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SUMMARY OF THE DOCTORAL THESIS

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Studies and research on the quantity and quality of groundwater in the Siret river basin

SUMMARY OF THE DOCTORAL THESIS

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INTRODUCTION

Groundwater represents the most important source of accessible freshwater, being used across all anthropogenic sectors, including agriculture, industry, domestic supply, and other key activities essential for human society [37].

Within this context, the present thesis examines the groundwater resources of the Siret River basin, focusing on the sector located between the confluence of the Moldova and Siret rivers and, toward the north, the area corresponding to the localities Gherăești, Iugani, and Mircești. This sector is bounded by the hydrogeological profiles associated with the Gherăești and Mircești boreholes, managed by the Siret River Basin Administration.

All figures and cartographic representations referenced in this extended abstract originate from the full version of the doctoral thesis, where they are included and numbered in their final form.

1. General aspects regarding groundwater

In this area of the Siret hydrographic basin, the phreatic aquifers—formed of sands and gravels with high permeability—are subject to pressures such as diffuse pollution from nitrogen-based fertilizers and reduced natural infiltration due to urbanization [14, 29]. Groundwater monitoring conducted by the Siret River Basin Administration (ABA Siret), through the borehole networks at Gherăești, Mircești, and Roman, provides essential information on piezometric levels and physico-chemical parameters, such as nitrates and ammonium, for the period 2014–2022 [41]. These data allow the evaluation of hydrogeological dynamics and water quality, forming a necessary foundation for the implementation of sustainable management strategies in accordance with the EU Water Framework Directive 2000/60/EC [42].

1.1. Aim and objectives of the thesis

The aim of this thesis is to characterize the spatial and temporal behavior of the phreatic groundwater in the Siret hydrographic basin, within the sector enclosed between the Siret–Moldova confluence and the hydrogeological profiles Gherăești–Mircești. The work addresses both quantitative and qualitative aspects, using piezometric and physico-chemical data provided by ABA Siret for the period 2014–2022.

The research relies on modern methods—geostatistical modelling (directional and omnidirectional kriging), functional interpolation, and GIS analyses—to obtain a detailed picture of the spatial and temporal variability of the aquifer. The main objectives include:

• mapping the spatial variations of groundwater levels through geostatistical methods;
• analyzing the depth distribution of aquifer layers in relation to geological structure;
• developing mathematical models describing piezometric fluctuations;
• estimating hydraulic conductivity and transmissivity;
• evaluating the temporal variability of physico-chemical parameters;
• verifying compliance with European and national regulations;
• developing an integrated GIS + geostatistics + interpolation methodological framework.

1.2. Structure of the thesis

The thesis is organized into six chaptersand introduction. The Introduction presents the context and relevance of the topic. Chapter 1 outlines the objectives and the structure of the thesis. Chapter 2 reviews the current state of research, focusing on legislation and relevant hydrogeological studies. Chapter 3 describes the methods used, including statistical processing, geostatistical modelling, functional interpolation, GIS analyses, and physico-chemical procedures. Chapter 4 presents the detailed results and their interpretation, based on the database, conceptual model, spatial schematization, hydrodynamics, and parameter analysis. Chapter 5 integrates the results obtained with the author's previous studies, generating a final product with practical applicability. Chapter 6 summarizes the general conclusions and outlines future research directions.

2. Current state of research on groundwater quantity and quality in the context of GIS techniques and geostatistics

This chapter presents the evolution of research in hydrogeology, from classical and empirical approaches to quantitative models based on physical laws and numerical methods supported by modern computational techniques.

From the foundational works of Darcy, who first defined groundwater flow through porous media, to the modern studies of Fitts (2022), the field of hydrogeology has undergone continuous development [16, 23]. The contributions of Dupuit, Theis, Bear, Freeze and

Cherry, as well as Domenico and Schwartz, added essential insights into the relationship between geological structure, permeability, and groundwater movement [4, 12, 15, 16, 18, 19, 22-24, 26, 38]. These studies continue to form the basis for interpreting piezometric levels and determining hydrogeological parameters in regional groundwater flow assessments.

The evolution of hydrogeological analysis through the introduction of geostatistics and GIS techniques—enabling detailed spatial representation of data through various interpolation methods such as Kriging and IDW (Inverse Distance Wheight) has become increasingly important and practically indispensable in estimating hydraulic conductivity, groundwater level, transmissivity, and other hydrogeological parametersi [3, 11, 23, 31, 40]. These tools have facilitated the identification of aquifer characteristics and the correlation between hydrogeological parameters and the lithology of the studied area. The integration of physico-chemical data into GIS has further allowed the characterization and visualization of groundwater chemistry, including the definition of hydrochemical facies, the identification of areas influenced by anthropogenic activities, and the assessment of water quality indices.

In Romania, modern investigative methods were consolidated through reference works by Scrădeanu (1996, 2001), Neagu (2017), and Vasile (2020), who applied contemporary numerical modelling and geostatistical approaches to aquifers in various regions of Romania [33, 35, 36, 39].

From a legislative standpoint, the protection and monitoring of groundwater are regulated by both European and national frameworks, such as the Water Framework Directive 2000/60/EC, Directive 2006/118/EC, Directive 91/676/EEC, Order 621/2014, and Government Ordinance No. 7/2023 [42-46, 48]. These documents establish requirements for groundwater quality, quantity, and monitoring, while also providing the legal basis for implementing management strategies at the level of River Basin Administrations.

3. Establishing the technical basis and research methodology for the quantitative and qualitative analysis of phreatic groundwater in the study area

Chapter 3 presents the technical basis and methodology used in the research, with all instruments and procedures aligned with the requirements of the Water Framework Directive 2000/60/EC and the Romanian Water Law 107/1996 [42].

The schematization was carried out through three components: spatial schematization (delineation of the aquifer based on lithology and hydrogeological cross-sections), parametric schematization (spatial distribution of porosity, hydraulic conductivity, transmissivity, and recharge), and hydrodynamic schematization (hydraulic conditions within the studied domain). The technical methodology includes the use of LiDAR technology, which operates by emitting and receiving laser pulses to generate 3D point clouds, essential for obtaining high-resolution digital terrain models [5, 25].

In parallel, the Geographic Information System (GIS) was employed to analyze the spatial distribution of hydrogeological parameters, integrate digital datasets, and generate thematic maps of piezometric levels, aquifer thickness, hydraulic conductivity, and additional parameters[1, 4, 10].

Geostatistical modelling represented a central component of the methodology, focusing on the assessment of spatial variability through histogramming, normalization, computation of directional and omnidirectional semivariograms, anisotropy determination (orientation, major/minor ranges), detrending where necessary, and fitting theoretical models based on the experimental semivariogram[13, 20].

Field methods included measuring piezometric levels in boreholes using mechanical and electrical water-level meters, as well as sensors with GPRS transmission. Field data collection also relied on a Zenith 35 Pro RTK GPS unit, necessary for determining monitoring points (DTM checkpoints, wells, ponds). The qualitative analysis of groundwater was conducted in accordance with current legislation (Government Ordinance 7/2023, Order 621/2014), considering both natural processes and anthropogenic influences affecting chemical composition [47, 48]. Physico-chemical data were interpreted and represented through thematic maps and Piper and Schoeller–Berkaloff diagrams[2, 27].

4. Quantitative and qualitative characterization of the phreatic aquifer in the upstream sector of the Siret–Moldova confluence

This chapter presents the results obtained within the case study conducted in this area, with the research structured along two major directions: the quantitative analysis and the qualitative analysis of groundwater.

The investigated area covers 174.36 km² and is bounded to the west by the Moldova River, to the east by the Siret River, to the north by the Gherăești–Răchiteni borehole alignment, and to the south by the confluence zone of the Moldova and Siret rivers. The eastern and western boundaries of the area, defined by the courses of the Siret and Moldova rivers, are clearly outlined through the meandering minor bed of the Siret and the braided channels characteristic of the MoldovaRiver.

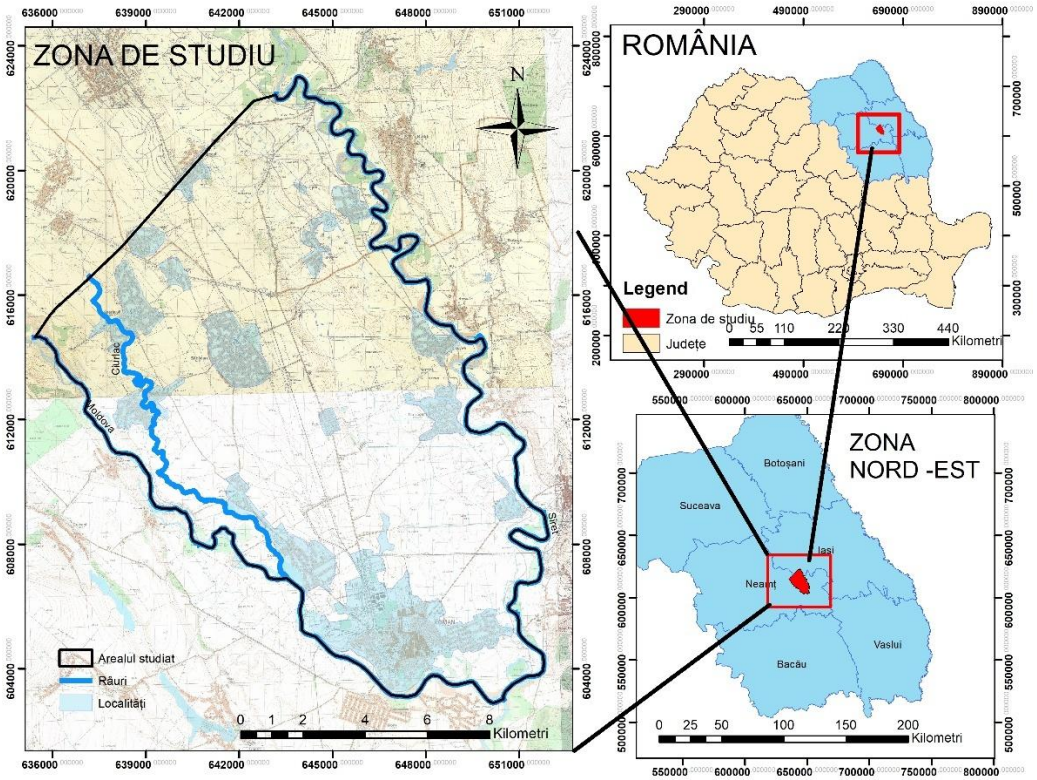


Fig. 4.1. Study area.

4.1. Hydrogeological and hydrological database used for the analysis of the aquifer in the study area

In the context of this doctoral research, more than 115 boreholes with depths of up to 35 m were initially analyzed. Following a rigorous evaluation and selection of borehole data, the final list was reduced to 49 boreholes. These boreholes belong either to the National Hydrogeological Network (17 boreholes), to water-supply systems serving nearby localities (8 boreholes), or to former state-owned agricultural enterprises such as former CAPs

(Agricultural Production Cooperatives) or IASs (State Agricultural Enterprises) from the localities of Tamășeni and Roman[41].

4.2. Development of the conceptual model for the analyzed sector

The conceptual model represents a simplified synthesis of the aquifer structure, grounded in geological, geomorphological, and hydrogeological data, and forms the basis for the three derived models: spatial, hydrodynamic, and parametric.

4.2.1. Spatial Schematization

Determining the spatial extent of a hydrostructure requires establishing the geometry within which groundwater flow occurs [17].

