SHAPING THE FUTURE OF TUNNELLING
Innovation, Sustainability and Safety

PROCEEDINGS OF THE SOUTHEASTERN EUROPE TUNNELLING CONFERENCE (SETC-2025)

Papers on Technical Subjects Related to Tunnelling and Underground Space Planning and Engineering

EDITED BY
DEJAN DIVAC, SANJA ZLATANIĆ, VESNA TRIPKOVIĆ,
SLOBODAN RADOVANOVIĆ AND NIKOLA MILIVOJEVIĆ

ITA TUNNELLING AWARDS 2025

SETC-2025
BELGRADE

ITA TUNNELLING AWARDS & SOUTHEASTERN EUROPE TUNNELLING CONFERENCE

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN AITES | ITA INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

ITA SERBIA
Serbian Association for
Tunnels and Underground Structures

PROCEEDINGS OF THE SOUTHEASTERN EUROPE TUNNELLING CONFERENCE (SETC-2025)

1–3 October 2025, Belgrade, Serbia

Edited by

Dejan Divac
ITA Serbia President, Serbia
Jaroslav Černi Water institute

Sanja Zlatanić
ITA-AITES Vice President, USA

Vesna Tripković
Jaroslav Černi Water Institute

Slobodan Radovanović
Jaroslav Černi Water Institute

Nikola Milivojević
Jaroslav Černi Water Institute

ITA SERBIA
Serbian Association for
Tunnels and Underground Structures

Publisher:

Serbian Association for Tunnels and Underground Structures (ITA Serbia)
https://about.ita-aites.org/members/member-nations/192-serbia

Jaroslav Černi Water Institute
office@jcerni.rs

Editors:

Prof. Dr Dejan Divac
Ms Sanja Zlatanić
Dr Vesna Tripković
Dr Slobodan Radovanović
Dr Nikola Milivojević

Graphic design:

Miloš Djoković

ISBN-978-86-82565-56-7

SHAPING THE FUTURE OF TUNNELLING

Innovation, Sustainability and Safety

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety contains the contributions presented at the ITA Awards & SETC-2025, held in Belgrade, Serbia, from 1 to 3 October 2025.

The papers cover a wide range of topics in the fields of tunnelling and underground engineering, including:

1. Advanced construction techniques
2. Use of new materials and machinery
3. Geological investigation and prediction
4. Numerical modelling
5. Instrumentation and monitoring/testing and inspection
6. Digital and information technology in design and construction
7. Strategic planning
8. Operational safety
9. Impact of climate change on tunnel infrastructure

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety aims to provide a useful resource for everyone engaged in tunnelling and underground engineering, from students and young researchers to experienced professionals and engineers.

PREFACE

The ITA Tunnelling Awards and the Southeastern Europe Tunnelling Conference (SETC-2025) were held from the 1st to the 3rd of October 2025 in Belgrade, Serbia.

The Serbian Association for Tunnels and Underground Structures (ITA Serbia) was honoured and proud to host this outstanding event of the international tunnelling community. Bringing together hundreds of distinguished experts, researchers, and industry leaders from across the globe, the event served as a dynamic platform for sharing knowledge, presenting innovations, and advancing scientific and technical excellence in the field of tunnelling and underground construction.

Serbia, with Belgrade as its dynamic capital, is experiencing a period of intensive infrastructure development, particularly in the domain of underground construction and sustainable urban mobility. Landmark projects such as the Belgrade Metro, tunnel connections, and urban underground infrastructure systems are transforming the city's transport network and enhancing its connectivity and sustainability. These projects demonstrate Serbia's growing expertise in modern tunnelling technologies, geotechnical engineering, and integrated urban planning, positioning Belgrade as a regional hub for innovation and progress in underground construction.

