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**MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES**
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# HIGH-RESOLUTION FACIES INTERPRETATION OF QUATERNARY SEDIMENTARY SERIES FOR HYDROGEOLOGICAL MODELLING OF THE NYÍRSÉG-HAJDÚSÁG GROUNDWATER BODY, NE HUNGARY.

Ph.D. BOOKLET

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# 1. INTRODUCTION

Modern hydrogeology revolves around the concept of gravity-driven groundwater systems and their three fundamental factors: basin geometry, basin geology, and the temporal changes in the water table (Tóth, 2009). These three factors converge to describe how groundwater flow transports various substances such as fluids, gases, solutes, colloids, particles, and heat from recharge areas to discharge sites. Therefore, from a hydrogeological perspective, the spatial distribution of geological heterogeneity has gained significant importance, as it is recognized as one of the three primary controlling factors in aquifer production (Buday et al., 2015), model calibration (Cooley, 2004), recharge estimation (McCord et al., 1997), and is also the primary factor influencing solute transport (Bianchi and Pedretti, 2017).

Additionally, defining an exact geological framework for a specific site may present challenges; however, creating a reasonable approximation using stratigraphic and sedimentological concepts is attainable. This approach facilitates the development of a comprehensive geological analysis that aligns with the objectives of groundwater investigations. In the context of geothermal or petroleum projects, the targeted depth range facilitates the concurrent evaluation of seismic and wireline log data. However, the situation differs when dealing with freshwater aquifers extending to depths of several hundred meters. Such depths prove too shallow for cost-effective seismic investigations and too deep for vertical geoelectric measurements (Kirsch, 2009). Consequently, wireline log correlations within this depth interval pose a challenge for additional 2D geophysical methods, which are essential for achieving the necessary horizontal resolution between wells.

This situation contributes to the underestimation of 3D regional hydrogeological models, leading to a greater reliance on 2D representations. These representations encompass not only the geometrical configuration of the rock framework but also hydrogeological data. This reliance on 2D representations persists despite the significant heterogeneity and anisotropy properties of rocks and sediments, which are the primary determinants of preferential flow paths and sources of uncertainty (Maliva, 2016).

Therefore, the current research presents a methodological approach that allows us to recognize the three-dimensional (3D) nature of the hydrogeological performance of the Southern Nyírség–Hajdúság Groundwater Body. This case study pertains to a complex aquifer system that has been exploited since 1830 due to its favorable specific yield capacity. Despite the abundance of wells, production data, hydrogeochemical information related to the study site, and previously published hydrogeological studies (Marton and Szanyi, 2000; Marton and Szanyi, 1997; Marton et al.,1980; Tóth and Almási, 2001), there is a conspicuous absence of a comprehensive 3D regional hydrogeological model with the necessary resolution to precisely define the spatial continuity of aquifer layers. This precision is crucial for effective and sustainable water protection and management, especially considering the current increase in water demands in the region.

The first attempt to create high-resolution log correlation at the location of Debrecen city was performed by Püspöki (2016a,b), leading to the hypothesis of the existence of an incised valley in the region. Afterward, an intensive database development campaign was launched at the S.A.R.A. to investigate whether the presumed incised valley could be identified within a palaeogeographical relevant context (Püspöki, 2018; Flores, 2019). This extended database facilitated the establishment of a high-resolution 3D model using a sophisticated modelling software package equipped with authentic geostatistical tools. This endeavor developed through collaboration between SARA and the Mikoviny Sámuel Doctoral School since 2019, aimed to evaluate the stratigraphic characteristics and facies distributions of the study area.

Considering the facts that the Southern Nyírség–Hajdúság Groundwater Body presents an ideal combination of geological complexity, data availability, and hydrogeological characteristics, the research at hand proposes a modelling workflow. The 3D geological model, developed using well-log correlation and geostatistical modelling, is comprehensively analyzed alongside the hydrodynamic and hydrogeochemical patterns derived from a densely spatially referenced hydrogeological dataset. This correlation between the geometry of the rock framework and the hydraulic system patterns of the aquifer yields a robust hypothesis of the aquifer system concept. This approach facilitates the transition from the conceptual model to 3D numerical modelling, where the generated insights into the distribution of geological heterogeneities are considered for the hydraulic characterization of the hydrostratigraphic units and the evaluation of numerical simulations in the calibration process.

The findings of this research hold significance for two main applications: (1) the description of porous aquifer systems with complex geological backgrounds and (2) water management planning, sustainable development, and contaminant transport modelling. Last but not least, it is crucial to emphasize the importance of understanding the regional-scale geometry for local modelling performance, particularly in the context of contaminant transport forecasting and water budget estimations.

