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Contribution of the Geodiversity knowledge to social, economic, and environmental health development

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Abstract

This article explores geodiversity within the context of Geosciences, emphasizing its central role in optimizing the generation, systematization, integration, and application of knowledge related to the physical environment and the sustainable use of natural resources. The proposed approach aligns knowledge and resource utilization with ecological constraints, incorporating environmental and social variables into territorial planning and development processes. As an integrative element of diverse geoscientific information bases, geodiversity provides essential technical and scientific support to key societal sectors, including mining, energy, agriculture, public health, urban planning, housing, civil defense, infrastructure, tourism, the environment, and territorial planning. In mining, geodiversity fosters knowledge and promotes the sustainable use of mineral resources essential for survival and quality of life. In the energy sector, its contributions encompass fossil fuels, minerals used in nuclear energy production, and renewable energy sources such as solar and wind. In agriculture, geodiversity aids in the use of fertilizers, soil remineralizers, and conditioners, while ensuring a vital water supply. In public health, the monitoring of water, soil, and air quality is directly supported by geodiversity-derived knowledge, which also informs urban planning by identifying suitable areas for sustainable development and securing construction materials. Geodiversity is equally critical in preventing natural disasters, enabling civil defense to monitor and mitigate risks associated with landslides, floods, seismic activity, and erosion. In infrastructure, whether social (schools, health posts, housing, sanitation, etc.) or economic (transportation and communication systems), geodiversity plays a pivotal role by supporting solutions that enhance societal quality of life. In tourism, geodiversity promotes culture, leisure, and entertainment through the development of geoparks in areas with notable geoscientific significance and the preservation of scenic landscapes. For the environment, geodiversity provides assessments of current and potential impacts, guiding the rehabilitation of degraded areas and the prevention of natural hazards. In territorial planning, geodiversity is indispensable for formulating regional development plans, ecological-economic zoning, and land use planning, as well as for the sustainable utilization of coastal and continental shelf environments. This intrinsic relationship between society and geodiversity is evident, as the production of minerals, water, and food is essential for human survival and socioeconomic development. As knowledge of geodiversity and its connections to land use and the environment expands, its role in shaping Public Policies and Territorial Development Plans becomes increasingly relevant. These policies encompass urban and rural occupation, infrastructure planning, and the sustainable use of mineral and water resources, guiding Municipal Master Plans, State Development Plans, and the National Territorial Planning Framework. Thus, geodiversity-as an integrative element of Geosciences and its connection to society-emerges as a cornerstone for promoting sustainable development.

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1. Introduction

Geodiversity, defined as the diversity of geological, geomorphological, soil, and abiotic processes that shape the planet, plays a fundamental role in providing goods and services to society (Gray 2008; Silva 2008). These goods, recognized as geosystem services (Van Ree et al. 2024; Eerola 2022), include essential resources such as arable land, groundwater, geothermal energy, and minerals, while also shaping landscapes that support activities like tourism and recreation. Geosystems also form the physical foundation of biodiversity by supplying nutrients for soil

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formation and terrestrial ecosystems, as well as serving as repositories for radioactive waste and CO_2 storage (Lateltin 2021). Understanding geological resources and processes, which are key components of geodiversity, is essential for the economic development of society (Smelror 2020).

Despite its significance, geoscientific information related to geodiversity remains underutilized in a systematic manner within territorial planning and management, particularly in public policies. Both national and international experiences highlight the importance of geoscientific information, knowledge, and learning (IKL) in designing and implementing effective and rational solutions that are cost- efficient, socio-environmentally beneficial, and, above all, sustainable.

This article provides a comprehensive review of the role of geodiversity in territorial planning, highlighting its relevance to sustainable development and its application across diverse geographic and social contexts (Figure 1). Through national and international examples, we demonstrate how geoscientific knowledge can serve as a strategic tool to address contemporary challenges such as unregulated urban expansion, natural disasters, and environmental degradation, offering a knowledge base for more effective and integrated policies.

Brazil has emerged as a pioneer in incorporating the concept of geodiversity into territorial planning, introduced in the 1980s in response to social and environmental demands (Silva 2008). Geodiversity maps, such as the one developed for the State of Rio de Janeiro in 2000, have proven fundamental in preventing issues like street collapses in the Pan-American Village, built for the 2007 Pan American Games. These maps warned of the areas unsuitability for urbanization due to the presence of compressible soils, demonstrating the importance of geoscientific information in preventing environmental and economic damage.

International experiences further underscore this importance. In Lithuania, environmental geological mapping began in 1989, resulting in maps that integrate information on geological-geomorphological units and geological resources (Baltrūnas et al. 2011). These maps serve as a foundation for national, regional, and local planning, promoting the rational use of natural resources. In China, the integration of multiple spatial plans has highlighted the importance of prospective geological work for territorial planning, particularly in areas prone to geological hazards (Yan 2019).

Other examples include the use of tectonic information in Argentina, where subsurface structures and geological deformations are considered essential for defining environmental units and planning the sustainable use of land in regions with active tectonics (Rodríguez et al. 2021). In Portugal, more than 150 years of geological mapping programs have been crucial for planning public infrastructure and assessing geological risks (Gomes et al. 2015).

These cases demonstrate how geodiversity knowledge can be applied practically and efficiently to address social and environmental demands while supporting economic development and enhancing quality of life.

This work presents a comprehensive review of geodiversity applications in territorial planning, highlighting exemplary cases and evidence of its importance for the sustainable management of natural resources. The review aims to synthesize existing practices and propose an agenda to strengthen the integration of geoscientific knowledge into public policies, particularly in contexts where unregulated land use and environmental degradation present significant challenges.

Drawing from the examples discussed, we argue that systematic incorporation geodiversity information can transform territorial planning, fostering more effective and resilient solutions to contemporary challenges. Thus, this article contributes to expanding the debate on the role of geosciences in building a sustainable future, grounded in technical-scientific knowledge and aligned with social and environmental demands.

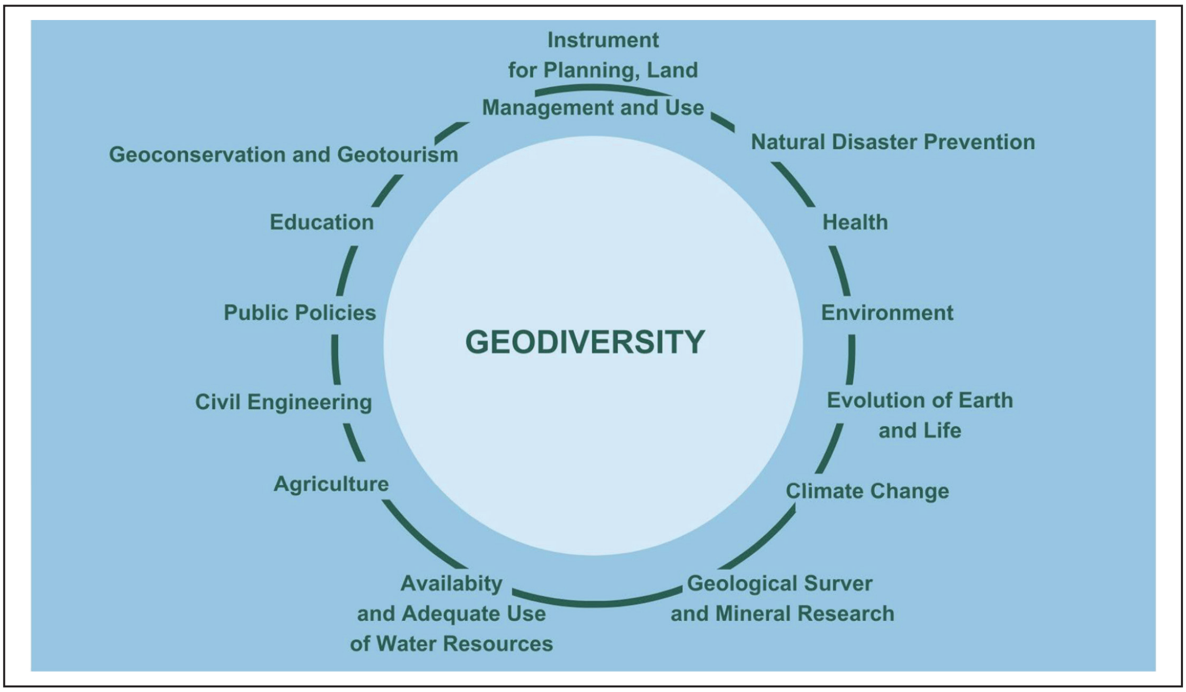


Figure 1. Main applications of geodiversity knowledge (Silva 2008).