The conference proceedings encompass a diverse range of nine thematic areas, reflecting the multidisciplinary nature and technological depth of modern tunnelling. Topics include advanced construction techniques, the use of new materials and machinery, geological investigation and prediction, numerical modelling, instrumentation, monitoring, testing and inspection, the application of digital and information technologies in design and construction, strategic planning, operational safety, and the impact of climate change on tunnel infrastructure. Together, these themes highlight the conference's focus on innovation, sustainability, and resilience in underground construction.

It is our sincere expectation that these proceedings will contribute meaningfully to the professional and scientific community, providing valuable insights for engineers, researchers, and decision-makers engaged in the development of underground infrastructure. The knowledge and experiences shared during SETC-2025 aim to foster innovation, collaboration, and sustainable practices, encouraging the continued advancement of tunnelling and underground construction in the years ahead.

Belgrade, October 2025

Prof. Dr Dejan Divac

Chair of the ITA Awards & SETC-2025 Organising and Scientific Committee
President of the ITA Serbia

ACKNOWLEDGEMENT

The Editors would like to thank and express their sincere gratitude to all members of the Scientific Committee for their effort and the valuable time devoted to reviewing the abstracts and manuscripts.

The SETC-2025 Organizing Committee, Scientific Committee, and Editors wish to express their sincere gratitude to the conference sponsors and exhibitors for their generous support and valuable contribution to the success of this Event.

ORGANIZING COMMITTEE

Chair: Dejan Divac (ITA Serbia)
Vice-Chair: Sanja Zlatanic
(ITA-AITES Executive Council, USA)

ITA Serbia:

Vesna Tripković, Serbia
Marijana Miletić-Radić, Serbia
Slobodan Radovanović, Serbia
Nikola Milivojević, Serbia
Ivana Mićević, Serbia

ITA-AITES:

Andrea Pigorini, ITA President, Italy
Helen Roth, ITA Executive Director
Sonia Salles, ITA Secretariat, France
Ioannis Fikiris, ITA ExCo - Greece
Soren Degn Eskesen, ITA Past President, Denmark
Monika Mitew-Czajewska, ITA past ExCo, Poland
Jenny Yan, ITA Past President, China
Gerard Seingre, ITA ExCo, Switzerland
Anne Brissaud, ITA Secretariat, France
Nick Chittenden, ITA ExCo, UK
Mike Rispin, UCA Past President, USA
Shani Wallis, ITA Media, UK
Rick Lovat, ITA ExCo, Canada
Gerhard Wehrmeyer, ITAtech, Germany

SCIENTIFIC COMMITTEE

Chairman: Prof. Dr. Dejan Divac, ITA Serbia President, Serbia

Co-Chairs:

Ms Sanja Zlatanić, ITA-AITES Vice President, USA
Dr Vesna Tripković, Serbia
Dr Nikola Milivojević, Serbia
Dr Slobodan Radovanović, Serbia

Members of the International Scientific Committee:

Prof. Dr Andreas Benardos, Greece
Prof. Dr Boban Stojanović, Serbia
Dr Cane Čekerevac, Switzerland
Prof. Dr Igor Jemcov, Serbia
Mr Ioannis Fikiris, ITA-AITES Vice President, Greece
Prof. Dr Jamal Rostami, USA
Prof. Dr Jelena Ninić, UK
Prof. Dr Jenny Yan, China
Prof. Dr Jurij Karlovsek, Slovenia/Australia
Prof. Dr Monika Mitew-Czajewska, Poland
Dr Neil Bar, Saint Vincent and the Grenadines
Dr Nikola Mirković, Serbia
Dr Petre Ene, Romania
Prof. Dr Rusanov Vladimir, Russia
Prof. Dr Srdjan Kostić, Serbia
Prof. Dr Vassilis Marinos, Greece
Prof. Dr Zvonko Tomanović, Montenegro
Prof. Dr Zlatko Zafirovski, North Macedonia

