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DETERMINATION OF GROUNDWATER REGIME IN A METAL MINERAL DEPOSIT BY DATA MINING AND SPATIAL INTERPOLATION IN THE CENTRAL REGION OF THE REPUBLIC OF CUBA

This study evaluates the groundwater regime in a metal mineral deposit in Cuba, combining statistical analysis, data mining and spatial interpolation of 15 504 historical records in 38 years. Kriging Regression was used (0.091 m prediction error) and bootstrap method to model the variability of the water table in an area of 4 174.55 kml between Ciego de Avila and Самагьеy regions. The results reveal flow patterns and recharge/discharge areas, with significant influence of morphometric parameters such as elevation and drainage network. The variability of the groundwater level in the mineral site (10.12–18.49 m) highlights the need for careful water management, especially due to mining pollution.

Keywords: *groundwater level, data mining, bootstrap method, spatial interpolation, kriging region, mineral deposit, Cuba*
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Introduction

The exploration of mineral deposits is an essential part of the mining activity. In spite of this, mining exploitation significantly large extensions of land and the lower layers of the soil, including groundwater reserves [1–3]. Pollution by mining residuals, especially in metal mineral deposits, compromises water quality for general uses [4–6]. Previous studies deal with the problems of groundwater related to metal mineral activity, such as gold [7–9] and other minerals [10–12], also highlighting the urgency of sustainable water management in

