Hydrogeological study of the Punta Gorda deposit for mining rehabilitation with agrominerals

Estudio hidrogeológico del yacimiento Punta Gorda para la rehabilitación minera con agrominerales

Elisbet Gamboa Matos* egamboa@geologia.ismm.edu.cu [1]
https://orcid.org/0009-0003-3536-3063
Giorvys Ramón Cuza Fernández gcuza@ismm.edu.cu [1]
https://orcid.org/0009-0007-7937-3502
Joel David González Rodríguez jdavid.gr005@gmail.com [1]
https://orcid.org/0009-0001-5329-0254
[1] University of Moa, Moa, Cuba
*Corresponding Author

Resumen: El presente estudio analiza las condiciones hidrogeológicas del yacimiento Punta Gorda (Moa, Cuba) como base para su rehabilitación minera mediante el uso de agrominerales. Se recopila y sistematiza información existente sobre parámetros clave como permeabilidad, porosidad, humedad y ascenso capilar, determinando su influencia en la dinámica del agua subterránea. Los resultados muestran un sistema acuífero complejo: las peridotitas agrietadas actúan como acuífero discontinuo (permeabilidad: 0.004–0.43 m/día), mientras que las lateritas funcionan como acuitardo (permeabilidad: 0.006–0.21 m/día), con humedad variable (17–95 %) y ascensos capilares de hasta 32.8 m. Se propone un marco de referencia para la rehabilitación, integrando datos hidrogeológicos con estrategias de aplicación de agrominerales, optimizando así la recuperación ecológica y reduciendo impactos ambientales.

Palabras clave: Hidrogeología, reforestación, producto fitoquímico, humedad del suelo

Abstract: This study analyzes the hydrogeological conditions of Punta Gorda deposit (Moa, Cuba) as a basis for mine rehabilitation using agrominerals. Existing information on key parameters such as permeability, porosity, moisture, and capillary rise was compiled and systematized to determine their influence on groundwater dynamics. The results reveal a complex aquifer system: fractured peridotites act as a discontinuous aquifer (permeability: 0.004–0.43 m/day), while laterites function as an aquitard (permeability: 0.006–0.21 m/day), with variable moisture content (17–95 %) and capillary rises of up to 32.8 m. A reference framework for rehabilitation is proposed, integrating hydrogeological data with agrominerals application strategies, thereby optimizing ecological recovery and reducing environmental impacts.

Keywords: Hydrogeology, reforestation, phytochemicals, soil moisture

Introduction

Cuba possesses one of the world's largest residual weathering deposits containing iron, nickel, and cobalt ores, which is known as *Punta Gorda* due to its geographical location (Rodríguez Infante, 1983; Vera Sardiñas *et al*., 2001; Rojas-Purón *et al.*, 2025). The first studies date back to 1969–1971, through a detailed exploration of the deposit's northern zone. During this period, it was determined that the area was characterized by an irregular, stable weathering crust, formed by large deposits of lateritic–nickeliferous and serpentinitic minerals (Tamayo, 1973). With more than 60% of its reserves exploited, the deposit has undergone several geological and hydrogeological studies; however, they are insufficient to establish its hydrogeological complexity.

De Miguel Fernández (2007) outlines the influence of hydrogeological processes on the formation and subsequent mineral enrichment of nickeliferous laterite deposits, defining the groundwater chemistry and hydrodynamic calculations to lay the foundations for the execution of a drainage project.

Sánchez-Sánchez *et al.* (2007) conducted a hydrogeological and engineering-geological characterization of *Punta Gorda* deposit where the groundwater regime was determined, the existing aquifers particularities were established, and the geotechnical characterization of lateritic horizons was carried out to design a natural drain system aimed at reducing moisture in the laterites.

De Miguel-Fernández (2009) presented drainage calculations for *Punta Gorda* deposit through a detailed hydrogeological study, in which high and low moisture content areas were identified. This allows for reducing the costs of drying nickeliferous material in furnaces and decreasing oil consumption.

