Region - Water Conservancy, 2026, Volume9, Issue2
DOI: 10.32629/rwc.v9i2.5579
ISSN Online: 2630-4902

Physical-geological model of the San Diego de los Baños karst aquifer, Pinar del Río, Cuba

Antonio J. Santibañez Rodríguez, Lisbeth Núñez Haugh, José Antonio Díaz Duque

Departamento de Geociencias, Universidad Tecnológica de La Habana (Cujae)

Abstract: The San Diego de los Baños karst aquifer has been scarcely studied from a geophysical perspective, resulting in a shortage of petrophysical data. Using the analogy principle, geological information from previous studies conducted in the area, and measured physical property data from zones with characteristics similar to this aquifer, boreholes distributed across the entire sector were modelled. This yielded the first physical-geological model for this karst aquifer. Three-dimensional physical parameter models were constructed, and the local gravitational and magnetic field responses generated by sources down to a depth of 400 metres were calculated. The electrical resistivity behaviour along the geological cross-section was also computed. A rational integrated suite of geophysical methods is proposed to support improved characterisation of the aquifer.

Key words: aquifer; rational suite of geophysical methods; Cuba; physical-geologic model; San Diego de los Baños

1 Introduction

Optimising the management and regulation of water resources to support their sustainable use is highly significant. This optimisation relies on advanced methods and techniques, which underpin modern aquifer investigations — aquifers represent one of the principal sources of freshwater. Modelling stands out among the most effective techniques for characterising aquifer architecture. It allows researchers to define subsurface geometry and map the distribution of physical properties, with particular focus on petrophysical attributes. Petrophysics bridges geology and geophysics. From this perspective, petrophysical modelling forms an essential step in developing physical-geological models (PGMs). A PGM offers a generalised, formal representation of the geological and physical attributes of the target unit and its host rock. It approximates in-situ conditions as closely as practicable and aligns with established fundamental understanding of the system.

Mineral-medicinal water aquifers are characterised by fractures of varied origins s that impart substantial geological and structural complexity to these aquifer systems. This feature is found in nearly all groundwater bodies across Cuba. The aquifers investigated generally contain more than one aquifer horizon. Owing to this high complexity, many of these systems (Menéndez, Fragua, Aurora, Elguea and San Diego) undergo mixing of waters sourced from distinct aquifer horizons with divergent chemical compositions. This leads to a very wide range of mineralisation values. Natural mineral and mineral-medicinal water aquifers are mostly confined or semi-confined, and in some instances they discharge as springs (Rodríguez, 1998).

Developing a PGM optimises aquifer investigations and reduces their cost, primarily because this representation

Copyright © 2026 by author(s) and Frontier Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/

approximates real subsurface conditions more closely. Its construction requires consideration of several components. First is the geological model of the target units, which incorporates key geological attributes: lithology, geometry, size, spatial position, structure and supplementary data. Second is the petrophysical model, which defines the main physical properties of the geological targets, including density, magnetic susceptibility, resistivity and chargeability. Third is the physical-field model, which characterises physical fields within the upper and lower half-spaces surrounding the geological targets.

Western Cuba hosts a range of geological and lithological settings that control the occurrence of mineral and mineral-medicinal springs with diverse physicochemical characteristics. Recent investigations across Cuba have been carried out by institutions including the National Institute of Hydraulic Resources (INRH), the Institute of Tropical Geography (IGT) and the Institute of Geology and Palaeontology (IGP), in partnership with multiple universities. The work of Fagundo stands out; much of his research career has focused on the geochemistry of mineral-medicinal water aquifers (Fagundo et al., 1996). In recent years, researchers have grown interested in geological-geophysical investigations based on geological structure modelling. García (2018) completed extensive work for his doctoral thesis, developing geo-electric models of various geological formations for geotechnical applications in areas adjacent to the San Diego de los Baños aquifer.

Although Pinar del Río Province has been the subject of multiple hydrogeological, hydrochemical and geophysical studies, geoscientific knowledge has not yet been adequately integrated. This gap prompted the launch of a national project coordinated by the University of Pinar del Río: "Assessment and Control System for Water Resources in the Central-Eastern Sector of the Guaniguanico Range". The project aims to integrate hydrogeochemical and hydrodynamic understanding of groundwater discharging from the central-eastern part of this mountain range. One participating institution is the Department of Geosciences at the José Antonio Echeverría Technological University of Havana, which undertakes the processing and interpretation of geophysical data. Despite the wide range of studies completed to date, none have specifically targeted the development of a physical-geological model for the San Diego de los Baños aquifer. Such a model is critical for clarifying the aquifer's internal structure and supporting the sustainable management of its water resources, to supply local residents and sustain health-tourism activities.

Accordingly, the present study defines its scientific problem as follows: the pronounced geological-structural complexity of the San Diego de los Baños aquifer introduces uncertainty regarding the sustainability of water-resource management. The corresponding scientific hypothesis is formulated as: developing the physical-geological model of the San Diego de los Baños aquifer will help reduce uncertainty associated with the sustainable management of its water resources.

This paper, which presents the outcomes of the research, sets its general objective as the geological-geophysical characterisation of the region hosting the San Diego de los Baños aquifer. Its specific objective is to develop the physical-geological model for this aquifer.

2 Location and characteristics of the study area

The study area lies within Pinar del Río Province, northwest of the town of San Diego de los Baños (Figure 1), which is the nearest urban centre. The municipality of Consolación del Sur is situated to the southwest, and Los Palacios municipality to the southeast. The site covers an area of 10 km², forming a strip roughly 1 km wide and 10 km long. It extends from the northwest of Baños de Bermejales to the settlement of San Diego de los Baños and encompasses the entire course of the San Diego River.