2. Geoscientific information survey

Over the past decade, academic activities related to geodiversity have shown a growing interest in the fields of geotourism and geoheritage. An analysis of the Web of Science database using the keyword “Geodiversity” identified 1,256 scientific articles, of which 84 are reviews, primarily concentrated in the categories of multidisciplinary (592), environmental sciences (509), geography (260), and geology (97), during the period from 2011 to 2024, with a marked increase from 2019 and 2024 (166 publications). When the keyword “Sustainable Development” is added, the number of publications decreases substantially to 258, including 27 review articles, predominantly in the multidisciplinary (126) and environmental (112) categories, covering the years from 2015 to 2024, with the highest concentration between 2021 and 2024 (166 publications).

The combination of the keywords “Geodiversity” and “Society” reveals a significant reduction to 65 publications, concentrated in the areas of environmental sciences (39), multidisciplinary (20), geography (13), and geology (6), with a focus on the period from 2021 to 2023. Finally, an investigation into interest in the field of “Territorial Planning” results in only 26 publications, primarily concentrated between 2022 and 2023. This prospective analysis unequivocally demonstrates the predominance of geodiversity applications in the fields of geotourism and geoheritage, highlighting a clear interest in issues related to environmental preservation.

This scenario underscores the need to broaden the applications of geodiversity, as proposed in this review article, to support the formulation of public policies from a more comprehensive perspective that addresses society’s emerging demands. In particular, this effort is aimed at public managers responsible for developing territorial planning policies.

To this end, this chapter aims to outline the main thematic areas of geosciences or developing geodiversity surveys, namely: geological mapping, marine geology, mineral potential, surface water resources, hydrogeology, geological risk events, environmental geochemistry, medical geology, ecological-economic zoning, oil and gas, geotourism, geoparks and sustainability.

2.1. Geological surveys

Geological mapping aims to establish knowledge of the spatial distribution, description, origin, and structural behavior of rocks on the Earth’s crust, providing a foundation for various fields such as hydrology, hydrogeology, geophysics, geochemistry, mineral potential, geological risk assessment, degraded area recovery, geotourism, and geoparks (Figure 2).

Geological mapping enables the identification of areas where geological units favorable for the discovery and economic exploitation of mineral deposits are located. These minerals are essential for various industrial sectors and, importantly, for agriculture, including soil correctives, remineralizers, and fertilizers. Additionally, it supports groundwater research (aquifers) by utilizing geological survey products (e.g., geological maps) in irrigation studies for agricultural areas.

Currently, mining contributes significantly to Brazil’s development, serving as a key driver for several crucial sectors of the economy, including energy, metallurgy, and steelmaking. It stimulates economic growth cycles, generates income, creates jobs, and increases tax revenues.

Geological mapping forms the foundation of geoscientific knowledge for the other products presented in this research. It must be conducted with the understanding that Brazilian society should be the primary beneficiary, with results applied to activities beyond mineral exploration.

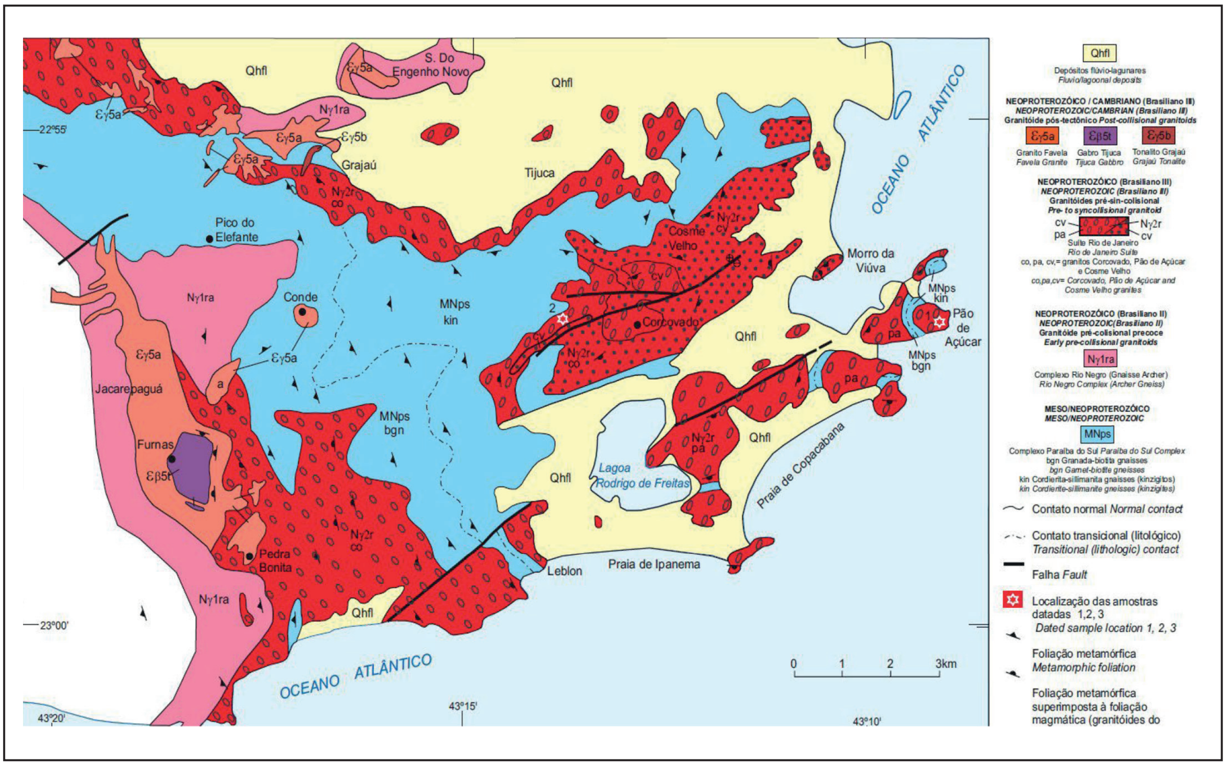


Figure 2. Simplified Geological Map of south side of Rio de Janeiro Metropolitan Area (Silva and Cunha 2001).

These activities promote economic development and social well-being, such as research aimed at increasing water availability in Brazil's semi-arid regions. The search for agricultural inputs that ensure food security and quality, the discovery of critical minerals essential for the energy transition and the development of low-carbon technologies, and the formulation and implementation of public policies to promote the sustainable development of the Amazon (Rosa-Costa et al. 2024).

2.2. Marine Geology

Marine Geology involves research activities in coastal areas, the legal continental shelf, and deep ocean regions beyond the limits of the Exclusive Economic Zone (EEZ). The goal is to produce geological information that supports mineral exploration and research activities, as well as the environmental management of the coastal zone, the Brazilian Continental Shelf, and adjacent international areas. Marine geodiversity products enable the analysis of geological influences on the formation of marine landscapes, oceanographic parameters, mineral deposits, geological hazards, geoconservation, and biodiversity support.