Mining at *Punta Gorda* deposit has been an important source of income for Cuba. However, it has also generated significant environmental impacts requiring attention and proper management, such as deforestation and biodiversity loss, soil and water contamination, landscape alteration and erosion.

Open-pit mining is one of the anthropogenic activities generating the greatest disturbances in natural forest systems, as it causes strong changes in ecosystem structure and functioning (Alday *et al*., 2010; Valois *et al.*, 2017; Torres Batista *et al*., 2022; Paredes-Vilca *et al*., 2024). These systems damaged by mining activity require ecological restoration measures (Valois *et al.,* 2022) that contribute to restoring the natural balance of the affected regions, but this requires a comprehensive knowledge of the area to be rehabilitated.

It is important to consider Mining Environmental Rehabilitation (MER) of *Punta Gorda* deposit in order to restore ecosystems damaged by open-pit mining and reduce the hydrogeological impacts that may occur in the study area. In this sense, MER is defined as the procedure by which negative impacts caused by mining activity are mitigated (Urbino Rodríguez *et al*., 2019).

In this context, the use of agrominerals emerges as an innovative and effective strategy to accelerate the devastated area recovery. An agromineral is an amendment added to the soil to positively influence its structure, physical-chemical characteristics, and fertility. They help retain moisture, reduce nutrient loss, regulate pH in acidic soils, and improve compact and hard soils (Orozco-Melgar & Cuza-Fernández, 2022; González-Cueto *et al*., 2023; De Carvalho Ribeiro *et al*., 2024).

Martínez-Bring *et al.* (2025) emphasize some of the benefits of using agrominerals in agricultural production: improved soil fertility, as ammonium-loaded tuffs provide essential nutrients for plants, such as nitrogen, which is fundamental for their growth and development; increased efficiency in nutrient absorption; and reduced environmental contamination, since the use of agrominerals based on ammonium-loaded tuffs can help reduce soil and water pollution.

Similarly, Fernández et al. (2024) underline the positive impact of using agrominerals on the hydrogeology of areas degraded by nickel mining. These minerals, such as calcareous rocks and zeolites, improve soil structure, increase porosity and water retention capacity, help reduce surface runoff and erosion (Ferrán & Soca-Núñez, 2023; Feijoo & Luna, 2024). Furthermore, they contribute to reducing acidity and provide essential nutrients for crops. Agrominerals not only influence soil fertility but also favor hydrogeological dynamics (Arjona-Mendoza, 2024). Therefore, an understanding *Punta Gorda* deposit hydrogeology will ensure adequate agromineral application during environmental rehabilitation of that mining area.

Materials and methods

The study was based on a comprehensive compilation and review of existing information on the hydrogeological characteristics of *Punta Gorda* deposit (permeability, porosity, moisture, and capillary rise). It is grounded in an interdisciplinary approach that integrates hydrogeological, mining and agronomic techniques. This information was exhaustively collected from a hydrogeological perspective of the area.

2.1 Computer tools used

The use of technological tools optimized the management, analysis, and synthesis of information: Mendeley reference manager was used to organize and cite sources efficiently. Information search and analysis was carried out through Google Scholar, a tool that offers a wide scientific article database and allows for results filtering to find relevant information.

Capillary rises were calculated on the basis of effective diameter and porosity using three methods —Kozeny, Mavis, and Laplaza-Sergueiev— taken from De Miguel-Fernández (2007).

3.1 Analysis of results

From a hydrogeological point of view, the *Punta Gorda* deposit area is characterized by two zones. The first one comprises the northern flank blocks, where a part of the reserves are flooded. It includes blocks T-46, T-47, T-48, S-45, S-46, U-48, U-49, where the greatest thicknesses of the aquifer horizons occur, with little variation in groundwater levels over time, meaning that ores are always flooded— this is the discharge zone (Almaguer Carmenate, 2001).