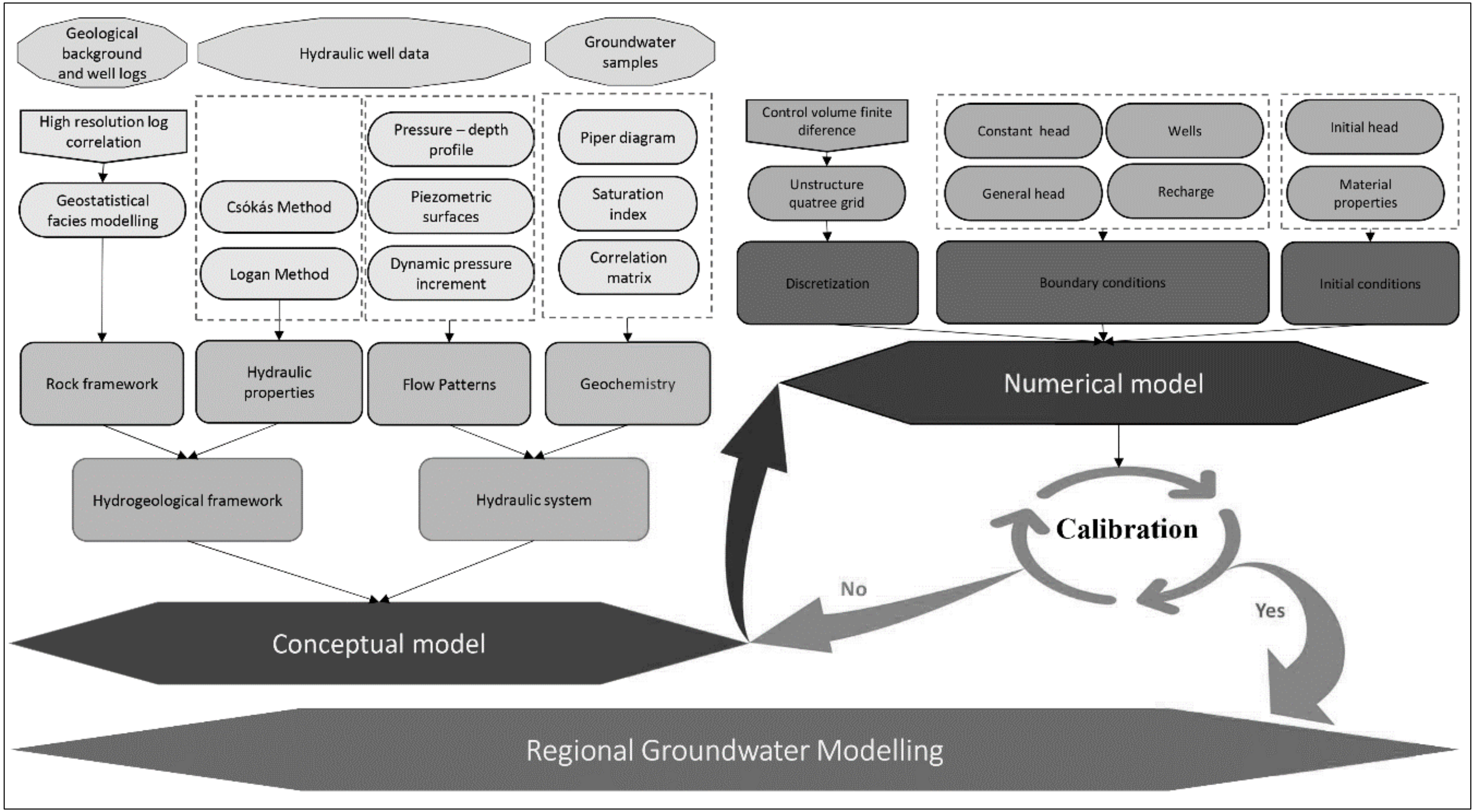


**Figure 1**. Implemented workflow for the regional groundwater modelling of the Nyírség-Hajdúság Groundwater Body.

## 2. APPLIED METHODS

The modelling process workflow encompasses two primary steps: (1) conceptualization and (2) numerical simulation, as shown in. This underscores the necessity of incorporating a variety of techniques into the process to explore the local and regional expressions of variability in the studied system properties, aligning with the objectives of the research.

The research was based on a multi-source database collected by various institutions between 1969 and 1975, encompassing a total of 512 production wells. Among these, 138 wells sourced from the National Geological and Geophysical Database of Wells (New Urbancsek Database) provided data on medium resistivity (R) (AM=40), self-potential (SP), natural gamma (GR), and geological log data for mapping the subsurface geology of the aquifer system. Only 22 wells have deep resistivity (AM=120) and mud resistivity data ($\rho_i$). A total of 367 wells contain datasets for calculating hydraulic parameters, including variables such as pumping rates (Q), drawdown (s), and screen section locations. Furthermore, 118 wells from the National Hydrogeochemical Database (NHD) were used to assess chemical characteristics and water types at the horizon depth of the major aquifer system.

### 2.1. Conceptual model

The initial phase of conceptualizing the aquifer involves establishing the geological framework. At this stage, high-resolution log correlation for stratigraphic discretization requires assumptions about the uniformity of the facies associations to explore the system's heterogeneity. Then, geostatistical methods such as object-based simulation or sequential indicator simulation will be utilized for mapping the 3D distribution of facies.

#### 2.1.1. Rock Framework

The 3D rock framework is developed in two steps: (1) conceptualization applying sequence stratigraphy, and (2) geostatistical simulation using Sequential Indicator Simulation and Object base Simulation. Sequence stratigraphy concepts (Cateneanu, 2022). Systematic log correlation is employed to identify stratigraphic bounding surfaces and define facies within the stratigraphic units, utilizing cross-sections that equidistantly display normalized spontaneous potential (SP) or/and gamma-ray (GR) on the left track and medium electric resistivity (AM=40) on the right track. The space between the logs is filled with lithology observed in cuttings during drilling. The criteria for identification of the stratigraphic key surfaces and the correspondent facies are log values, log shape, stacking patterns, vertical dimensions, and lithological descriptions, as illustrated in **Figure 1**.