An example marine geodiversity survey is the work of Maia (2013) who produced the Geodiversity Map of the Areas Adjacent to the Vitória-Trindade Submarine Chain (Figure 3), and addressed morphophysiographic and surface geology aspects of the region's sea floor. This work resulted in scientific and educational records on the geological history of the Brazilian eastern continental margin and the South Atlantic (Figure 3).

2.3 Mineral potential

Mineral production on the continent has significantly contributed to the country's development. In 2019 and 2020, mineral industry's contribution (extraction and processing) to Brazil's GDP was approximately 3.2% (Santos 2021).

The discovery of mineral deposits is often associated with the development of high-quality infrastructure, technological innovation, and industrial growth. For instance, the following mineral resources have seen increased use across various sectors: iron ore (in steelmaking), gold (for hoarding and jewelry), phosphorus and potassium (in agriculture), copper (as an electricity conductor in wires and cables), lithium (used in batteries for electric vehicles, cell phones, laptops, etc.), and tungsten (used in high-temperature applications due to its heat resistance). Other key minerals include cobalt, graphite, manganese, niobium, nickel, tantalum, rare earth elements, titanium, and vanadium. Various studies highlight the growing importance of so-called "minerals of the future," whose demand is expected to increase significantly in the coming decades due to their applications in high-tech products. These minerals are used in the production of batteries for cell phones, electric and hybrid vehicles and solar and wind energy generation systems, playing a crucial role in the development of clean and renewable energy. The intensified utilization of these mineral resources is essential for global energy transition and decarbonization processes (Figure 4).

The use of mineral products in agriculture enhances agricultural productivity, stimulates the expansion of food production (as plants require minerals in the soil to grow), increases local employment opportunities, reduces the need for agricultural product imports, and contributes to the country's economic growth.

Brazil possesses rocks with agro-mineral potential (containing macro and micronutrients) that can be used in soil remineralization to enhance agricultural productivity, benefiting not only large producers but especially family farming. Mining generates a significant volume of rocks and materials that are often unused but can be repurposed in accordance with the principles of the circular economy, which emphasizes waste reduction and material reuse.

Utilizing rock materials typically discarded in mining not only expands employment opportunities but also promotes sustainability by reducing environmental impacts. These practices increase per-hectare productivity, improve production and income, and contribute to lowering food prices.

According to the Ministry of Mines and Energy (MME 2023), Brazil's geological complexity positions the country among those with the largest mineral reserves globally, particularly those classified as strategic by MME decree. With the potential to meet the growing demand driven by the energy transition to low-carbon sources, Brazil could become a global leader in supplying mineral commodities.

Mineral water is the most important nutrient and is abundantly available in the country. It is obtained directly from natural springs or extracted from groundwater, without the addition of any salts or chemical elements, making it a 100% natural product. Water is essential for life, and mineral water, often bottled, is frequently the first to reach people in situations of risk or illness.

2.4. Surface water resources

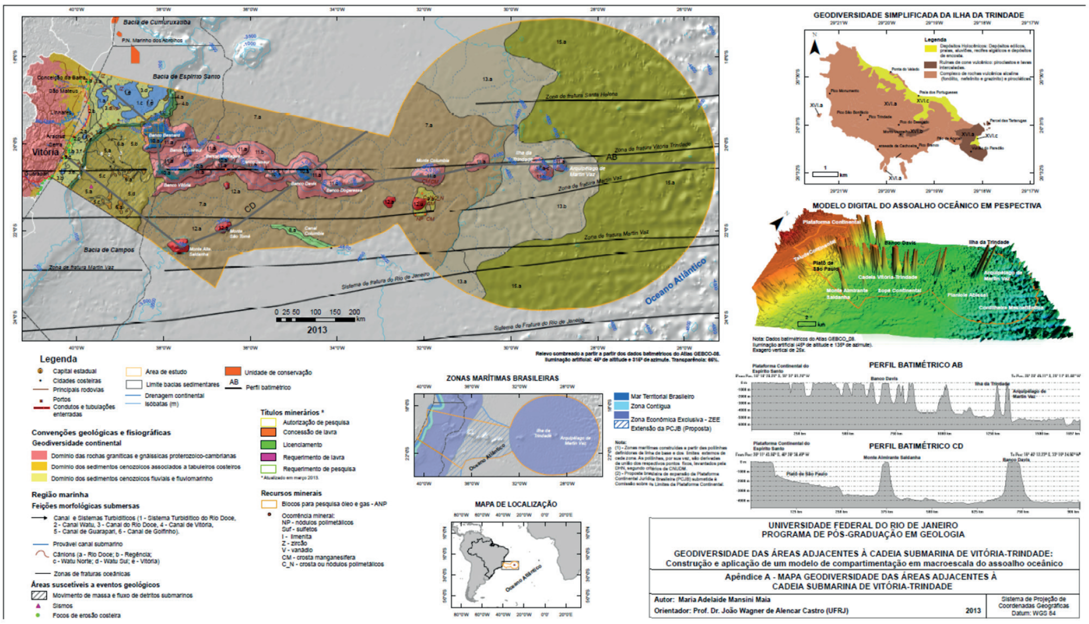
Surface water resource surveys aim to support the effective management and utilization of water resources. As such, basic surface water surveys are essential for ensuring universal and equitable access to safe and potable water for all. The quality of water sources, such as rivers, must be regularly monitored and analyzed.

Historically, these surveys have also support studies for energy projects. For example, hydrological data can identify rivers that are not suitable for the construction of a hydroelectric plant due to insufficient water volume. In such cases, alternative energy solutions can be explored to meet local demand.

Hydrological and rainfall data monitored by the National Hydrological Network (RHN), as shown in Figure 5, are processed and organized as continuous records, forming historical series of hydrological data series. These historical series consist of data collected, analyzed, and stored in a database made available to users by the National Water Resources Information System (SNIRH). This monitoring information serves as the foundation for determining water availability across Brazilian territory, providing planners and managers with reliable hydrological data to support activities such as managing risks related to floods and severe droughts (SGB-CPRM 2024a).

2.5. Hydrogeology

In today's globalized world, the study of groundwater is becoming increasingly important as a tool for addressing water supply issues and pollution control, both of which