4.2.1.1. Digital Terrain Model

As part of the spatial schematization of the aquifer, the digital terrain model was constructed by combining LiDAR (5×5 m) and SRTM (30×30 m) rasters. Accuracy was verified through 206 RTK measurements, with error deviations ranging between +0.77 m (P198) and –1.31 m (P68), values considered acceptable for the DTM.

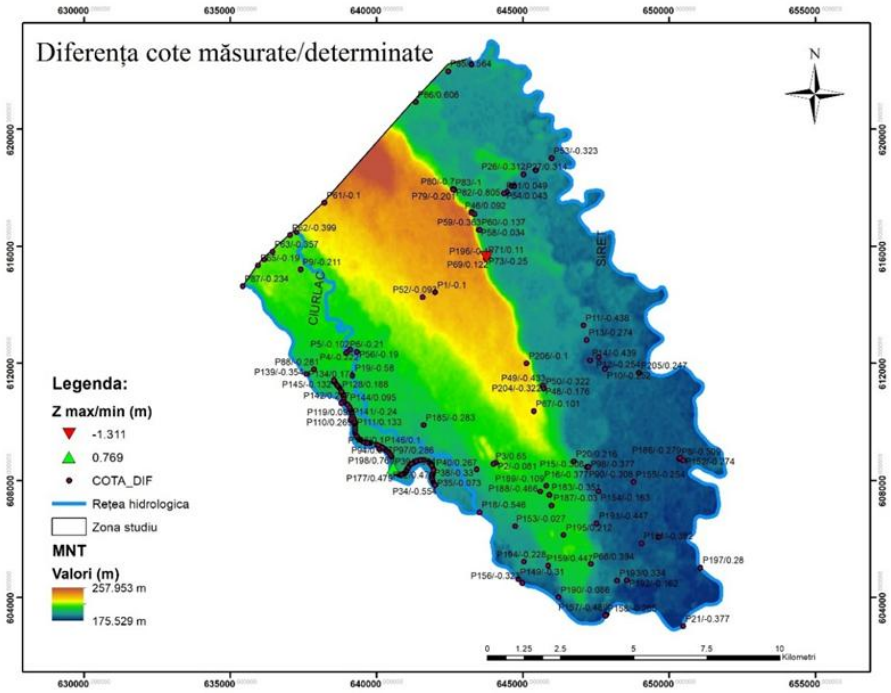


Fig. 4.8. Spatial distribution of field-measured points

Within this stage of spatial schematization, based on the analyzed boreholes, maps of aquifer thickness and bedrock depth were generated. These maps highlighted sedimentary distributions controlled by floodplains and terraces, with well-defined permeable zones in the western sector. Ordinary Kriging and IDW were used as interpolation methods [32].

The thickness of the porous–permeable layer (Fig. 4.10), determined from the analyzed boreholes, varies significantly across the study area, from 0.7 to 6.9 m. These values reflect the configuration of the Moldova and Siret river terraces, a feature clearly illustrated in the map shown in the following figure.

The depth of the aquifer bed (Fig. 4.11) ranges from 3.5 to 27.8 m, with shallower values in the floodplains of the Moldova and Siret and greater depths on the higher interfluves (Traian, Săbăoani, Gherăești). The distribution of iso-depth contours reflects the direct influence of relief and lithology on the structure of the aquifer.

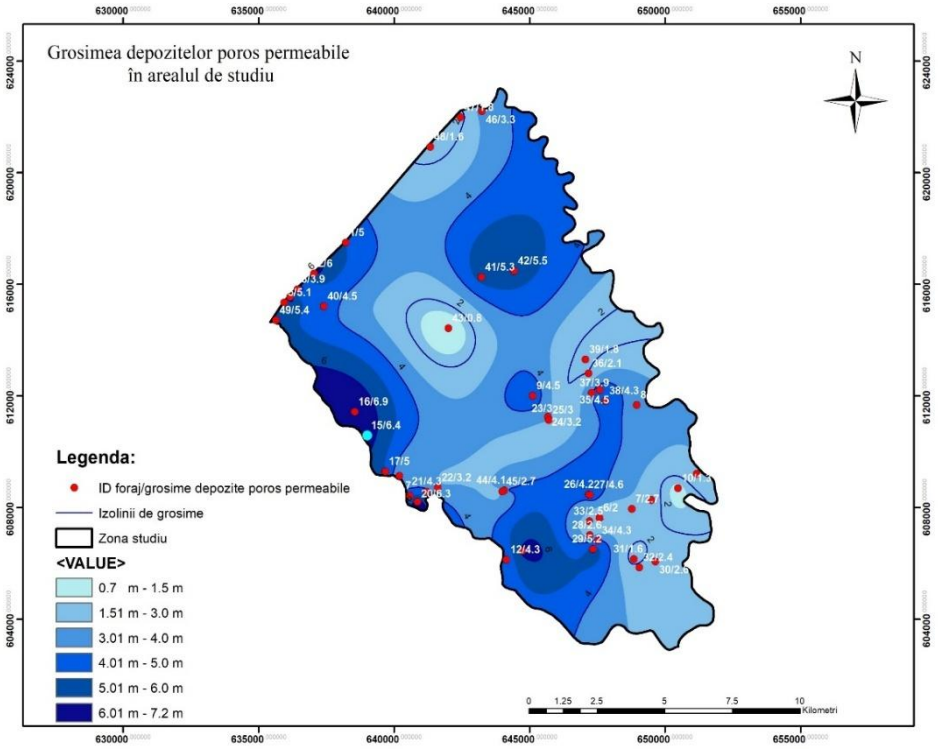


Fig. 4.10. Map of porous–permeable layer thickness relative to the land surface.

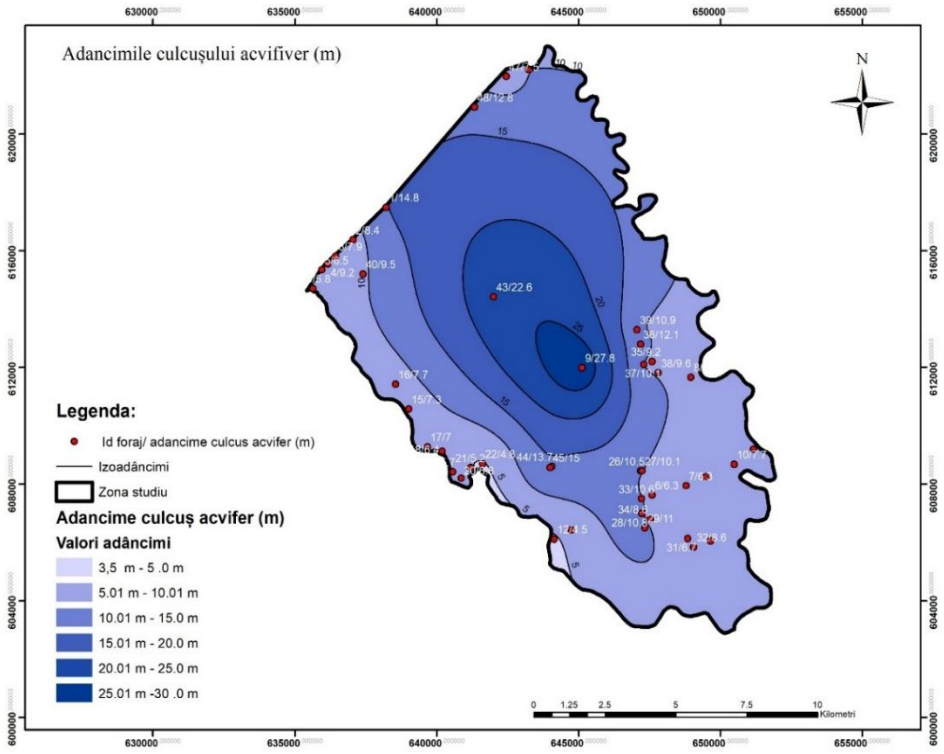


Fig. 4.11. Contour map of the aquifer bed depth.

4.2.2 Hydrodynamic schematization of the aquifer

The purpose of the hydrodynamic schematization stage is to establish the energetic framework in which groundwater flow occurs within the analyzed aquifer system.

4.2.2.1. Hydrodynamic spectrum of the aquifer

To obtain and analyze the spatial variation of the hydrostatic level, field measurements were carried out between 20–21 September 2019, using data from 97 measurement points: 10 boreholes belonging to ABA Siret, 45 wells measured in the field, 8 ponds and lakes intersecting the phreatic aquifer, and additional points located along the Siret and Moldova rivers (13 and 21 points respectively), as shown in Fig. 4.12.

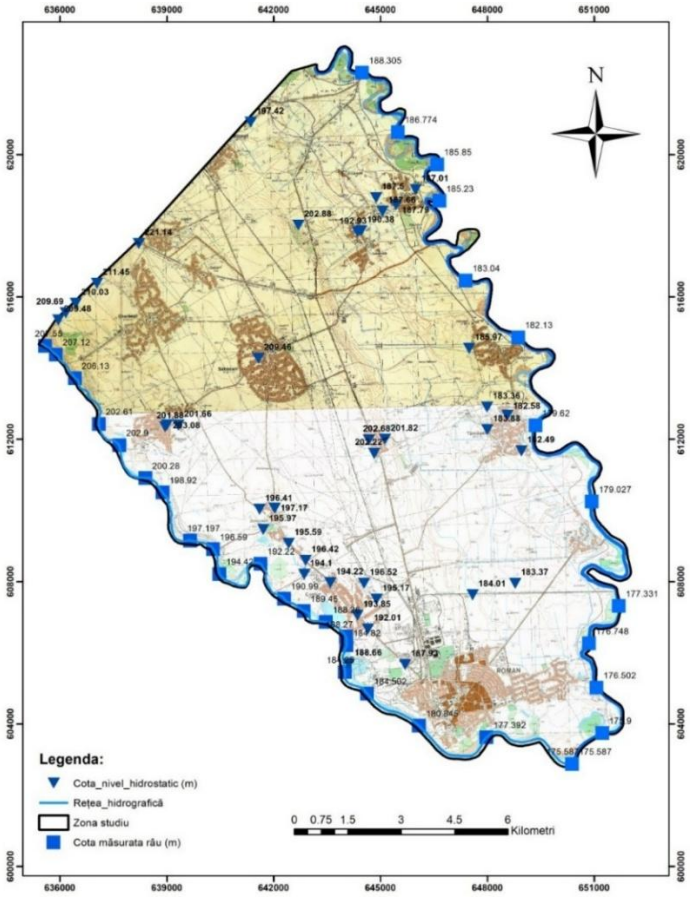


Fig. 4.12. Spatial distribution of piezometric points and hydrostatic levels measured in the field during 20–21 September 2019.

4.2.2.2. Hydrodynamic spectrum of the aquifer through statistical analysis

The aim of this analysis is to characterize the hydrodynamic spectrum of the aquifer by identifying spatial trends, statistical variability, and the structure of spatial correlation of piezometric levels, as well as evaluating the performance of the theoretical models (spherical, Gaussian, and exponential) through cross-validation.

