

Advanced Hydrogeological Modelling Tools for Metro - Groundwater Interaction Studies

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Abstract: Groundwater represents one of the most important resources for water supply, industrial production, and ecosystem preservation, which is why its sustainable use and protection from pollution are of paramount importance. Modern challenges such as rapid urbanization, climate change, and increasingly stringent legal regulations demand precise hydrodynamic analyses of groundwater flow regimes that often exceed the capabilities of traditional methodologies. In this context, the development and application of specialized software tools and platforms represent a key step forward in the modernization of the hydrogeological profession.

This paper presents experiences in the development and application of software systems designed for the preparation, analysis, and interpretation of hydrogeological data; execution of a large number of parallel numerical simulations, including simulation of the tunnel lining within the schematized layers of the mathematical model; automatic generation of results and reports; and data archiving. The importance of these tools is emphasized in the analysis of complex hydrogeological systems, particularly in the context of hydrodynamic modelling of spatially heterogeneous aquifers and the simulation of various exploitation or contamination scenarios.

The presented software tools enable high operational efficiency, reduce the risk of human error, and significantly shorten the time required for the preparation of technical studies, factors that are particularly important in decision-making and water resource management planning as it is illustrated on the example of the Belgrade Metro project. Process automation and the ability to conduct scenario-based analyses contribute to improved risk assessment, optimization, and timely response in emergency situations. In addition to technical advantages, the tools also offer centralized data management and support for collaborative work among multiple experts on the same project, thereby enhancing the quality and transparency of professional practice.

The application of modern software platforms in the field of hydrodynamic groundwater flow analysis represents an indispensable tool for achieving sustainable management of this valuable resource, as well as for further advancement of professional practice and scientific research in this domain.

Keywords: groundwater; hydrodynamic analysis; collaborative platform

1. Introduction

Groundwater is one of the most important natural resources, both in terms of providing drinking water and in the context of industrial, agricultural, and ecological sustainability. Managing this resource is becoming increasingly complex due to rising water consumption, climate change, urbanization, and industrial development - all of which affect the quantity and quality of groundwater (Foster et al., 2008; Howard, 2007). In this context, accurate hydrodynamic analysis of groundwater flow is essential for effective exploitation planning, aquifer protection from contamination, and the preparation of technical studies and environmental impact assessments (Bear, J., 1979; Domenico and Schwartz, 1998).

Traditional methods of hydrogeological analysis, while still valuable for certain aspects, are often insufficient to meet the demands of modern practice, which involve processing large volumes of data,

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modelling complex geological structures, and performing numerous computational variants for various exploitation or contamination scenarios (Anderson et al., 2015; Zheng and Bennett, 2021). Under such circumstances, the development of software tools and platforms for hydrodynamic modelling represents one of the most significant advances in the modernization of hydrogeological practice. These tools enable process automation, enhance the accuracy of analyses, and significantly reduce the time required to carry out complex calculations.

Software tools developed for this purpose encompass a wide range of functionalities, starting from the preparation, analysis, and interpretation of input data, through the execution of numerical simulations of groundwater flow, to the visualization of results, report generation, and data archiving. A key feature is the ability to perform a large number of calculations in parallel, which enables experts to quickly evaluate various scenario alternatives whether related to planning extraction activities, assessing the impact of infrastructure projects on groundwater regimes, or analysing remediation measures in cases of contamination.

The implementation of such tools significantly contributes to reducing the risk of human error, standardizing procedures, and increasing transparency, thereby enhancing the confidence of investors, regulatory authorities, and the broader professional community in the results of the analyses. In addition, modern software systems enable centralized data management, collaborative work among multiple experts on the same projects, as well as seamless integration with field monitoring or other databases.

The aim of this paper is to provide a concise overview of the development and application of software tools and platforms specialized in hydrodynamic analysis of groundwater flow, with a focus on the benefits they offer in terms of efficiency, accuracy, and reliability of calculations. By presenting the functionalities of these systems, the paper highlights their potential to enhance professional practice, accelerate decision-making, and improve management of this valuable natural resource, thereby creating the conditions necessary for sustainable use and protection of groundwater under contemporary challenges.