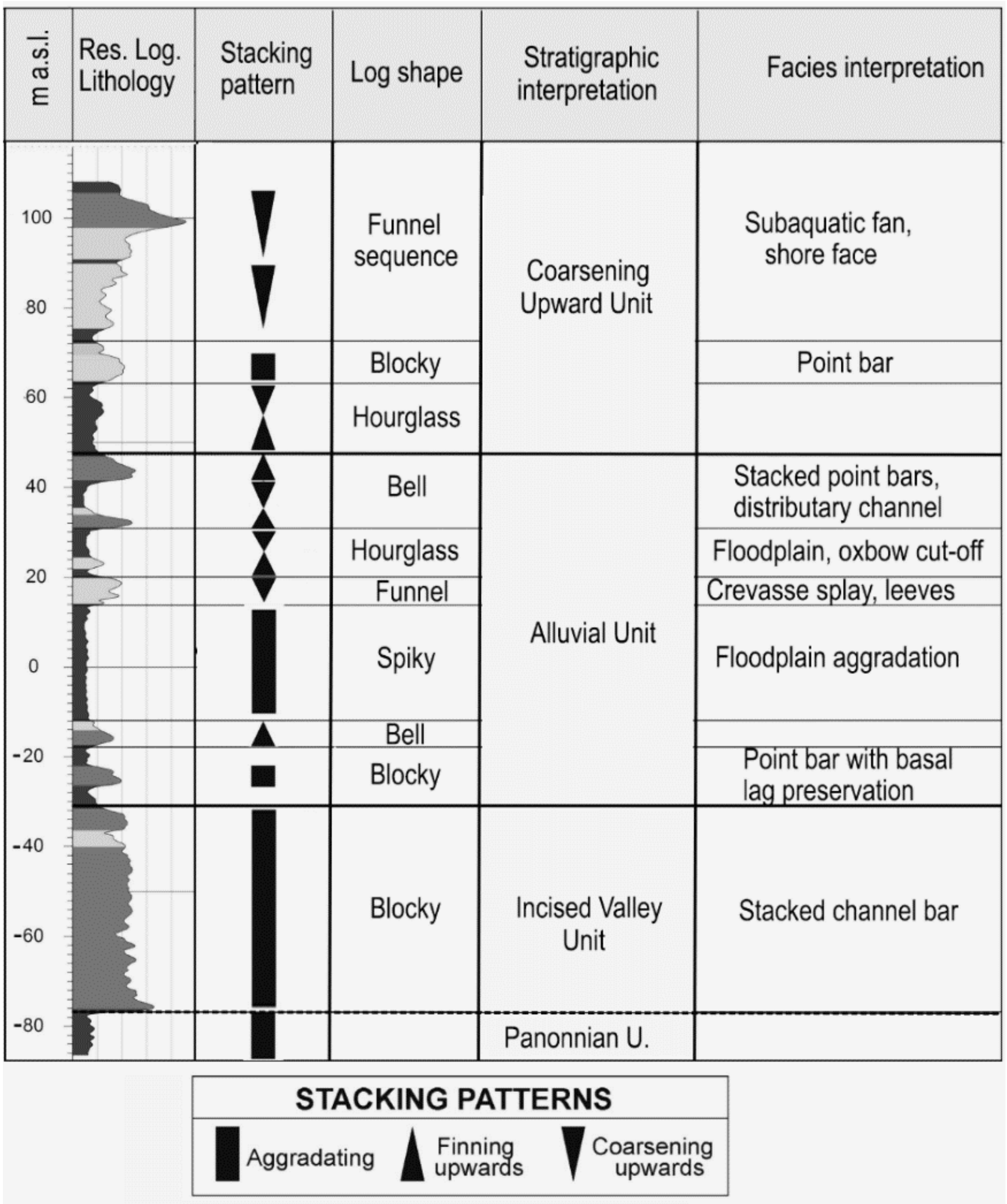


**Figure 1.** Resistivity log facies analysis observed in well data from the study area. The shape, scale, and stacking patterns log analysis (Cateneanu, 2022).

Furthermore, the geostatistical modelling workflow begins with the grid structuring to discretize the model domain. The stratigraphic surfaces serve as both: structure, and bounding surfaces. These surfaces define the domain of interest for modelling, enabling the pooling and application of statistics, as they represent the outer constraints of the interest volume (specific stratigraphic units). The layering of the volume domain involves identifying distinct regions, often representing facies, uniformly distributed within the stratigraphic unit. This step divides the domain into sections associated with a subset of the data, involving the upscaling of logs and defining boundaries.

The trend model construction focuses on modelling the locally varying direction of continuity and the locally variable mean or categorical proportion of the statistical inputs across all locations within the volume of interest. Once the framework, regions, trends, and variable integration have been defined, geostatistical algorithms can be applied to estimate and simulate the spatial distribution within the framework. This research utilizes two available algorithms: sequential indicator simulation and object-based stochastic simulation.

The sequential indicator method is a variogram-based approach that assesses the probability of transitioning from the current category to any other category, without considering order relationships. This method is rooted in the concept of Gaussian Simulation and extended to the Indicator-based model of uncertainty (Pyrcz and Deutsch, 2014). The SIS method (Deutsch and Journel, 1998) is employed in geological settings characterized by undefined geometries and high variability, particularly when anisotropy and variograms play a significant role, like in the case of the Coarsening Upward Unit and the Pannonian Unit.

The object-based modelling method (Deutsch and Wang, 1996) is designed to represent the idealized geometry of facies and is commonly used in fluvial reservoir modelling. In this method, parameterized architectural geometries are sequentially placed into the model domain until global proportions and data conditioning criteria are met (Deutsch and Tran, 2002). The method relies on two primary considerations: geometric parameterization, which characterizes geological heterogeneity in the model domain, and the placement of background facies during model initialization. The visual appeal of the results is attributed to their application in replicating idealized architectural element geometries. These geometries are constructed through high-resolution log correlation and trend models.

### 2.1.2. Hydraulic properties

A preliminary estimation of the horizontal hydraulic conductivity can be achieved by application of Logan (1964) method in unconfined and confined aquifers using **Equation 1** and **Equation 2**, respectively:

$$k_h = 2.43 \frac{Q}{s\,(2m-s)}, \quad (1)$$

$$k_h = 1.22 \frac{Q}{s.m}, \quad (2)$$

where $Q$ is the pumping rate, $s$ is the reported drawdown, and $m$ is the aquifer thickness.