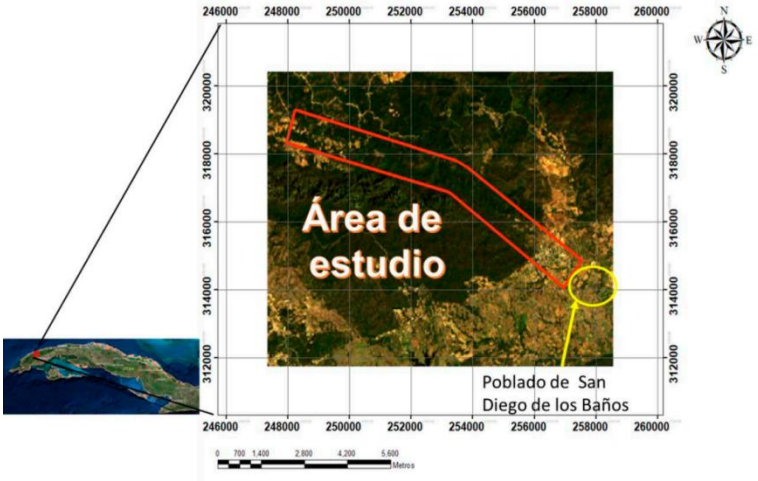

Figure 1. Geographical location of the study area. San Diego de los Baños Sector (SSDB), Bermejales Sector (SBMJ)

The regional relief consists of karstic limestone elevations (mogotes) with dome shapes and vertical slopes, together with slate mountain ranges and slate hills. Valleys enclosed among them are termed marginal karst plains. Slate hills are characterized by rounded summits and heavily eroded slopes of variable gradients. Surface karst features such as dogtooth ridges and dolines are well developed. Elevations across the area range from 50 to 200 m. The terrain is undulating with steep slopes, which become gentler toward the settlement of San Diego de los Baños.

Vegetation in the area corresponds to soil type and relief. Large pine forests predominate on slate hills of the San Cayetano Formation (Fm.). Typical trees of conical karst grow on the mogotes of the Artemisa Formation. Thorny evergreen shrubs are mainly found in the lower flat areas (Lima, 2009).

The main surface watercourse of the region is the San Diego River, also known as the Caiguanabo River along a section of its course. It flows from west to east and is characterized by a narrow, deep channel, with meanders developed in some reaches. Its most important tributaries are the Las Catalinas River and the El Flamenco Creek, which flow from north to south. These two streams have their own tributaries that augment discharge during the rainy season (Peláez et al., 1990).

The study area belongs to the Sierra del Rosario Structural- Facies Zone. The sedimentary record consists of terrigenous sequences of the San Cayetano Fm. (J_1–J_3ox) and Francisco Fm. (J_3ox), as well as carbonate deposits of the Artemisa Fm. (J_3^{th}–K_1). Deposits of the San Diego de los Baños subzone crop out in the southern part of the occurrence, represented by flyschoid sequences of the Capdevila Fm. and terrigenous sediments of the Manacas Fm. The general tectonic framework of the province is complex, with widely developed fault and fold dislocations and large, intricate structures formed by orogenic phases that affected the Cuban geosyncline. North of the Pinar Fault lies the Guaniguanico Structural- Facies Zone. Tectonics are simpler to the south, in the San Diego de los Baños area, where strata are subhorizontal, nearly monoclinal and dip southwards. These two zones are separated by the Pinar Fault, the most significant fault structure controlling the regional tectonic evolution (Peña, 2000).

An aquifer horizon hosted in fractured and karstified limestones of the Upper Jurassic Artemisa Formation is widely distributed in the study area. It is generally unconfined and exhibits substantial variability in key hydrogeological parameters: the filtration coefficient ranges from 1.0 to 14.0 m/d, with yields of 0.6–10.1 L/s. Calcium bicarbonate-type groundwater prevails outside the mineral- medicinal water deposits, with a mineralization of 0.8 g/L. These aquifers are recharged by infiltration of a fraction of local atmospheric precipitation. Groundwater is discharged into the fluvial network, principally the San Diego River, with localized discharge via karst springs whose discharges vary from 0.5 to 15 L/s (Lima, 2009).

The regional impermeable base is formed by terrigenous deposits of the San Cayetano Formation, widely spread across the region. This unit consists of siltstones and quartz sandstones, which only host sporadic percolation water within fractured zones. Tectonic slices of these terrigenous sediments commonly overlie Jurassic carbonate deposits and act as an impermeable cover. Finally, groundwater associated with fault zones is linked to mineral-medicinal waters, which occur in both the San Diego and Bermejales sectors, as well as at other occurrences such as Cueva de los Portales, Loma del Infierno, La Güira and Los Cuartones, among others (Peña, 2000).

3 Data acquisition and processing

To construct the physical-geological model of the San Diego de los Baños aquifer, the general features of the available geophysical datasets (gravity, magnetic, electrical and physical property data) were considered, together with their description and the applied processing techniques.

Gravity and magnetic data for the study area were provided by the IGP (Mondelo & Sánchez, 2011). Geo-electrical survey data were supplied by the National Office of Mineral Resources (ONRM). These data come from a detailed prospecting survey carried out in the San Diego de los Baños-Bermejales sector in 1990 by the working group led by Eng. Roberto Peláez. It should be emphasized that this is the only study with available geophysical data for the area (Peláez et al., 1990).

The contour interval for Bouguer anomaly mapping was set at 0.5 mGal, with an interpolation error of ±0.35 mGal for 10 % of the observation points. Magnetometric data are mainly derived from the airborne gamma-spectrometric and magnetic survey (LAGEM) at a scale of 1:50,000, acquired from 1979 to 1993. In areas without flight lines, magnetic data at 1:500,000 compiled by O. N. Soloviev and co-workers in 1963 were adopted. No interpolation error was computed for the magnetometric maps, because the original gridded datasets of the 1:50,000 LAGEM survey were used for map production. The adopted base zero value was 43 000 nT. The digital elevation model with a spatial resolution of 25×25 m (USGS, 2005) was provided by the Department of Geosciences, Technological University of Havana.

Only core data, descriptions of well geological columns, detailed geological cross-sections and vertical electrical sounding (VES, SEV) data from the survey by Peláez et al. (1990) are available for the study area, together with regional survey studies completed by the Council for Mutual Economic Assistance (CAME) in 1986. For this reason, the principle of analogy was adopted to obtain petrophysical data. Lithological descriptions from well geological columns and detailed geological cross-sections of the sector were correlated with well data from the CAME II survey (Martínez et al., 1988). The latter dataset includes magnetic susceptibility and density measurements acquired from drill cores sampled at regular intervals of 5–10 m down to the total well depth.

Lithological descriptions compiled by wellsite geologists enabled the comprehensive characterization of boreholes, combined with in-situ magnetic susceptibility and rock density data. As a result of the detailed prospecting survey, data are available for 14 boreholes approximately 400 m deep, together with four geological profiles 1000 m long, striking northeast–southwest. These profiles document the formations and lithologies occurring within the sector and facilitate improved stratigraphic correlation with boreholes from the CAME II survey (Martínez et al., 1988).

Using all available information from the survey by Peláez et al. (1990) and the CAME II survey (Martínez et al., 1988) and applying the principle of analogy, physical property values (density, magnetic susceptibility and resistivity) were assigned to the formations shown on the existing geological cross-sections of the study area. To build the database for these property values, 220 boreholes with physical property data were modelled, with an average spacing of 200 m and a maximum depth of 400 m. The overall workflow of the study is shown in Figure 2.