TABLE OF CONTENTS

ADVANCED CONSTRUCTION TECHNIQUES

Gained Experience from the ongoing construction of the line-cross of the Metrolines U2 x U5 and following considerations of the new designed U5 Extension in Vienna 3
Dietmar Bach, Helmut Schweiger, Andreas Rohrmoser and Dejan Eybl

Soil fixing technologies used in the construction of cross passages in the Moscow metro 13
Andrey A. Dolev, Elena E. Deplani, Dmitry S. Konyukhov, Valerij P. Kivluk

Analysis of primary NATM support under limited anchor capacity: implications for steel ribs and lattice girders 21
Milan Uljarević, Andrija Rašeta and Dragan Bojović

Adaptation of tunnelling technical solutions to urban conditions: Case study Sava - Danube slope Tunnel 31
Nikola Divac, Slobodan Radovanović, Jovan Šaponjić, Uroš Mirković, Nikola Mirković and Dejan Divac

An innovative technical solution for the inclusion of a diaphragm wall into the construction system for the building of underground structures in an open pit 43
Tengiz Kobidze and Dmitry S. Konyukhov

Overcoming TBM Launch Challenges in Doha's WWDT Project 53
K. Gaurav Singh, H. Vigil Fernandez, J.B. Stypulkowski and K. Saif Al-Khayareen

USE OF NEW MATERIALS AND MACHINERY

Next-Generation of readily biodegradable foaming agents for EPB TBMs 65
Mike A. Sposetti

Design and construction of FRC tunnel precast segment with fibre enabled carbon footprint reduction 75
Benoit de Rivaz

EPB TBM design for deep-overburden and long-distance tunnelling construction 87
Yin Yuefeng, Pang Peiyan, Cao Shulei, Yang Lin, Chen Ling and Zhao Qian

Reducing the Carbon Footprint by Innovations in Tunnel Construction 95
Srdjan Spasojević

Analysis of EPB TBM Torque Calculation and Component Assessment: A Case Study of Mashhad Metro Line 3 105
Ebrahim Farrokh, Davood Lotfi and Mehdi Dalir

GEOLOGICAL INVESTIGATION AND PREDICTION

Unveiling correlations between transient tunnel deformations and in-situ geomechanical parameters derived from tunnel seismic data 117
Jozsef Hecht-Méndez, Thomas Dickmann, Carlos Andres Giraldo

Advanced Hydrogeological Modelling Tools for Metro - Groundwater Interaction Studies 127
Vladimir Lukić, Vesna Tripković and Milenko Pušić

Southeastern Europe Tunnelling Conference (SETC-2025)
1-3 October 2025, Belgrade, Serbia

DOI: 10.5937/SETC25013L

Advanced Hydrogeological Modelling Tools for Metro - Groundwater Interaction Studies

Vladimir Lukić[a], Vesna Tripković[a] and Milenko Pušić[a]*

[a] Jaroslav Černi Water Institute, Belgrade, Serbia; vladimir.lukic@jcerni.rs, milenko.pusic@jcerni.rs, vesna.tripkovic@jcerni.rs

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,

*Corresponding author: vladimir.lukic@jcerni.rs (V. Lukić).

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 ($Kf < 10^{-8}$ m/s) or poorly permeable ($1\times10^{-8} < Kf < 1\times10^{-6}$ 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 ($1\times10^{-6} < Kf < 1\times10^{-4}$ 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 ($1\times10^{-4} < Kf < 1\times10^{-2}$ m/s) are present along Sections 1 and 2 of the route (Makiš field), as shown in Fig. 1.