2. Challenges of Metro and Groundwater Interaction (Tunnels and Stations)

The construction of the Belgrade metro is based on the light metro concept (light rail transit), which prioritizes lower construction costs compared to a traditional heavy metro system.

Given the complex geomorphological and geological conditions of the Belgrade area, the construction methods for the metro are primarily limited to three approaches:

- **Deep excavation (Deep Tunnel)**, which utilizes specialized boring machines known as tunnel boring machines (TBMs) or "moles."
- **Shallow excavation (Cut and Cover)**, where the soil is first excavated, necessary infrastructure is installed, and then the area is backfilled, allowing for further construction of other structures on top.
- **At-grade construction**, where instead of backfilling, the excavation remains open. This approach, in addition to reducing construction costs, can offer other advantages.

The Belgrade metro study (JČWI, 2022) covers a network of three light metro lines, which can be upgraded to a high-capacity metro system:

- **Line 1** has a total length of 21.3 km, of which 11.3 km are in deep excavation (TBM tunneling), 7.7 km in shallow excavation (Cut & Cover), and 2.3 km at-grade. Along this route, 23 metro stations are planned (13 in deep excavation, 7 in shallow excavation, and 3 at-grade).
- **Line 2** spans 19.2 km, with 9.8 km in deep excavation (TBM) and 9.4 km in shallow excavation (Cut & Cover). This line includes 20 metro stations (9 in deep excavation and 11 in shallow excavation).
- **Line 3** covers the southeastern and southwestern parts of the city.

The constructed metro tunnel alignment and station structures are isolated from the surrounding environment by a waterproof concrete lining, thereby protecting them from direct contact with groundwater. The interaction between the metro system and groundwater can be considered from the perspective of potential resulting issues, depending on:

- whether the metro is in the construction or operational phase,
- whether the focus is on the tunnel route or the station site (zone),
- the excavation methods used,
- geological conditions,
- and the existing infrastructure along the route.

In general, it can be considered that an operational metro does not have direct contact points with groundwater. Such contact may occur only in cases of accidental infiltration, either as water ingress into the metro structures or as the leakage of fluids (often contaminated) into the surrounding groundwater.

Unlike the operational phase, the construction phase of the metro is subject to much more demanding conditions. Shallow excavation (Cut & Cover) is carried out under dry conditions. Station construction is particularly challenging, as it takes longer and often requires extensive dewatering measures. When using the deep excavation method (TBM), in addition to conventional dewatering techniques, new waterproofing technologies are also applied (e.g., special concrete).

A characteristic feature of the Belgrade metro is that its route passes through rock masses with diverse and complex hydrogeological conditions. The rocks are sedimentary, Quaternary, and pre-Quaternary in age (Tertiary and partially Mesozoic).

The issue of metro and groundwater interaction in Belgrade should also be viewed in the context of various existing interactions between groundwater and urban infrastructure, as well as land use. It is important to highlight the following:

- Dense urban zones, which often require (and implement) management of groundwater regimes through various drainage measures for structures.
- Peripheral, less densely populated urban zones, with or without established sewage systems.
- Green belts (forests and parks).
- Planned and developing settlements within urban areas, both with and without prior land filling (e.g., planned settlement construction in the Makiš field, and the initiated development of the EXPO settlement on the left bank of the Sava River). Land filling significantly alters the natural conditions for groundwater existence and its regime.
- Utility, transport, and industrial infrastructure (e.g., the marshalling yard in the Makiš field, located adjacent to Line 1, poses a potential risk of groundwater contamination).
- Groundwater sources - Belgrade's water supply is significantly dependent on wells with horizontal drains installed along the banks of the Sava River (99 wells in total, with over 60 located in the central urban core). The well capacity is determined by inflow (infiltration) from the river as well as from the alluvial aquifer (from the hinterland).
- Agriculture – agricultural production is developed on the outskirts of the city. In the alluvial zone of the flat terrain (Makiš field), there is a drainage system consisting of canals and a pumping station used to regulate the groundwater regime.