DOMÍNIO FISIOGRÁFICO		COMPARTIMENTOS DA GEODIVERSIDADE MARINHA	
MARGEM CONTINENTAL	Plataforma Continental do Espírito Santo	1 - Bioconstruções holocênicas na Plataforma Continental do Espírito Santo	1.a - Recifes de algas coralíneas (PC interna de São Mateus-Abrolhos) 1.b - Recifes de briozoários (PC interna de Regência) 1.c - Recifes de algas coralíneas (PC externa de São Mateus-Abrolhos) 1.d - Recifes de algas coralíneas (PC externa de Regência) 1.e - Recifes de briozoários (PC externa de São Mateus-Abrolhos) 1.f - Recifes de briozoários (PC externa de Regência)
		2 - Depósitos terrígenos holocênicos na Plataforma Continental do Espírito Santo	2.a - Depósitos lamosos (Delta do Rio Doce e Itaúnas) 2.b - Depósitos arenolamosos (PC interna de São Mateus-Abrolhos) 2.c - Depósitos arenolamosos (PC interna de Regência)
		3 - Depósitos bioclásticos holocênicos na Plataforma Continental do Espírito Santo	3.a - Depósitos de areia e cascalhos biodetríticos (PC interna de São Mateus-Abrolhos) 3.b - Depósitos de areia e cascalhos biodetríticos (PC interna de Regência) 3.c - Depósitos de areia, lama e cascalho biodetríticos (PC interna de Regência) 3.d - Depósitos de areia, lama e cascalho biodetríticos (PC externa de São Mateus-Abrolhos) 3.e - Depósitos arenolamosos, areia e cascalho biodetríticos (PC externa de Regência) 3.f - Depósitos de cascalho, biodetritos e lama (PC externa de Regência)
	Talude Continental do Espírito Santo	4 - Depósitos de fluxo gravitacional e movimentos de massa holocênicos no Talude Continental do Espírito Santo	4.a - Depósitos arenolamosos e de fluxo de lama/detritos (Talude superior) 4.b - Depósitos arenolamosos, turbiditos biodetríticos e fluxo de lama/detritos (Talude inferior)
	Sopé Continental do Espírito Santo	5 - Sistemas turbidíticos e leques submarinos cenozoicos do Platô de São Paulo	5.a - Depósitos turbidíticos e leques submarinos arenoargilosos 5.b - Depósitos turbidíticos e leques submarinos arenoargilosos soerguidos por halocinese 5.c - Depósitos arenolamosos e de fluxo de lama/detritos 5.d - Depósito arenolamosos e de fluxo de lama/detritos soerguido por halocinese
		6 - Halocinese no Platô de São Paulo	6.a - Diapiros e afloramentos de sal-gema
		7 - Depósitos pelágicos cenozoicos no Sopé Continental do Espírito Santo	7.a - Depósitos arenolamosos e de vasas calcárias retrabalhados por corrente de fundo
		8 - Depósitos de canais submarinos profundos cenozoicos no Sopé Continental do Espírito Santo	8.a - Canais turbidíticos arenolamosos profundos
		9 - Depósitos autigênicos cenozoicos no Sopé Continental do Espírito Santo	9.a - Nódulos e crostas polimetálicos
		10 - Bioconstruções em bancos submarinos oceânicos	10.a - Recifes de algas coralíneas e/ou briozoários
		11 - Lavas e intrusões de rocha vulcânica sódico-alcalinas e subsaturadas em sílica da porção submersa da Cadeia Vitória-Trindade (montes e bancos submarinos)	11.a - Complexo de fonolitos , picrito e nefelinitos recoberto por depósitos de encosta 11.b - Complexo de rochas vulcânicas recobertas por fluxo de detritos e sedimento pelágicos retrabalhados por corrente de fundo
		12 - Intrusões de rochas vulcânicas de composição e idade indeterminadas em montes submarinos isolados no Sopé Continental do Espírito Santo	12.a - Rochas vulcânicas recobertas por depósitos de encosta submarina
MARGEM OCEÂNICA	Planície Abissal do Brasil	13 - Depósitos pelágicos e turbiditos cenozoicos associados à rochas vulcânicas da crosta oceânica na Planície Abissal do Brasil	13.a - Depósitos de vasas calcárias e turbiditos argilosos 13.b - Depósitos argilosos retrabalhados por corrente de fundo e afloramento de basalto
		14 - Lavas e intrusões de rocha sódico-alcalinas e subsaturadas em sílica, piroclastos diversos e depósitos holocênicos da porção emersa da Cadeia Vitória-Trindade (Ilha da Trindade e Arquipélago de Martin Vaz)	14.a - Complexo de fonolitos, nefelinitos e piroclástica 14.b - Ruínas de cone vulcânico: piroclastos e lavas intercaladas 14.c - Depósitos holocênicos
	Cordilheira Mesoatlântica	15 - Derrames de rochas vulcânicas da crosta oceânica e zona de ascensão magmática do Flanco Oeste da Cordilheira Mesoatlântica associada e sedimentação pelágica terrígena e vulcanogênica cenozoica	15.a - Depósitos argilosos associado a cinzas vulcânicas e afloramento de basaltos toleíticos

Figure 3. Geodiversity Map of the Areas Adjacent to the Vitória-Trindade submarine chain (Maia 2013).

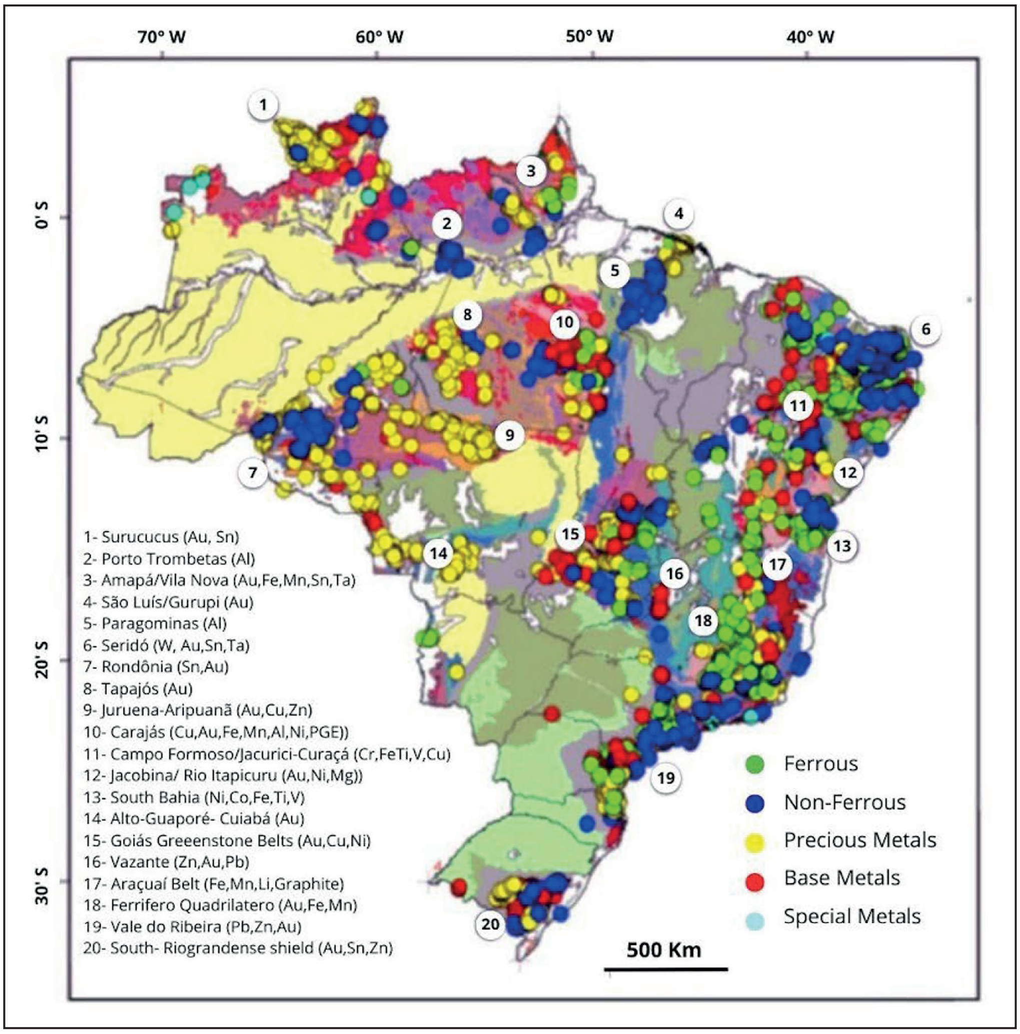


Figure 4. Metallogenic provinces and mining districts of Brazil (Klein et al. 2018).

are intrinsically linked to human activities. In recent years, population and socio-economic growth, including mining activities, have not only increase water demands but also contribute to rising environmental pollution. Hydrogeology, the science that studies the occurrence, movement, and quality of groundwater, has expanded in interdisciplinary scope over the last 160 years and is increasingly recognized as an environmental science. As such, it plays a decisive role in the management of water resources.

The products generated by hydrogeological surveys (Figure 6) are related to groundwater and contribute to the agricultural sector by facilitating water supply, particularly for activities such as irrigation. Hydrogeological maps (groundwater maps) for example, assist in the characterization and identification of aquifers or suitable locations for water supply for public use and the irrigation of Brazilian agricultural production (Jacques et al. 2021).