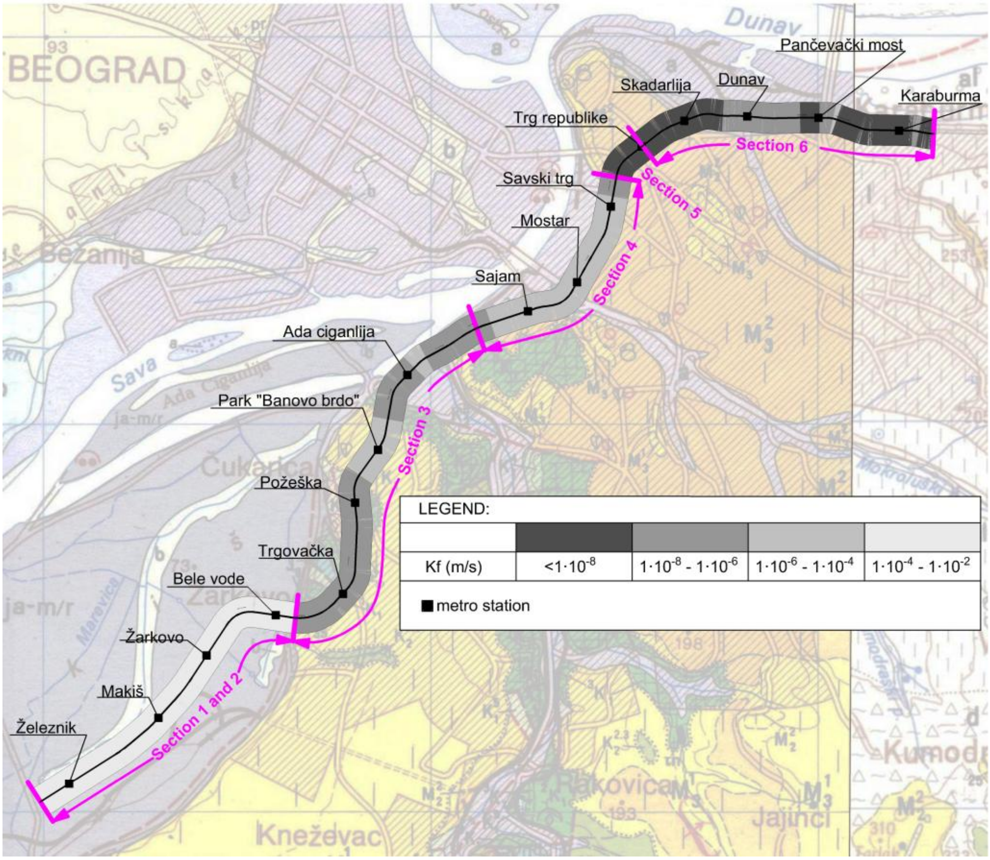

Fig. 1. Zoning of rock masses along Line 1 of the metro route by degree of permeability (based on filtration coefficient values), schematic representation.

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.

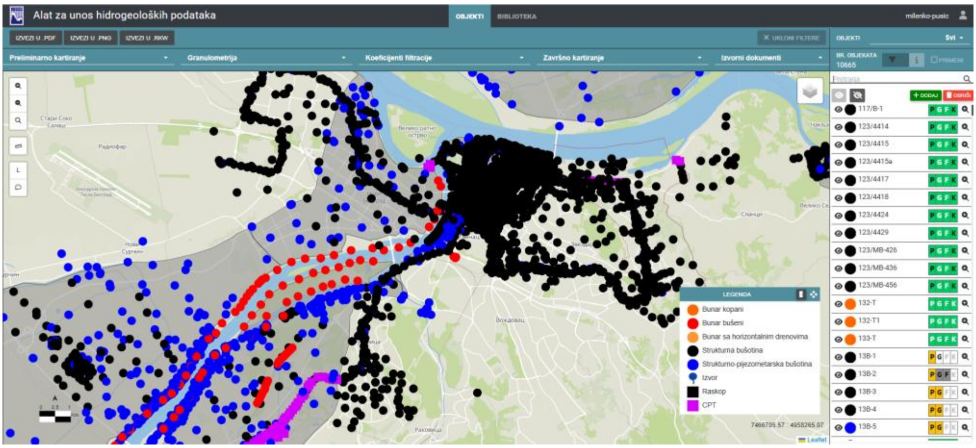

Fig. 2. Map from HGIS showing the objects.