For the analysis of the interaction between the Belgrade metro and groundwater, it is necessary to understand the current natural and artificial (anthropogenic) conditions of the groundwater regime.

3. Methodological Approach to Hydrodynamic Analyses (Studies and Design Support)

The methodological approach to analysing the interaction between the Belgrade metro and groundwater stems from the established objectives and guiding criteria. The foundation for this approach included defining and elaborating primary and secondary goals of the hydrodynamic analysis, selecting and presenting output results, as well as addressing other requirements such as a unified data repository, maximum automation of certain processes, reliability, and efficiency in problem-solving.

The core component of the analysis lies in the application of mathematical modelling methods of groundwater flow regimes, the development of hydrodynamic models, and the flexibility of their use under different conditions.

The primary objectives of the hydrodynamic analysis were to determine the impact of metro construction on the existing groundwater regime both during and after the construction phase. In this context, it was necessary to identify and quantify changes in the existing groundwater regime caused by the construction and operation of the metro, specifically to define potential changes in groundwater levels, identify locations of possible groundwater infiltration into ongoing works and completed structures, quantify the inflow volume, and establish protective measures against groundwater intrusion. Additionally, based on the results of the conducted analysis, a monitoring project was planned as part of the system to protect groundwater from contamination originating from the metro as a potential source.

As secondary objectives of the analysis, assessments of the metro's impact on existing and future land users within the immediate and broader network zones were emphasized. Among these, the most significant are the impacts on dense urban areas (buildings), municipal, transport, and industrial infrastructure, and especially the city's groundwater source located along the banks of the Sava River.

The characteristics of hydrodynamic models are directly dependent on the properties of the porous media through which the metro construction is planned, with permeability being the most significant factor. The metro route passes through genetically, lithologically, and hydrogeologically diverse formations, predominantly composed of sedimentary rocks, which can be broadly categorized as:

- Alluvial (Quaternary) sediments of the Sava and Danube rivers, and
- Neogene and older sediments of the hinterland alluvium and the Belgrade uplands.

The alluvial sediments of the Sava and Danube rivers consist of **unconsolidated** rocks, characterized by typical intergranular porosity and pronounced continuous layering, predominantly extending horizontally. Sediments along parts of the metro route in the hinterland of the Sava and Danube rivers are primarily composed of limestones, marls, sandstones, and conglomerates. These rocks belong to the category of **consolidated** formations and are often tectonically disturbed, exhibiting fault and erosional discordant structures. The porosity of these rocks is fracture or fracture-cavernous (in the case of limestones), with hydraulic conductivity being very low or negligible, except for locally highly permeable zones.

As an example, the results of the analysis and categorization of the hydraulic conductivity of the rock masses (porous media) along the planned route of Line 1 of the Belgrade metro are presented, based on filtration coefficient values (Fig. 1). The majority of Line 1's route passes through practically impermeable ($K_f < 10^{-8}$ m/s) or poorly permeable ($1 \times 10^{-8} < K_f < 1 \times 10^{-6}$ m/s) rock masses. This primarily applies to the entire Section 5, nearly the entire Sections 3 and 6, as well as the marginal parts of Section 4.

Moderately permeable rocks ($1 \times 10^{-6} < K_f < 1 \times 10^{-4}$ m/s) dominate Section 4 and are also locally present within Section 3. Considering the structure of the rocks found here (both consolidated and unconsolidated), all the aforementioned types of porosity are encountered.

Highly permeable rocks ($1 \times 10^{-4} < K_f < 1 \times 10^{-2}$ m/s) are present along Sections 1 and 2 of the route (Makiš field), as shown in Fig. 1.

