Hydrotechnical aspects of sustainable land development in complex groundwater conditions

Željka Rudić, Vladimir Lukić, Dejan Miloševa, Emilija Stošić, Goran Nikolić

Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Pinosava, Belgrade, Serbia
(corresponding author: zeljka.rudic@jcerni.rs)

Article history:
Received: August 31, 2022
Revision: September 12, 2022
Accepted: September 15, 2022

Abstract: This paper aims to present the application of systematic analyses to ascertain sustainable land development in complex groundwater conditions. Today, Serbia is a big construction site where investments in capital projects are expected to be intensified in the following years. Large land development projects are "Novi Sad Waterfront" in the City of Novi Sad, the Serbian-Chinese Industrial Park, and "Makiško Polje" in the City of Belgrade. These projects will be developed in sites often under the impact of high groundwater and/or in the vicinity of water intakes. When considering the land use change in such surroundings, planning and enforcing adequate water management is necessary. This paper will focus on resolving several issues (reducing groundwater tables to the desired levels, the necessity for ground backfilling, and protecting groundwater sources) by developing simulation models using MODFLOW. The simulation models assess ground backfilling requirements and develop optimal drainage strategies for long-term management. They represent just one segment in our approach toward achieving integrated water management. Developed models accompanied by monitoring and data management system make the project sustainable in future exploitation.

INTRODUCTION

Sustainable urban development emerges as an important planning goal in many jurisdictions seeking to cope with urbanization pressures [1]. Since urbanization is irreversible, we need to use its potential and be adaptive for sustainable urban development. In general, sustainable land use can be defined as land use that satisfies the needs of the current generation and maintains the opportunities for the needs of future generations [2]. Therefore, sustainable urban development encompasses smart planning and careful use of resources (water, gravel, and other materials) for building and developing smart cities [3, 4, 1].

Recently, rapid land use change has been witnessed in Serbia. Moreover, capital project investments are expected to intensify in the following years. Rapid urbanization contributes to the many contemporary issues and challenges that confront urban areas, especially when considering extreme climate events. We are already witnessing often occurrence of severe drought and heavy precipitation followed by flooding, as foreseen by the Intergovernmental Panel on Climate Change [5]. Economic sectors such as agriculture, forestry, tourism, and recreation are directly affected by climatic conditions and our everyday life and housing conditions. More extreme precipitation events that cause flooding will significantly affect areas that already have problems with excess water. The high groundwater table, in addition to flat topography and low permeability soils, increases the risk of excess water's adverse impact.

The aesthetic beauty of most natural rivers has made lands adjacent to them attractive sites for residential and recreational development. But this land is usually subject to flooding and/or high groundwater levels, thus complex water conditions. The correct development of land near rivers and various water bodies has a tremendous health-improving effect on the urban environment and improves its living conditions [6]. Adequate planning of water structures and integral water regime management are crucial to achieving these goals. It is necessary to reach the required level of protection without severe environmental impact through optimization of the water regime management. To make urban areas resilient at the inception stage, the efficiency in urban planning can significantly affect preparedness and capacities to recover [3].

This paper will focus on large urban development projects in Serbia, "Novi Sad Waterfront" in the City of Novi Sad, the Serbian-Chinese industrial park, and "Makiško Polje" in the City of Belgrade. These projects will be developed in sites along large rivers, often under the impact of high groundwater or/and in the vicinity of water intakes. When considering the land use change in such surroundings, planning and enforcing adequate groundwater management is necessary. This paper aims to highlight the necessity of systematic planning and management in the urban development of areas with complex groundwater conditions, which are particularly sensitive to the adverse effect of excess water.

INTEGRATED WATER MANAGEMENT IN SPATIAL PLANNING

Integrated water management can be practiced at many scales and has to address challenges in water resources, water and sanitation service provision, flood risk management, and the protection of the water environment. Hence, the interrelationships between water, spatial planning, and disaster risk reduction must be considered. As stated in the introductory chapter, urban development challenges in riverside areas are complex and require developing a comprehensive or integrated water management framework. Our approach to achieving integrated water management in vulnerable areas during spatial planning involves several steps surrounding establishing a data management or decision support system.