The work starts with geological, petrophysical and geophysical information archived in the geological repositories of IGP and ONRM. Input files were created within the Oasis Montaj software platform (GEOSOFT, 2008), and voxel[1] models of physical properties (3D physical parameter models) were generated. These serve as the starting model for the GMSYS 3D module to compute potential fields. Anomalies calculated from the voxel models represent only the local components of the gravitational and magnetic fields. This is because the voxel domain extends to a maximum depth of 460 m (the deepest borehole), with its upper boundary defined by the digital elevation model. Maps of physical parameters were derived from the 3D physical parameter models.

As the final result, the physical- geological model is constructed. It comprises the geological model, petrophysical model and physical field model (gravity, magnetic and modelled resistivity). Subsequently, a rational integrated suite of geophysical methods for characterizing this type of aquifer is defined, considering the model characteristics and the reviewed literature.

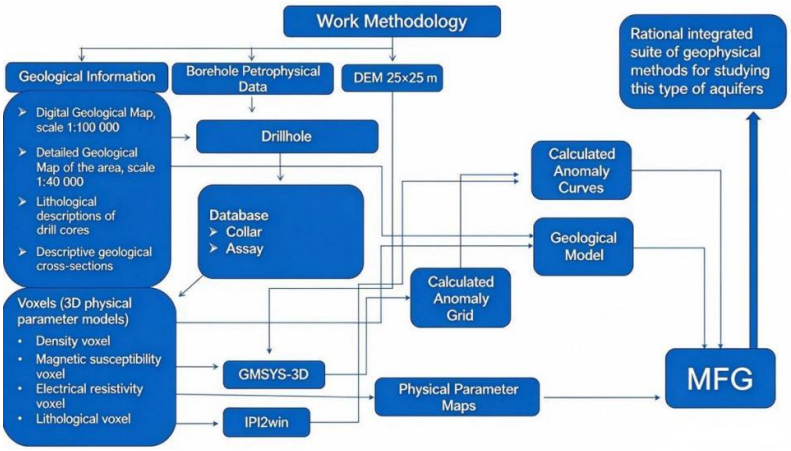

Figure 2. Work methodology for data processing

3.1 Development of 3D physical parameter models

To construct a voxel, the 3D extension with the Gridding option was used. Two interpolation methods are available for this task: Kriging and Inverse Distance. The Kriging interpolation method was selected rather than Inverse Distance, because it was verified that the latter produced less distinct results and exhibited interpolation errors when the blanking value was increased. Another parameter that must be considered is the cell size, which is calculated by the software based on the spatial distribution of data within the study area; the software recommends the optimal value. The default setting is 50 m², but other values (5, 25 and 100 m²) were tested to compare outputs and select the most suitable one. The blanking option 4 was set as the predefined value.

Blanking is a command directly related to cell size. Points within the study area that lie farther away than the distance specified by the program are displayed as blank spaces. The default value is four, which means any voxel node outside a range of four cells will be blanked. If the cell size is increased excessively, there is a risk of losing resolution. A cell covering a large area will be influenced by multiple measurements, so the program assigns an average value to the cell, and the lateral and vertical variations of physical properties cannot be characterized.

For the construction of the 3D lithological model, a voxel was generated using the AGSO coding standard, and codes corresponding to each lithology identified in the depth cross-sections were added to this standard based on borehole core information. The main limitation is that lithological descriptions cannot be interpolated, as they are textual or lithology codes rather than numerical values; consequently, rocks belonging to different lithologies and geological formations may

[1] A voxel is the cubic unit that makes up a three- dimensional object.

be displayed with the same colour, and the software does not allow modification of this colour legend. Further difficulties include the limited tools available in Oasis Montaj for fault representation, and the fact that the colour scheme does not comply with the geological mapping standards adopted in Cuba

3.2 Calculation of physical fields

GMSYS 3D cannot model two physical properties simultaneously. For this reason, two separate modelling runs were carried out: one using density data and the other using magnetic susceptibility data. Forward calculation requires no blank spaces within the voxels, because the computation adopts the Parker algorithm based on the Fast Fourier Transform (FFT), and the matrix used for data transformation must be complete. The voxels imported into GMSYS 3D as input models had a cell size of 25 × 25 m and a blanking value of 16 cells. This cell size was selected given that the surface extent of the study area is approximately 10 km² and the spacing between boreholes is roughly 150 m.

Models were constructed from the DEM down to a depth of 530 m. An intermediate layer density of 2.67 g/cm³ was adopted for Bouguer anomaly calculation. Other required input parameters for the software include the simulated measurement surface and the observed anomaly. The DEM was selected as the measurement surface to assume that all data were acquired on the ground surface. The Bouguer ΔG anomaly grid was used as the observed anomaly dataset. The calculated anomalies are shown in Figure 3.

To obtain the calculated ΔT magnetic anomaly, the background susceptibility was set to $0 \times 4\pi \times 10^{-6}$ SI, with a magnetic field inclination of 51.26°, declination of −0.49°, and intensity of 45524.56 nT. These parameters were calculated by the software using the International Global Reference Field (IGRF) for the coordinates of the study area and the year 1986, when the survey was carried out. The measurement height was 60 m, consistent with the flight altitude of the LAGEM survey in this area. The grids of calculated anomalies, which have been reduced to the pole, are presented in Figure 4.

To verify the correspondence between the physical properties of rocks and the calculated anomalies, a profile was laid out across San Diego de los Baños, for which geological information and geographic coordinates are available (Peláez et al., 1990). Two- dimensional sections were extracted from the 3D density and magnetic susceptibility models built in GMSYS 3D along this profile. For the resistivity physical field model, apparent resistivity geoelectric section data down to an approximate depth of 200 m were used. These data originate from Vertical Electrical Sounding (VES, Spanish: SEV) surveys carried out by Peláez et al. (1990).

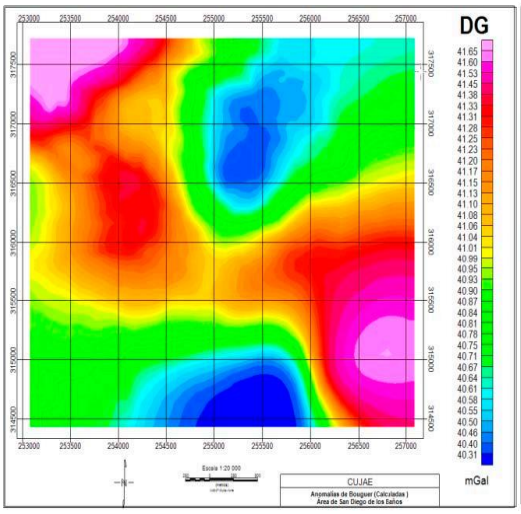

Figure 3. Calculated ΔG anomalies for the San Diego de los Baños sector.