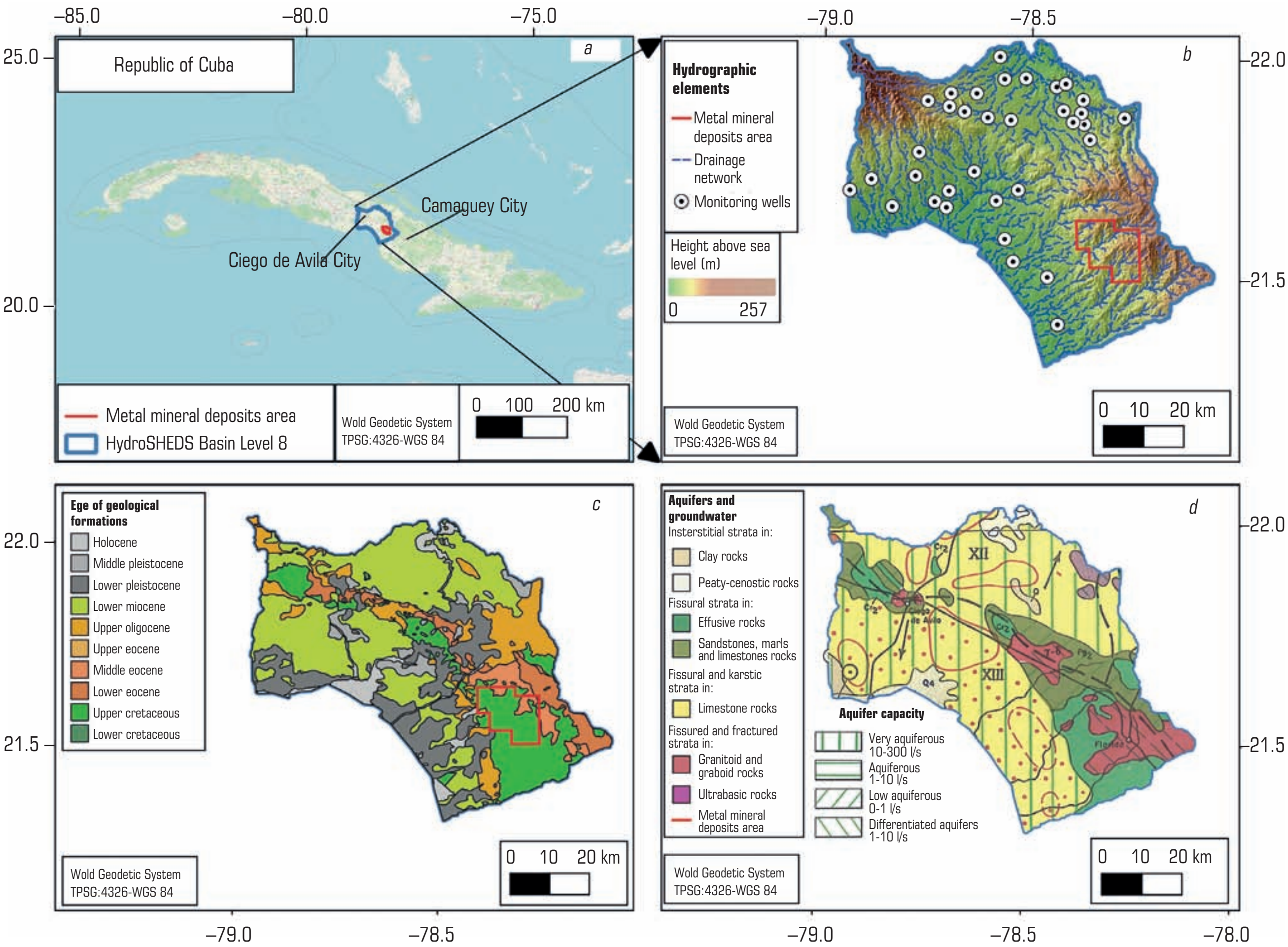

Fig. 1. Characteristic of study area:
a – geographical location of study area, Republic of Cuba, Ciego de Avila city and Camaguey city; *b* – relief, hydrographic elements, well monitoring network and metallic mineral deposits; *c* – geological formations and geological ages; *d* – hydrogeological schema 1:1 000 000 and productivity of formations

the face of water stress exacerbated by change climate and its impacts on groundwater [6]. Due to the effects of climate change, many mining operations are expected to face the increase in water stress conditions in the next two decades [13]; therefore there must be strict regulatory and monitoring measures to guarantee the protection of water resources [14].

Future studies should consider the impact of mining on habitat quality to provide a more complete evaluation of environmental responses [15]. The problems related to the public management of natural resources [16, 17], mainly their evaluation, are of exceptional importance and relevance [18], given that geological exploration is increasingly concentrated in the least explored areas [19] and that underground water resources are essential for drinking water supply [20].

In Cuba, the mining industry has a negative impact on the environment on the regions. It should be noted that among the most significant consequences are the deforestation of more than 5000 hectares of forest lands, contamination of inner and seawater bodies. Several pollutants such as sulfates, arsenic and heavy metals have been studied (Ni, Cr, Mn, etc.) [21–24].

In hydrogeological terms, the water table contains valuable information about the aquifer [25], and its dynamics reflects the response of the groundwater system to climatic changes and anthropogenic activities [26], such as mining exploitation. In [27] it is considered that changes in the level of groundwater at regional scale provide information on groundwater storage changes during a specific period to climatic and environmental variations. Therefore, in the current context, for the evaluation of underground water resources it is important water [28–30].

The evaluation of the variability of the groundwater level (GWL), influenced by natural and anthropogenic factors, is essential in mining exploration, especially in Cuba, where aquifers are vital for social and economic development. However, methodological empty persists to analyze the groundwater regime in Cuban metal mineral deposits, without historical records prior to mining exploration studies.

Therefore, the objective of this study is to analyze the average characteristics of the groundwater regime in a metal mineral site in the central region of the Republic of Cuba, based on the analysis and spatial interpolation of historical records of 38 years of Groundwater level in 34 adjacent observation wells. This approach will allow to infer the historical hydrogeological conditions in the site, without the need for direct previous studies, providing a solid basis for the planning and management of water resources in local mining exploitation.

Hydrography and relief

Taking into account that remote -site remote sensing materials capture almost the entire earth's surface [31], the digital model of the relief (DEM) of [32] and Hydrosheds level 8 [33] data was used, both on Google Earth Engine Data Catalog, to delimit a hydrogeological basin of 4 174.55 km^2 in the center of Cuba, between blind man Ávila and Camagüey (**Fig. 1*a***). The relief occurs between the average sea level (0 m) and 257 m high, fundamentally flat (75% of the area ≤ 0.43° of inclination), has a dense drainage network (0.544 km/km^2) and high infiltration superficial (43% of precipitation) [34] which favors the processes of rainfall infiltration and the formation of groundwater.