Trend analysis of piezometric values

Based on Fig. 4.13 and Fig. 4.14, the trend analysis of piezometric values indicated a clear decrease along the West–East direction ($R^2 \approx 0.73$), and a more moderate variation along the South–North direction ($R^2 \approx 0.33$). This confirms the presence of anisotropy along the general NW–SE direction, justifying the subsequent directional modelling

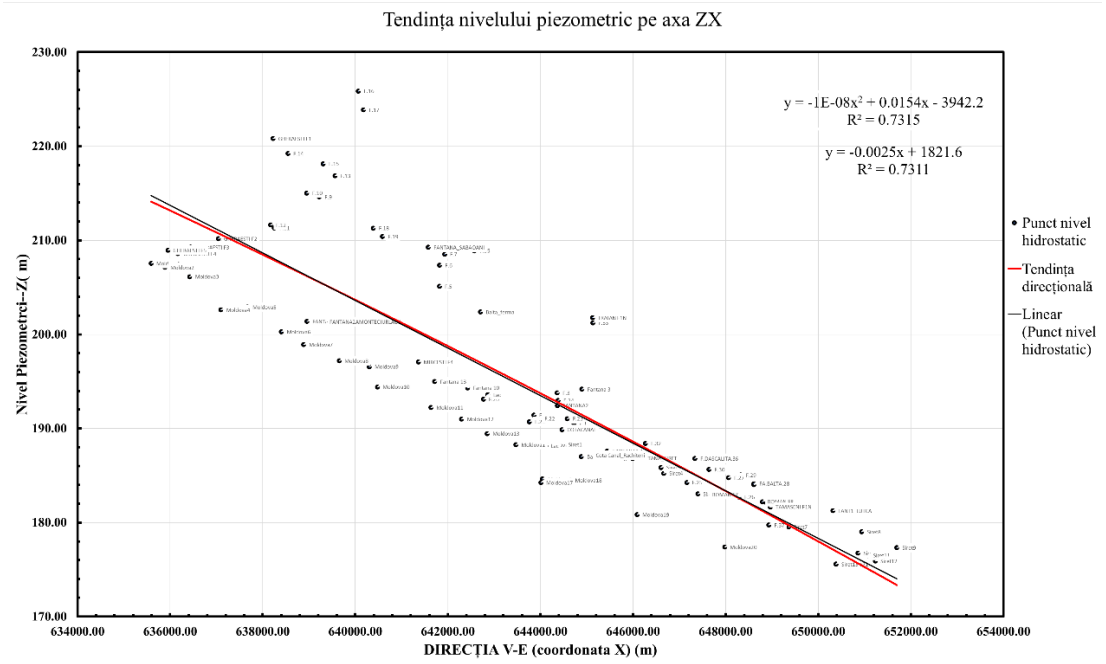


Fig. 4.13. Trend of piezometric level along the West–East direction.

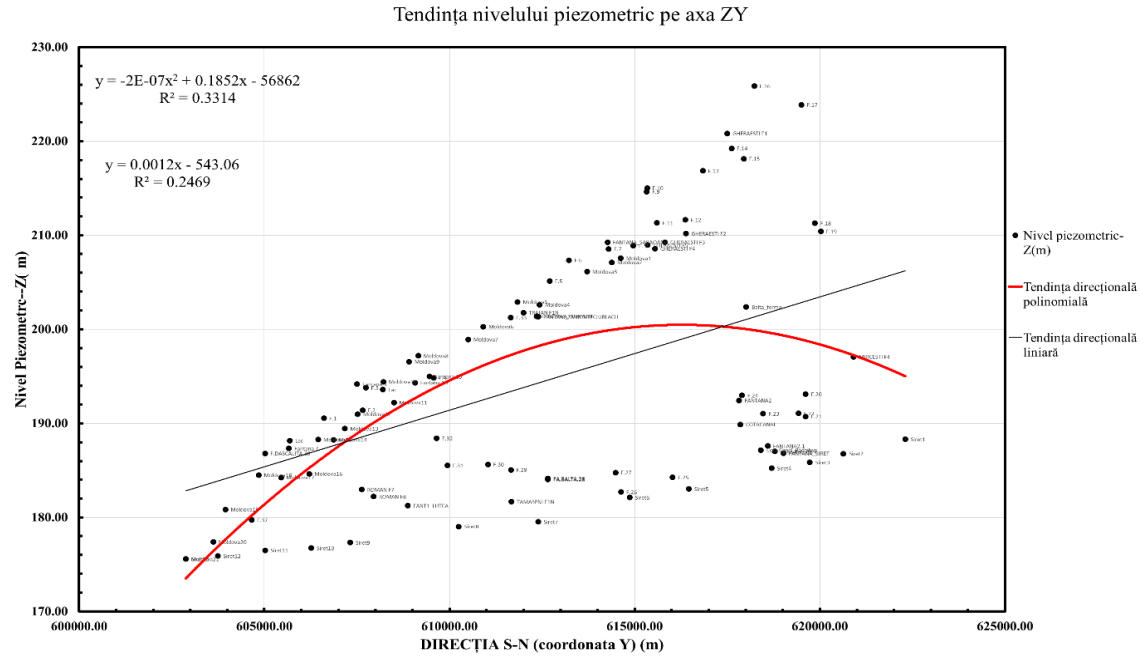


Fig. 4.14. Trend of piezometric level along the South–North direction.

Analiza tendinței spațiale realizată în ArcMap 10.8 a arătat că nivelul piezometric prezintă o variație polinomială de ordinul 2, cu o scădere generală NV–SE (Moldova - Siret).

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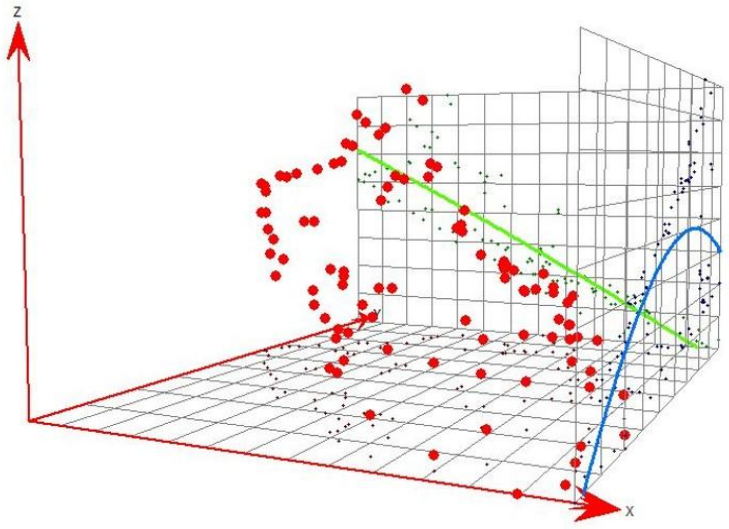


Fig. 4.17. Spatial trend analysis – 3D distribution of piezometric level in ArcMap 10.8.

To characterize the spatial structure of piezometric values, experimental semivariograms were generated along the main continuity direction identified through trend analysis..

For the interpolation of piezometric levels, three theoretical models were tested—Gaussian, Spherical, and Exponential—using the same variographic parameters and the same principal direction of anisotropy. The spatial variability analysis of piezometric levels highlighted a clear anisotropy along the NW–SE axis, driven by the relationship between morphology and sedimentary structure. Based on this, geostatistical modelling was performed directionally, and the Gaussian model provided the best interpolation results.

Table 4.4. Cross-validation results for the three theoretical models.

Variogram model	**ME**	**RMSE**	**MSE**	**RMSSE**	**ASE**
Spherical	–0.04908	2.15885	–0.01536	0.82369	2.55887
Gaussian	–0.03622	**2.00864**	–0.01307	**0.99839**	**1.99229**
Exponential	–0.04415	2.37194	–0.01264	0.78221	2.92724

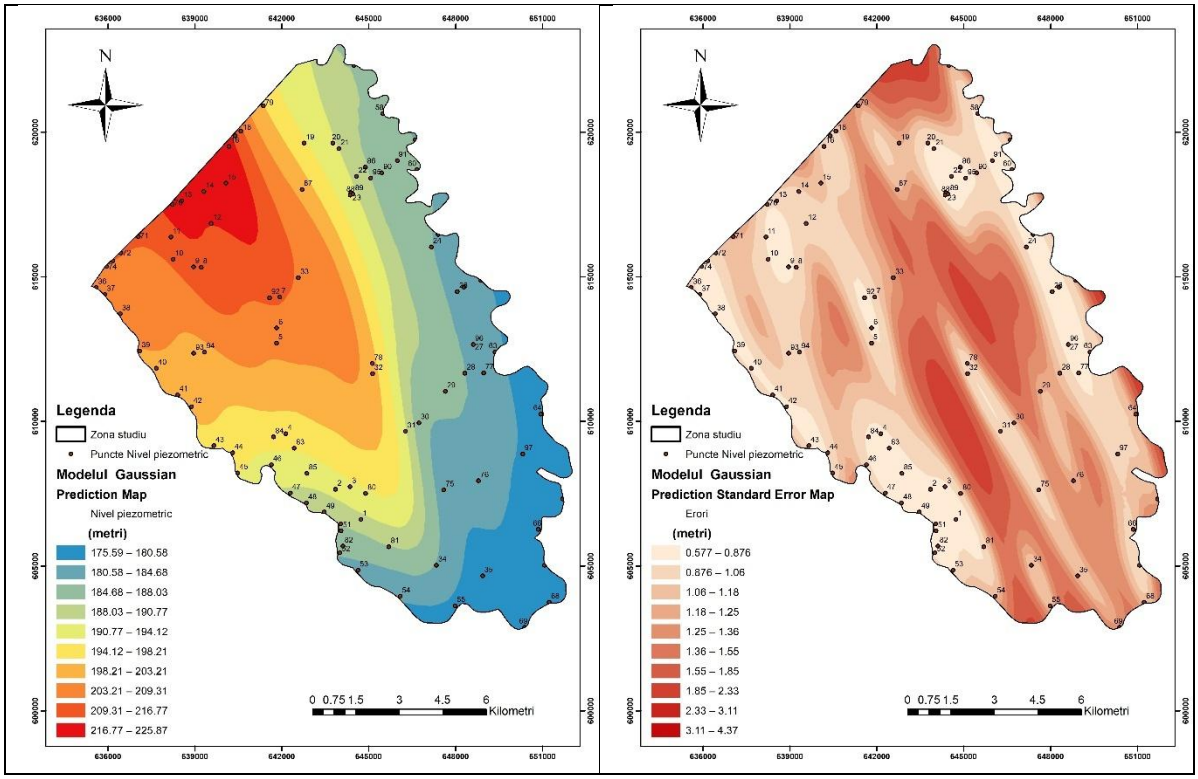


Fig. 4.29. a) Predicted piezometric level map – Gaussian model; b) Prediction error map – Gaussian model.

The piezometric surface obtained through Gaussian kriging shows a regional decline of the hydrostatic level from west to east, confirming the main flow direction Moldova → Siret. The total elevation difference is approximately 40–45 m across the entire length of the study area, and the hydraulic gradient varies between 1–1.5‰ in the western sector, 2–2.5‰ in the central area, and up to 3–3.5‰ toward the Siret floodplain. The higher values in the Gherăești–Traian area and the lower ones near the Siret reflect the direct control exerted by relief and lithology on groundwater flow.