2.6. Geological hazard prevention products

Geological maps assist in preventing problems related to natural disasters of geological origin. Various types of maps, such as those indicating susceptibility to flooding and landslides, can aid in protecting lives and preserving houses, schools, hospitals, and other infrastructure.

Risk prevention products, such as geological risk maps (Figure 7), susceptibility charts, geotechnical maps, hazard maps, emergency actions, and training courses, aim to enhance the understanding of the physical environment and the geological processes that may occur due to extreme climatic events. By using these tools proactively and incorporating them into urban planning, it is possible to support populations that may be affected by natural disasters, such as those occurring in Teresina-PI and Atafona-RJ (Figure 8), through management and preventive planning actions. These efforts contribute to making communities safer, more resilient, and more sustainable.

In flood-prone areas, flood warning systems can notify authorities and the communities in advance of potential hydrological risks (flooding and overflow). This enables preemptive actions, such as evacuating residents from their homes and relocating them to safe areas, which can save lives and reduce damage. Currently, 17 critical event warning systems (floods) are installed and operated by SGB-CPRM (Figure 9), serving more than 72 municipalities and benefiting 8.3 million people.

2.7. Environmental geochemistry

Regional-scale geochemical maps depict the geographical distribution of chemical elements in soil, water, stream sediment, air (dust), and food. These maps serve as an exceptional tool for estimating the geochemical baseline (background) at a given scale, which is essential for environmental monitoring, and they provide a comprehensive overview of the geochemical landscape. The resulting geochemical database has a wide range of applications, including mineral exploration and research, agriculture, forestry, land-use planning, environmental monitoring, medical and forensic science, and more. These applications utilize spatial geochemical data to gain valuable

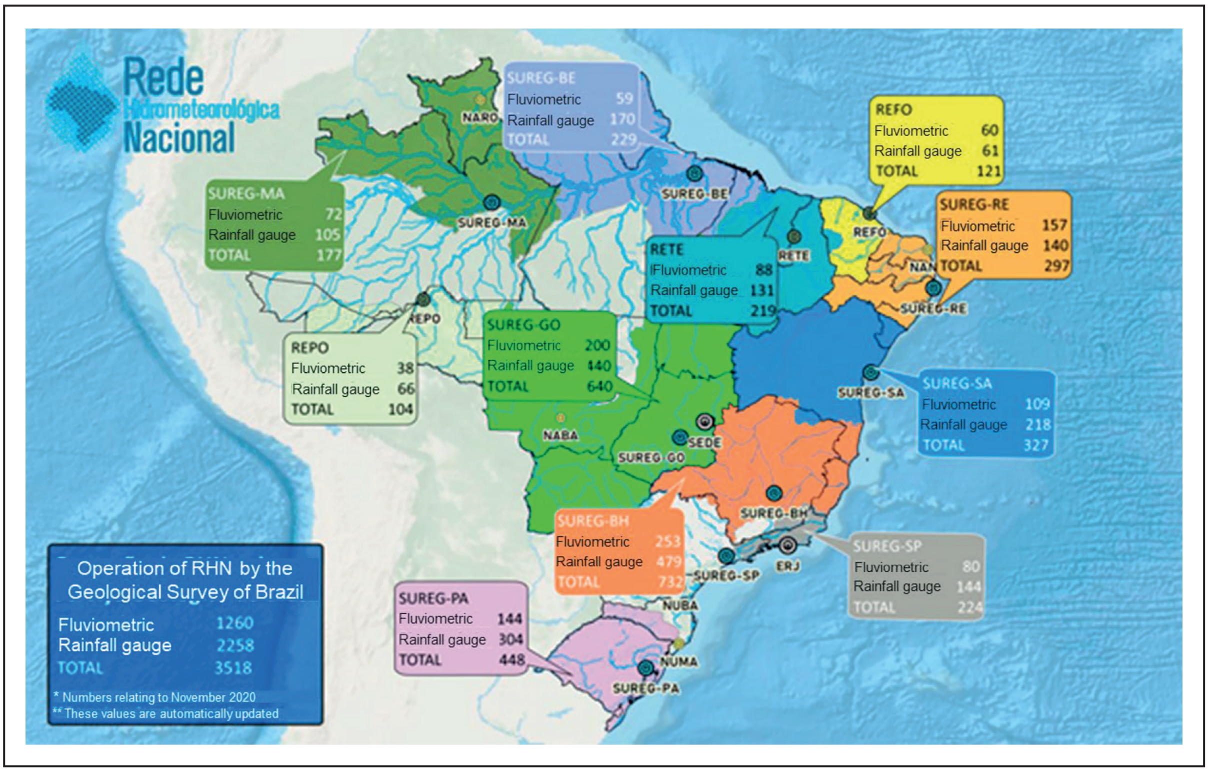


Figure 5. Location of river basins monitored by the National Hydrological Network (RHN) (SGB-CPRM 2024a).

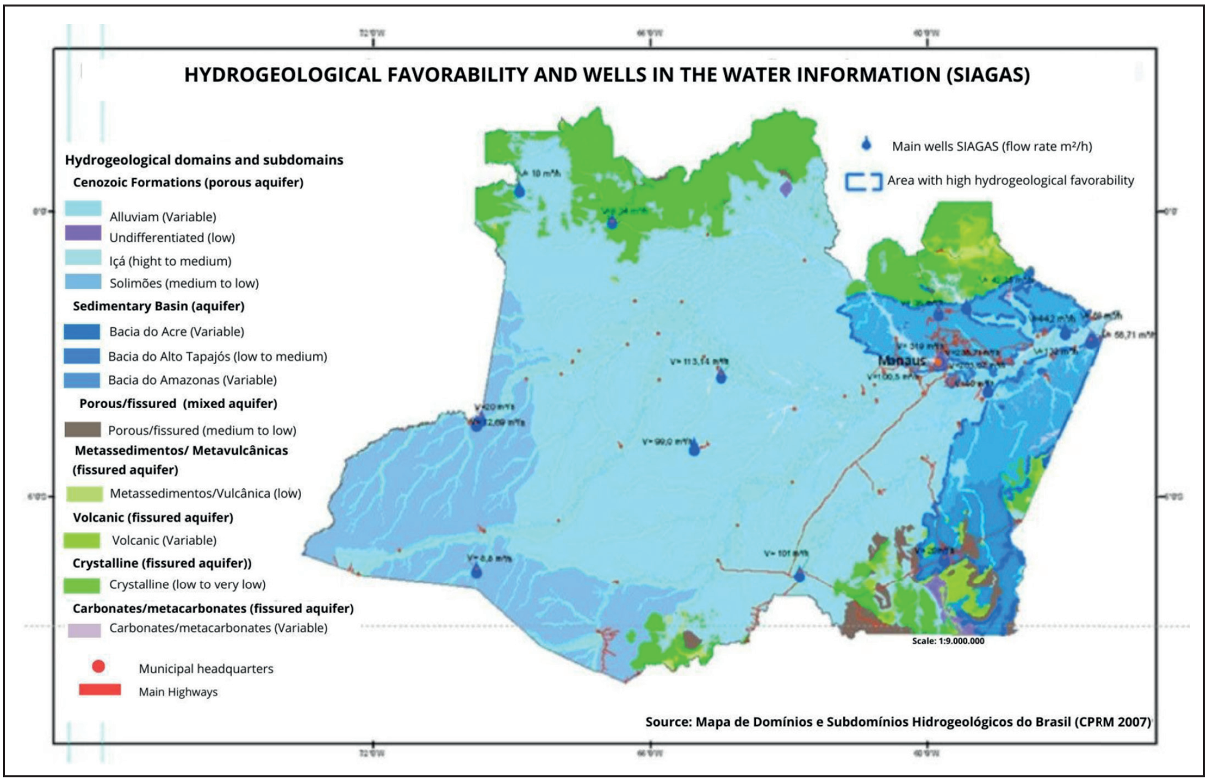


Figure 6. Geodiversity cartogram of the State of Amazonas (Maia et al. 2010).