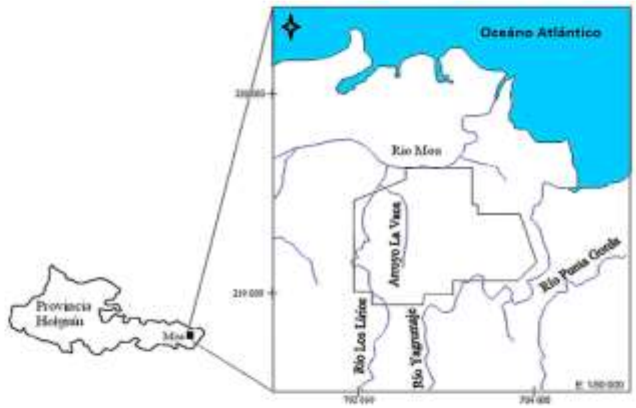

Figure 1. Geographic location map of Punta Gorda deposit (Almaguer-Carmenates *et al.*, 2014).

The second zone comprises the rest of the deposit where the laterites contain no water, except for local sectors which, during dry periods, have no water or small aquifer thicknesses —less than two meters most of the times.

The main groundwater source is atmospheric precipitation, which are abundant in the area —daily values range between 1 mm and 235.5 mm. The rest of the deposit presents no major hydrological difficulties for mining. The deposit is crossed by three main surface streams: Los Lirios River to the northwest, Yagrumaje River to the east-southeast, and La Vaca Stream in the central part.

Groundwater in Punta Gorda deposit follows the terrain morphology, with predominant flows towards the north in most of the area, possibly having different and even opposite directions towards the main surface water courses. The gradient varies between 0.03° and 31.7°.

The aquifer rocks (cracked serpentinites) exhibit flow through the contact zone with the impermeable crust, where lateral water movement occurs. Water movement is mainly driven by capillary rise, varying between 0.0 m and 25.5 m, the highest values correspond to the complete, still unaltered-by-mining section.

In Punta Gorda deposit, there is an aquifer complex formed by two stratified or layered aquifer horizons. The first one is represented by laterites, consisting of two layers: the first one is called Structural Ochres with Pellets (abbreviated as OICP in Spanish) and the second one is subdivided into Initial Structural Ochres (OII), Final Structural Ochres (OEF), and Initial structural ochres (OEI), (De Miguel-Fernández, 2004). The deepest aquifer horizon is represented by layers 3 (highly leached rock) and 4 (cracked rock).

Table 1. Characterization of Punta Gorda deposit´s aquifer complex (De Miguel-Fernández, 2004)

Aquifer Horizons	Lithology
Laterites	Gravelly-silty sand with coarse fractions consisting of iron pellets, with low plasticity (Layer 1 - OICP)
	Highly plastic clayey silt (Layer 2 - OII, OEF, OEI)
Serpentinites	Highly leached rock, present in form of silty-gravelly sand with clay and serpentinite fractions (Layer 3)
	cracked rock (Layer 4)

3.1. Hydrogeological Parameters

3.1.1. Aquifer Thickness

In the drillings performed, the saturated and aquifers thicknesses were fully penetrated, except for the aquifer of the fractured peridotites (serpentinites), where, in in accordance with the research, it was drilled only 5 m below the top of the peridotites upon water appeared at higher elevations, and up to about 3 m below the water appearance elevation in the peridotites (De Miguel-Fernández, 2007).

Within the territory, the average thickness of altered peridotites is about 30 m. When it comes to laterites, the saturated zone does not truly represent an aquifer, since there is practically no lateral water circulation due to the existing lithology; therefore, this zone can be considered an aquitard. The saturated thicknesses penetrated in the laterites range from 0 m to 27.6 m and depend on the terrain's relief and its erosion base. Laterites' greatest thicknesses are found in the deposit's highest areas (De Miguel-Fernández, 2007).

3.1.2. Permeability

Permeability, represented by the filtration coefficient, is variable in both laterites and peridotites. In laterites, it ranges between 0.006 and 0.21 m/day. The average values per layer are: Layer 1 - 0.106 m/day, Layer 2 - 0.043 m/day (De Miguel-Fernández, 2007).