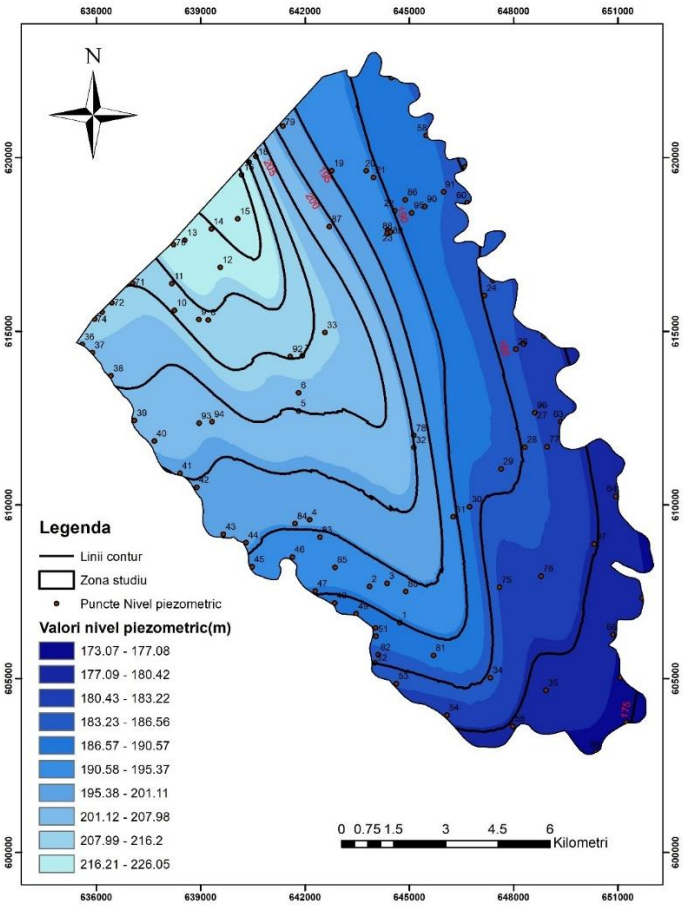


Fig. 4.35. Groundwater flow direction.

4.2.2.3. Analysis of groundwater level variation

The analysis of hydrostatic level variation over the period 2014–2022, correlated with rainfall data from the Nicolae Bălcescu station, highlights a general decreasing trend of the phreatic level in all seven monitored boreholes. This evolution is associated with the reduction in rainfall input, as most of the analyzed years recorded precipitation values below the 2010–2022 multiannual average, with extremes ranging from 1154.4 L/m² in 2016 to only 399.5 L/m² in 2022.

The decline of phreatic resources is therefore directly correlated with diminishing precipitation, with the highest groundwater levels typically occurring during summer and the lowest during the winter season.

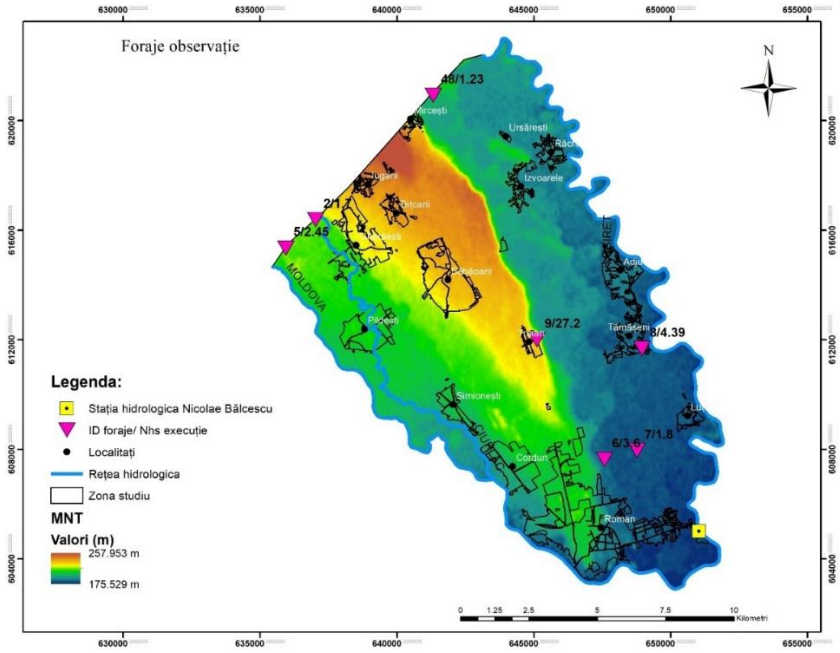


Fig. 4.36. Spatial distribution of piezometric boreholes..

4.2.2.4. Mathematical modelling of the piezometric level

The 2014–2022 piezometric time series was analyzed using functional modelling in TableCurve 3D, in order to identify long-term trends in the phreatic level. The 3D surface generated for each month (e.g., Fig. 4.51) shows a coherent, stable variation, without discontinuities or breaks in the aquifer's behavior.

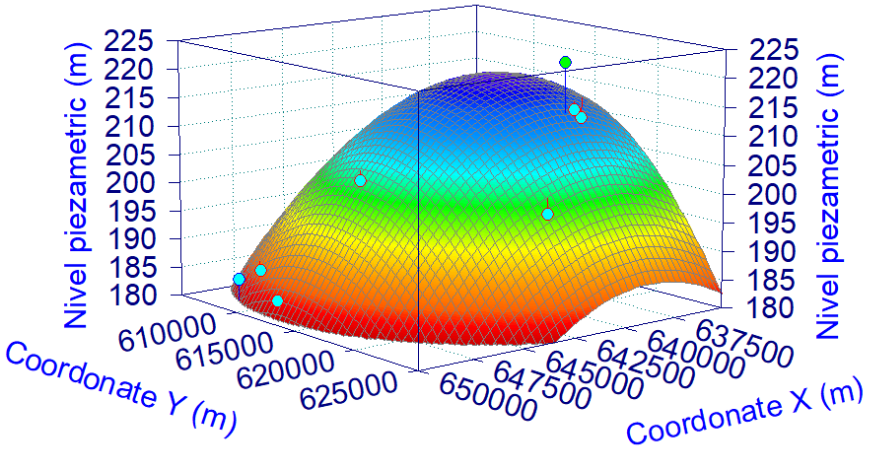


Fig. 4.51. Continuous surface of piezometric level variation for June 2014.

Mathematical modelling confirms a slow and steady decline of the hydrostatic level over the analyzed period, correlated with the reduction in precipitation. The model fits displayed high fidelity (R^2 ~0.91–0.92), supporting the stability of the interpretation..

4.2.3. Parametric schematization of the aquifer

The parametric schematization focused on determining hydraulic conductivity (K) and transmissivity (T), the two key parameters that define the aquifer's capacity to allow groundwater flow and discharge through the full saturated thicknesss.

4.2.3.1 Hydraulic conductivity

Hydraulic conductivity, a fundamental parameter of groundwater flow, was determined from 34 observation points, with K values varying substantially across the area (9.95–171.72 m/day), in accordance with the lithological heterogeneity highlighted in Fig. 4.53

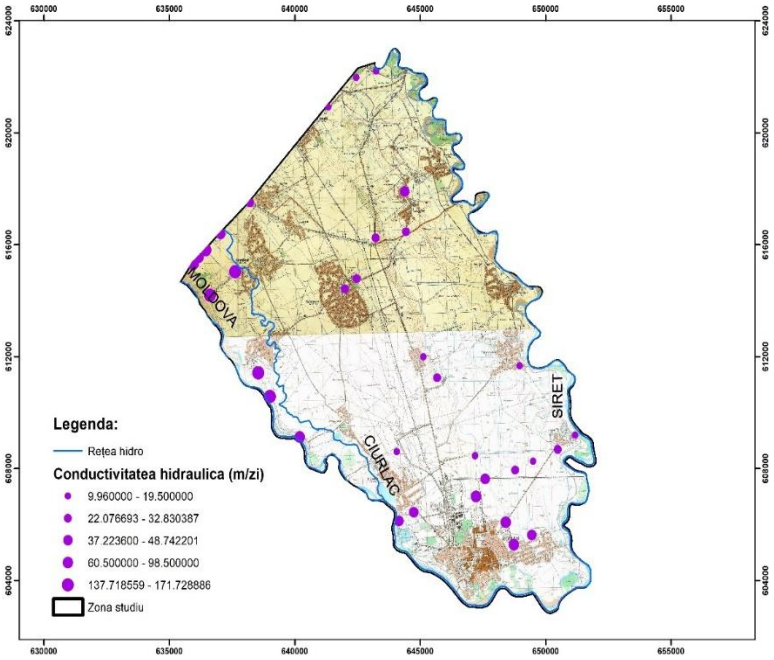
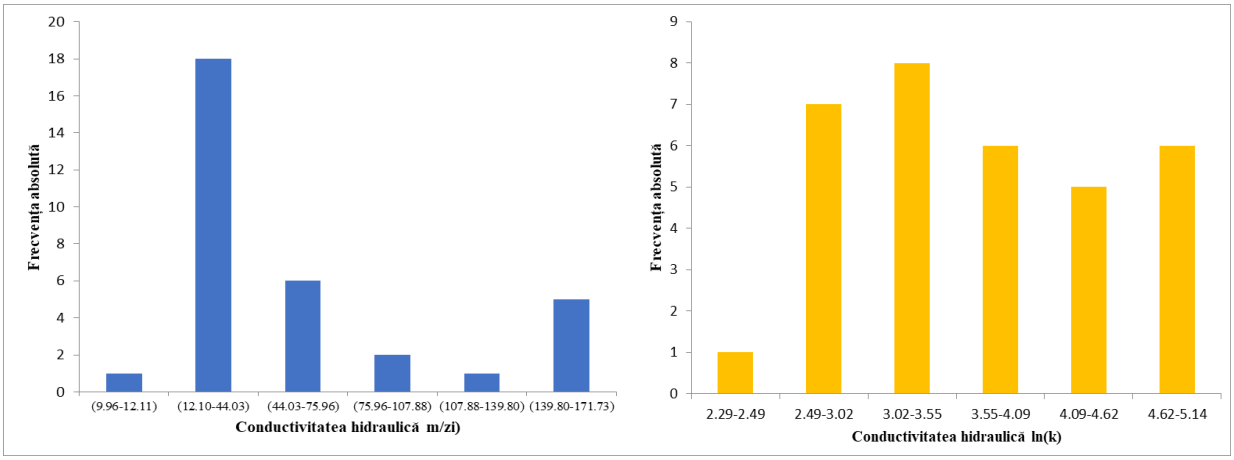


Fig. 4.53. Hydraulic conductivity in observation points..

4.2.3.1.1. Analysis of the global distribution of hydraulic conductivity

The raw distribution of K values is strongly skewed (skewness 1.33; range 161.77 m/day), which required the application of a logarithmic transformation. This reduced the

skewness to 0.42 and produced a much more homogeneous distribution, as illustrated in the two histograms (Fig. 4.54)



a) b)

Fig. 4.54. a) Histogram of hydraulic conductivity values; b) Histogram of log-transformed hydraulic conductivity values.

4.2.3.1.2. Analysis of spatial dispersion

To determine the optimal interpolation model for hydraulic conductivity, three theoretical semivariogram models were tested — Gaussian, Spherical, and Exponential — and evaluated using standard validation indicators (ME, RMSE, ASE, RMSSE, R^2). The results summarized in Table 4.10 show that the Gaussian model provides the best agreement between observed and predicted values, and was therefore selected for generating the final map of K distribution in the study area.

Table 4.10. Comparison of theoretical models through cross-validation.