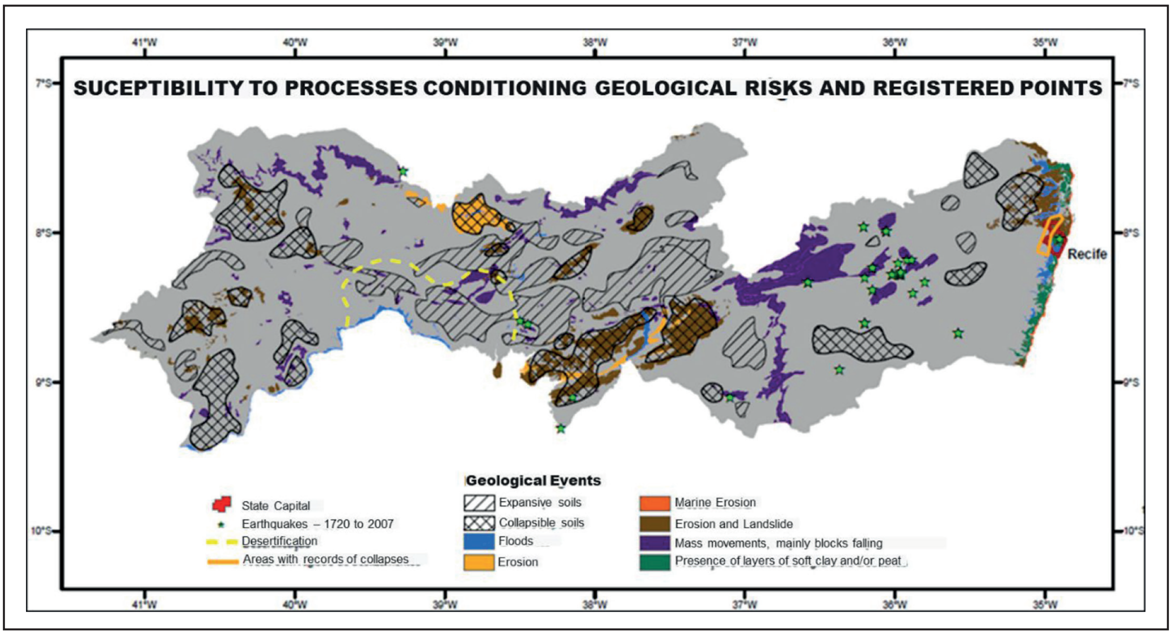


Figure 7. Geological risk cartogram of the state of Pernambuco (Pfaltzgraff et al. 2010).

Figure 8. Subsidence in Teresina-PI and coastal erosion in Atafona-RJ.

insights into various topics, including but not limited to: (1) interpreting the spatial variation of elements; (2) understanding the geochemical characteristics of different environmental compartments; (3) delineating large-scale patterns such as metallogenetic provinces; (4) exploring relationships between geochemical, geomedical, and epidemiological data; (5) urban geochemistry and land-use planning; and (6) ensuring food security and clean water, among many other applications. In addition to these uses, environmental geochemistry can outline the distribution patterns of the investigated elements in both the physical environment and parts of the biotic environment, identifying zones that may be harmful or beneficial to environmental health. This constitutes essential information for understanding the physical environment (Silva et al. 2023).

2.8 Medical Geology

Medical geology studies the influence of the abiotic (non-living) components of the planet, specifically geological factors, on t human and animal health. For example, gases emitted from an active volcano can affect the air we breathe and, consequently, our health. Similarly, excessive fluoride in drinking water can lead to diseases like dental fluorosis, where teeth become dark, stained, and brittle. Everything derived from nature, including what we eat, drink, and even the air we breathe, is fundamental to our health and quality of life (Jacques 2020).

In China, a bone deformation disorder (Figure 10) affects growth, leading to deformities, joint swelling, chronic pain, and general weakness. Approximately 1 to 3 million Chinese people have been affected due to low selenium levels in the soil, which is positively associated with selenium and iodine deficiency in the diet (< 0.025 mg/kg in grain).

2.9. Ecological-Economic Zoning (EEZ)

Ecological-Economic Zoning (EEZ) is a tool primarily used by federal, state, and municipal policymakers and managers for the strategic planning of socio-economic development in specific regions. It helps identify and prioritize areas based on their environmental fragility and potential for economic activities, considering natural resources , human life, animals, vegetation, existing infrastructure, and the broader economic and social context.

EEZ products help identify areas with economic potential and environmental sensitivity, such as native vegetation fragments or aquifer recharge zones, which should be

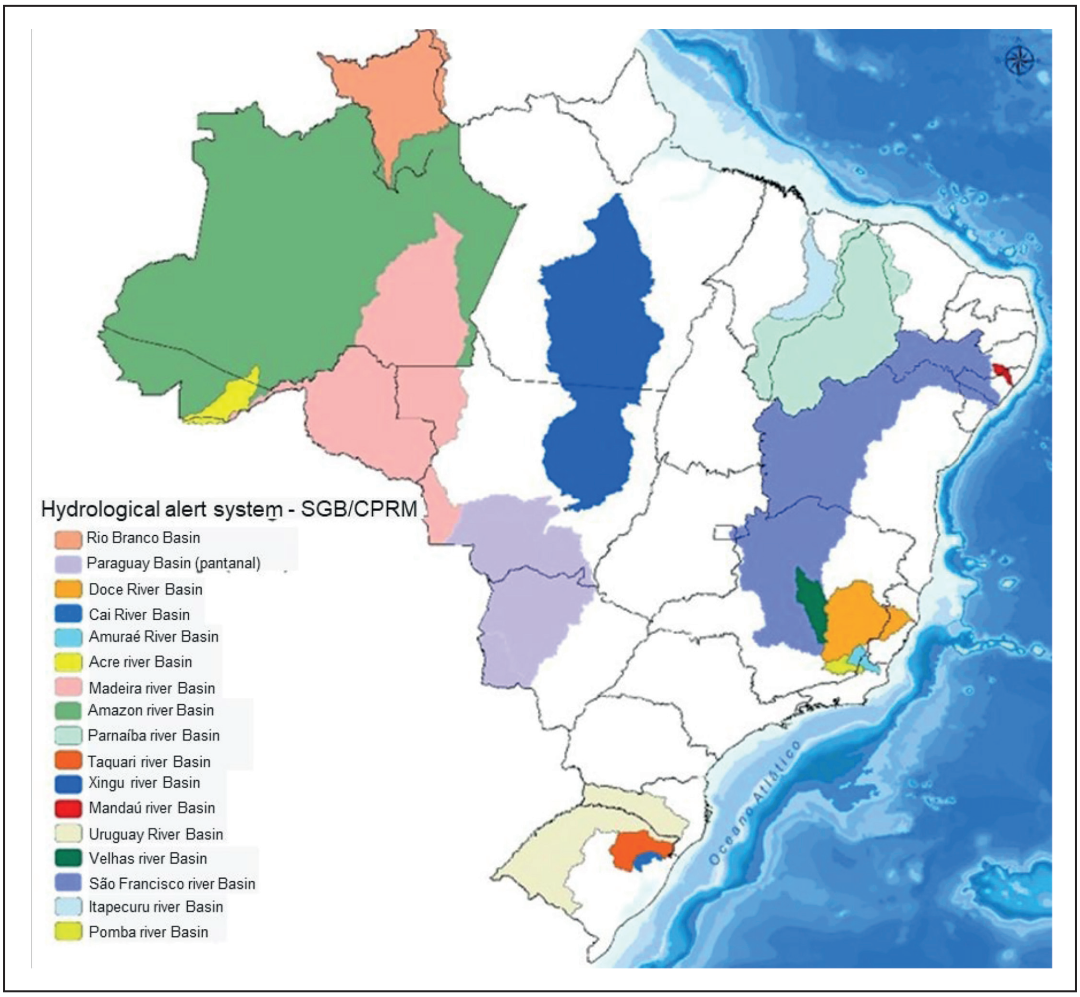


Figure 9. Location of Critical Event Warning Systems (SACE) in 17 river basins (SGB-CPRM 2024b).

designated for protection and preservation. EEZ also enables the delineation of regions undergoing desertification or with limited water availability, both of which impact the habitats of specific animal and plant species.