For vertical continuous estimation of the horizontal hydraulic conductivity, the inversion-based Csókás (1995) method can be applied for boreholes where available self-potential (SP), natural gamma (NG), medium (AM=40) resistivity, long (AM=120) resistivity logs, as well as the resistivity of the drilling mud ($\rho_i$) is known. The estimation is done by applying the **Equation 3:**

$$k = C_k \frac{\varphi^3}{(1-\varphi)^4} \frac{\left(\log\frac{R_0}{R_w}\right)^2}{\left(\frac{R_0}{R_w}\right)^{1.2}}, \quad (3)$$

where $\varphi$ is the porosity, $R_0$ is the resistivity of the rock, and $R_w$ is the resistivity of the formation water. $C_k$ is the proportional constant, calculated as follows:

$$C_k = 855.7 C_t {C_d}^2, \quad (4)$$

where $C_t$ is a constant that varies according to the formation temperature ($T$) as $1 + 3.37 * 10^{-2}T + 2.21 * 10^{-4}T^2$, and $C_d$ is the site constant proposed to be $5.22 * 10^{-4}$ for medium well-sorted sediments with a formation factor ($F$) less than 10. The formation factor is derived from **Equation 5:**

$$F = \frac{R_0}{R_w} \quad (5)$$

2.1.3. Flow patterns

Three are the hydrodynamic parameters that characterize groundwater flow in a basinal environment (Tóth, 2009): Hydraulic head ($h$); regional patterns of pore pressure ($p$); and vertical pressure gradient ($\gamma$). Based on the statement of Darcy's principle (Darcy 1856) which asserts that groundwater always flows from areas of high potential energy to areas of low potential energy in the direction of declining hydraulic head ($h$), the hydraulic head values measured in the aquifer system are interpolated to create the piezometric surface of each hydrostratigraphic unit (HU) allowing analysis of the flow pattern within each HU.

Hubbert (1940) validated Darcy's hypothesis by demonstrating the physical nature of the hydraulic head and its relation with the fluid's mechanical energy, under the assumption that groundwater flow velocities are negligibly low ($v \approx 0$), and the fluid is slightly compressible ($\rho \approx constant$), the expression of the fluid potential can be simplified to:

$$\theta = gz + \frac{p - p_0}{\rho} \quad (6)$$

The pressure ($p$) in a point ($P$), at the base of the manometers is:

$$p = \rho g \varphi + p_0\,, \quad (7)$$

where $\varphi$ is the height of the water column above $P$, and $p_0$ is the atmospheric pressure on the fluid's surface in the manometer. Considering:

$$\varphi = h - z \,, \qquad (8)$$

where $h$ is the hydraulic head and $z$ is the elevation head at the given observation point $P$ in meters. Then, a pressure-depth ($p(d)$) can assist in the analysis of the regional pore pressure increments and their gradients (Tóth 2009). It is constructed in a cartesian coordinate system, wherein the vertical axis represents depth below the land surface, and its origin is at $d = 0$. The horizontal axis represents pore pressures ($p$) calculated for each point using **Equation 7**. And, the elevation of the water table below the land surface is denoted with $d_0$. The utilization of a pressure-depth profile ($p(d)$) instead of a pressure-elevation profile ($p(z)$) allows for the application of a unified hydrostratigraphic reference line for all measurement points, irrespective of their differences in elevation (z) location.

The vertical pressure gradient ($\gamma$) is an expression of the direction and intensity of the vertical flow (Tóth, 2009). It is illustrated by the variation of the pressure in two surface points at different depths. For static fluids, the pore pressure increases with depth at a rate equal to the specific weight of the fluid (nominal pore pressure). However, for fluids in motion, the vertical component of flow causes it to increase according to:

$$\gamma = \frac{\mathrm{d}p}{\mathrm{d}d} \qquad (9)$$

The dynamic pressure increment ($\Delta p$) is defined as the difference between nominal and dynamic pressure. It is an indicator of the vertical flow direction from the water table. A positive increment (+$\Delta p$) suggests an upward flow, whereas a negative increment ($-\Delta p$) suggests a downward flow. For the calculation of the dynamic pressure increment, the following equation is used:

$$\Delta p = \gamma_{st}.\Delta h = p_{dyn} - p_{st} \,, \qquad (10)$$

where $\gamma_{st}$ is the gradient of the static fluid, $\Delta h$ is the difference between the heads representing the static and flowing conditions. The static pressure term ($p_{st}$) can be calculated regardless the actual condition is static or dynamic. It is a calculated value of hypothetical static pressure also known as nominal hydrostratigraphic pressure, calculated by:

$$p_{st} = \rho g \varphi_{st} = \gamma_{st}(d - d_0), \qquad (11)$$

while the dynamic pressure term ($p_{dyn}$) is determined by the measured pressure in the point P or water level in an open well.

### 2.1.4. Geochemistry

The analytical accuracy of the measurements of cations and anions in the water samples within a limit of ±5% is obtained from the ionic balance error (IBE) (Sasamoto et al., 2004).

$$\mathrm{IBE} = [(\mathrm{TC} - \mathrm{TA})/(\mathrm{TC} + \mathrm{TA})] \times 100\ , \qquad \textbf{(12)}$$

where TC is the sum of the total cations and TA is the sum of the total anions

Piper plot (Piper, 1944) is used for the definition of the hydrogeochemical facies, and the ratio of major ions was investigated to approximate the water-rock interaction processes, including mineral weathering and ion exchange. The $Ca^{2+}$+$Mg^{2+}$/$HCO^{3-}$ +$SO_4{}^{2-}$ ratio was calculated in mEq/L. Values smaller than 1 refer to silicate weathering or ion exchange **(Equation 13)**; meanwhile, values greater than 1 indicate carbonate weathering or reverse ion exchange **(Equation 14)** (Rajmohan and Elango, 2004).