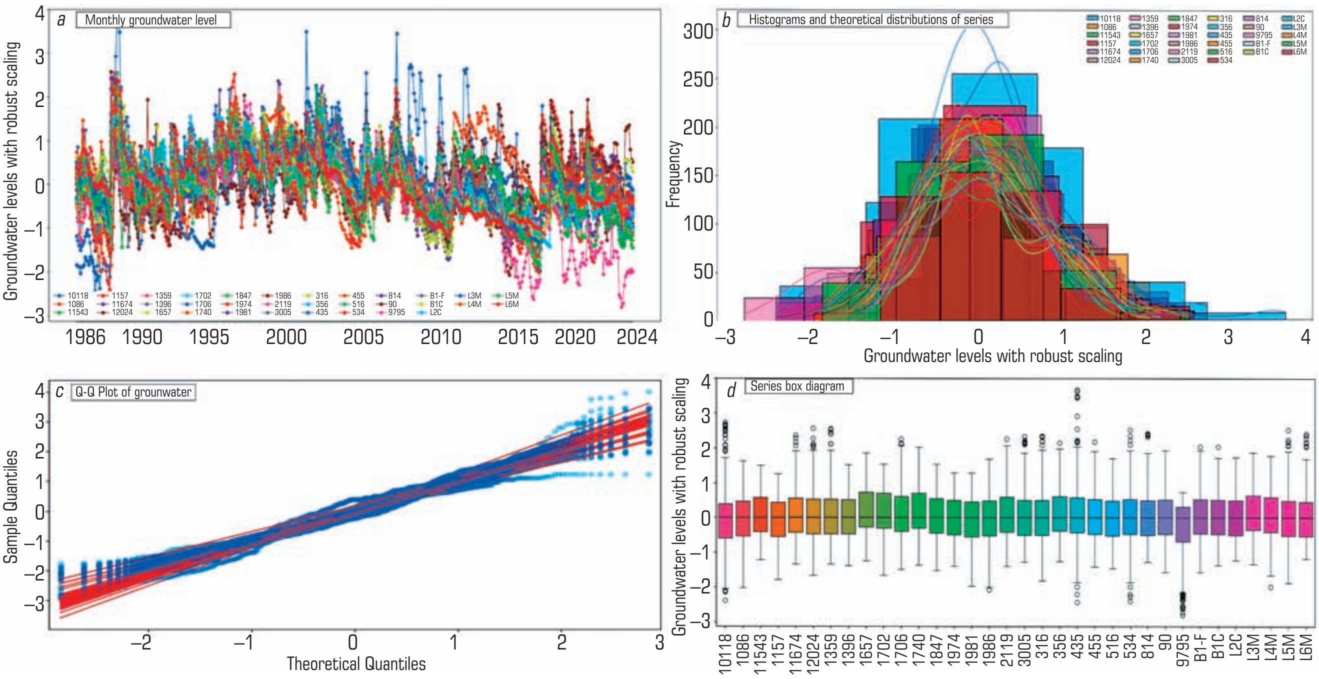

Fig. 2. Analysis exploratory data:
a – historical monthly groundwater level scaling; *b* – histograms and theoretical distributions; *c* – Q–Q interquartile graphic; *d* – box diagram of data distributions

In that respect various geoenvironmental factors play an important role in the groundwater status of an area [35], therefore to analyze the variability of the groundwater level (GWL), they considered the parameters: Elevation Above Sea Level (EASL), Channel Network Base Level (CNBL), Relative Slope Position (RSP), Valley Depth (VD), Channel Network Distance (CND), Slope (S), Plan Curvature (PLC), Convergence Index (CI), LS-factor (LSF), Topographic Wetness Index (TWI), Analytical Hillshading (AH), Profile Curvature (PRC), Aspect (A), Closed Depressions (CD). All determined by the *Basic Terran Analysis* algorithm of the SAGA GIS 9.2.0 software, for which it will allow to extract the average values of the morphometric parameters on a radius (5 343.68 m) of influence in each well.

Geology and hydrogeology

From studies carried out in 1965, the hydrogeological map of Cuba scale 1: 1 000 000 (**Fig. 1*d***) high productivity limestone aquifers (10–300 l/s) and in the area of the deposits of the deposits of Metallic mineral studied a variable productivity (1–10 l/s), despite the presence of failures and fissures cause the storage of groundwater in these areas, thus indicating a complex interaction between geology and water resources.