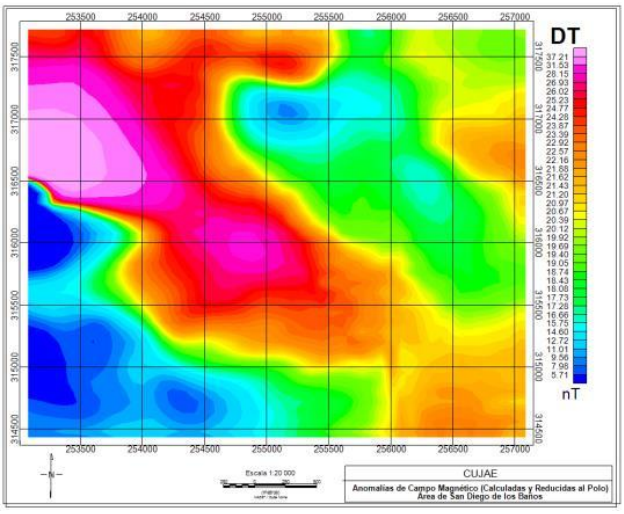

Figure 4. Calculated ΔT anomalies for the San Diego de los Baños sector.

The plots were digitized and inversely modeled using the IPI2WIN software (Moscow State University, 2000). The resistivity behavior was modeled with a maximum AB electrode spacing of 1,000 m to reach an investigation depth of 250 m. A pseudosection was generated for each Vertical Electrical Sounding (VES) point (7 VES points along the profile, spaced at 150 m). This makes it possible to characterize the resistivity distribution and identify the curve types that the VES surveys may yield in the study area. In preparation for a new field survey, the expected response curve types were estimated (Figure 5).

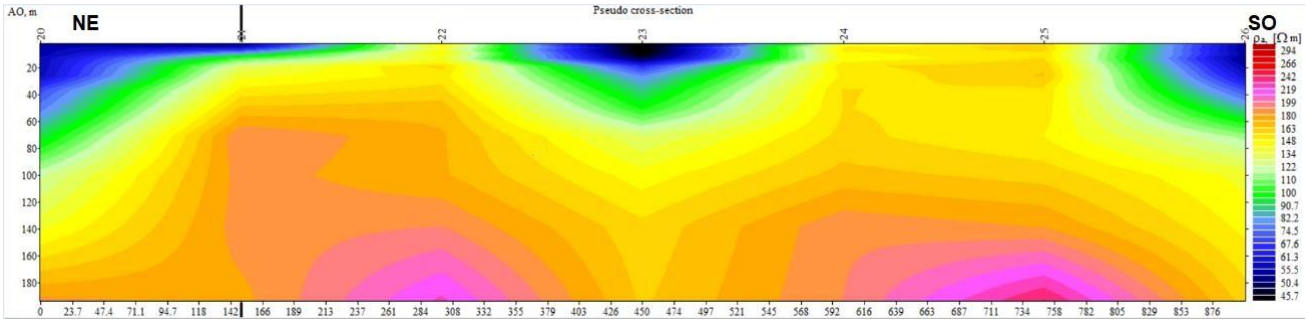

Figure 5. Electrical resistivity pseudosection for the San Diego de los Baños profile

3.3 Preparation of physical parameter maps

To prepare the physical parameter maps for the San Diego de los Baños region, horizontal slices were extracted from the density and magnetic susceptibility voxels (Figures 6 and 7), and a vertical slice was extracted for resistivity (Figure 8), from the 3D physical parameter models covering the entire study area. A voxel cell size of 25 cubic metres and the Kriging interpolation method were adopted. The slice was taken as close to the maximum depth as possible, to represent the modelled physical property variations at the greatest possible depth. The plan view of the voxels allows the surface values of the physical parameters to be observed.

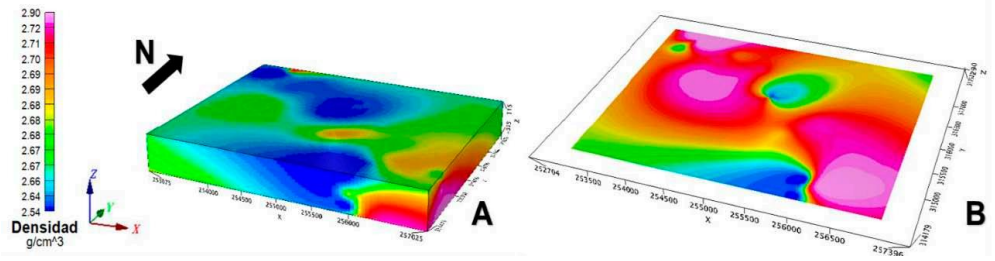

Figure 6. Density voxels for San Diego de los Baños: A) surface values; B) values at a depth of 390 m

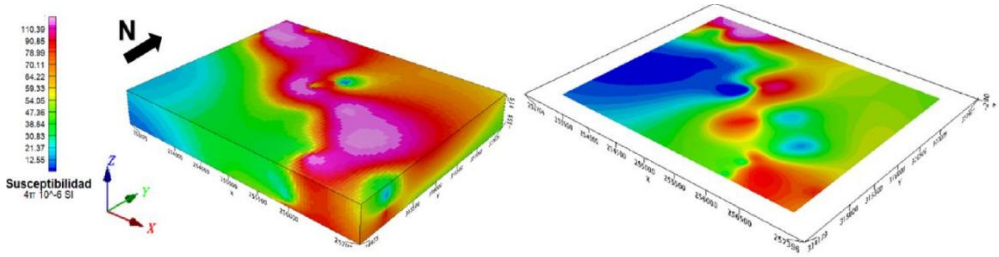

Figure 7. Magnetic susceptibility voxels for San Diego de los Baños: A) surface values; B) values at a depth of 390 m

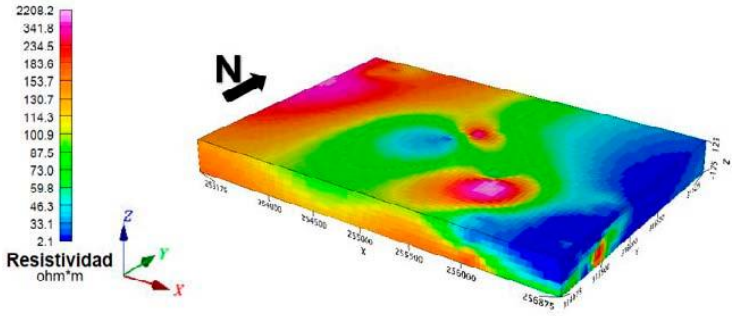

Figure 8. Electrical resistivity voxels for the San Diego de los Baños sector

4 Physical–geological model of the San Diego de los Baños aquifer

4.1 Description and characterisation of the geological and hydrogeological model for the San Diego de los Baños sector

The geological model for the study area was built based on the pre-existing geological model developed by Peláez et al. (1990). The depth of the water table, derived from borehole data acquired during this survey, was added to that model.