$$\mathrm{Ca^{2+}} + 2\mathrm{NaX} \rightarrow 2\mathrm{Na^{+}} + \mathrm{CaX_2} \qquad \textbf{(13)}$$

$$2\mathrm{Na^{+}} + 2\mathrm{CaX_2} \rightarrow \mathrm{Ca^{2+}} + 2\mathrm{NaX} \qquad \textbf{(14)}$$

Furthermore, the mineral saturation in the groundwater of the aquifer system is determined by calculating the Saturation Index (SI) (Appelo and Postma, 2005) for calcite, dolomite, aragonite, gypsum, and halite using PHREEQC according to **Equation 15**:

$$\mathrm{SI} = \log \frac{\mathrm{IAP}}{\mathrm{K_{sp}}} \qquad \textbf{(15)}$$

where, IAP refers to the ion activity product, and $K_{sp}$ is the solubility product at a given temperature. If the value of the saturation index equals zero, the water is in a chemical equilibrium state with the mineral. A positive value of SI indicates that the groundwater is oversaturated, while a negative value refers to it being undersaturated concerning the mineral species. Finally, the two-dimensional relationships between the physicochemical parameters can be analyzed by Spearman's correlation matrix.

## 2.2. Numerical model

The numerical simulation takes place to iteratively solve the governing flow equation to assess the hydraulic head distribution for the discretized geometry under the established initial and boundary conditions. Then, the calibration process is carried out to minimize the difference between the calculated and observed hydraulic head distribution.

### 2.2.1. Discretization

To address complex geometric aquifers, a code that supports Unstructured Grids (USG) is selected with the primary goal of achieving a more accurate representation of the aquifer's geometry. MODFLOW-USG is one such version that utilizes Control-Volume Finite-Difference (CVFD) Approximation (Panday et al., 2013). The design of the horizontal nodal spacing must align with the modelling objectives, maintaining a balance between reasonable runtimes and ease of data management and visualization of results. The primary constraint in the decision-making process is the size of the problem domain. It is also crucial to consider factors such as solution accuracy, the location of calibration targets, configuration of perimeter boundaries, heterogeneity of parameters, faults, conduits, barriers, and sources and sinks (Anderson et al., 2015). The required number of layers in the model domain is selected to represent the vertical variability in hydrostratigraphy and/or simulation of vertical changes in hydraulic heads. Usually, one layer is equivalent to a hydrostratigraphic unit, although more than one layer can be assigned to a single unit to capture changes in hydraulic properties or the hydraulic system within the unit.

### 2.2.2. Boundary conditions

The boundary conditions define the mathematical constraints in the solution of the flow equation but also serve as sources and sinks of water within the system (Anderson et al., 2015). There are three primary mathematical approaches:

*Specified head (Dirichlet conditions):* In this approach, a specific value of hydraulic head is assigned at the boundary location. In Modflow, various packages can be applied to set up specified head conditions, including IBOUND, and Time-Variant Specified Head, as described in the online manual.

*Specified flux (Neumann conditions):* In this case, the derivative of the head at the boundary is specified. The specified flux condition can be introduced in Modflow through the Flow and Head Boundary, Recharge, as well as the Well package, as detailed in the online manual.

*Head-dependent flux boundaries (Cauchy or mixed condition):* The flow across the boundary is calculated using Darcy's law, which employs a gradient determined as the difference between a specified head outside the boundary and the head computed by the model at the node located on or near the boundary. In Modflow, the options available for designating this category include General-Head Boundary, Drain, Drain-Return, River, Evapotranspiration, Stream, Lake, Multi-Node Drawdown Limited Well, and Multi-Node Well packages.

### 2.2.3. Initial conditions

Initial conditions are related to the setup of the starting head of the flow domain and the first estimation of the material properties. Hydraulic conductivity ($k$) is often assumed to be constant within a given layer. However, geological materials. While the assumption of isotropic horizontal conductivity ($k_h$) can be considered correct in many scenarios ($k_x = k_y$), the presence of fractures, sedimentary structures, or other geological features within the aquifer may introduce significant anisotropy that must be carefully considered ($k_x/k_y$) leading to preferential directions of the flow paths (Maliva, 2016).

Vertical anisotropy, represented by the ratio between horizontal and vertical hydraulic conductivity ($k_x/k_v$), prevails in many groundwater scenarios, attributed to stratigraphic features, fractures, and heterogeneity within a model layer, resulting in a preferential horizontal flow direction. Although vertical anisotropy can be measured through specialized tests these tests are rarely performed in practice. Consequently, vertical anisotropy is typically estimated during the calibration process. Regarding the effective porosity, even though it does not feature in the governing equation of groundwater flow, its significance becomes apparent in particle tracking applications, where it plays a crucial role in velocity calculations.

### 2.2.4. Calibration

Calibration targets, usually heads and fluxes, are used for comparison with the simulated equivalent values computed in the model domain in the post-processing of the model results. The parameters are adjusted within reasonable ranges in sequential forward runs of the model until it produces an acceptable match.

## 3. NEW SCIENTIFIC RESULTS

Following the established workflow for the application of the above-exposed methods on the constructed database of the Southern Nyírség-Hajdúság Groundwater Body, I was able to achieve the next new scientific results:

**Thesis 1. 3D stratigraphic units' definition**

I constructed the 3D geological interpretation of the Southern Nyírség-Hajdúság Groundwater Body by applying high-resolution log correlation. I identified three bounding surfaces within the top 285 meters depth of the sedimentary record in the region. With the developed 3D geological model, I defined the spatial continuity of the stratigraphic units within the study area. Also, I was enabled to identify an incised valley deposited in stratigraphic discordance on Pannonian sediments, subsequently buried by an alluvial sequence and a fluvial-lacustrine sequence, verifying the hypothesis of Püspöki (2016a, b).