Nr.	Model	ME	RMSE	MSE	RMSSE	ASE	R^2
1	SPHERICAL	0.0199	0.4886	0.0097	0.8858	0.5741	0.6689
2	GAUSSIAN	0.0055	0.4870	-0.0024	0.8697	0.5735	0.6712
3	EXPONENTIAL	0.0266	0.5011	0.0127	0.9553	0.5772	0.6522

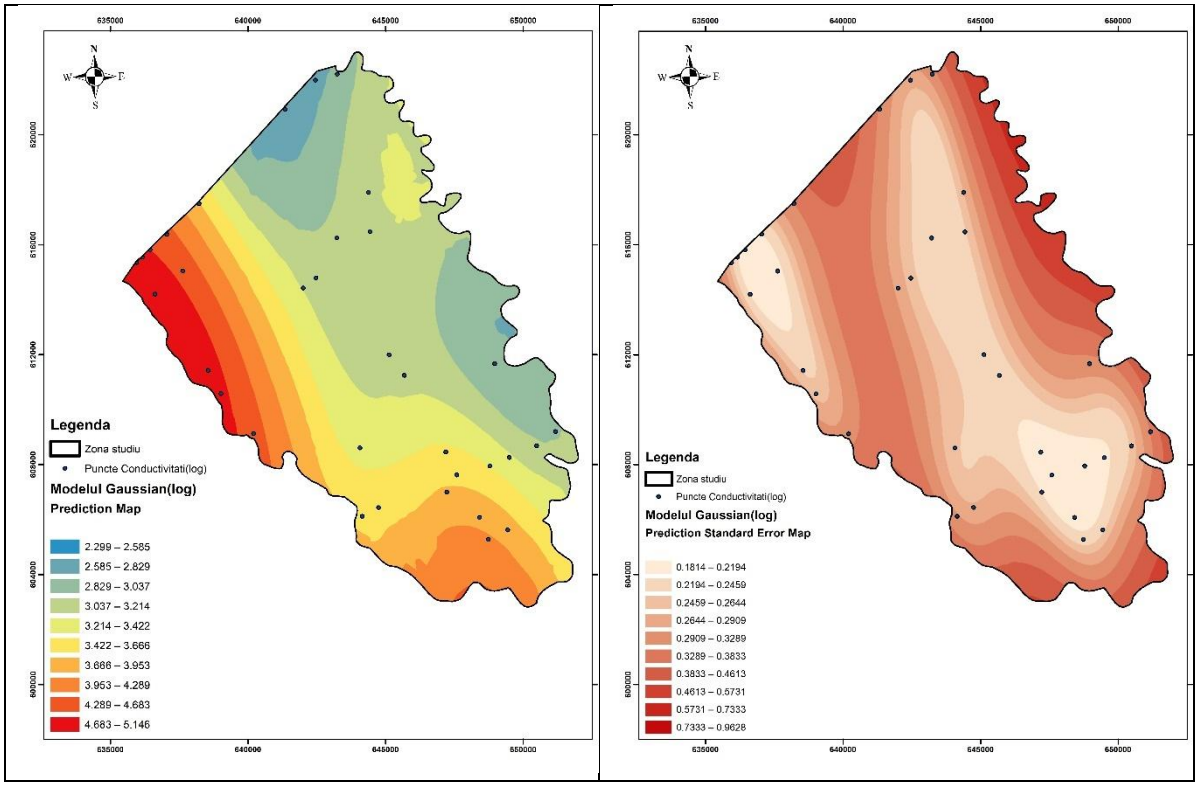


Fig. 4.62. a) Map of predicted hydraulic conductivity (log K) – Gaussian model;b) Map of prediction errors (log K) – Gaussian model.

The logarithmic-value map obtained using the Gaussian model was then subjected to inverse transformation using the EXP function available in ArcGIS 10.8 [21, 30], in order to return the data to the original scale (m/day). This procedure produced the final map of interpolated hydraulic conductivity across the entire study area.

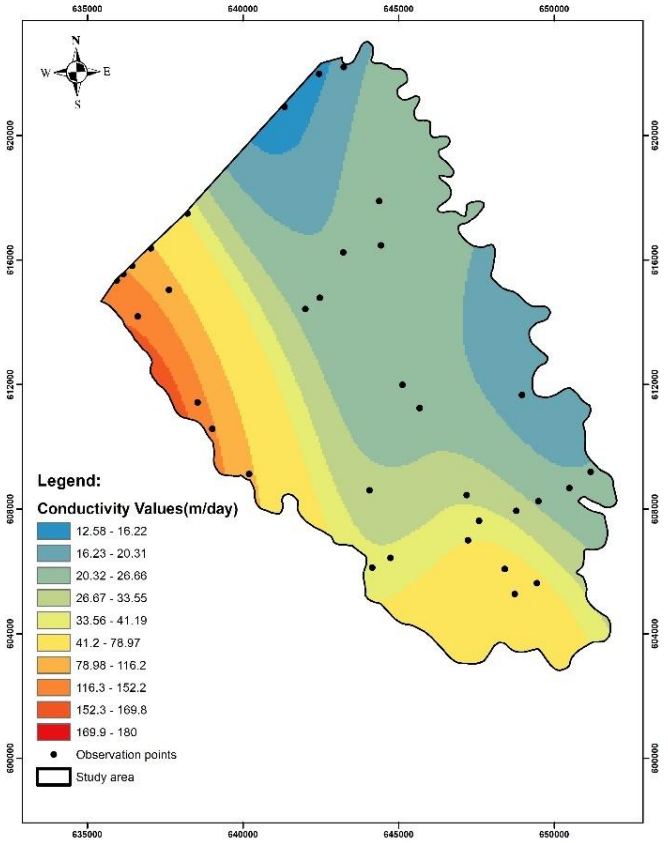


Fig. 4.65. a) Hydraulic conductivity map (m/day).

4.2.3.2 Transmissivity

Transmissivity was calculated based on hydraulic conductivity and the thickness of the saturated layer, and interpolated using the Gaussian model, which provided the best validation results, with $R^2 \approx 0.87–0.89$ (Fig. 4.66). High transmissivity values are concentrated on the lower terraces of the Moldova River, where coarse deposits are predominant, while low values appear in the northern and eastern zones, where fine-grained lithologies dominate. The final map confirms the lithological control on the spatial distribution of transmissivity in the study area (Fig. 4.67).

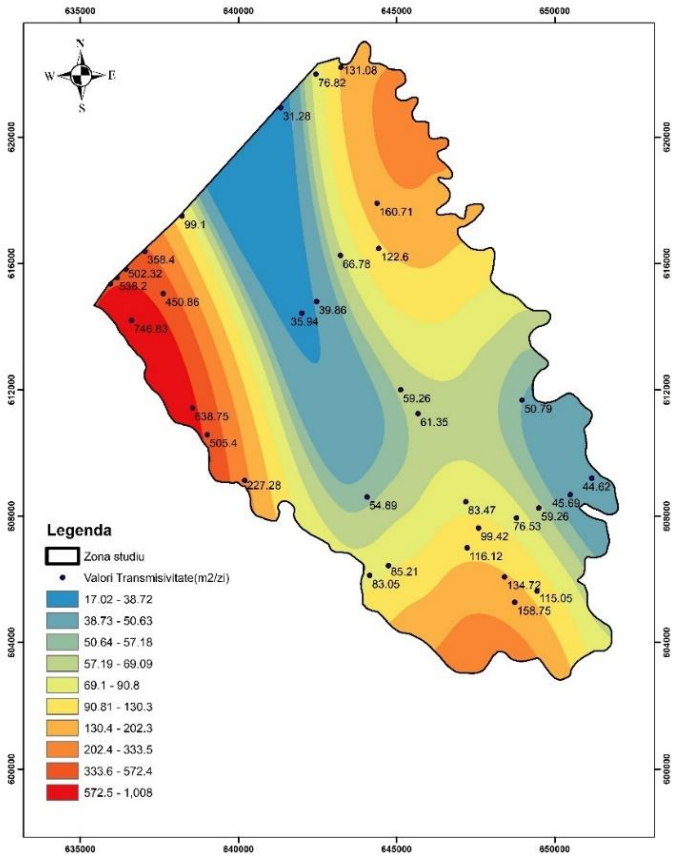


Fig. 4.66. Map of transmissivity distribution (m²/day).

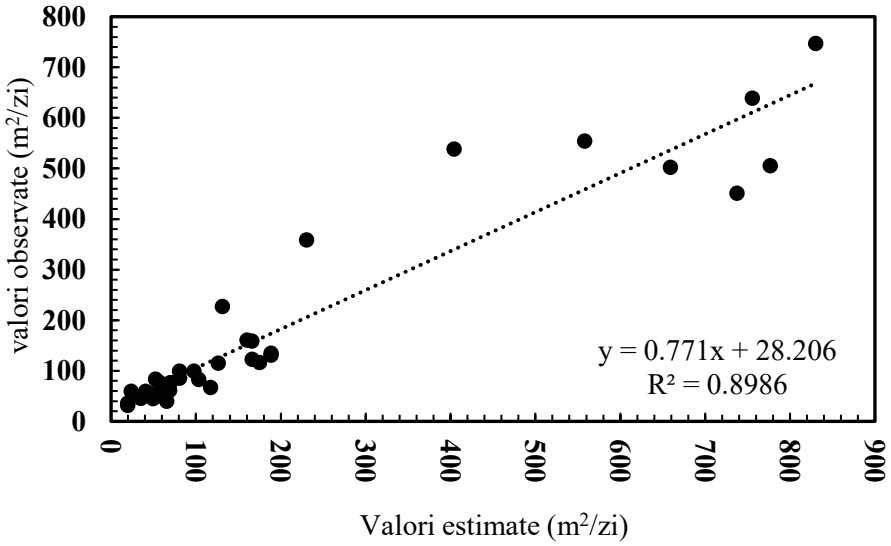


Fig. 4.67. Scatter plot of T (observed vs. estimated) with linear regression.

4.3. Physico-chemical characterization of groundwater

The hydrochemical analysis included two sampling campaigns (2021 and 2022) conducted in 12 representative boreholes within the area between the Siret and Moldova rivers. Major ion concentrations were statistically processed, spatially analyzed in ArcGIS, and interpreted using Piper and Schoeller–Berkaloff diagrams to determine water type.

The 12 sampling points (Fig. 4.68) include boreholes from the National Hydrogeological Network (BH1–BH5), industrial wells (WI1–WI5), and local water intakes (WD1–WD2). Most ions show only minor variations between the two years, maintaining the same chemical structure throughout the study area.