2.10. Oil and gas

Oil and natural gas are the primary global energy resources, accounting for approximately 60% of the global energy supply. As fossil fuels, they are essential for various industries, transportation, electricity generation, and heating. Oil and natural gas are versatile raw materials processed in refineries and petrochemical complexes to produce fuels and a wide range of other products such as lubricants, plastics, and a wide range other products, without which modern society would be inconceivable.

However, the growing demand for these resources raises environmental concerns. The combustion of oil and gas is one of the largest sources of CO_2 emissions, contributing to global warming. Additionally, oil and gas exploration and production in sensitive areas, such as deep waters, pose ecological challenges that require technological advancements.

In Brazil, the oil and gas sector is vital to the economy, representing a significant share of the country's energy matrix. In 2023, Brazil achieved record annual oil and gas production, averaging 4.344 million barrels of oil equivalent per day (boe/d). For the first time, national average production exceeded 4 million boe/d, with more than 75% coming from the pre-salt layer. This milestone positions Brazil as one of the world's largest producers (ANP 2023). The Santos Basin is the primary hub of this production, utilizing advanced technologies such as 4D seismic imaging and ultra-deep drilling.

Natural gas is becoming increasingly important in Brazil's energy matrix, complementing electricity production during water crises and serving as a lower-carbon transition fuel compared to other fossil fuels. The gas distribution infrastructure is expanding, with new pipelines and incentives for industrial and vehicular use.

The sector's governance is regulated by the National Petroleum, Natural Gas, and Biofuels Agency (ANP), which organizes exploration block auctions and oversees production. Brazil faces the challenge of balancing oil and gas exploration and production with global sustainability demands. Technologies related to carbon capture, storage, and use (CCSU), as well as the development of biofuels and hydrogen, represent promising pathways for reducing net emissions.

Although the oil and gas sector will remain crucial to Brazil's economic development, its future will depend on its ability to innovate and adapt to the growing demand for cleaner energy sources.

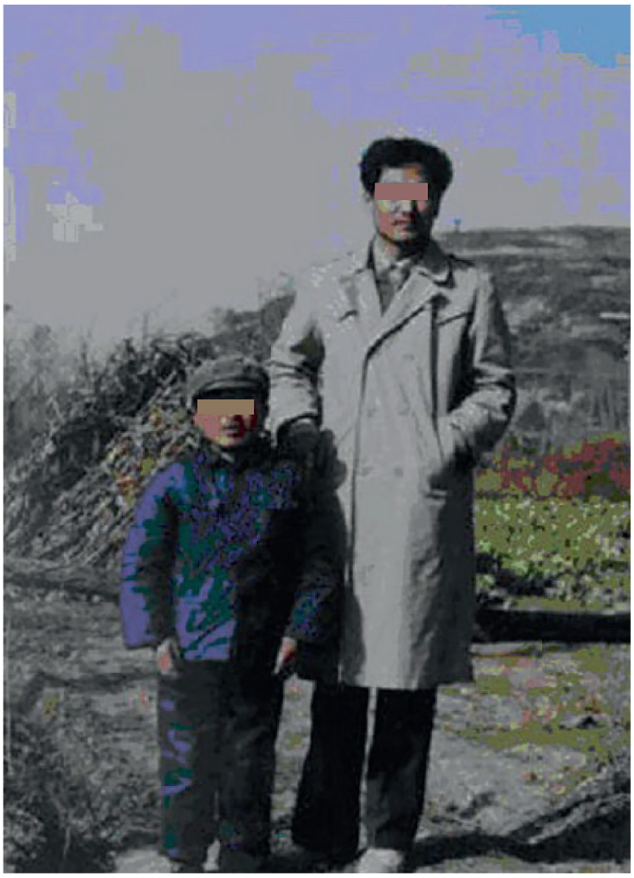


Figure 10. A patient with Kashin-Beck disease (bone deformation) compared to a person of normal height (Baoshan et al. 2010).

2.11. Geotourism and geoparks

Tourism in Brazil is an important driver of economic and social development and has undergone significant transformations in recent decades due to economic, environmental, social, and cultural changes. Geotourism, a form of ecotourism, focuses on the geodiversity of natural landscapes, including rocks, landforms, soils, and geodynamic processes. Identifying areas for geotourism development creates employment opportunities, promotes economic growth alongside environmental preservation, and fosters education, research, and the dissemination of geoscientific information, and knowledge.

In support of the National Tourism Plan, geodiversity provides resources for national parks, geoparks, and other nature tourism areas (Figure 11). These resources visitor experiences and offer area managers tools to manage the physical environment, complementing the existing efforts focused on biodiversity. Several publications on Geoparks in Brazil exist, such as those by Mansur (2010), Schobbenhaus and Silva (2012), Nascimento et al. (2015).

Geodiversity supports the Ministry of the Environment's initiatives by providing methodologies for the development and implementation of studies and projects related to Ecological-Economic Zoning. It also assists in the restoration of areas affected by mining, industrial, and agricultural activities, facilitating the return of animal and plant species to their original habitats. Additionally, geodiversity enables the identification of major geosystems that shape the national territory (various natural components such as rock, landforms, soil, and water), through the analysis of the rock composition, highlighting their limitations and potential. Groundwater studies contribute to planning for society's water needs, ensuring the continuity of Earth's life cycles (Jacques et al. 2021).

2.12. Sustainability

The study and understanding of geosciences are essential for developing resource extraction that meet humanity's needs without compromising availability for future generations. A deeper understanding of the environment is crucial to ensure the responsible use of natural resources, allowing future generations to benefit from them. In the context of geosciences, the significance of water cannot be overstated. Our planet is home to diverse ecosystems that include living beings and their environments, and the hydrosphere, encompassing seas, lakes, rivers, groundwater, ice, and rain, plays a crucial role in the water cycle, ensuring its circulation among ecosystems (Jacques et al. 2021).

However, it is important to highlight that in the mining sector, the concept of progress, historically associated with technical, scientific, and economic development, has been the subject of intense criticism. In *The Myth of Progress* (2014), Gilberto Dupas illustrates how this concept has become synonymous with environmental destruction and growing social inequalities (Dupas 2014). In mining, these contradictions are particularly evident, with predatory practices often justified in the name of economic efficiency and productivity, while neglecting the prevention of socio-environmental impacts, environmental conservation, and sustainability.

In this regard, it is essential to remember that in 1987, the *Our Common Future* report (World Commission on Environment and Development 1987) introduced the concept of sustainable development, defined as a process that seeks to meet the needs of the present without compromising the ability of future generations to meet their own needs. This report helped dissolve the dilemmas of “development vs. environment” and “competitiveness vs. sustainability”. It promoted the understanding that enhancing economic efficiency (competitiveness) must consider the use of natural resources in accordance with principles of environmental efficiency (sustainability), and it advanced the notion that productivity, which measures the efficiency of human and production capital as indicators of competitiveness, must also account for the intensity of natural capital use by incorporating sustainability indicators (Calaes 2005).

There is an urgent need to redefine the concept of progress by regulating the logic of pure capital accumulation and strengthening humanistic values. Progress must incorporate traditional knowledge, prioritize sustainability, and promote social justice. Science and technology should be directed toward collective well-being and committed to environmental preservation, fostering a future where progress is not limited to technical advancement but also serves as a force for innovation, equity, social justice, and sustainability.