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.

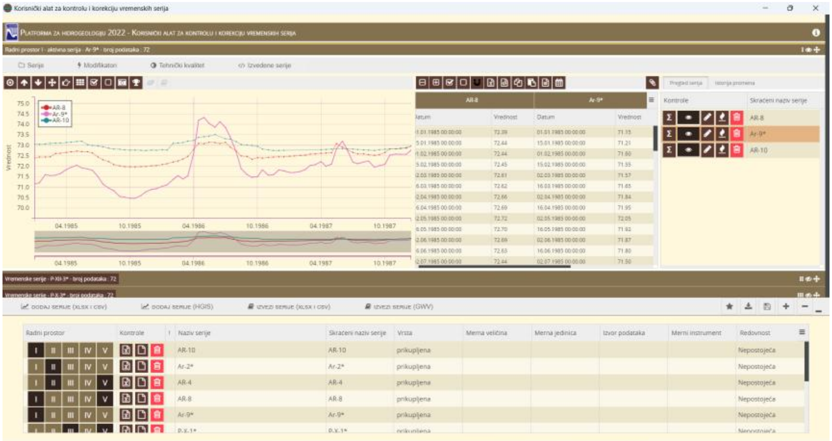

Fig. 4. Diagram from the Time Series Correction Tool, multi-diagram view

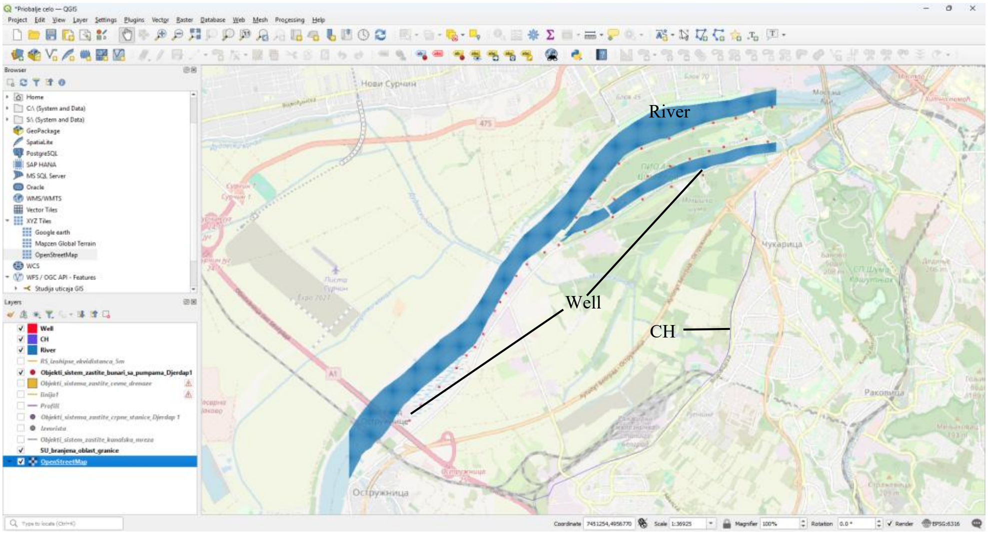

Fig. 5. Site image showing the model and boundary conditions (Source: QGIS).

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 Černi 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.