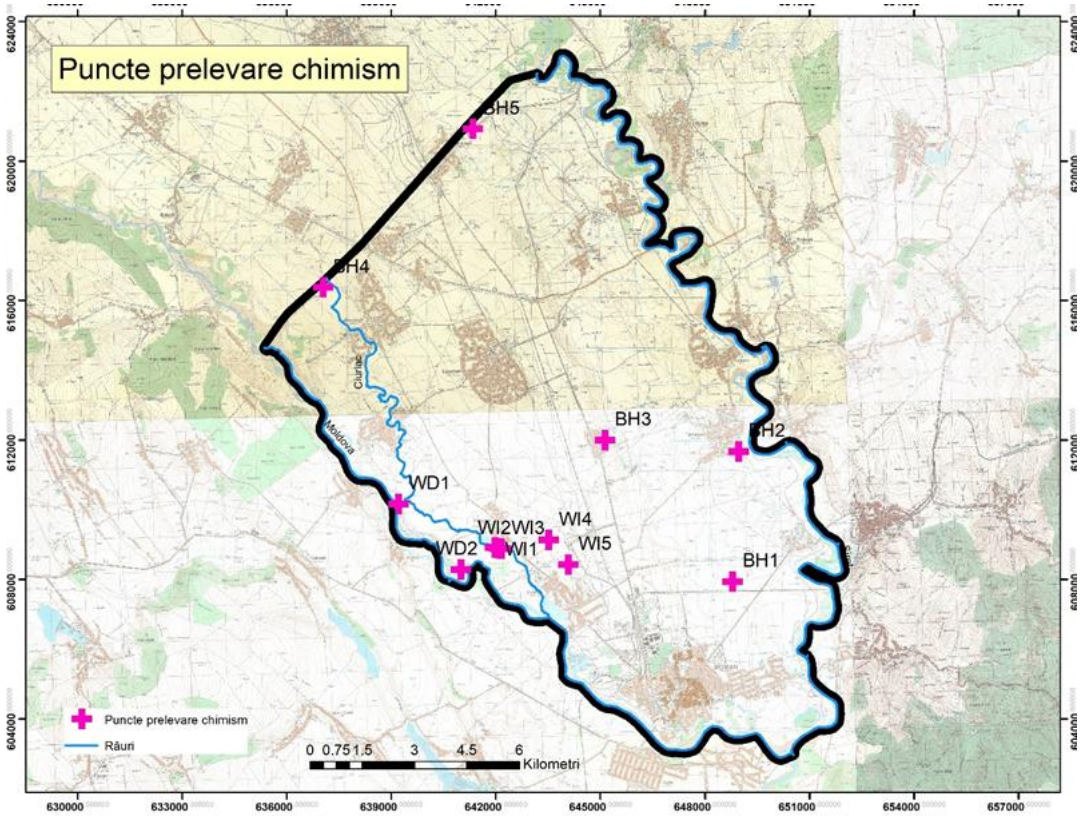
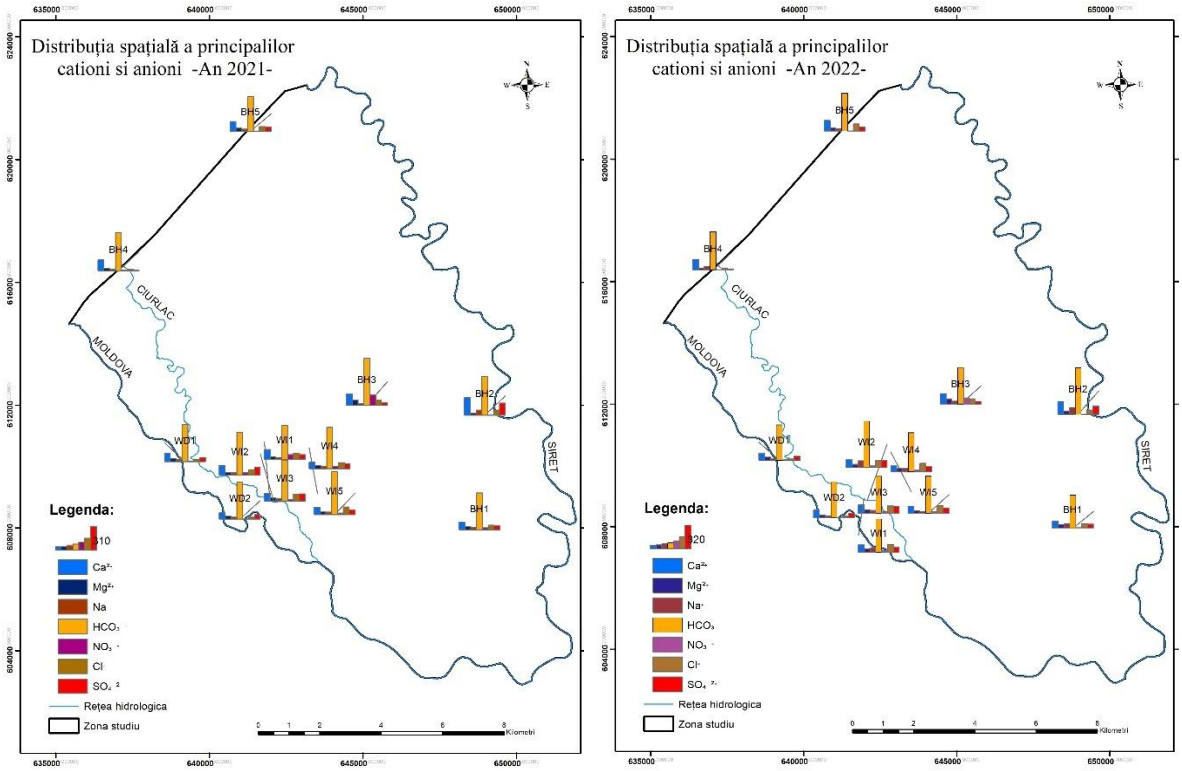


Fig. 4.68. Spatial distribution of the boreholes from which chemical samples were collected.

Percent composition of major ions



a) b)

Fig. 4.71. Percent distribution of major anion and cation concentrations: a) 2021; b) 2022.

The analysis of the data shows that the dominant hydrogeochemical facies is calcium–bicarbonate (Ca–HCO_3) in both analyzed years, typical of aquifers hosted in freely circulating gravel and sand deposits. The HCO_3^- ion records the highest concentrations, followed by calcium and magnesium, indicating a system mainly controlled by carbonate dissolution processes. Chloride (Cl^-) and sulfate (SO_4^{2-}) are present in low to moderate concentrations, without significant regional variations.

The only notable increases in sulfates were observed in boreholes BH2 and WI2, where values reached 161.5 mg/L and 103.66 mg/L in 2021, and 110 mg/L and 98.5 mg/L in 2022. These values suggest a localized influence, possibly related to sediment composition or nearby anthropogenic activities, without affecting the general structure of the aquifer. Aside

from these local anomalies, no major exceedances of quality parameters were recorded that would indicate marked contamination or shifts in facies between the two years.

The physico-chemical analysis for 2021 and 2022 indicates that the aquifer maintains a stable Ca–HCO_3 facies, with minor interannual variations. The Piper and Schoeller diagrams confirm the compact grouping of samples within the bicarbonate water field, reflecting a homogeneous composition and the absence of significant pollution processes in the area.

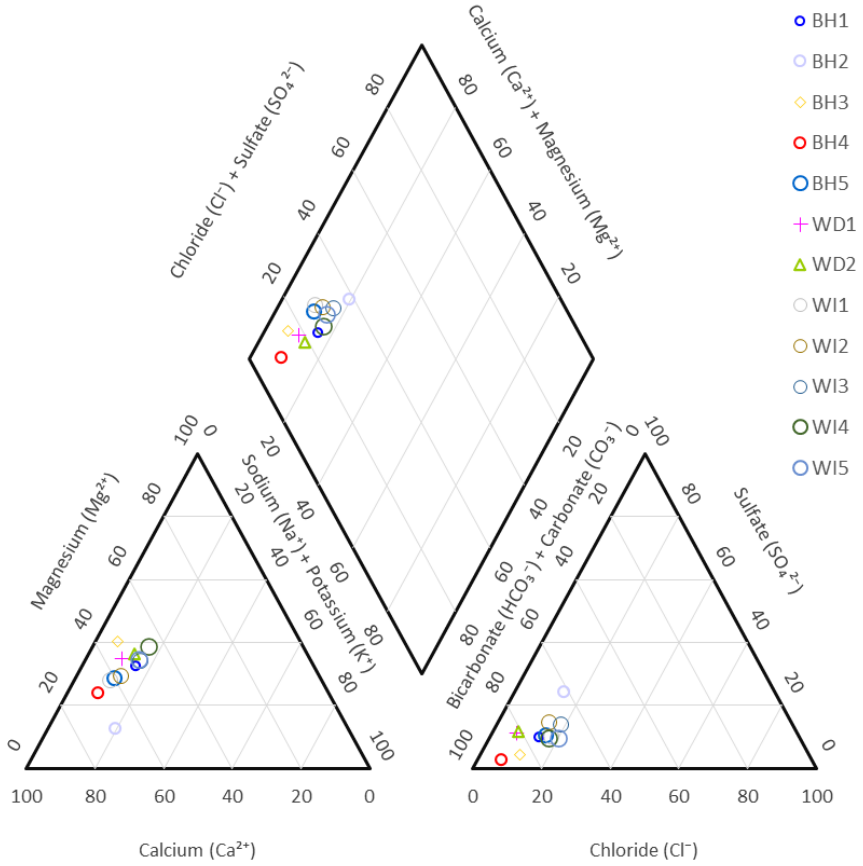


Fig. 4.72 Piper diagram for measurements from 2021.

According to the Piper diagram[34] shown in Fig. 4.72, the dataset for 2021 confirms the dominance of calcium cations and bicarbonate anions, resulting in a calcium–bicarbonate water type.

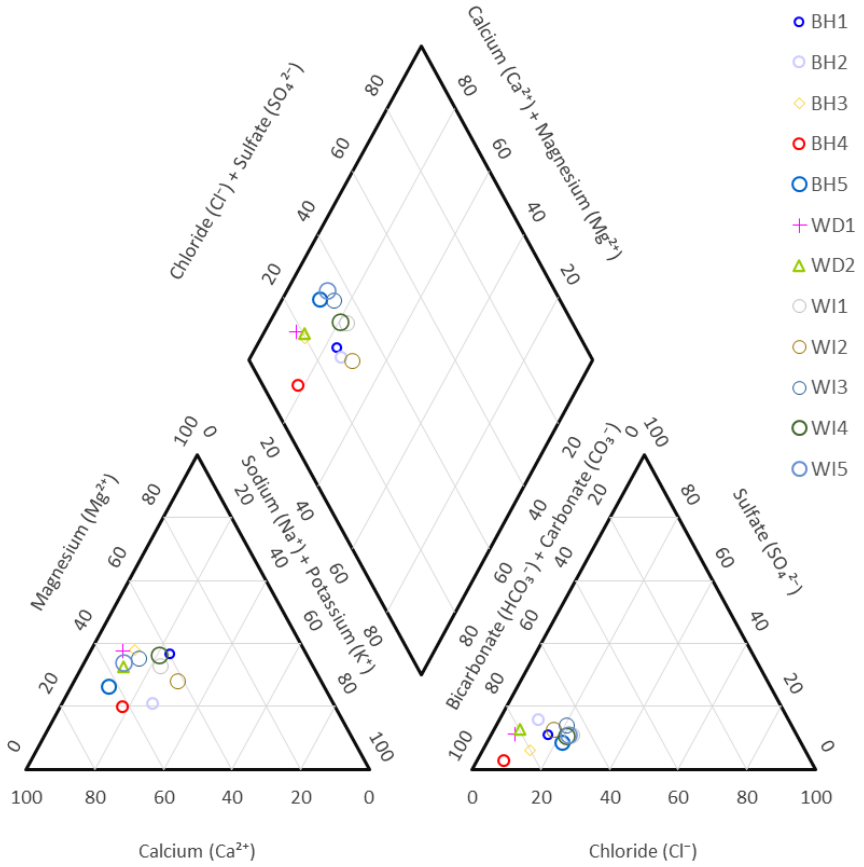


Fig.4.73. Piper diagram for measurements from 2022.

The analysis for 2022 does not indicate significant changes compared to 2021. Only BH1, WI5, and WI2 show a less clearly defined dominant cation type. However, anions remain predominantly bicarbonate, and the overall water type remains calcium–bicarbonate.