According to the Geological Map of Cuba [36] from the Cuban Institute of Geology and Paleontology, 1:100 000 scale, in the study area there are formations of different geological epochs (**Fig. 1*c***), such as; the Lower Cretaceous presents the Mata formation, composed of microgranular limestones, silicitas, flint, conglomerates and clays. During the Upper Cretaceous, intrusive igneous complexes such as gabro-plagiarism and granodioritic, together with gabrosienic, show varied mineralogy. Sedimentary and volcanic formations such as Durán, Camujiro, Caobilla and Piragua, exhibit conglomerate mixtures, sandstones, limestones and volcanic rocks. The Presa Jimaguayú formation consists of biogenic and detritic limestones fundamentally.

In the Lower Eocene, the Vertientes contains calcareous, volcanomictic, marls, grave and conglomerate sandstones. The Middle Eocene includes Maraguan, with sandstones, marls, limolites and limestones, and Florida, with carbonated gaps, limestones and marls. The Upper Eocene shows the Camarones formation, with conglomerates and polymicic sandstones. The Upper Oligocene presents Tamarindo, with limestones, traps and marls, and flint, with diabasous, gabros and ultramaphytes conglomerates. The Lower Myocene includes Güines, with biodetritic's limestones and dolomites, and Arabos, with clays, clay limestones and marls. The Lower Pleistocene shows Guevara, with clays, sands and gravels, and the Middle Pleistocene, Villarroja, with clays, sands and gravels. The Holocene contains palustres, alluvial and eluvial-colluvial deposits with plant remains, silt and sand.

Data analysis

Monthly records (1986–2024) of 34 wells were analyzed (15 504 data) of the National Institute of Hydraulic Resources of Cuba [37]. The data were subjected to robust scaling (**Fig. 2*a***) for processing non-normal distributions (Eq. 1). The exploratory analysis revealed complex statistical characteristics and predominant non-normal distributions (**Fig. 2*b***) (confirmed by Shapiro–Wilk, Anderson–Darling and Lilliefors in 27/31 wells), evidenced by moderate asymmetries (Skewness between –1.04 and 0.74) and variable kurtosis (kurtosis from –0.92 to 1.88). Observing in the Q-Q diagram (**Fig. 2*c***) dispersion at the ends, as in series 435, 9795 and 10118 (**Fig. 2*d***), which could be inferred presence of atypical values.

Heterocedicity is observed in 61% of the wells (Fligner–Killeen $p < 0.05$) and significant temporary self-correlation (lags in the Dickey–Fuller test increased from 1 to 18 months). Stationary tests show contradictions: while Dickey–Fuller increased suggests stationary in 90% of cases ($p < 0.05$), Kwiatkowski–Phillips–Schmidt–Shin rejects stationary condition in 94% ($p < 0.05$), indicating possible presence of unitary tendencies or roots.

$$X_{scaled} = \frac{X - median(X)}{IQR(X)}, \quad (1)$$

where X_{scaled} represents the resulting scaled value; X is the original value of the data; *median* (X) is the median of the data column X; *IQR* (X) is the interquartile range of the data column X.

The bootstrap is a data mining method for non-normal temporal series, which estimates sample distribution quantiles without Normal assumption [38], by analyzing hydrometeorological variables, obtains precise intervals of empirical distribution [39]. Bootstrap was applied in *python* with *scipy.stats* and *numpy* library's to quantify weighted extreme statistical parameters (Q1, Q4, Q2-Q3) of the water table. For the adjustment goodness tests, the