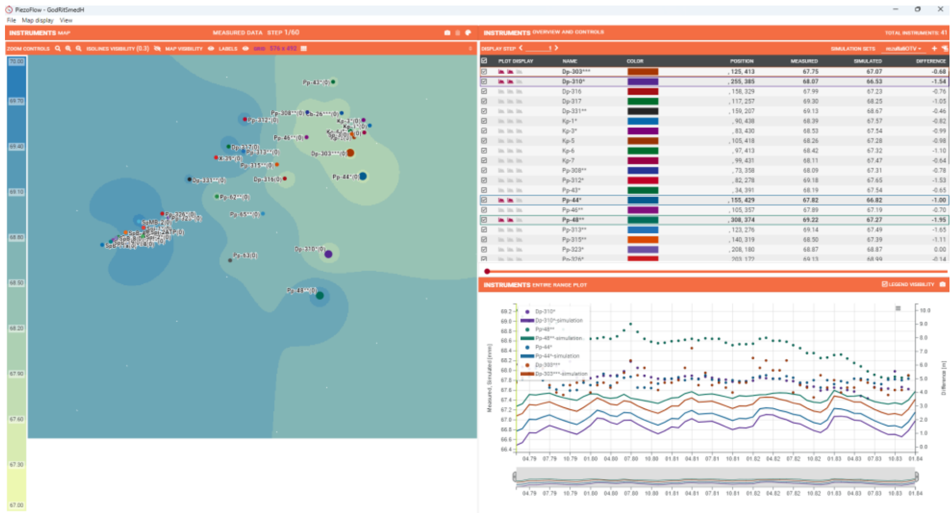

Fig. 6. PiezoFlow interface showing interaction between tabular, spatial (map), and temporal (diagram) views.

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.

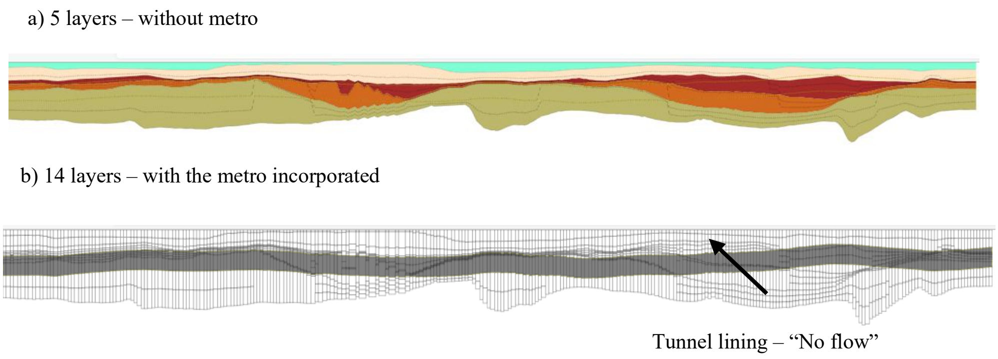

Fig. 7. Simulation of the tunnel lining within the schematized layers of the mathematical model.

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.

Acknowledgements

UNESCO center II category Water for Sustainable Development and Adaptation to Climate change (WSDAC) – Belgrade, Serbia.

References

Anderson, M.P., Woessner, W.W., Hunt, R.J., 2015. Applied Groundwater Modeling: Simulation of Flow and Advective Transport (2nd ed.). *Academic Press*.

Bear, J., 1979. Hydraulics of groundwater, McGraw-Hill series in water resources and environmental engineering. *McGraw-Hill*, New York.

Domenico, P.A., Schwartz, F.W., 1998. Physical and Chemical Hydrogeology (2nd ed.). *John Wiley & Sons*, New York, Inc.

Foster, S., Lawrence, A., Morris, B., 2008. Groundwater in Urban Development: Assessing Management Needs & Formulating Policy Strategies. *Water P-Notes*, No. 18. http://hdl.handle.net/10986/11748

Howard, K.W.F. (Ed.)., 2007. Urban Groundwater, Meeting the Challenge: IAH Selected Papers on Hydrogeology 8 (1st ed.). CRC Press. https://doi.org/10.1201/9780203947050

Jaroslav Černi Water Institute (JČWI), 2022. Study of the Belgrade metro Line 1 and groundwater interaction, Book 4, geological structure and hydrogeological characteristics of the terrain. pp. 1-207

Zheng, C., Bennett, G.D., 2021. Applied Contaminant Transport Modeling (2nd ed.). *Wiley*.