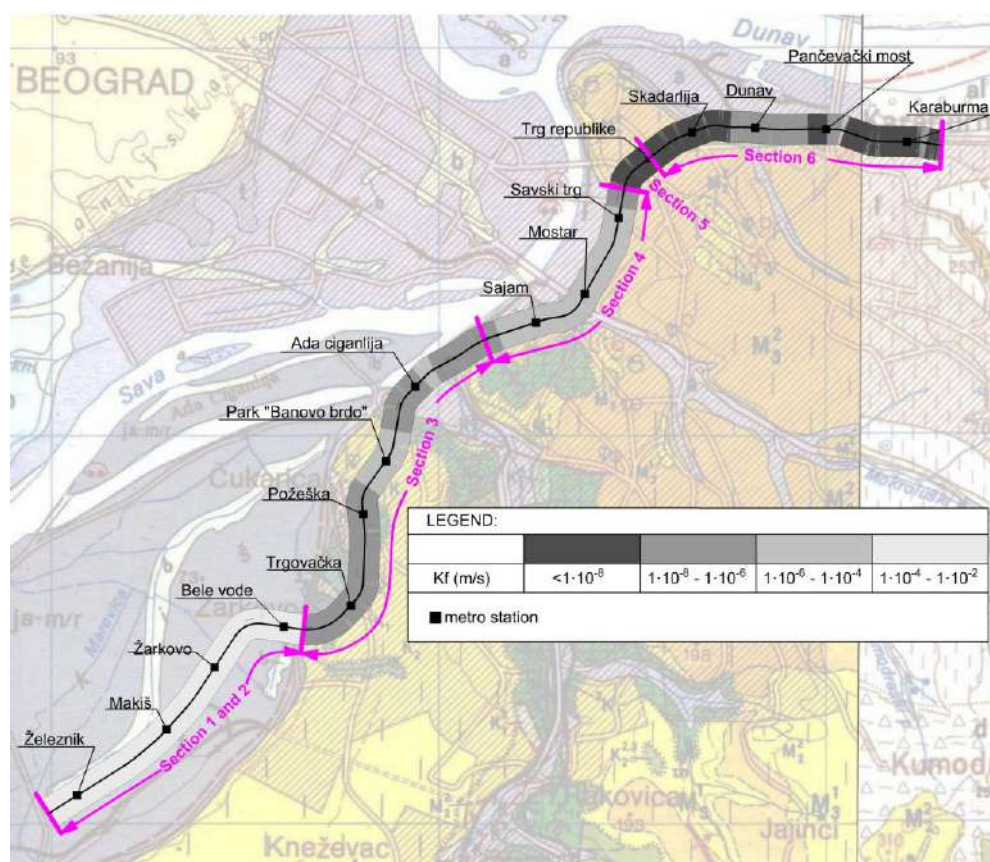


Fig. 1. Zoning of rock masses along Line 1 of the metro route by degree of permeability (based on filtration coefficient values), schematic representation.

Based on the analysis of the presented results, the selection of the number and characteristics of groundwater models was carried out. Groundwater regime analyses were performed using larger (regional) models both with and without the inclusion of the metro route, while on local (detailed) station models, the mutual impacts of their construction and surrounding groundwater were examined.

In the process of comparative analysis of the groundwater regime before and after metro construction, multiple variant calculations were performed. The calculations covered a long-term period (1/1/2005-12/31/2014), enabling a multi-parameter analysis of groundwater levels under varying hydrological conditions.

The calculation results are presented as differences in groundwater levels between the computed values before and after metro construction, shown for minimum and maximum piezometric levels within the historical hydrological record, as well as under extreme conditions (1% probability). Comparison of the results for both scenarios indicated whether mutual interaction exists and, if so, the extent to which it is manifested.

To efficiently and rationally address such a large and complex task, it was necessary to introduce innovation throughout the process. This involved thorough advance planning of all phases and steps, as well as the optimal use of available expert and personnel resources, which resulted in the creation of a dedicated project document. This document, allowing necessary adjustments and variations during the

work, formed the foundation for the entire project's execution. Maximum software utilization, automation, and centralized management of data and results were applied.

The major benefits of this approach included increased efficiency (speed, resource savings, cost reduction), versatility (variety of design alternatives), solution consistency (all derived from the same initial data source), and more.

4. Collaborative Platform (Process Workflow)

The hydrodynamic analysis involved the initial development of “macro” models (along the metro route) aimed at analysing groundwater interaction before and after metro construction. These macro models were created using the Modflow software package. Subsequently, “local” models for metro stations were developed to analyse their interaction with groundwater during construction. The local models were developed using the Plaxis3D software package.