The mineral-medicinal waters of this aquifer originate from infiltration, governed by the following mechanism: meteoric precipitation falls in the recharge zone located in the Sierra de la Güira. The water infiltrates through deep vertical fractures and vertical karst features down to depths of 1.5–2.0 km. It is heated by the geothermal gradient, then rises along the numerous young fault planes in the area. Abundant carbonaceous material and disseminated sulfides within the sequence lead to sulfate generation in the water; these sulfates are subsequently reduced by bacteria to hydrogen sulfide. (Fagundo, 2005).

The San Diego de los Baños aquifer complex (Figure 9) is associated with fractured and karstified limestones (fractured limestones predominate) belonging to the Artemisa Fm., which contain disseminated sulfides and carbonaceous matter and crop out in the deposit area. These limestones are partly covered by chaotic sediments of the Manacas Fm. To the southwest, chaotic sediments of the Cacarajícara Fm. occur with an approximate thickness of 20 m in a wedge-shaped body.

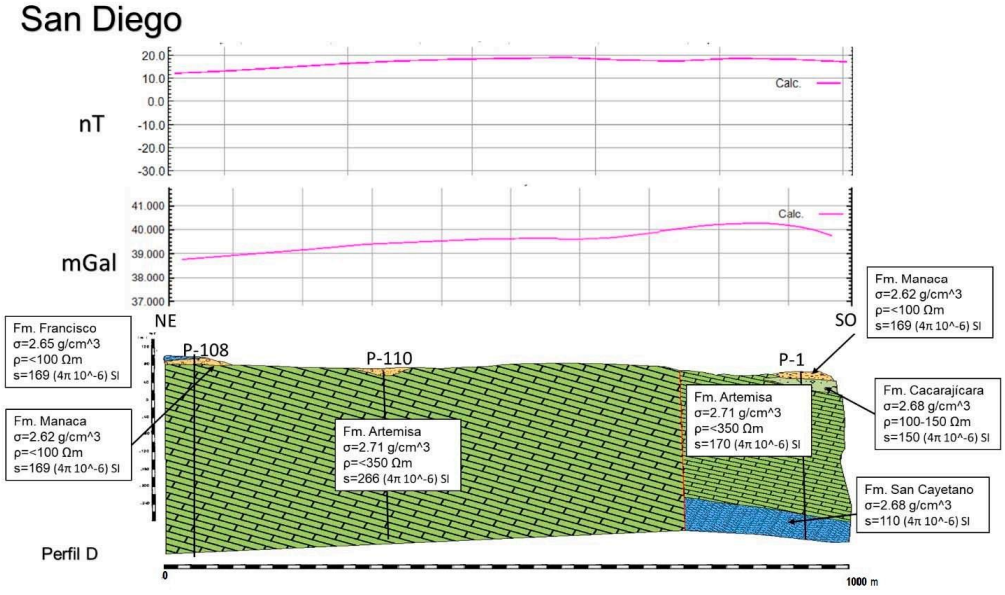

Figure 9. Geological-hydrogeological model of the San Diego de los Baños sector (Modified after Peláez et al., 1990)

Most faults in this sector are vertical and displace the thrust planes. The thickness of the aquifer complex horizon is approximately 350 m. Four aquifer zones are recognised (0–60 m, 60–120 m, 120–200 m, 200–280 m), together with a fifth layer (280–320 m). The first four zones are hosted within the limestones of the Artemisa Fm., while the fifth layer corresponds to deposits of the San Cayetano Fm., which acts as an aquitard. Water in the uppermost horizon is calcium-bicarbonate type with a temperature of 30 °C. Water in the remaining layers changes to calcium-sulphate type, starting at 31 °C and reaching up to 46 °C at greater depth.

4.2 Description of the petrophysical model

For the construction of the petrophysical model, synthetic property wells were modelled, since direct measurements of the physical properties of the rocks in this sector were not available. The modelling was carried out following the principle of analogy, using petrophysical data from the CAME II Pinar del Río survey (Martínez et al., 1988).

The density voxel with smoothing using 16 cells and a voxel size of 25 m³ (Figure 6) can be regarded as the 3D density model for the San Diego de los Baños area. It characterises the rocks and clearly distinguishes the low-density rocks of the terrigenous formations (San Cayetano Fm. and Manacas Fm.) from the higher-density carbonate formations (Artemisa Fm. and Cacarajícara Fm.). The maximum density values reach 2.90 g/cm³ and the minimum 2.54 g/cm³. Maximum values occur at greater depth owing to the confining pressure of the strata, while minimum values correspond to near-surface zones, caused by rock weathering; additionally, most terrigenous formations crop out at the surface.

The 3D magnetic susceptibility voxel model processed with 16-cell masking smoothing, with a single voxel volume of 25 m³ (Figure 7), can be adopted as the representative 3D magnetic susceptibility model for the San Diego de los Baños area. Magnetic susceptibility values generally decrease with depth, ranging from the near surface to the base of the inverted model. The low magnetic susceptibility anomalies cropping out in the southern part of the study area correspond to the surface exposure of the Artemisa Formation. The high magnetic susceptibility anomalies occurring at depth, spatially coinciding with the occurrence zones of the Artemisa Formation, are attributed to pyrite and serpentinite infilling fractures within this stratigraphic unit.

The 3D electrical resistivity voxel model processed with 20-cell masking smoothing, with a grid spacing of 5 m (Figure 8), represents the subsurface electrical response of rock units across the San Diego de los Baños study area, with a maximum effective investigation depth of 200 m. High resistivity zones on the model correspond to the limestone units of the Artemisa Formation, while low resistivity values are associated with the terrigenous clastic rocks of the Manacas and Cacarajícara Formations.