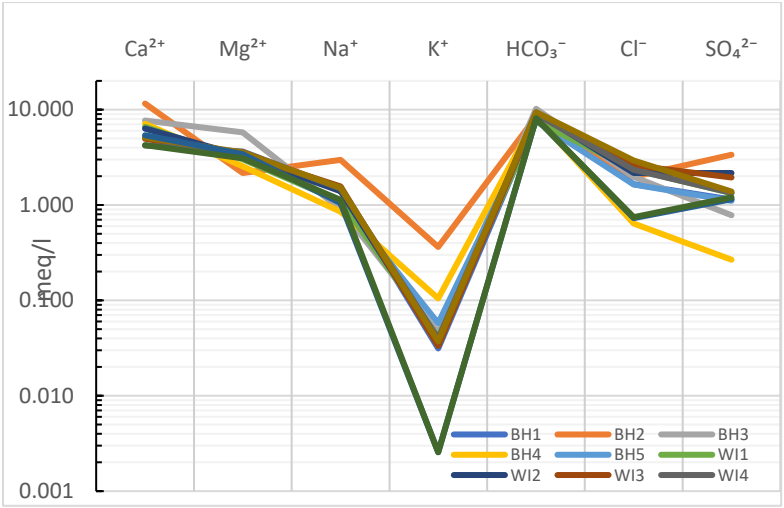


Fig.4.74 Schoeller–Berkaloff diagram for measurements from 2021.

On the Schoeller–Berkaloff diagram corresponding to the 2021 samples, all boreholes align consistently, indicating the same calcium–bicarbonate water type. A similar trend is visible across all samples, with slightly higher values for sulfates and magnesium. Overall, these observations support the result obtained from the Piper diagram [34].

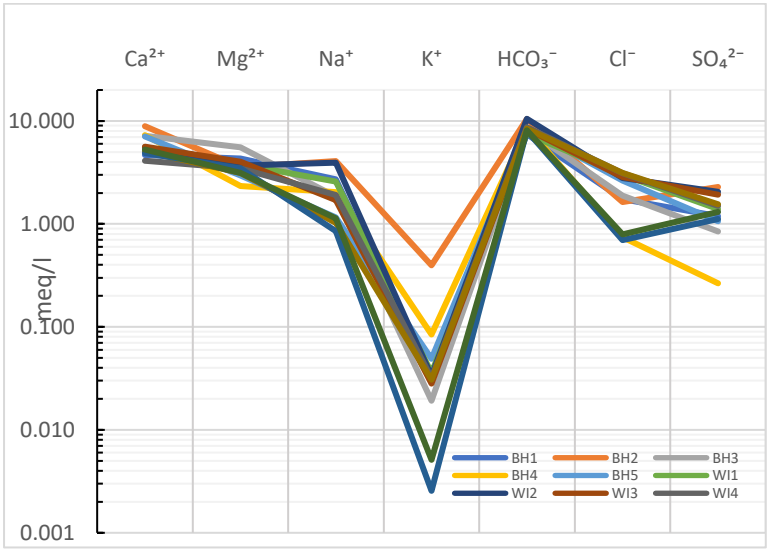


Fig. 4.75. Schoeller–Berkaloff diagram for measurements from 2022.

5. Integration of hydrogeological and geospatial analyses in the characterization of the phreatic aquifer in the Siret–Moldova sector

The integration of hydrogeological and geospatial parameters aims to obtain a single indicator of aquifer favorability, by combining hydraulic conductivity (K), transmissivity (T), groundwater potential (GPZ), inverted piezometric level (NP_inv), and land use/land cover (LULC). The GPZ and LULC layers originate from previous studies conducted by the author, published separately, and are used here as validated thematic products, fully compatible with the rest of the dataset and serving to support the interpretation of aquifer parameter distribution [6, 7] .

To allow a comparative evaluation of the rasters, 130 randomly distributed points were generated, with a minimum spacing of 250–300 m between them, ensuring that all thematic classes (K, T, GPZ, NP_inv, LULC) were represented. The values extracted at these points constitute the common sample used for all statistical analyses (histograms, boxplots, correlations, internal distributions).

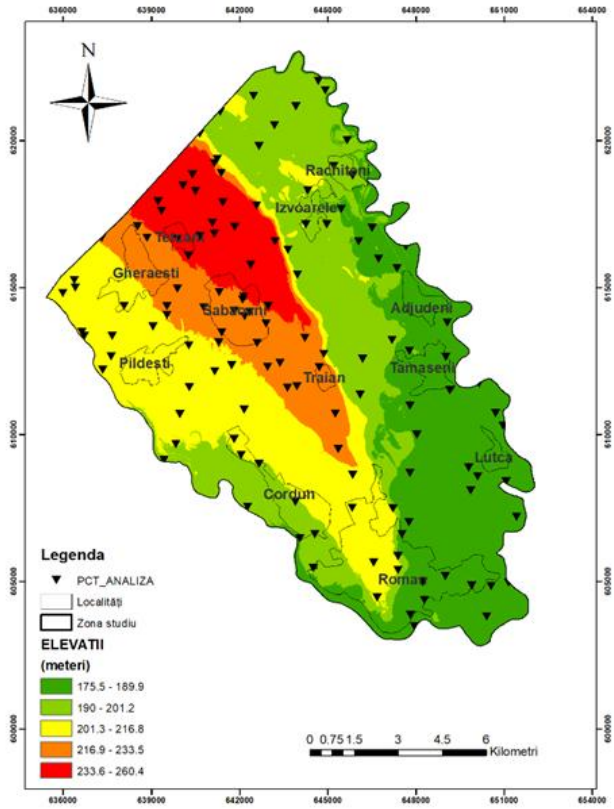


Fig. 5.4. Spatial distribution of analysis points

Tabelul 5.1. Distribution of points across thematic classes..

Clasă	LULC	Număr	Zone potențial acvifer	Număr
1	Water bodies	17	GPZ 2(low)	28
2	Tall vegetation	17	GPZ 3(medium)	21
3	Low vegetation	23	GPZ 4 (high)	41
4	Agricultural land	52	GPZ 5 (very high)	40
5	Built-up areas	21	–	–

5.1. Integrated statistical analysis of hydrogeological (K, T, NP) and thematic parameters (LULC, GPZ)

The statistical analysis performed on the 130 points selected according to LULC and GPZ classes highlighted the actual variability of hydrogeological parameters in the area. The histograms clearly show the heterogeneity of K and T, with conductivity values concentrated in the 20–60 m/day range and transmissivity values locally exceeding 800 m²/day, characteristic of the coarse deposits found in the floodplain and lower terraces. The piezometric level generally varies between 185 and 215 m, capturing the natural transition from the higher interfluves toward the Siret–Moldova area.

Boxplots confirm the differences between classes: transmissivity increases systematically with GPZ potential, and NP is lowest in high-GPZ classes, indicating the zones most favorable for groundwater accumulation and circulation. The Pearson matrix shows a strong relationship between K and T ($r \approx 0.93$) and a negative correlation between NP and GPZ (≈ -0.75), while links with LULC are weak, reinforcing the conclusion that aquifer parameters are primarily controlled by sedimentary structure and morphology, rather than land use.

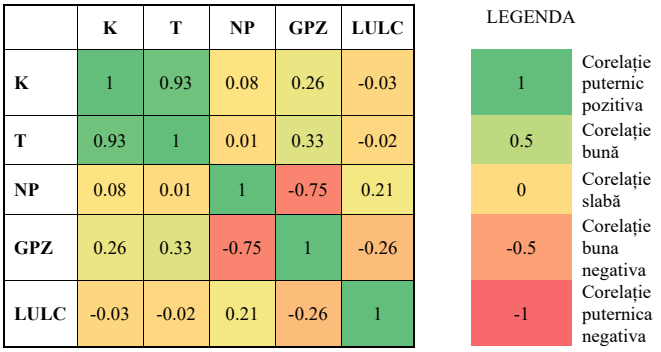


Fig. 5.8. Pearson correlation matrix and associated heatmap for variables K, T, NP, GPZ, and LULC

5.2. Integrated hydrogeological favorability map for groundwater management

All rasters were rescaled to a common 1–5 scale according to the importance of each class and combined through a weighted model (K = 0.15; T = 0.15; GPZ = 0.30; NP_inv = 0.25; LULC = 0.15), in order to obtain a comparable representation of hydrogeological conditions across the entire area.

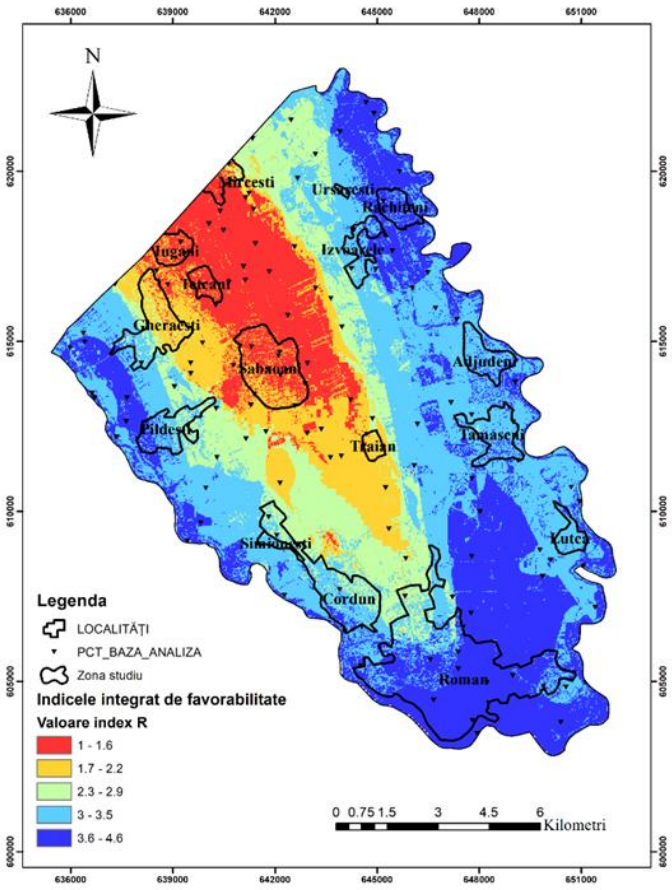


Fig. 5.12. Integrated map of hydrogeological favorability.

The integrated index map (R_final), with values between 1 and 4.55, shows a clear transition from the high, low-permeability interfluve zones of Săbăoani–Gherăești East–Upper Traian–Pildești (R_final < 1.6), to the intermediate terraces with reduced–moderate favorability (1.6–2.9), and towards the floodplain and very low terraces of the Siret and Moldova rivers (R_final > 3.5), where the best hydrogeological conditions are concentrated — large saturated thicknesses, high K and T, and low piezometric levels.

Overall, the index confirms the geomorphological and lithological control: maximum potential is associated with coarse alluvial deposits in the floodplain, while minimum potential corresponds to elevated interfluves with low permeability. The statistical analysis of the 130 points (SD ≈ 1.0, skewness ≈ –0.27) confirms that the integrated map is robust and can be used as an operational tool for assessing aquifer potential and managing groundwater resources in the Siret–Moldova sector.

5.6. Integration of the groundwater quality index in the study area

To evaluate groundwater quality in the upstream sector of the Moldova–Siret confluence, the Water Quality Index (WQI) analysis for 2021–2022 was also included, calculated based on the physico-chemical parameters monitored in the local observation points. The applied methodology is identical to that used in the previous study conducted in the Roman–Gherăești area[8], allowing for a direct comparison of results.

The WQI index was calculated following the standard methodology (weight Wi and score Qi) [9, 28], and the analysis shows that the groundwater has, overall, very good quality: in 2021, approximately 75% of the points fell into the "excellent" class and 16.6% into the "good" class, while in 2022 the proportion of "excellent" waters increased to 83.3%. The few deviations are associated only with local influences (NH_4^+, NO_2^-), without any connection to the structure of the aquifer .