Geosciences play a fundamental role in achieving several Sustainable Development Goals (SDGs) established by the United Nations. Mining, for instance, contributes to poverty eradication, by serving as a catalyst for industrial development. In sustainable agriculture, agro-minerals are crucial for ensuring food security and achieving the zero-

Figure 11. Itaimbezinho Canyon, RS, and Lençóis Maranhenses, MA.

hunger SDG. Health and well-being benefit from geosciences through hydrology, risk prevention, and medical geology. Quality education is supported by museums, libraries, and educational programs focused on geosciences.

Hydrology also contributes to providing clean water and adequate sanitation, while the exploration and research of strategic minerals are essential for generating clean and affordable energy. Increased mineral production drives skilled labor development and economic growth, while the availability of minerals for construction promotes innovation and infrastructure development. The reduction of inequalities is supported by the expansion of employment opportunities in mining and geotourism.

More sustainable cities and communities can be achieved through disaster prevention and early warning systems, while sustainable consumption and production are facilitated by the circular economy, including waste reuse in mining, soil remineralization, water conservation and recycling, and the adoption of energy efficiency measures. Climate action is driven by the application of hydrological data and geological risk prevention. The preservation of life on land and in water, as well as the restoration of degraded areas, is supported by geoconservation initiatives and ecological-economic zoning.

In the 2023 Social Balance of the SGB-CPRM (SGB-CPRM 2024a), sixteen geoscientific products and services were evaluated in in terms their economic, social and environmental impacts. The so-called “social profit” demonstrates how much the economy and society benefit from the products and services offered by public companies, which do not aim for economic profit, but rather prioritize public value and collective well-being. In 2023, social profit reached US$ 1,127,421,573.00 (using the conversion rate of US$ 1 equivalent to R$ 5,76) with a revenue of US$ 111,719,902.00, indicating that for every US$ 1.00 invested in SGB-CPRM, the return to society was US$ 10.09. This indicator reflects the amount society saved or stopped spending by using these products and services. The evaluation highlights the importance of geoscientific products and services and their significant contribution to improving quality of life and promoting sustainable development in Brazil.

Finally, geosciences also contribute to promoting peace, justice, and effective institutions through ethical practices and governance, as well as by strengthening national and international partnerships and agreements. Figure 12 (CPRM 2020) ethical practices the comprehensive relationship between geosciences and the 17 SDGs.

3. Conclusion

The products developed by geoscience professionals (geologists, geographers, hydrological engineers, geophysicists, etc.) should be utilized by all stakeholders involved in public policy formulation and management, whether they are linked to government bodies (executive, legislative, or judicial branches) or to private companies and organizations.

In both cases, the geoscientific knowledge generated and disseminated translates into societal benefits, reflected in the efficiency, safety, and sustainability of economic infrastructure projects (e.g., transportation, energy, communication) and social infrastructure (e.g., housing, sanitation, education, healthcare, sports, leisure, culture, and entertainment). Additionally, geoscientific products promote, enable, and support enterprises that provide essential goods and services, including those from the mineral industry.

It is also worth noting that geodiversity studies have proven to be excellent tools for planning and territorial management, providing technical support to various sectors, particularly those reliant on land use, such as:

Mining: Discovery and utilization of mineral resources.

Energy: Petroleum, gas, coal, peat, hydropower, nuclear, wind, and solar energy.

Agriculture: Soil fertility and deficiencies, fertilizers, soil amendments, and water availability.

Public Health: Water, soil, air, and food quality.

Urban Planning: Identification and characterization of factors that influence the limitation or expansion of urban occupation.

Housing: Availability of mineral resources and assurance of supply for construction materials.

Civil Defense: Landslides, floods, earthquakes, land subsidence, etc.

Transportation: Location, planning, safety, and durability of infrastructure projects.

Tourism: Inventory of geodiversity resources and scenic areas.

Environment: Diagnosis and recovery of affected areas, preparation of Environmental Impact Assessments (EIA) and Impact Reports (RIMA).

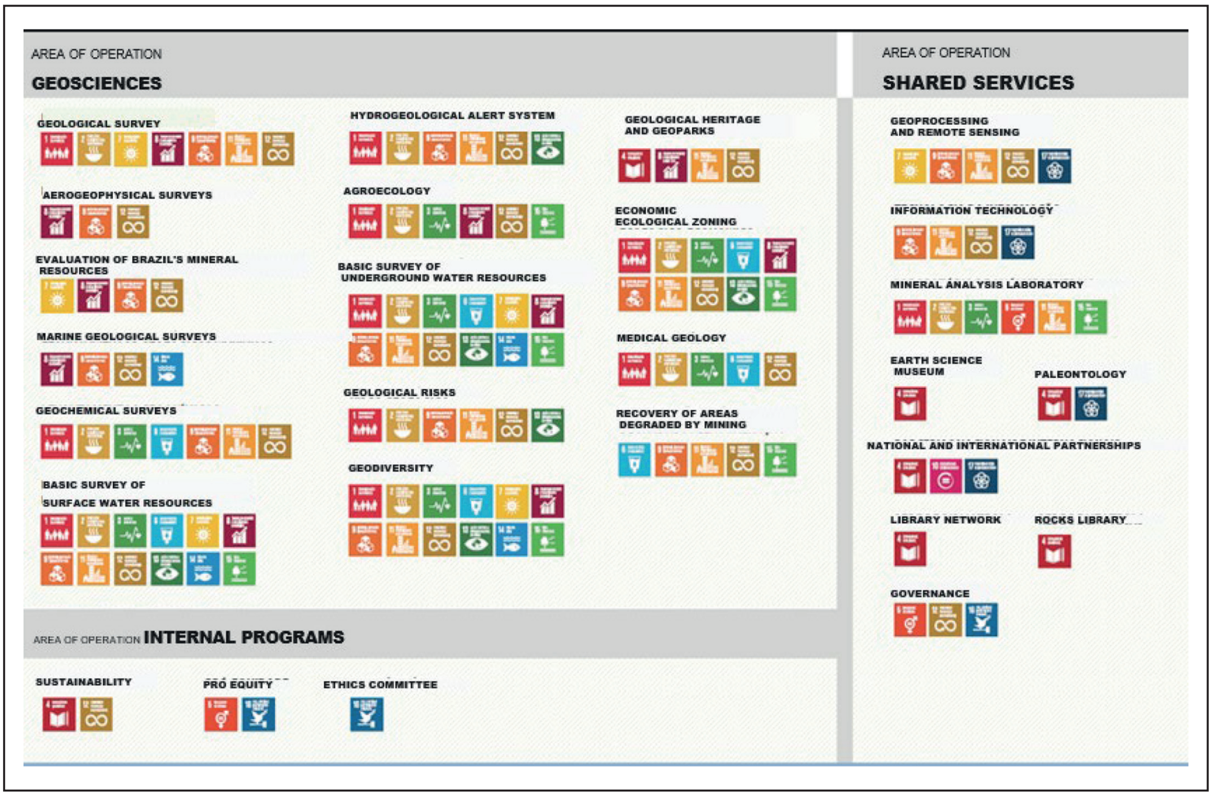


Figure 12. Relationship between geosciences and the SDGs (CPRM 2020).

Territorial Planning: For public institutions, watershed committees, private companies, and government programs, including ecological-economic zoning, territorial planning, continental shelf studies, and coastal environments management.

In summary, as geosciences enhance our understanding of land and environmental suitability and limitations, geodiversity has increasingly supported the formulation of public policies related to urban and rural development, infrastructure, and the sustainable economic use of mineral and water resources. This aligns with Municipal Master Plans, State Development Plans, and the National Territorial Planning Strategy.

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