4.3 Characteristics of the geophysical field model

The physical fields represent the response obtained by applying the forward problem to the combination of the geological-hydrogeological model and the petrophysical model, showing the calculated anomalies of physical properties for the given geological section. The calculated Bouguer anomaly curve (Figure 10) is quasi-horizontal because the density distribution within this section exhibits little variation (on the order of tenths of g/cm³). The ΔG values range from 39.2 to 40.5 mGal, which correspond well to the density distribution, with densities varying from 2.62 to 2.72 g/cm³.

The magnetic field curve (Figure 11) shows an increasing trend along the NE–SW profile, although the variation is small (10 to 20 nT). The minimum values of the curve correspond to the magnetic contrast between deeply buried rocks of very low magnetic susceptibility (16 to $21\times4\pi\times10^{-6}$ SI) in the NE part of the profile and shallower rocks with higher susceptibility (40 to $101\times4\pi\times10^{-6}$ SI). In the SW section, the magnetic contrast is nearly zero (rocks with magnetic susceptibility of 50 to $101\times4\pi\times10^{-6}$ SI), which results in a quasi-horizontal magnetic anomaly curve.

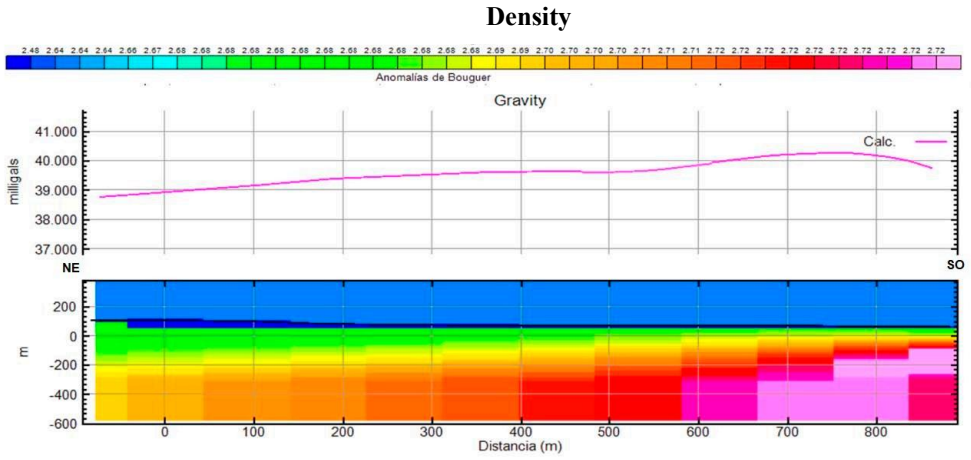

Figure 10. Calculated ΔG anomaly curve (Bouguer anomalies)

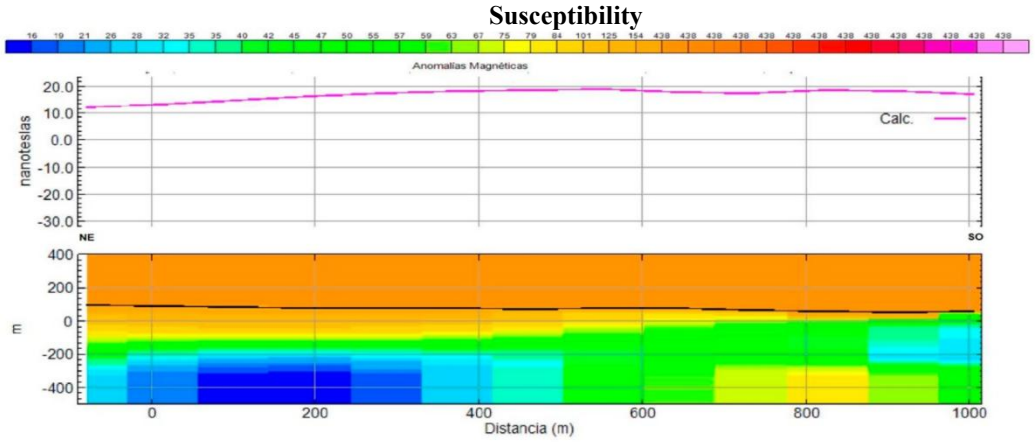

Figure 11. Calculated ΔT anomaly curve (Magnetic field anomalies) of the San Diego de los Baños sector

The geoelectric section characterizing San Diego de los Baños (Figure 12) covers the uppermost 200 m depth and correlates with the proposed geological model for the San Diego de los Baños sector. This area is dominated by carbonate rocks of the Artemisa Fm. (280 Ωm), while the minimum resistivity values correspond to terrigenous rocks outcropping from the Manacas Fm. (approximately 50 Ωm).

Electrical resistivity data were not available to characterize the terrigenous horizon of the San Cayetano Fm. The vertical electrical soundings (VES) carried out in this area by Peláez et al. (1990) used a Schlumberger array with a maximum AB spacing of 1000 m, reaching only approximately 250 m depth.

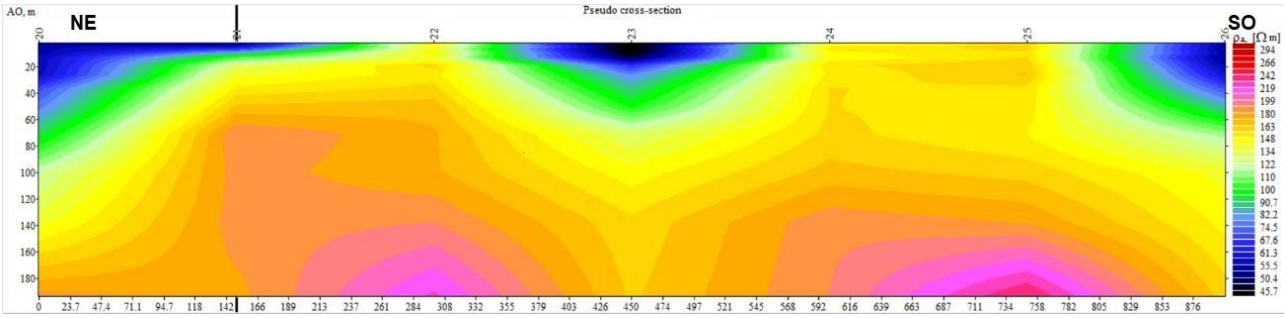

Figure 12. Geoelectrical cross-section of the San Diego de los Baños sector, NE–SW trending

4.4 2D physical geological model of the San Diego de los Baños aquifer

Profile D, trending NE–SW for the San Diego de los Baños sector, is defined as the 2D model that generally

characterizes these sectors. Three boreholes are located along Profile D, with known lithological columns. In addition, the geological characterization of the area from the survey by Peláez et al. (1990) was adopted as the geological framework for this physical geological model (MFG). Using this dataset together with data from the CAME II Pinar survey and applying the principle of analogy, a total of 110 modelled boreholes were generated across the entire study area. Physical property values were assigned interval by interval along each borehole (e.g., where a modelled borehole intersects rocks of the San Cayetano Fm., physical property values measured from CAME II Pinar survey boreholes intersecting the San Cayetano Fm. were assigned). The integration of the above models yields the 2D physical geological model (MFG) of the San Diego de los Baños aquifer (Figure 13).