Decision support systems bring together data and knowledge from different areas and sources to provide users with information beyond the usual reports and summaries. The decision support system includes information systems that perform data acquisition, management, and visualization, as well as models that can perform simulation and optimization [7, 8]. Decomposition of detected or potential problems in the investigated area and defining the criteria regarding land protection from the adverse water impact are the basic steps that usually influence the other components, such as monitoring design, applied modeling tools, etc.

Hydrometric data underpins water regime management. Accurate and comprehensive hydrometric data are critical to planners and decision-makers at all levels. The increasing need to manage natural resources, especially when considering the often impacts of climate change, is driving the need for detailed water and natural resources data. The problem of reliable data shortage is widespread and shouldn't be underestimated or overlooked [7]. The evaluation of the economic benefits of reliable data is challenging. Still, it can be considered in terms of the sum of benefit value at a site, such as the improved design of flood protection works, the improved design of bridges and culverts, the reduction of flood damages through the introduction of flood warning systems, avoidance of increasing pumping costs, avoidance of unsound investment decisions, and similar [9]. Therefore, a monitoring network has to be designed to provide sufficient high-quality data. Thus, the obtained database is the core of the decision support system. It consists of fully operational datasets, the primary sources for further analysis, modeling, and scenario developments.

The core of the information system consists of software and hardware organized to perform several functions, such as collection, processing, storage, transmitting, and disseminating data. An essential part of such a structure is modeling software that can process and make simulations of historical data and simulations for different predicted conditions. The simulation model accurately represents the water system's operations, handling all physical constraints and protection criteria or operational targets. Water issues usually have several aspects that integrated models optimally cover. An integrated model aims to couple different (hydrologic, hydrodynamics, or similar) models that illustrate physical interactions between the climate, surface waters, groundwater, land surface, etc. Modeling results in the planning phase lead modelers and designers to solutions that do not have to be conservative, i.e., enabling investors to find adequate trade-offs while considering investment decisions. All the software/hardware components of the decision support system developed at the planning phase can be complemented with the control system in the realization phase and placed in a control center. The role of a control center is data exchange, control of water structures, and issuing recommendations and warnings on upcoming situations that may cause direct or indirect damage in the area.

All listed steps and activities aim to find the optimal solution that will address problems efficiently and effectively in the planning phase and enable sustainable system operation for people and nature in the realization phase.

LAND DEVELOPMENT IN COMPLEX GROUNDWATER CONDITIONS – CASE STUDIES IN SERBIA

In the following chapters, we introduce the results of three groundwater models developed as a part of complex hydrotechnical analyses of large development projects (Figure 1). Groundwater models help investigate different issues, and several studies have developed numerical simulations of groundwater in urban areas. Turner et al. [10] listed several examples of applied groundwater modeling in urban areas, such as predicting local groundwater level impacts as a result of a proposed road tunnel construction project (Basel, Switzerland), indicating the effect of the proposed Cardiff Bay barrage on groundwater levels (Cardiff in Wales, UK), examination of the impact of changing recharge distribution due to urbanization on the water table over a 12-km^2 area (North Recklinghausen, NRW, Germany).

The analyses of groundwater regimes in case studies elaborated in this paper were done using MODFLOW, developed by McDonald and Harbaugh, with the support of the U.S. Geological Survey. Data input and interpretation of the results were made using the interface Groundwater Vistas, version 8 (Environmental Simulations, Inc.). Software numerically solves the three-dimensional groundwater flow equation for a porous medium using a finite-difference method [11, 12].

***Figure 1**. Map of the Republic of Serbia with indicated project locations*

"Novi Sad Waterfront"

The City of Novi Sad stretches on the left and right banks of the Danube River. The left bank is leveled and represents part of the alluvial plain of the Danube River, while the right bank rises sharply towards the slopes of Fruška Gora. In accordance with modern tendencies in the development of cities, Novi Sad intends to reach the banks of the river. Respecting the configuration and occupation of the banks, the broader area of Kamenicka Ada has been chosen for these purposes, and it is located in the flood zone.