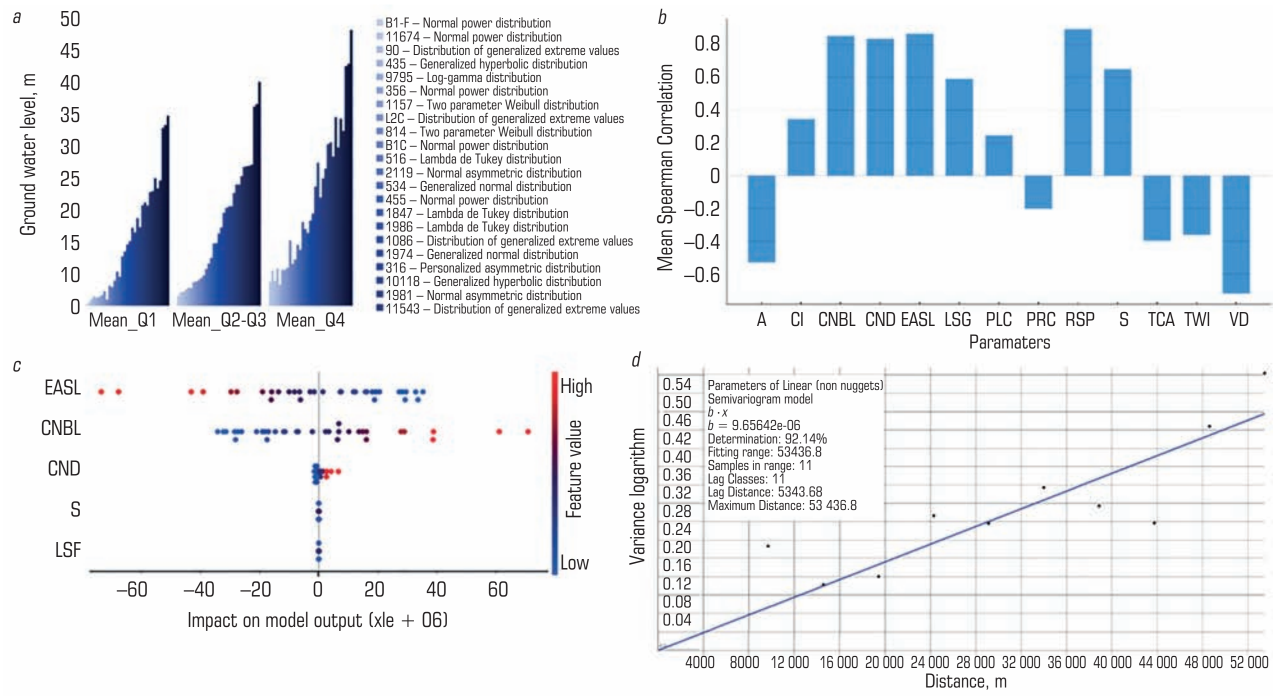

Fig. 3. Data analysis results:
a – data distributions by wells and mean GWL for quantiles; *b* – Spearman's (Rho) coefficients by morphometric parameters; *c* – ranking SHAP of Explain Model Widget; *d* – Kriging Regression semivariogram with regression residuals of predictors

logarithm of the likelihood function (*Log_Likelihood)* [40], Akike Information Criterion (AIC) [41] and Bayesian Information Criterion (BIC) [42], Pearson's coefficient (R^2) and Medium Absolute Error (MAE) prediction to select the distribution of better adjustment in each series of data.

Spatial correlation and interpolation GWL

The Kriging Regression method is widely used in ecology, mining and water resources [43]. Its application for estimation purposes implies modeling the spatial correlation of the variables by means of the diverse, based on the sampling data [27]. Therefore, in extensive hydrogeological data deficit, spatial interpolation techniques can be used, such as the Kriging Regression, based on historical records of nearby wells for space prediction and geological mapping can be used as the primary method to understand the geological structure [44].

For prediction groundwater levels (GWL), morphometric parameters of the relief were analyzed in Orange Data Mining (**Fig. 3*b***). The Correlation Widget tool revealed Spearman (Rho) correlations (201 552 evaluations), useful in non-normal data, while Linear Regression Widget and Explain Model Widget evaluated the influence of morphometric parameters by comparing the model prediction error in the presence or not of each parameter.

Kriging regression was used for spatial interpolation, estimating correlated variables from the variogram and predictors residues (**Fig. 3*c***). To obtain the minimum historical level maps (GWL_min), maximum (GWL_max) and the range of variation (ΔGWL), the prediction errors of interpolations were taken into account according to equations (2), (3) and (4):

$$GWL_{min} = GWL\_Q1 - STD\_Q1; \quad (2)$$

$$GWL_{max} = GWL\_Q4 + STD\_Q4; \quad (3)$$

$$\Delta GWL = GWL_{max} - GWL_{min}, \quad (4)$$

where: *GWL_Q1* and *GWL_Q4* are the average GWL L levels of quartiles Q1 and Q4, respectively; STD_Q1 and STD_Q4 is the standard deviation of spatial interpolation error for 5% confidence interval.