Permeability in peridotites ranges between 0.004 and 0.43 m/day, although values exceeding 3 m/day can be found in fault zones. In peridotite layers, the permeability represented by the filtration coefficient reaches the following average values: Layer 3 - 0.044 m/day, Layer 4, excluding fault zones - 0.14 m/day (De Miguel-Fernández, 2007). Permeability in Layer 4 (cracked peridotites) is more than three times greater than the one in leached peridotites (Layer 3) and that of the laterites (Layer 2). Besides, it is 1.3 times greater than the permeability of the laterite cover stratum (Layer 1) (De Miguel-Fernández, 2007).

3.1.3. Water yield

The water yield determined for laterites— due to their importance in the mining-industrial process—is low. It is expressed in l/s·m of drawdown and presents values below 0.1 l/s·m (De Miguel-Fernández, 2007).

In most of the laterite distribution area, water yield is predominantly of capillary origin, resulting from saturation driven by capillary rise from greater depths, with the aquifer peridotites underlying the laterites as a source. (De Miguel-Fernández, 2007).

During rainy periods, oversaturation of the laterite thickness develops in the upper part of the section as a consequence of rainwater infiltration to depths where infiltration from the surface is balanced by the existing saturation due to capillary rises and uplift pressure from the fractured peridotites (De Miguel-Fernández, 2007).

3.1.4. Capillary Rises

Capillary rise properties of laterites were determined according to a methodology based on the granulometry of the analyzed sediments and their porosity (Table 2). The calculations performed determined that capillary rises in the laterites range between 0 and over 26 m. The lowest values are consistent with lateritic thicknesses of Layer 1, which presents the coarsest granulometry, with rises ranging between 0 and 3.4 m. In Layer 2, the granulometry is finer, and capillary rises range between 20 and 32.8 m.

Table 2. Calculation of average capillary rise (De Miguel-Fernández, 2007)

Data		Calculation Formula H_c (m)	Average Capillary Rise H_c — (m)	Author
Average Porosity(n)	Effective Diameter D_e (mm)			
0.6	0.002	$H_c = 0.0446\frac{1-n}{n}\cdot\frac{1}{D_e}$	14.87	Kozeny
		$H_c = \frac{0.0306}{De}\sqrt[3]{\left(\frac{1-n}{n}\right)^2}$	21.32	Mavis-Tsui
		$H_c = \frac{0.0306}{De}$	15.3	Laplaza-Sergueiev

In most of Punta Gorda deposit, laterites lie directly on leached and aquifer peridotites. The contact zone between these lithological differences is the main pathway for groundwater circulation in the laterites (Layers 2 and 3). Therefore, the determined capillary rise potential in the laterites, based on their granulometry, becomes effective as the base of these sediments is in direct contact with water.

In the cracked peridotites, capillary rises are effective on the base of the groundwater stabilization level (due to saturation) caused by uplift pressures from their basement, where confined waters with moderate pressures exist.

Taking into account the studied laterite granulometry, whose diameter ranges between 0.0018 and 0.0022 mm, corresponding to 10% of the sample weight, and assuming an average of 0.0020 mm for calculations and an average porosity of 60% (n=0.6), the average capillary rise that can occur in the deposit, calculated by three different methods, yields a value of Hc = 17.14 m.

3.1.5. Laterite Moisture Content

Under natural conditions, rocks contain a greater or lesser amount of water. In soils and rocks lying above the groundwater level, water content varies depending on temperature, atmospheric pressure, air humidity, evaporation, atmospheric precipitation, etc. Natural moisture content is determined from rock samples with undisturbed structures. The moisture content magnitude is determined in laboratory conditions through gravimetric moisture calculation, expressed in % (de Miguel-Fernández, 2012).

Moisture content in laterites varies between 17.1 and 47.3 %, in Layer 1, and between 31.4 and 94.9 %, in Layer 2. This difference in values is because Layer 1 has coarser granulometry and the evaporation process acts directly upon it.