In a broader sense, the analyzed terrain consists of four parts: the area of Kamenička Ada and Ribarsko Ostrvo (of more significant interest), the settlement of Kamenjar, and the urban fabric on the coast (the settlements of Telep, Adice, etc.; Figure 2).

The plan is to arrange the area of Kamenička Ada and Ribarsko Ostrvo hydrotechnically, i.e., to promote it to a defended zone. The hydrotechnical development of the Kamenička Ada and the shipyard involves the construction of a new embankment next to the Danube River, that is, the transformation of the existing inundation into the defended zone, the backfilling of the newly protected area, and the construction of a rowing trail. To assess the impact of the mentioned changes in the area on the groundwater regime in the broader area of Kamenička Ada, it was necessary to form a mathematical model of the groundwater flow.

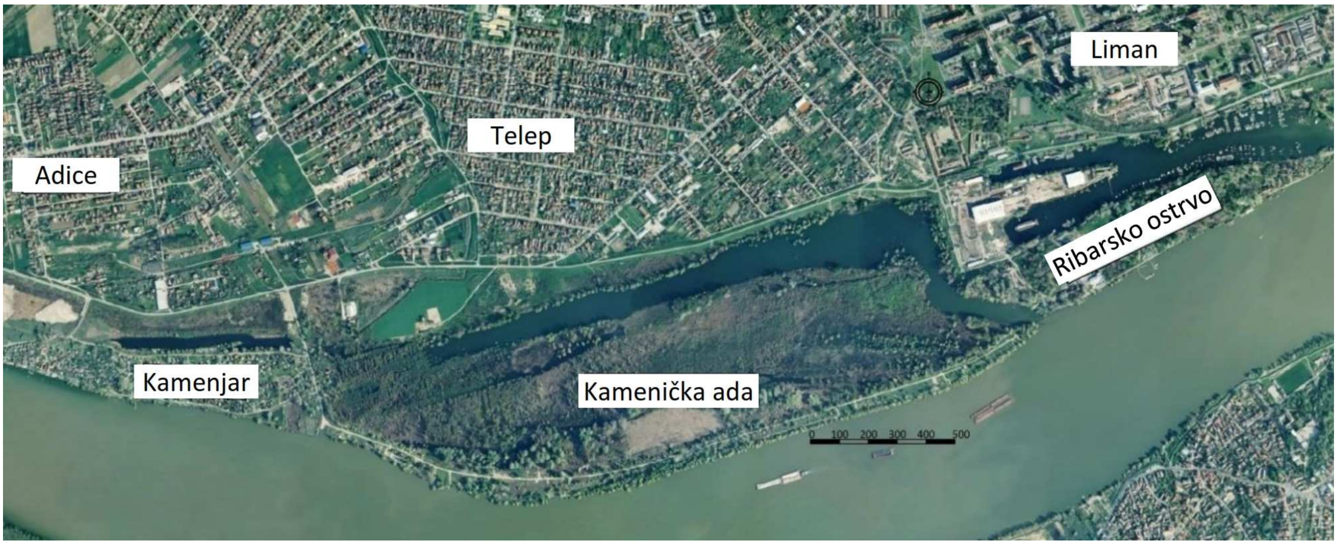

Figure 2. *The wider zone of Kamenička Ada*

The concept of solving the problem is such that, based on the analysis and necessary reinterpretation of all available information and basic design data, a hydrogeological and then a hydrodynamic (mathematical) model of the groundwater flow in the broader area of Kamenička Ada is formed. Then, on the formed mathematical model, a series of hydrodynamic computations were used to calibrate the model and observe the influence of the factors acting in historical conditions over a more extended period. After that, a simulation of the groundwater flow in the area was carried out on the calibrated model under the conditions of land development with the application of appropriate technical measures, such as backfilling, the construction of drainage systems, and the construction of a rowing trail. By comparing the computation results on the model under current conditions and conditions of hydrotechnical development, it is possible to see the potential effects of changes on the groundwater regime in the area.

A mathematical model and its calibration were formed in line with the above-mentioned methodological procedures. Model calibration was performed in non-stationary conditions of groundwater flow. In the first step, the so-called "manual" calibration was performed, during which computations were made, and afterward, a preliminary sensitivity analysis of the results to changes in the calibrated parameters. In the second step, the model calibration was continued and completed by an automatic process using modern software. The calibrated model was verified by comparing the computed and observed values of groundwater levels at observation structures (Figure 3).