The task required an integrated approach, logically connecting all phases of the solution and executing them efficiently. Several major steps in this process can be distinguished.

4.1. Step 1 - Task Analysis, Site Assessment, and Preparation of Materials

After analyzing the tasks to be performed, the process begins with identifying the main stakeholders affected by the changes in the groundwater regime (urban facilities, city infrastructure, municipal groundwater source, etc.). Their requirements regarding the maintenance of the groundwater regime under the new conditions (post-metro construction) are then defined.

Data are collected and entered into newly developed databases: HGIS (Hydrogeological Information System), HTO (HydroTechnical Database), HIS (Hydraulic Information System), and GIS (Geographic Information System). These systems (HGIS, HTO and HIS) are relatively new and have the specific purpose of storing and managing data necessary for the development of hydrodynamic, geomechanical, hydraulic, and hydrological models.

In the HGIS (Fig. 2) database, data on boreholes (drilling results and laboratory analyses of samples) are entered and subsequently transformed into a form and format suitable for direct import into numerical hydrodynamic and geomechanical models. This process provides initial information about the geological environment of the groundwater model and the boundary conditions required for calculations.

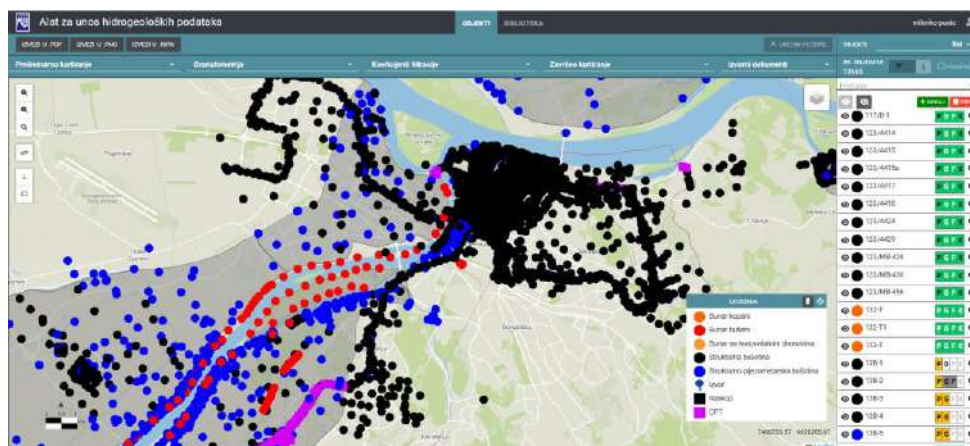


Fig. 2. Map from HGIS showing the objects.

Additionally, data and input layers for the altered-state models are prepared, including elements such as the metro route alignment, planned land filling, urbanization, changes in land use, and other relevant modifications.

4.2. Step 2 - Analysis of Requirements, Site Conditions, and Preparation of Input Data

To assist users in schematizing hydrogeological layers, which are later used for developing numerical groundwater models, a custom-built tool called the 'Hydrogeological Layer Schematization Tool' has been developed. This tool enables both automatic and semi-automatic extraction of typical hydrogeological layers. Based on the filtration coefficients of each lithological layer and the desired number of schematized layers, the algorithm assigns each lithological unit to one of the predefined schematized layers. This ensures horizontal continuity of the layers while maximizing the homogeneity of material properties within each individual layer.

Within the Clustering tab, a graphical representation is displayed to the user (Fig. 3). Each vertical line on the graph represents a single lithological unit of the object, with the values on the y-axis indicating the depth of the mapped interval, and the values on the x-axis representing the filtration coefficient defined for that interval. Lines of the same colour represent intervals that the algorithm has identified as belonging to the same layer.



Fig. 3. Application interface after data upload, selection of the number of schematized layers, and basic settings configuration.