**Thesis 2. Correlation between geological framework and hydrodynamic patterns**

In the absence of 2D geophysical data in the region, I supplemented log correlation at the studied depth with hydrogeological and hydrogeochemical data as independent sources to validate stratigraphic contacts and delineate the hydrostratigraphic units of the aquifer system. I assessed the horizontal uncertainty between logs by examining patterns observed on piezometric surfaces, pressure conditions, and geochemical characteristics, which serve as expressions of the geometric distribution of the geological framework. Through the estimation of horizontal hydraulic conductivity of the sand bodies using the Logan Method, I was able to identify coarser grain sizes for the Incised Valley Unit compared to the surrounding units. The spatial distribution of the estimated hydraulic conductivity aligns with the proposed geometry of the paleo-valley, with a noticeable change in values occurring at the boundary of the defined stratigraphic unit.

From the analysis of the hydrodynamic conditions, I discerned the hydraulic connectivity of the layers through hydraulic windows occurring in areas with high water extraction rates. This resulted in the development of a semi-confined hydraulic behavior within the aquifer system. Additionally, I was able to corroborate the gravity-driven flow regime mentioned previously by other researchers. I observed two main disturbances in the regional flow direction: (1) An elongated perturbation observed along the same strike direction as the paleo-valley, attributed to the higher hydraulic conductivity pathway within the Incised Valley Unit. (2) Another perturbation attributed to hydraulic windows connecting the IVU-AU vertically, and IVU-LMU horizontally. The presented fact leads to a depression in the dynamic pressure increment and hydraulic head at the center of the study area, specifically at the Debrecen Waterworks Sites.

Furthermore, I recognized the dominance of a downward flow direction and under-hydrostatic pressure conditions ($\gamma_{st} < \gamma_{dyn}$) in the system. I established that the Incised Valley Units exhibited the highest depression, with a hydrostatic gradient ($\gamma_{dyn}$) of 6.06 kPa/m, compared to the surrounding units where the pressure gradient ($\gamma_{dyn}$) exhibited values of 9.74 kPa/m for the CUU, 8.37 kPa/m for the AU, and 7.43 kPa/m for the LMU.

Finally, from the geochemical analysis, I recognized that the primary aquifer is distinguished by a Ca-Mg-$HCO_3$ water type, whereas the lateral surrounding aquifer exhibits Na-$HCO_3$ water type. Furthermore, the saturation index values indicated a transition from under-saturated to supersaturated states for calcite and dolomite minerals along the spatial extent of the Incised Valley Unit (IVU). These findings align with the observation that the heterogeneity introduced by the primary aquifer significantly influences the flow pattern, resulting in higher flow velocities within the IVU.

**Thesis 3. 3D facies modelling**

I developed a facies model for the stratigraphic units to characterize the complexity and geological heterogeneity within them. Utilizing the density of available well-log information, I applied object-based simulation to stochastically model the 3D spatial distribution of depositional elements for the Alluvial Unit and Incised Valley Unit facies. Simultaneously, I employed sequential indicator simulation to describe the spatial distribution of lithofacies within the Coarsening Upward Unit and Pannonian Unit.

The modeled internal grain size variability within these units, represented by facies helps me to estimate that: (1) The Pannonian Unit is constituted by 42.33% sand and 57.67% silt. (2) The Incised Valley Unit primarily consisted of coarse grain size with 98.4% of channel belt facies proportions and a lower 1.6% of fine grain sediments of floodplain facies. In contrast, the Alluvial Unit four facies proportions are estimated as follows: a primary channel belt (16.67%), three secondary channels (21.80%), an avulsion cycle (13.92%), and floodplain deposits (47.04%). Finally, (4) the Coarsening-Upward Sequences, represented by three lithologic facies, are comprised of sand (42.6%), silt (6.25%), and clay (51.15%).

Using the 3D facies model, I assessed the volume of each facies and subsequently calculated the apparent hydraulic conductivity for the four aquifer layers. Hydraulic conductivity values were determined as a continuous log using the Csókás method for 19 selected boreholes, as reported in the research conducted by Mohammed et al. (2024.

**Thesis 4. 3D regional numerical modelling**

I performed a numerical simulation of the created conceptual model of Southern Nyírség-Hajdúság Groundwater Body to prove the hydraulic behavior of the geological framework. I have addressed an acceptable calibration of the model implementing layer zoning for the distribution of horizontal hydraulic conductivity. The zonation is done according to the facies model insights. This decision was driven by the constraint that the model could not achieve a higher level of vertical discretization for the layers, primarily due to limitations within the modelling code, particularly concerning cell saturation and the wide-to-depth ratio of the model. I reported a water budget for the calibrated model domain at a regional water scale calculated as follows: a total of 128058.2 $m^3$/d originated from effective infiltration of precipitation, 36582.98 $m^3$ entered from the specified head boundary sides, 24769.3 $m^3$/d exited the system through the specified head boundaries, while 103402.2 $m^3$/d were discharged through production wells, and 36480.67 $m^3$/d are outflow from the rivers and streams. The comparison between the calculated hydraulic head in the simulation and observed values of it. The residual heads vary between 20 m and -15 m.

**Practical applicability**

In this study, the newly acquired scientific results offer profound insights into the regional-scale hydrogeological interpretation of the Southern Nyírség-Hajdúság Groundwater Body. By delivering a comprehensive three-dimensional geological description of one of Hungary's most critical aquifer systems, this research effectively addresses a notable gap in our understanding.