Results and discussion

Results of the statistical analysis of groundwater levels, by means of the Bootstrap adjustment of various distributions, the most appropriate functions to model the data were determined (**Fig. 3*a***). The lowest value of Pearson's coefficient was $R^2 = 0.935$, so they seem to be strongly connected with groundwater dynamics in the study area, and the maximum MAE was 0.378 m, being 4.28% of the general IQR range. The wells 10118, 12024, 1657, 1740 and L3M present the highest average levels (16–37 m) indicating possible recharge areas. The wells 11674, 435, 9795 and B1-F show the lowest average levels (1–3 meters), suggesting greater discharge zone. The standard deviation (STD) varies between 0.81 and 3.92 meters, reflecting the monthly fluctuation in each well. The wells with the highest STD (L3M, 10118, 1657) exhibit greater variability, possibly influenced by rainfall, hydrological droughts or excessive exploitations.

In the Spearman correlation analysis, used to establish the linear relationship between the groundwater level as a dependent variable and the 13 morphometric parameters analyzed (see Fig. 3*b*), to understand how landform affects groundwater level variations. In **Fig. 3**, using Linear Regression Widget, in Orange Data Mining software, the importance of each predictor variable was analyzed as a prediction model (horizontal access in Fig. 3*c*) based on SHAP (SHapley Additive exPlanations) values using Explain Model Widget for each parameter using Linear Regression Widget, EASL (Rho = 0.869), CNBL(Rho = 0.856) y CND (Rho = 0.838) the most significant parameters.

The experimental semivariogram model (Fig. 3*d*) determined with a Pearson's coefficient $R^2 = 0.924$, confirms quasilinear relations established by the above methods. The standard error of prediction of the Kriging Regression interpolation for the average GWL (**Fig. 4*b***) has a maximum of 0.345 m and a minimum of 0.0002 m, with an average of 0.091 m. The standard deviation of the error is 0.068 m, indicating a relatively low dispersion of errors around the average. These values suggest that geostatistical predictions of the water table are generally precise, with minimal errors in most areas.

The groundwater levels (GWL) analysis in the hydrogeological basin (**Fig. 4*a***) revealed significant spatial variability in historical values ranging from –3.93 m and 174.11 m, and an average of 21.39 m. The high standard