Punct de probă	WQI 2021	Clasă 2021	WQI 2022	Clasă 2022
BH1	57.602	Medie / Acceptabilă	14.267	Excelentă
BH2	25.535	Bună	16.351	Excelentă
BH3	27.026	Bună	22.049	Excelentă
BH4	18.633	Excelentă	18.229	Excelentă
BH5	14.141	Excelentă	82.038	Slabă
WI1	30.173	Bună	30.064	Bună
WI2	21.635	Excelentă	22.457	Excelentă
WI3	14.196	Excelentă	15.392	Excelentă
WI4	13.435	Excelentă	14.261	Excelentă
WI5	18.088	Excelentă	18.347	Excelentă
WD1	6.144	Excelentă	6.014	Excelentă
WD2	4.305	Excelentă	7.186	Excelentă

LEGENDA

WQI	Clasificare
0-25	Excelentă
26-50	Bună
50-75	Medie/acceptabilă
75-100	Slabă
>100	Nepotabilă

Fig. 5.14 Evaluation of WQI values in the analyzed points.

A WQI map was not generated because the number of points is limited and their spatial distribution is uneven. Under these conditions, an interpolation would not have been relevant. The analysis was therefore maintained at the level of individual borehole values, which best reflect the actual situation.

There is no direct correlation between hydrogeological parameters (K, T, NP) and the WQI values, suggesting that the observed issues are linked to local anthropogenic influences rather than to the structure or dynamics of the aquifer..

6. General conclusions

Based on all the analyses presented, the general conclusions of the study highlight both the hydrogeological particularities of the Siret–Moldova sector and the practical applicability of the results. The following section presents the final conclusion, which synthesizes the essence of the entire scientific approach

A. Regarding the opportunity and relevance of the topic

The topic is both current and necessary, considering the increasing pressure on shallow groundwater resources in the Roman–Gherăești–Mircești area, where the aquifer is extensively used for both public and private water supply. The available data had previously been dispersed across various reports or borehole logs, without a coherent and unified spatial analysis.

The study therefore fills a real gap in local research: no complete geostatistical modelling of hydraulic conductivity and transmissivity existed, no integrated favorability map (K–T–LULC–NP–GPZ) had been produced, and information regarding groundwater quality was fragmented and lacked a common interpretive framework. The study comes at an opportune moment, aligned with the requirements of Directive 2000/60/EC, which calls for an integrated evaluation of groundwater resources using modern GIS and geostatistical methods.

B. Regarding the theoretical and methodological foundation of the research in the study area

The theoretical foundation of the study is based on the classical principles of hydrogeology (Darcy's law, Dupuit–Theis concepts) and on modern approaches to the characterization of phreatic aquifer parameters. This framework enabled the definition of the conceptual model and the parameters analyzed (K, T, NP).

Methodologically, the study integrates current techniques used in hydrogeological investigations: GIS processing (ArcGIS – Spatial Analyst, Geostatistical Analyst), variogram analysis, anisotropy detection, kriging interpolations, functional modelling (TableCurve 3D), as well as statistical validation methods (ME, RMSE, RMSSE, R^2). The database was compiled from multiple sources: LiDAR and SRTM for the DTM, RTK measurements, borehole logs, piezometric levels, and physico-chemical analyses.

The modelling of the 2014–2022 piezometric series allowed monitoring of the temporal evolution of the hydrostatic level in parallel with precipitation variations. Additionally, integrating hydrogeological parameters with thematic maps (LULC and GPZ — previously developed for the same area) enabled the transition toward multicriteria analysis and the construction of the integrated favorability map, which is essential for the final interpretation.

Complementing the quantitative analysis, the methodology also includes determining the WQI index for 2021–2022, calculated using the standard formula applied in recent literature, allowing qualitative aspects to be incorporated into the overall aquifer assessment.

C. Regarding the experimental verification and validation of the data used in the analysis

The conceptual model and the vertical distribution of the aquifer were established based on lithological information from 49 boreholes in the area, which were used to define the thickness and depth of the aquifer layer. This structural framework was subsequently used to verify the experimental data presented below.

Data validation was based on correlating the models with field measurements and on statistical checks. The digital terrain model (LiDAR + SRTM) was confirmed through more

than 200 RTK measurements, and the piezometric level distribution was verified at 97 points, resulting in a stable piezometric surface across the entire study area.

The 2014–2022 piezometric series modeled in TableCurve 3D yielded R^2 values between 0.9129 and 0.924, confirming the accuracy of the temporal trends. The Gaussian model selected for interpolation showed the best cross-validation performance (RMSE ≈ 2 m).

The K and T parameters were statistically analyzed and are consistent with local lithology, while the hydrochemical data (2021–2022) confirmed a stable HCO_3–Ca facies. Overall, all datasets are consistent and suitable for use in the final analysis.finală.

D. Regarding the originality of the work

The originality of the study results from the application and combination of eleven hydrogeological, geostatistical, mathematical, hydraulic, hydrochemical, and multicriteria modelling approaches, all carried out using data that were manually collected, verified, and processed. Together, these models applied at the scale of the Siret–Moldova sector provide a complete picture of the aquifer's structure, dynamic functioning, and water quality, using a coherent set of spatial and temporal analyses:

Modelling the thickness of the porous–permeable layer revealed a variation between 0.7–6.9 m and allowed the delineation of zones where the permeable layer is well developed, providing the first complete picture of aquifer thickness in the area.

• Modelling the depth of the aquifer bed showed values ranging between 3.5–27.8 m, completing the vertical structure of alluvial deposits and outlining the true distribution of the productive layer.

• Topographic modelling (DTM), derived from LiDAR + SRTM and validated through 206 RTK measurements, confirmed a precise raster (–1.31 m to +0.77 m), suitable for hydrogeological analyses.

• Piezometric modelling (kriging + variography), based on 97 points, identified the main direction of spatial continuity (~157°) and showed that the Gaussian model produced the best estimation, resulting in the first fully validated piezometric map for the entire sector.

• Temporal modelling of hydrostatic levels (TableCurve 3D) revealed a gradual decline in the phreatic level (R^2 = 0.9129–0.924), correlated with decreasing precipitation between 2010–2022.

• Statistical analysis of K, T and NP (histograms, boxplots, descriptive indicators) demonstrated high variability in K, the need for logarithmic transformation, and coherent distributions supporting subsequent geostatistical interpretation.

• Hydraulic conductivity (K) modelling through ordinary kriging identified higher values in the western sector, consistent with coarse deposits, with K predominantly 20–60 m/day and maxima >100 m/day.

• Transmissivity (T) modelling highlighted large variations driven by the thickness of the saturated layer, with extreme values >800–900 m^2/day, providing the first detailed T map for the area.

• Hydrochemical modelling (Piper and Schoeller diagrams) confirmed a stable bicarbonate–calcium facies (HCO_3–Ca) for both analyzed years (2021–2022), with minor local variations in sulfates.

• WQI modelling showed that most points fall into the "good" and "excellent" classes, with no major changes in aquifer behavior.

• Integrated K–T–NP–GPZ–LULC modelling generated the first composite hydrogeological favorability map (R_final), synthesizing the aquifer's structure, dynamics, and surface conditions.

• The field campaign (RTK + piezometric measurements) provided the calibration basis for all stages, with ~200 RTK points and 97 piezometric determinations — a level of verification not present in previous studies of the area.

• Integration of GPZ and LULC maps (previously obtained through AHP and geospatial classification) directly contributed to the structure of the integrated map, with GPZ receiving the highest weight (0.30).

Overall, the originality of this study derives from the combination of 11 distinct modelling approaches, validated with real data and integrated into a coherent framework. While the area has been studied locally, existing works cover only partial sectors (western or eastern) and do not capture the entire region in a unified form. The present research offers the

first comprehensive integration of hydrogeological, geostatistical, and geospatial data for the entire Siret–Moldova sector.

E. Regarding the future development pathways of the research

Although the study provides a solid understanding of the aquifer, several limitations remain, related to the relatively small number of boreholes, the uneven distribution of hydrochemical sampling points, and the variable precision of the DTM. In the future, expanding the observation network, periodically updating the LULC layer, and developing a 2D/3D numerical model (MODFLOW/FEFLOW) could significantly refine the results.

Even though some data limitations exist (natural for an area of this size), the general conclusions remain stable, and the framework established here can be confidently used as a starting point for more advanced studies or for applications in other areas of interest.

F. Valorisation of the results of the studies and research conducted

Articles under review or in the process of publication in ISI-ranked journals:

Petrut-Liviu Bogdan, Valentin Nedeff, Mirela Panainte-Lehadus, Dana Chitimuș, Narcis Barsan , Florin Marian Nedeff, *Geostatistical Assessment of Hydraulic Conductivity for Sustainable Groundwater Management in the Siret–Moldova Confluence Area, Romania*

Articles published in ISI-ranked journals:

Bogdan, P.-L.; Nedeff, V.; Panainte-Lehadus, M.; Chitimuș, D.; Barsan, N.; Nedeff, F.M. Delineation of Groundwater Potential Zones Using Geospatial Techniques. Case Study: Roman City and the Surrounding Area in the Northeastern Region, Romania. *Water* **2024**, *16*, 3013. https://doi.org/10.3390/w16213013.

Articles published in Proceedings

1. P. -L. Bogdan et al., "Applications of the GIS and Remote Sensing methods in the Land use and cover maps. Case study: Roman city and the surroundings of the Northern side area," 2022 8th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE), Ruse, Bulgaria, 2022, pp. 1-5, doi: 10.1109/EEAE53789.2022.9831397.

2. P. -L. Bogdan, V. Nedeff, M. Panainte-Lehaduș, O. Irimia and E. Moșneguțu, "Integrated Assessment of Groundwater Quality: A Case Study of the Roman City and its Northern Surroundings," 2024 9th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE), Ruse, Bulgaria, 2024, pp. 1-7, doi: 10.1109/EEAE60309.2024.10600508.

International conferences

1. Plenary presentation at The 16th International Conference of OPROTEH, May 25-27, 2021, Bacău: **Petrut Liviu Bogdan**, Valentin Nedeff, Narcis Barsan, Mirela Panaintelehadus, Emilian Mosnegutu, Dana Chitimus , -*Applications of the GIS and remote sensing methods in the Land use and cover maps. case study: Roman city and the surroundings of the north side area*.

2. **Petruț-Liviu Bogdan**, Valentin Nedeff, Narcis Bârsan, Mirela Panainte-Lehăduș, Dana Chițimuș, Florin Nedeff, Claudia Tomozei, Robert Gazda- *Delineation of groundwater potential zones using geospatial techniques.Case study: Roman city and the surroundings of the Northern side area The 18th International Conference poster, OPROTEH 2023, Bacău, Romania.*

3. **Petrut-Liviu Bogdan**, Valentin Nedeff, Narcis Barsan, Mirela Panaintelehadus, Dana Chitimus, Florin Marian Nedeff, Diana Carmen Mirila, Emilian Mosnegutu, Claudia Tomozei -*Estimating groundwater level in Roman city and northern counties using geostatistical methods: ordinary kriging and semivariograms,* abstract ,OPROTEH 2025, Bacău, Romania.

4. **Petrut-Liviu Bogdan**, Valentin Nedeff, Narcis Barsan, Mirela Panainte-Lehadus, Dana Chitimus, Florin Marian Nedeff., Applications of the GIS and Remote Sensing methods in the Land use and cover maps. Case study: Roman city and the surroundings of the Northern side area, participare, 8th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE), Ruse, Bulgaria, 2022

5. **Petrut-Liviu Bogdan**, Valentin Nedeff, Mirela Panainte-Lehadus, Oana Irimia, Emilian Mosnegutu -Integrated Assessment of Groundwater Quality: A Case Study of the Roman City and its Northern Surroundings, participare, 9th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE), Ruse, Bulgaria, 2024.

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