The significance of this aquifer system has been underscored by continuous research efforts aimed at various water utilization purposes, thereby amplifying the relevance and substance of the findings presented here. The meticulously tested and calibrated aquifer system geometry, based on hydrogeological data spanning from 1969 to 1971, holds immense potential for updating hydraulic conditions and formulating new scale exploration models ranging from local to regional scales. These findings are poised to drive progress in sustainable groundwater management practices within the region, particularly amidst escalating water demands from local communities, agricultural activities, and industrial sectors. The reported results constitute invaluable contributions to informed decision-making and the formulation of efficient strategies aimed at ensuring the long-term accessibility and optimal utilization of groundwater resources in the area.

Furthermore, the methodology employed in this research has introduced a practical approach that capitalizes on the strong correlation between geological geometry and hydrogeological patterns. This methodology facilitates the construction of a reliable conceptualization of porous media aquifer systems, especially in scenarios where 2D geological information collection is hindered by geological conditions such as depth, compaction, heterogeneity, and horizontal extension. Moreover, this approach has demonstrated its efficacy in conducting hydrogeological modeling, thereby ensuring a comprehensive understanding of the three-dimensional nature of aquifer characteristics.

Overall, the findings and methodology presented in this research offer tangible practical applicability, guiding future endeavors in groundwater management and resource utilization while advancing our understanding of complex hydrogeological systems.

## 4. AUTHOR INDIVIDUAL INVESTIGATION WORK

### Journal papers

Camacho, C.O., Zabala, N.V., and Flores, Y.G. (2020) "Estimación del coeficiente de permeabilidad del suelo en la ciudad de Macas -Ecuador utilizando permeómetro de carga variable". *Dominio de Las Ciencias* 6(3): 78–94.

Flores, Y., Camacho, C., Miklós, R. and Szűcs, P. (2020) "Comparision of the general hydrogeological conditions of the Karst Water Bodies of Hungary and Ecuador". *Geosciences and Engineering: A Publication of the University of Miskolc* 8(13): 131–153.

Ilyés, C., Wendo, V.A.J.A., Carpio, Y.F. and Szűcs, P. (2021) "Differences and similarities between precipitation patterns of different climates". *Acta Geodaetica et Geophysica* 56(4): 781–800. Doi: 10.1007/s40328-021-00360-6.

Gómez, F., Flores, Y. and Vadászi, M. (2022) "Comparative analysis of the K-Nearest-Neighbour Method and K-Means cluster analysis for lithological interpretation of well logs of the Shushufindi Oilfield, Ecuador". *Rudarsko-Geološko-Naftni Zbornik* 37(4). Doi: 10.17794/rgn.2022.4.13

Flores, Y.G., Eid, M.H., Szűcs, P., Szőcs, T., Fancsik, T., Szanyi, J., Kovács, B., et al. (2023) "Integration of Geological, Geochemical Modelling and Hydrodynamic Condition for Understanding the Geometry and Flow Pattern of the Aquifer System, Southern Nyírség–Hajdúság, Hungary". *Water* 15(16): 2888. Doi: 10.3390/w15162888.

Mohammed, MusaabA.A., Szabó, N.P., Flores, Y.G. and Szűcs, P. (2024) "Multi-well clustering and inverse modelling-based approaches for exploring geometry, petrophysical, and hydrogeological parameters of the Quaternary aquifer system around Debrecen area, Hungary.". *Groundwater for Sustainable Development* 24:101086. Doi: 10.1016/j.gsd.2024.101086.

### International conference proceedings

Flores, Y., Püspöki, Z. and Szűcs, P. (2022) "Hydrogeologic modelling of Hajdúszoboszló Aquifer System to demonstrate the importance of geological heterogeneity spatial distribution over the flow paths", *International Doctoral Seminar 2022.* Trnava: AlumniPress.

Flores, Y., and Szücs P. (2022). Cartographic delineation of Karst Bodies in the Ecuadorian Amazon Region. *Conference: Štiavnické Bane*, Slovakia 2022.08.25. - 2022.08.27. Košice, Kassa: Institute of Geosciences, Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical university of Košice, 7 p.

**Conferences presentations**

Flores Y.; Szűcs P. (2019) Geological heterogeneity and anisotropy: A scale problem in hydrogeologic modelling. *Doktoranduszok Fóruma 2019*. Miskolc, Miskolci Egyetem.

Flores Y.; Szűcs P. (2001) Stratigraphic sequence of the Old Tisza Valley incision. Hajdú-Bihar county, Hungary. *Doktoranduszok Fóruma 2021*. Miskolc, Miskolci Egyetem.

Flores Y.; Szűcs P.; Puspoki Z. (2022) Conceptual model redefinition of Southern Nyírseg - Hajduság Shallow Groundwater Aquifer System applying log-correlation for stratigraphic interpretation. *Youth Performers Day 2022*. EAGE Student Chapter, University of Miskolc.

Flores Y.; Szűcs P; Puspoki Z. (2022) Hydrogeologic modelling of Hajdúszoboszló Aquifer System to demonstrate the importance of geological heterogeneity spatial distribution over the flow paths. Szomolány vára, Slovakia 2022.04.27. - 2022.04.27. Trnava: *International Doctoral Semina*r Language: English | ISBN: 9788080962920

## 5. REFERENCES IN THE BOOKLET


Anderson, M.P., Woessner, W.W. and Hunt, R.J. (2015) *Applied Groundwater Modelling. Simulation of Flow and Advective Transport*. 2th Edition. London: Academic Press. DOI: 10.1016/c2009-0-21563-7.

Appelo, C.A.J. and Postma, D. (2005) *Geochemistry, groundwater and pollution*. 2th Edition. London: CRC Press. DOI: 10.1016/0016-7037(94)90585-1.

Bianchi, M. and Pedretti, D. (2017) Geological entropy and solute transport in heterogeneous porous media. *Water Resources Research* 53(6): 4691–4708. DOI: 10.1002/2016WR020195.