The primary objective of groundwater model calibration is to obtain representative characteristics of the schematized layers. For comparison, the model results (groundwater levels and balance components) are evaluated against corresponding measured data in the form of time series. Unfortunately, under local conditions, measured data are often affected by errors of various origins. A *Time Series Correction Tool* is used for comparative validation and adjustment of these data. Only after thorough analysis and necessary corrections are the time series used in the calibration process (Fig. 4).

The boundary conditions of the model are derived based on the analysis of natural conditions and available data and are stored in the corresponding databases (HIS, HTO and GIS). The shapefile (shp) format contains data on the spatial, physical, and hydraulic characteristics of the boundary conditions, as well as the associated time series (Fig. 5), all in formats suitable for the development of numerical models.

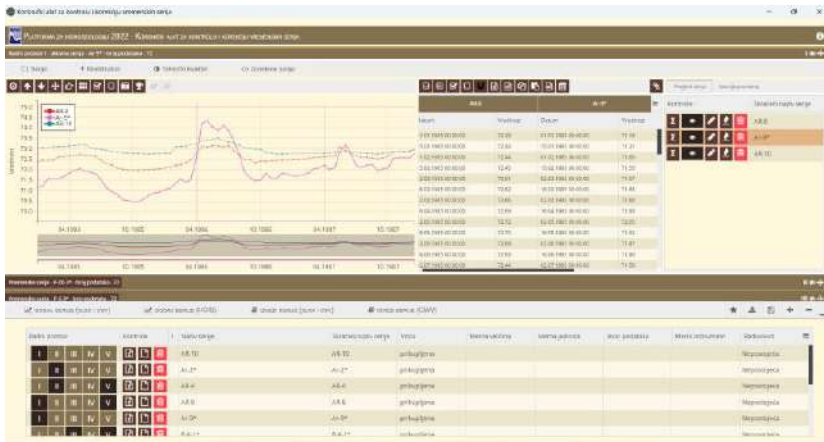


Fig. 4. Diagram from the Time Series Correction Tool, multi-diagram view

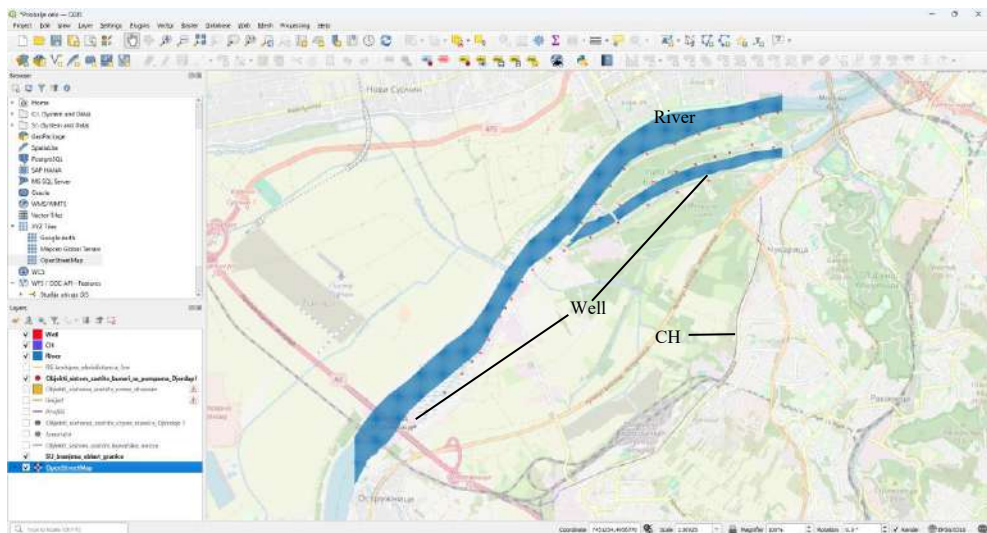


Fig. 5. Site image showing the model and boundary conditions (Source: QGIS).

Hydrodynamic calculations are performed using the MODFLOW platform under transient conditions, with grid generation based on the finite difference method. The initial version of the model is developed using a professional (commercial) user application, specifically GW Vistas (GWV) by importing shapefiles (shp) from the GIS platform.