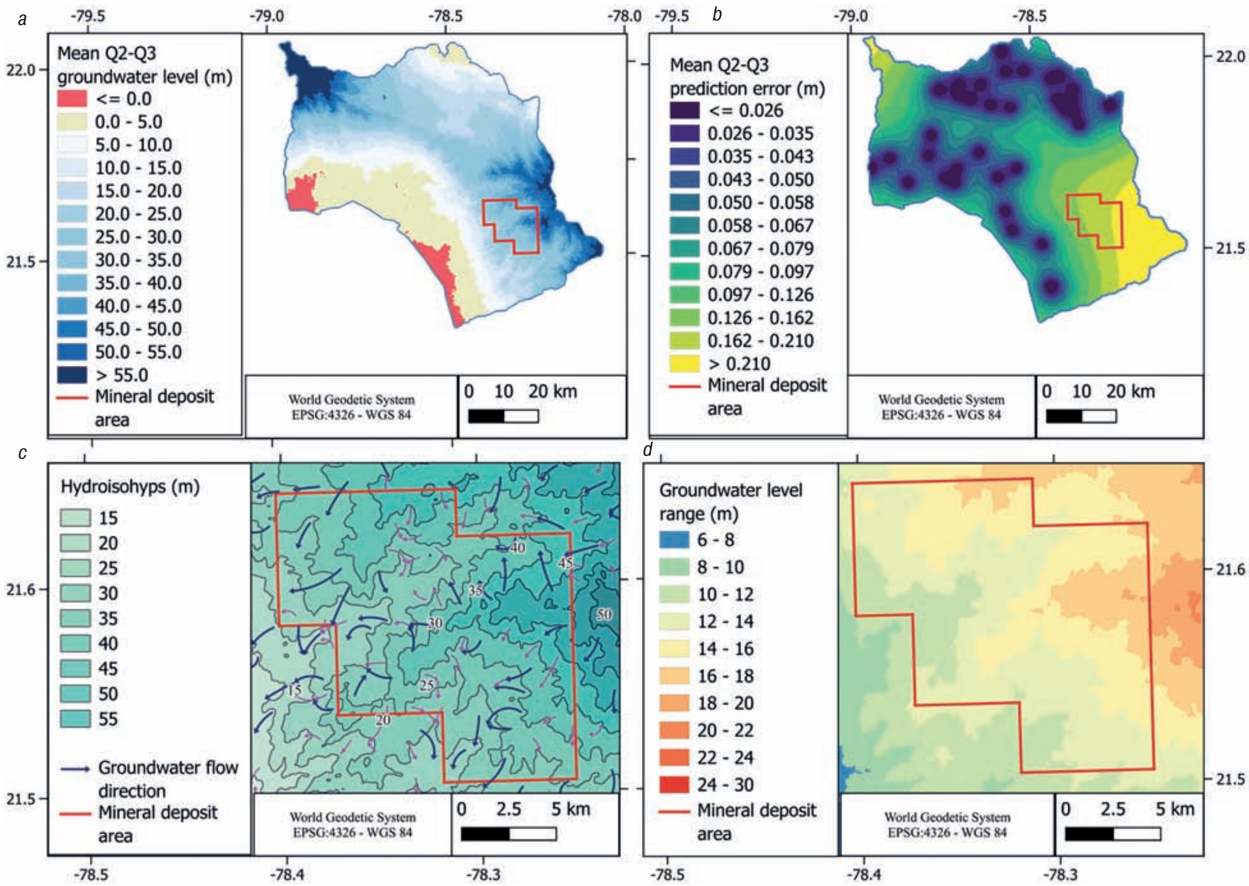

Fig. 4. Spatial data analysis:
a – mean groundwater levels of quartiles Q2-Q3; *b* – kriging regression spatial prediction error for Q2-Q3 quartiles in the mineral deposit; *c* – hydroisohypses and direction of groundwater flow studied; *d* – range of variation of groundwater levels

deviation (18.83 m) underlines this dynamic. The areas with the highest variation (> 20 m) are 2.1% of the basin, while 22.2% are areas with lower variation (<6 m). The distribution of groundwater follows the patterns of relief, with predominant flow to the north and south. The recharge areas are identified in the central part of the basin, characterized by high variability of the water table, woody drainage and coverage density. The discharge areas are found in coastal limits, where values are observed below sea level, which may be due to an excessive exploitation regime, which is necessary to take measures to mitigate the salinization of the aquifer.

In the mineral deposit area (**Figs. 4c and 4d**), the water table shows a symmetric distribution with average of 33.52 m and median of 32.84 m. The standard deviation is 6.39 m, with a variation range of 31.12 m. This variability underlines the need for careful water management, since mining activity can impact the quality and availability of groundwater. This information is crucial for the integrated sustainability of water and mineral resources in the area.

Conclusions

The study demonstrates the viability of evaluating the groundwater regime in mining deposits using historical records and space interpolation techniques. The Kriging Regression application, together with the Data Mining of non-normal series via Bootstrap, allowed to generate detailed maps of the water table variability with average very low prediction error (0.091 m). These maps reveal flow patterns and recharge/discharge areas, providing a solid basis for the management of water resources in the region.

The morphometric parameters, especially the elevation above sea level (EASL), the Channel Network Base Level (CNBL) and Channel Network Distance (CND), significantly influence the variability of the GWL. Spearman's correlation analysis (Rho ≥ 0.838) and the results of the SHAP model identified these variables as key predictors, underlining the importance of considering topography and drainage network in the hydrogeological modeling of mining areas.

The GWL levels, average of 33.52 m and temporary variability between 10.12 m and 18.49 m, the direction of the flow in the area of the metal mineral site highlights the need for careful water management in the exploitation of the metal mineral site studied. The information generated is crucial to mitigate the potential impacts on the quality and availability of groundwater, especially in the context of climate change and water shortage. The implementation of monitoring and control measures to protect aquifers and guarantee the sustainability of water and mineral resources in the region is recommended.

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