Buday, T. et al. (2015) Sustainability aspects of thermal water production in the region of Hajdúszoboszló-Debrecen, Hungary. *Environmental Earth Sciences* 74(12): 7511–7521. DOI:10.1007/s12665-014-3983-1.

Cateneanu, O. (2022) *Principles of sequence stratigraphy*. Second Edition. Radarweg: Elservier. ISBN: 9780444533531.

Cooley, R.L. (2004) A theory for modelling ground-water flow in heterogeneous media. U.S.G.S, Reston, Virginia. DOI: 10.3133/pp1679.

Csókás, J. (1995) Determination of yield and water quality of aquifers based on geophysical well logs. *Magyar Geofizika* 35(4): 176–203.

Darcy, H. (1856) *Les fontaines publiques de la ville de Dijon*. Edited by V. Dalmont. Paris: Libraire des Corp Impériaux des ponts et chussées et des Mines.

Deutsch, C. V. and Journel, A.G. (1998) *GSLIB: geostatistical software library and user's guide*. 2th Edition. Edited by A.G. Journel. Oxford University Press.

Deutsch, C. V. and Tran, T.T. (2002) FLUVSIM: A program for object-based stochastic modelling of fluvial depositional systems. *Computers & Geosciences* 28(4): 525–535. DOI:10.1016/S0098-3004(01)00075-9.

Deutsch, C. V and Wang, L. (1996) Hierarchical Object-Based Stochastic Modelling of Fluvial Reservoirs. *Mathematicul Geology* 28(7): 857-800. DOI: 10.1007/BF02066005.

Flores, Y. G. (2019) Complex analysis of hydrogeological behaviour of Hajduszoboszlo aquifer to demonstrate the advantage of fluvial facies interpretation. MSc Thesis. University of Miskolc. Miskolc.

Hubbert, M.K. (1940) The Theory of Ground-Water Motion. *The Journal of Geology* 48(8,1): 785–944. DOI: 10.1086/624930.

Kirsch, R. (2009) *Groundwater Geophysics. A tool for hydrogeology*. 2th Edition. Berlin: Springer-Verlag. DOI: 10.1007/978-3-540-88405-7.

Logan, J. (1964) Estimating Transmissibility from routine production tests of water wells. *Groundwater* 2(1): 35–37. DOI: 10.1111/j.1745-6584.1964.tb01744.x.

Maliva, R.G. (2016) *Aquifer Characterization Techniques Schlumberger Methods in Water Resources Evaluation Series No. 4*, Springer International Publishing. DOI: 10.1007/978-3-319-32137-0.

Marton, L., Erdélyszky, Z. and Vinzenz, R. (1980) A környezeti izotópok vizsgálata Debrecen és a Nyírség rétegvizeiben. *Hidrológiai Közlöny* 2: 85–94.

Marton, L. and Szanyi, J. (1997) Kelet-magyarországi pleisztocén üledékek geostatisztikai vizsgálata. 1. A transzmisszivitás térképezése. *Hidológiai Közlöny* 77(5): 233–248.

Marton, L. and Szanyi, J. (2000) A talajvíztükör helyzete és a rétegvíz termelés kapcsolata Debrecen térségében'. *Hidrológiai Közlöny* 80(1): 3–13.

McCord, J.T., Gotway, C.A. and Conrad, S.H. (1997) Impact of geologic heterogeneity on recharge estimation using environmental tracers: Numerical modelling investigation. *Water Resources Research* 33(6): 1229–1240. DOI: 10.1029/96WR03755.

Panday, S. et al. (2013) MODFLOW – USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation. USGS, Reston, Virginia. DOI: 10.3133/tm6A45

Piper, A.M. (1944) A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union* 25: 914–928. DOI: 10.1029/TR025i006p00914.

Püspöki Z. (ed) (2016a) *A Debrecen I – II vízmű telepek és környezetének szekvenciasztratigráfiai feldolgozása* (Report on sequence stratigraphic investigation in the sourroundings of I – II well fields of Debrecen). Budapest, SARA data store.

Püspöki Z. (ed) (2016b) *A debreceni TEVA telephely rétegsorának értelmezése az I – II vízmű telepek és környezetük szekvenciasztratigráfiai modelljében* (Interpretation of the TEVA site in the sequence stratigraphic model performed for the sourroundings of I – II well fields of Debrecen). Budapest, SARA data store.

Püspöki Z. ed (2018) *Nagy felbontású fácies korrelációs vizsgálat Debrecen-Dél területen* (High resolution log correlations at Debrecen-South region). Budapest, SARA data store.

Pyrcz, M.J. and Deutsch, C. V. (2014) *Geostatistical Reservoir Modelling*. 2th Edition. Oxford University Press.

Rajmohan, N. and Elango, L. (2004) Identification and evolution of hydrogeochemical processes in the groundwater environment in an area of the Palar and Cheyyar River Basins, Southern India. *Environmental Geology* 46: 47–61. DOI: 10.1007/s00254-004-1012-5.

Sasamoto, H., Yui, M. and Arthur, R.C. (2004) Hydrochemical characteristics and groundwater evolution modelling in sedimentary rocks of the Tono mine, Japan. *Physics and Chemistry of the Earth* 29(1): 43–54. DOI: 10.1016/j.pce.2003.11.003.

Tóth, J. (2009) *Gravitational Systems of Groundwater Flow. Theory, evaluation, utilization*. New York: Cambridge University Press. DOI: 10.1017/CBO9780511576546.

Tóth, J. and Almási, I. (2001) Interpretation of observed fluid potential patterns in a deep sedimentary basin under tectonic compression: Hungarian Great Plain, Pannonian Basin. *Geofluids* 1: 11–36. DOI: 10.1046/j.1468-8123.2001.11004.x.