Existing features of the GW Vistas (GWV) application, such as sensitivity analysis and PEST (Parameter ESTimation) are used for model calibration. The progress of model calibration is monitored using the proprietary application "PiezoFlow" developed by Jaroslav Černý Water Institute (JČWI). This software is designed to display the spatial distribution of calibration objects (piezometers, wells, etc.) on a map, along with measured and calculated parameter values presented as time series (piezometric levels, flows, etc.).

On the graphical display (diagram) it is possible to select one or multiple time series (objects) for simultaneous viewing (Fig. 6). The tool also allows importing and displaying multiple consecutive results from successive calibration calculations.

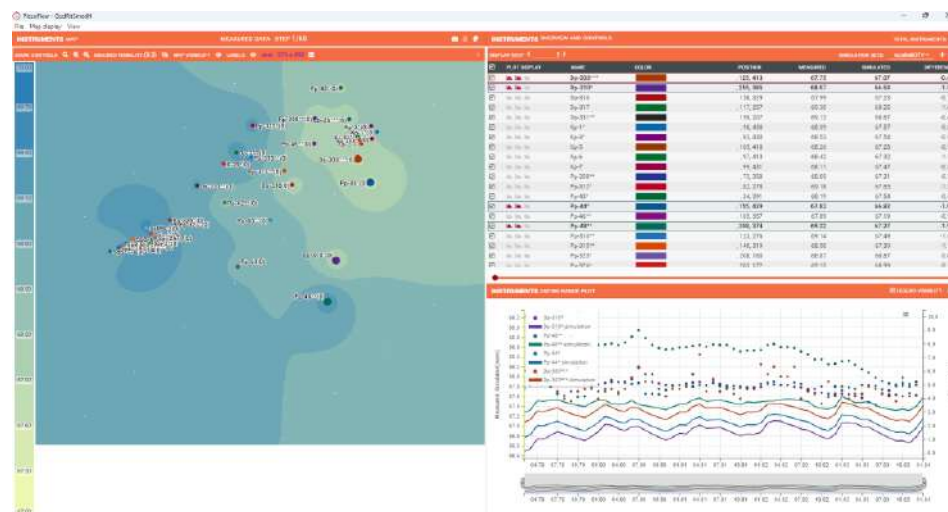


Fig. 6. PiezoFlow interface showing interaction between tabular, spatial (map), and temporal (diagram) views.

4.3. Step 3 - Hydrodynamic Analysis

Upon completion of groundwater model calibration, based on the simulation of groundwater flow under existing conditions, necessary updates and modifications are introduced into the model to support the analysis of the interaction between structures (tunnels, metro, underground and above-ground facilities) and groundwater.

As a concrete example of hydrodynamic analysis, the metro route will be presented. The metro route is simulated by adding an additional layer to the established model. The waterproof tunnel lining is represented by a “No Flow” boundary condition. By incorporating the metro route, the initial 5-layer model (Fig. 7a) is subdivided into 14 new layers; in other words, the model geometry is refined into smaller segments within the layers where the tunnel lining passes through (Fig.7b). This results in a reconfiguration of the model that enables simulation of groundwater flow under conditions specified by the project. The process is fully automated, according to the original algorithm of JČWI.

a) 5 layers – without metro



b) 14 layers – with the metro incorporated

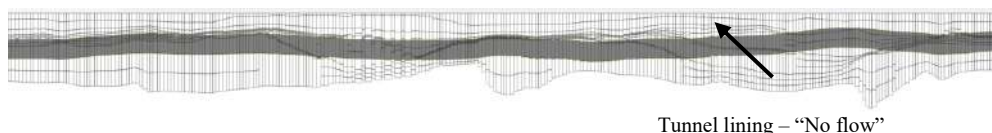


Fig. 7. Simulation of the tunnel lining within the schematized layers of the mathematical model.

For the analysis of groundwater flow in the metro station zones, detailed models with customized spatial schematization are used. Three-dimensional finite element (MKE) models for the considered stations were developed using the Plaxis 3D software package. This commercial software provides solutions for both stress-strain and flow (filtration) analyses by employing the finite element method.