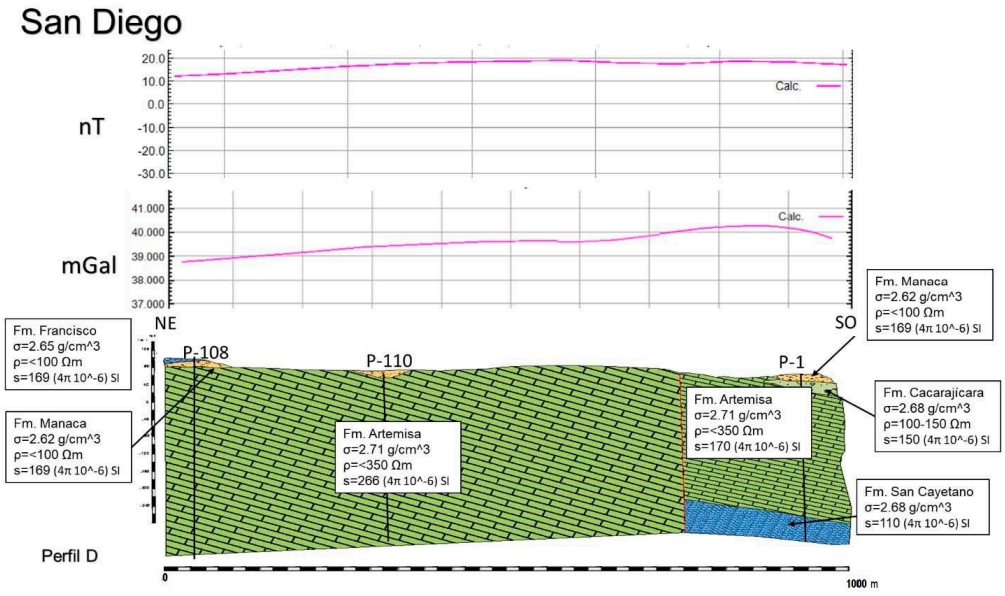

Figure 13. Physical-geological model of the San Diego de los Baños aquifer.

This model illustrates how rock physical properties (density, magnetic susceptibility and electrical resistivity) affect the calculated physical fields. Since the variations in magnetic susceptibility and density within this sector are very low, the potential field responses also show little variation. Nevertheless, electrical resistivity values exhibit a satisfactory contrast, which enables characterization of geoelectrical cross-sections and their correlation with geological cross-sections. These resistivity data are, however, depth-limited: the input data come from VES surveys with a maximum penetration depth of 250 m.

Integration of all model information for San Diego de los Baños allows the following zoning: Northeastern zone: The gravity field shows minima (38.8 mGal). This feature is related to the low density contrast between the surficial terrigenous sedimentary rocks of the Manacas and Francisco Fms. (2.62 g/cm³–2.65 g/cm³) and the carbonate sediments of the Artemisa Fm. (2.71 g/cm³), which extend downward. The magnetic field is nearly constant at approximately 15 nT, owing to the low contrast between the Manacas and Francisco Fms. rocks, whose average magnetic susceptibility is similar to that of the Artemisa Fm. rocks. Resistivity in this zone is characterised by low electrical resistivity values (50 Ω·m) for the terrigenous and chaotic rocks of the Manacas and Francisco Fms., and high values (300 Ω·m) for the deep carbonate rocks of the Artemisa Fm.

Central zone: The gravity field shows intermediate values (39.5 mGal), and the curve begins to display an upward trend. This is caused by an increasing contrast between higher-density rocks (limestones of the Artemisa Fm.) and a thin outcropping layer of the Manacas Fm. Rocks of the Artemisa Fm. predominate and exert a stronger control on the gravity response. The magnetic field in this zone is relatively steady and reaches the maximum values of the study area (20 nT),

under conditions of low magnetic susceptibility contrast. The Artemisa Fm. occupies almost the entire zone, with contrast only against a thin layer of the Manacas Fm., which has lower susceptibility. Electrical resistivity behaves similarly to the northeastern zone: a thin low-resistivity layer is linked to the Manacas Fm., while a deep, extensive high-resistivity layer corresponds to the Artemisa Fm.

Southwestern zone: The gravity field reaches maximum values (40.3 mGal), controlled by the slight contrast between the Artemisa Fm. rocks (2.71 g/cm³) and the Manacas and Cacarajícara Fms. rocks, which have an average density of 2.68 g/cm³. Although this is the maximum gravity value, the variation along the curve is on the order of tenths of a milligal. This is a typical feature of potential fields across the whole study area, caused by the low variability in rock density. The magnetic field behaves similarly to the central zone, also governed by the weak contrast between the Manacas, Cacarajícara and Artemisa Fm. rocks. Electrical resistivity in this southwestern zone shows a low-resistivity layer linked to the Manacas and Cacarajícara Fms., and an extensive deep high-resistivity layer corresponding to the Artemisa Fm. The modelled VES data adopted a maximum AB spacing of 1000 m, so the sandstone layer of the San Cayetano Fm. could not be characterised. This constitutes a limitation of the model.

4.5 Rational complex of geophysical methods for the study of deep karst aquifers of the San Diego de los Baños type

To establish the rational integrated suite of geophysical methods (Table 1), the physical geological model (MFG) derived for the San Diego de los Baños aquifer was considered. The selection is based on the geological setting, petrophysical properties and physical field responses of the aquifer, together with the areal extent of the study area and an extensive literature review on the application of geophysical methods for characterising deep karst aquifers.

Detailed analysis of the physical geological model (MFG) allows prediction of the potential-field responses expected in this area. Since density and magnetic susceptibility vary little, the modelled curves are considered reliable, as these methods rely on property contrasts. Nevertheless, higher-resolution gravity and magnetic surveys are recommended given the small study area (approximately 10 km²). Existing surveys are only at 1:50,000 scale and cannot validate the derived model results. Electrical resistivity data are only available down to 250 m depth. These data greatly help identify the contacts between different geological formations but do not fully characterise the aquifer. Therefore, a VES survey reaching 400 m depth is recommended. Induced Polarization (IP) is proposed as an experimental method. Geological evidence indicates disseminated pyrite mineralization, which may account for the sulphate waters. Using the same time-domain equipment during the VES campaign, chargeability can be determined, with expected values around 45 ms.