In Layer 2, the highest moisture values are recorded at greater depths and in contact with Layer 3 and the aquifer peridotites. Moisture in these layers is directly influenced by the pressures existing in the waters contained and circulating within the peridotites, up to levels where those pressures equilibrate. Above the elevation influenced by uplift pressures, the moisture content of laterites is directly influenced by capillary rise processes occurring through the laterites from the zone of moisture caused by underlying pressures, or directly from the waters contained in the peridotites.

Another aspect influencing laterite moisture is the roughness on the top of the fractured aquifer peridotites, because the points where it presents depressions filled with laterites present a high saturation, and water may, in some cases, be found at shallow depths (piezometric level).

During rainy periods, saturation occurs in the upper part of the laterites due to rainwater infiltration from the ground surface. This saturation in depth extends downwards until it equilibrates with the existing moisture due to capillary rises and uplift pressure from the fractured peridotites (De Miguel-Fernández, 2007).

4. Hydrogeological parameters interpretation

4.1. Aquifer Thickness

The hydrogeological results indicate a complex system where cracked peridotites act as a discontinuous aquifer, with limited saturation, suggesting fracture-dependent flow and a shallow water table. On the other hand, laterites, which exhibit variable saturated thicknesses (0–27.6 m) and lack lateral circulation, act as an aquitard by retaining water but do not allow its efficient transmission, especially in elevated areas where thickness is determined by relief and erosion.

This duality between fractured aquifer in peridotites and hydraulic barrier in laterites evidences a critical spatial heterogeneity for water management, highlighting the need for complementary studies (pumping tests or modeling) to quantify hydraulic parameters and assess resource sustainability.

4.2. Permeability

The data show significant variability in permeability, represented by the filtration coefficient, between laterites and peridotites. In laterites, the it ranges between 0.006 and 0.21 m/day, with average values per layers reflecting a progressive decline: Layer 1 (0,106 m/day) presents a higher permeability than Layer 2 (0,043 m/day).

On the other hand, in peridotites, the range is wider (0.004–0.43 m/day), with exceptionally high values in fault zones (>3 m/day). Layer 4 (fractured peridotites) stands out, with a average value of 0.14 m/day (excluding faults), which exceeds Layer 3 (0.044 m/day) and the Layer 2 laterites by more than three times, and Layer 1 laterites by 1.3 times.

This suggests that fracturing in the peridotites favors more efficient hydraulic flow, while laterites, especially in lower layers, act as less permeable strata. The influence of faults in the peridotites highlights their critical role in infiltration dynamics, potentially creating preferential pathways for water.

4.3. Porosity

The water yield values in laterites are low (less than 0.1 l/s·m of drawdown), reflecting a limited water flow capacity in these materials. This characteristic is mainly attributed to the capillary origin of the water, where saturation occurs through capillary rises from the underlying peridotites, which act as aquifers.

During rains, oversaturation occurs in the upper laterite strata due to rainwater infiltration, which equilibrates at certain depths with the pre-existing saturation generated by capillary processes and uplift pressure from fractured peridotites.

This dynamic equilibrium between surface infiltration and capillary rise underscores laterites hydrogeological complexity and highlights their dual behavior: low permeability under dry conditions and temporary storage capacity during rainy events. The interaction between these factors is key to understanding their role in mining-industrial processes, where water management must consider both capillary retention and seasonal moisture pulses.

4.4. Capillary Rise

The findings of the study on capillary rises in the laterites of Punta Gorda deposit reveal significant variability depending on the granulometric characteristics and sediment porosity. In Layer 1, having coarser granulometry, rises are minimal (0–3.4 m), while in Layer 2, as texture is finer, they reach notably higher values (20–32.8 m), with an average value of 26.0 m. This difference underscores the critical influence of granulometry on capillary rise capacity, where finer particles favor greater heights due to higher surface tension and porosity (60% in this case).

Laterite’s location, directly above leached and aquifer peridotites, facilitates hydrodynamic interaction, especially in the lithological contact zone, which acts as the main pathway for groundwater circulation. This allows the theoretical capillary rises, calculated on the base of the effective diameter (De = 0.0020 mm) and porosity, to manifest in practice. Calculations performed using three different methods converge on a average value (Hc = 17.14 m), confirming the consistency of the results and their applicability to the deposit's geological context.