For generating the model and performing groundwater regime calculations, a *Hydrogeological Analysis Support Platform* has been developed. Based on the previously established parameters of the calibrated model and the “reconfigured” model incorporating the metro route and current conditions from the GIS database, the Platform creates the groundwater model and executes the corresponding calculations.

The information necessary for creating groundwater models comes from various sources and can be grouped into three categories:

1. **Hydrodynamic inputs:** These include information about the model geometry, material properties of the soil and riverbeds (of the Sava and Danube Rivers), recharge from the hinterland, infiltration, and groundwater evaporation for the observed analysis period, among others. These data originate from the process of creating and calibrating groundwater models and may have multiple versions.
2. **Hydraulic inputs:** These consist of data on river profiles and water levels, which define the boundary conditions within the groundwater model. They are derived from the corresponding hydraulic calculations and may also exist in multiple versions.
3. **Hydrotechnical and other structures and their operating regimes:** This category includes the positions and geometric characteristics of hydrotechnical structures that must be considered for the given conditions, as well as their operating regimes. Positions and geometric data are obtained from the GIS database, while operating regimes are defined through the Platform.

For each completed calculation, it is possible within the *Platform* to generate appendices containing the calculation results in a predefined format according to the project requirements.

4.4. Step 4 - Final Processing and Storage of Results

For each calculation performed within the *Platform* for Supporting Hydrogeological Analyses, it is possible to generate appendices displaying the obtained results as specified by the project requirements. The *Appendix Generation Tool* was developed specifically to produce reports presenting the calculation outcomes.

Models, their inputs and components are stored in the so-called Project Repository (DAP), which is organized/divided into sections based on jobs (contracts or tasks being executed). The repository has two main purposes:

1. Storage of calibrated models, and
2. Storage of predictive calculation models defined by the Project assignment being addressed.

The difference between the mentioned types of models lies in the fact that calibrated models are based on real, measured data, whereas predictive models contain elements that are modified to a greater or lesser extent in accordance with the tasks being addressed. These modified elements essentially represent the assumptions or scenarios defined by the task setter.

5. Conclusion

The development of modern software tools and platforms for data preparation, analysis, and correction, as well as for simultaneous execution of numerous complex calculations, represents a significant contribution to the modernization and digitalization of processes across various engineering disciplines. This is especially evident in the field of hydrodynamic analyses of groundwater flow, where the complexity of natural systems and variability of hydrogeological parameters demand increasingly advanced computational methods and the processing of large volumes of data.

The implementation of the presented tools has enabled significantly more efficient handling of spatial and temporal data sets, their precise analysis and correction, as well as automation of processes that were previously highly demanding and prone to human error. The parallel execution of numerous

complex numerical simulations allows for the analysis of varying field conditions and their impacts on the groundwater regime, as well as the assessment of aquifer contamination risks. This substantially reduces the time required for the preparation of studies and expert evaluations, which is particularly important in the context of increasingly stringent regulatory requirements and the need for rapid response in crisis situations.

Generating results and reports through such platforms provides a high level of transparency and enables both experts and decision-makers easy access to key information for further planning and management of water resources. Particularly valuable is the capability for systematic archiving of all computational data, results, and analysis variants, which facilitates monitoring long-term changes in the groundwater regime, evaluating previous analyses, and simplifying the reuse of data in future projects.

The implementation of these solutions significantly contributes to improving the quality of hydrogeological studies and enables an interdisciplinary approach to addressing complex issues related to groundwater protection and exploitation as it is illustrated on the example of the Belgrade Metro project. Besides the technical advantages, such tools enhance collaboration among different professional profiles within teams, facilitating centralized work, faster information exchange, and synchronized decision-making.

Further development of software platforms in this field, particularly toward integration with real-time field data collection systems, the use of artificial intelligence for predictive modeling and advanced analyses, as well as improvements in result visualization, opens new possibilities for even more reliable and faster solutions. It is believed that such tools will play a key role in the future management and protection of groundwater, both in engineering practice and scientific research, where high-quality analysis and prediction of groundwater regimes are crucial for the sustainable use of this valuable resource.

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