Table 1. Rational integrated suite of geophysical methods for investigating deep karst aquifers of the San Diego de los Baños type

Order of application	Geophysical method	Scale	Grid	Description
1º	Gravimetric	1:1,000	100×10	One NE–SW longitudinal profile, 5 km long; 4 SSW–NNE transverse profiles, each 1 km long.
2º	Magnetic			
3º	Vertical Electrical Sounding (VES)	1:2,000	200×20	50 SSW–NNE profiles, each 1 km long, spaced 200 m apart, with a measurement interval of 20 m. Schlumberger array with AB = 800 m. At least one parametric VES in the study area.
4º	Induced Polarization (VES-IP)			Time-domain acquisition. Same profiles and array configuration as VES, acquired simultaneously using the same equipment.

5 Conclusion

The 2D physical geological model of the San Diego de los Baños aquifer integrates three components: the geological and hydrogeological model developed from Peláez et al. (1990); the petrophysical model constructed by modelling and interpreting formation-specific physical properties (density, magnetic susceptibility and electrical resistivity) using the principle of analogy; and the physical field model computed along the geological section with physical property values assigned to each lithology.

From the constructed physical geological model, it is observed that density and magnetic susceptibility values exhibit little variation, which is reflected in the calculated curves of the ΔG gravity anomaly field and ΔT magnetic anomaly field. Density ranges from 2.62 to 2.72 g/cm³, and magnetic susceptibility ranges from 2.01×10^{-4} to 3.58×10^{-4} SI.

The electrical resistivity values calculated from the physical geological model of the San Diego de los Baños aquifer can differentiate the electrical signatures of the various geological formations in the study area. Low resistivity values (50 Ω·m) correspond to rocks of the Manacas, Francisco and Cacarajícara Formations, while widespread deep high-resistivity values (300 Ω·m) are associated with the carbonate rocks of the Artemisa Fm. The sandstones of the San Cayetano Fm. could not be characterised, as their depth exceeds the penetration range of the electrode array used. This limitation should be considered in future investigations.

The integrated suite of geophysical methods for investigating deep karst aquifers consists of detailed potential-field methods (gravity and magnetometry), followed by vertical electrical sounding with a dense survey grid to characterise the various lithologies in the area. Induced polarisation may be adopted as an experimental complementary method if evidence of secondary pyrite is found in the study area; secondary pyrite indicates the occurrence of mineral-medicinal water associated with fault zones.

Acknowledgements

The authors thank the Institute of Geology and Palaeontology, the National Office of Mineral Resources and the Department of Geosciences of the Technological University of Havana for the support provided to carry out this scientific research. Gratitude is also expressed to the Department of Geology of the University of Pinar del Río for coordinating the national project that supports this work.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Fagundo J., Pérez Franco D., García J. y Morell I. (eds). (1996). "Contribuciones a la Hidrogeología y Medio Ambiente en Cuba". Publicacions de la Universitat Jaume I. Castelló de la Plana, España. 388 pp. ISBN 84-8021- 104-0.

[2] Fagundo, J., González, P., Carillo-Rivera, J., Antigüedad, I., Peláez, R., Suárez, M., Melían, C., Hernández, R. y Cáceres, D. Caracterización hidrogeoquímica del sistema de flujo local-regional de la Sierra del Rosario (cuba) 2005.

[3] García J. (2018). "Modelos de resistividad eléctrica en formaciones geológicas de la cuenca Los Palacios, Cuba occidental". Tesis de Doctorado. Departamento de Geología, Facultad de Ciencias Técnicas, Universidad de Pinar del Río, Cuba.

[4] GEOSOFT (2008). "Oasis montaj 7.0. Manual release" . Toronto, Canada. 107 pp.

[5] Lima B. (2009). "Comportamiento Hidrológico de la Cuenca San Diego-Bermejales". Trabajo de Diploma. Departamento de Geología, Facultad de Geología y Mecánica, Universidad de Pinar del Río. Cuba.

[6] Martínez D., Fernández R., Reinoso R., Chang J. C., Fernández O., Valido A., Peláez R., Núñez R., Hernández J., Rodríguez P., Shalva S., Vázquez M., Yunttsky V., Precedo S., Touchenko V., Shirueg V. y Cofiño C. (1988). Informe

sobre los resultados del levantamiento geológico y búsqueda a escala 1:50 000 en la parte central de la provincia de Pinar del Río. Instituto de Geología y Paleontología, Servicio Geológico de Cuba. La Habana.

[7] Mondelo F. y Sánchez R. (2011). "Mapas geofísicos regionales de gravimetría, magnetometría, intensidad y espectrometría gamma de la República de Cuba, 1: 2 000 000 hasta 1: 50 000". Repositorio del Instituto de Geología y Paleontología. La Habana, Cuba.

[8] Moscow State University (2000). "IPI2Win User Manual" . Moscow, Russian Federation. 33 pp.

[9] Peláez R., Olivares M., Núñez R. y Valdivia M. (1990). "Informe para la búsqueda detallada y exploración orientativa de las aguas minero-medicinales San Diego – Bermejales" . Fondo Geológico, Ministerio de la Industria Básica, 179 p.

[10] Peña B. (2000). "Caracterización de Sistemas Hidrominerales en el Distrito Físico Geográfico Pinar del Río". Tesis de Maestría. Facultad de Geografía, Universidad de La Habana. Cuba.

[11] Rodríguez R. (1998). "Características de las aguas minerales y medicinales de Cuba" . Acta Geológica Hispánica, España. Vol. 33, pp. 373-393. ISSN: 0567-7505.

[12] USGS (2005). "Shuttle Radar Topography Mission (SRTM)". United States Geological Survey. Disponible en:http://srtm.usgs.gov

Author contributions

Antonio J. Santibañez Rodríguez https://orcid.org/0000-0002-6556-3985

Performed data acquisition, processing and interpretation; wrote the final report; contributed to research design.

Lisbeth Núñez Haugh https://orcid.org/0000-0002-0927-9963

Participated in data interpretation and assisted with research design.

José A. Díaz Duque https://orcid.org/0000-0003-0032-4681

Conceived the project idea and implemented the research design; provided the theoretical framework, especially for physical-geological models; took part in result analysis; reviewed and revised the final manuscript.