precipitation events, characteristic of free aquifer response to recharge variations. The strong correlation between monthly precipitation and aquifer water level changes confirms the direct hydraulic connection between surface infiltration and groundwater storage.

Cristo et al. (2010) conducted a comprehensive cluster analysis of coastal aquifer hydrochemistry across the eastern Rio de Janeiro coast, including Armação dos Búzios, identifying hydrochemical groupings across the region. The study revealed that Búzios occupies an intermediate position between highly saline coastal zones and fresher inland systems, characteristic of coastal aquifers experiencing both marine and continental influences.

The predominance of sodium-chloride type waters reflects the combined influence of marine salt aerosol deposition and limited seawater mixing. The absence of significant bicarbonate suggests limited carbonate dissolution, consistent with the granitic and gneissic source rocks

that lack carbonate minerals. Hard water classifications are common, reflecting the absence of significant carbonation processes in the weakly acidic groundwaters.

Seabra et al. (2008) produced maps of coastal aquifer vulnerability to contamination across the region including Armação dos Búzios, indicating that areas around the Mangue de Pedra, including recharge zones, are classified as exhibiting moderate to high vulnerability to contamination. The combination of shallow water tables, coarse-textured sediments in the Barreiras Formation, limited protective soil cover in coastal areas, and high evapotranspiration rates create conditions favoring rapid contaminant transport.

The potential for saltwater intrusion exists throughout the coastal zone, though the direct manifestation of classic saltwater wedges may be limited by the distinctive hydrogeological setting. Rather, the primary salinity concerns relate to marine aerosol deposition in the semi-arid environment and localized seawater-groundwater mixing zones at submarine discharge locations.

4 RESULTS

The installation of photovoltaic solar energy systems constituted a central technical result of this study. The systems were designed to supply energy exclusively for water abstraction and distribution, addressing the chronic limitations of the local electricity grid, characterized by intermittency and restricted spatial coverage.

Figure 4 - Installation of photovoltaic energy panels

The photovoltaic installations enabled autonomous operation of pumping systems, eliminating dependence on external energy sources and reducing operational costs. Field performance demonstrated adequate energy generation under local climatic conditions, confirming the technical feasibility of decentralized renewable energy as a structural component of water security strategies in quilombola territories.

In the Zebina nucleus, hydrogeological assessments led to the implementation of a groundwater abstraction system. An existing well was initially evaluated and showed limited yield. Based on geological observations and site-specific criteria, a new well was located and drilled.

Figure 5 - observation of the well drilled in the Zebina nucleus

In the Origens nucleus, surface water sources were identified as more suitable for localized abstraction. Springs and small watercourses were evaluated, and flow measurements indicated the feasibility of small-scale surface water capture for non-potable and complementary uses.

A surface water abstraction system was therefore implemented to support local activities. As in the Zebina nucleus, the system was integrated with photovoltaic energy supply, ensuring energy autonomy. Although the available flow does not meet the demand of the entire quilombola territory, the intervention provides localized water access and reduces pressure on groundwater resources.

The socioeconomic survey revealed a community characterized by strong territorial attachment, economic vulnerability, and heterogeneous living conditions. A significant proportion of respondents were young adults, while older residents played a central role in maintaining cultural memory and territorial identity.

Access to water and electricity emerged as critical challenges. Water supply relies largely on irregular and alternative sources, while energy limitations constrain both domestic routines and productive activities. Importantly, respondents reported health problems associated with environmental conditions, particularly respiratory issues linked to dust generated by unpaved roads with intense vehicle traffic.

These findings provided a detailed understanding of community needs and priorities, serving as a foundation for the definition of future intervention strategies within the territory.

5 DISCUSSION

Despite the positive results related to water access, the study identified limitations in water quality, particularly concerning salinity, which restricts direct potability of some sources. Salinity is influenced by local hydrogeological conditions typical of coastal environments, including proximity to marine systems and geochemical interactions between groundwater and host rocks.

From a hydrogeoethical perspective, ensuring access to water is insufficient if quality constraints compromise health and dignity. Therefore, future interventions must address water quality alongside quantity, reinforcing the principle that the human right to water includes safety and acceptability, not merely availability.

Based on the observed salinity levels, water treatment solutions should be considered to enable future potable use. Potential strategies include small-scale desalination technologies, such as low-pressure reverse osmosis systems, combined with pre-treatment and post-treatment stages to ensure chemical stability and taste acceptability.

The adoption of decentralized treatment units, integrated with photovoltaic energy systems, represents a feasible pathway for improving water quality without increasing dependence on external infrastructure. Such solutions align with hydrogeoethical principles by prioritizing health protection, technological appropriateness, and community autonomy.

The implementation of additional groundwater and surface water abstractions in strategic locations would increase total available volume and expand the number of residents positively impacted. This decentralized model enhances resilience, reduces vulnerability to system failure, and respects the spatial distribution of households across the territory.

An important contribution of the socioeconomic survey was the identification of dust-related health problems associated with unpaved roads and high vehicle circulation. From a technical and ethical standpoint, the use of water for periodic dust suppression emerges as a socially relevant and preventive intervention.

The installation of small water abstraction points near roads with intense traffic would allow controlled wetting, reducing airborne particulate matter and mitigating respiratory issues reported by residents. This use of water expands the conventional scope of water supply projects by incorporating public health protection as a legitimate objective of water management.

The integration of energy autonomy, water abstraction, water quality considerations, and socioeconomic data demonstrates the value of a hydrogeoethical approach in guiding

interventions in vulnerable territories. Rather than prioritizing maximum extraction, the proposed strategies emphasize equity, health, sustainability, and community well-being.

Future projects in the Quilombo Baía Formosa should therefore advance along three complementary lines:

(i) improvement of water quality through appropriate treatment; expansion of decentralized water abstractions to increase territorial coverage; and innovative uses of water to address environmental health challenges, such as dust suppression.

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Dandara Santos Rodrigues

Rio de Janeiro, Brazil

+55 997318684

dandara@geologia.ufrj.br