Furthermore, the study highlights that the rises are effective only after sediment saturation, driven by uplift pressures from the fractured peridotite basement, where confined waters exert moderate pressures. This mechanism explains not only the observed values but also their spatial distribution, linked to the lithological and structural variations of the terrain. Together, the data provide a quantitative basis for understanding the hydrological behavior of laterites and their interaction with underlying aquifers, relevant for water resource management and infiltration studies in the area.

Además, el estudio destaca que los ascensos son efectivos solo tras la saturación de los sedimentos, impulsados por subpresiones desde el basamento fracturado de peridotitas, donde las aguas confinadas ejercen presiones moderadas. Este mecanismo explica no solo los valores observados, sino también su distribución espacial, vinculada a las variaciones litológicas y estructurales del terreno. En conjunto, los datos proporcionan una base cuantitativa para entender el comportamiento hidrológico de las lateritas y su interacción con los acuíferos subyacentes, relevante para la gestión de recursos hídricos y estudios de infiltración en la zona.

4.5. Moisture Content

The variation laterite´s moisture content is directly related to the granulometric characteristics and hydrodynamic processes in each layer. In Layer 1 (17.1–47.3% of moisture content), the coarser texture and direct exposure to surface evaporation explain its lower values. In contrast, Layer 2 (31.4–94.9%) registers higher a moisture content in depth, especially near the contact zone with aquifer peridotites, due to the influence of groundwater uplift pressures and capillary rises that balance moisture from deeper zones.

During rainfall, surface infiltration temporarily saturates the upper part of the laterites, but this effect attenuates with depth as it equilibrates with upward flows from the peridotites. These combined mechanisms (evaporation, capillarity, hydrostatic pressures, and structural heterogeneities) define laterites moisture profile, highlighting its dependence on lithological factors and hydrogeological dynamics.

4.6. Relationship between hydrogeological parameters and the use of agrominerals in mine rehabilitation

Punta Gorda deposit's hydrogeological results reveal key characteristics that can be used for rehabilitation by means of agrominerals. The duality between fractured peridotites (discontinuous aquifer) and laterites (aquitard) suggests that groundwater management is fundamental for any rehabilitation strategy.

Agrominerals such as zeolites, bentonites, or natural phosphates could be used to improve moisture retention in laterites, especially in Layer 2, where capillary rises are significant (20–32.8 m). These materials, containing a high cation exchange capacity and porosity, could stabilize moisture in dry zones (e.g., Layer 1), regulate nutrient release in saturated areas, mitigate erosion, and promote environmental reforestation.

Furthermore, the presence of fractures in the peridotites (with filtration coefficients from 0 to 0.43 m/day) indicates that agrominerals could be used to seal preferential pathways and reduce water loss due to rapid infiltration, optimizing its availability for plants and microorganisms. In zones with high uplift pressure from the basement, agrominerals could act as moisture buffers, balancing seasonal rainfall and capillarity pulses. The fine granulometry of Layer 2 (60% porosity) would facilitate the incorporation of these minerals, while their interaction with the aquifer peridotites would ensure a sustainable water supply.

Conclusions

It was determined that Punta Gorda deposit presents hydrogeological heterogeneity, with laterites (low permeability) and peridotites (high permeability in fractures), requiring differentiated strategies for its rehabilitation.

Groundwater flows predominantly towards the north, influenced by relief and fractures. Moisture in laterites depends on capillary rises and uplift pressures from peridotites.

Agrominerals can mitigate acidity, improve water retention (due to their high porosity), and stabilize nutrients, especially in zones with high capillary moisture (Layer 2).

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Author's Contribution according to CRediT Taxonomy

Elisbet Gamboa Matos: Conceptualization/Investigation/Methodology/Validation/Visualization/ Writing – review & editing.
Giorvys Ramón Cuza Fernández: Conceptualization/Supervision/Methodology/Writing – review & editing.
Joel David Gonzáles Rodríguez: Data curation/Resources/Validation