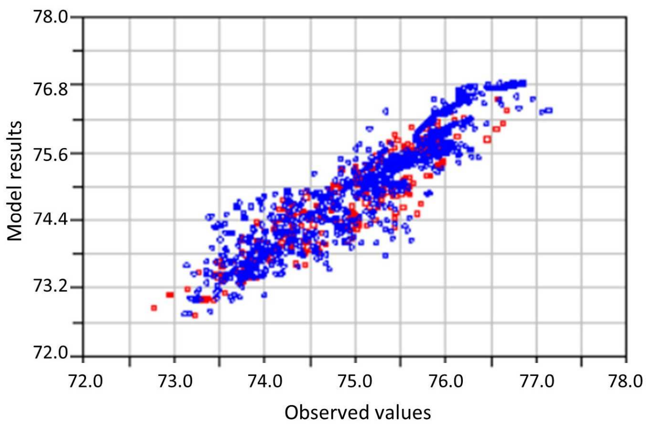

Figure 3. *Comparison of the observed and computed values of the groundwater levels*

In line with the defined methodology, a series of hydrodynamic computations were performed in the existing terrain configuration conditions for different hydrological conditions (2006, 2010, $Q_{1\%}$, $Q_{0,1\%}$). Computations were also performed in non-stationary conditions of groundwater flow in an interval of one (1) day. After that, the mathematical model was reconfigured in line with the proposed changes in the area (moving the line of protection, formation of the marina and rowing trail, and partial backfilling; Figure 4), and for the changed land conditions, computations were performed for identical hydrological conditions as in the current conditions.

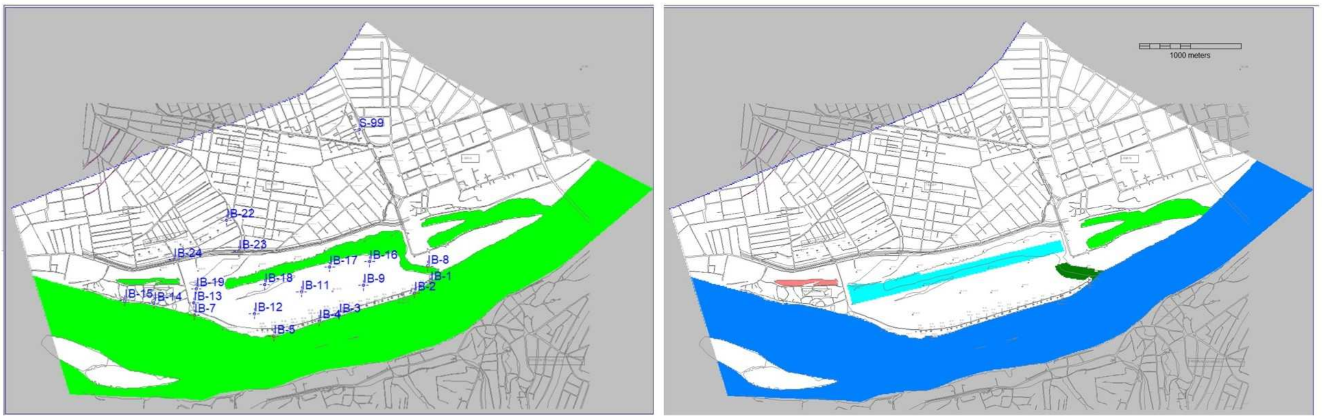

Figure 4. *The configuration of the mathematical model of Kamenička Ada in the current conditions (left) and the designed requirements (right)*

Based on the conducted hydrodynamic computations in the current and designed conditions, a comparison of the obtained results was made, that is, an overview of the potential impacts (positive or negative) of the proposed changes in the area on the groundwater regime in the wider area. The results of the performed computations are presented by isoline maps of piezometric heads for certain hydrological conditions (Figure 5) and charts with changes in piezometric heads for the current and designed land conditions at specific observation points (Figure 6).

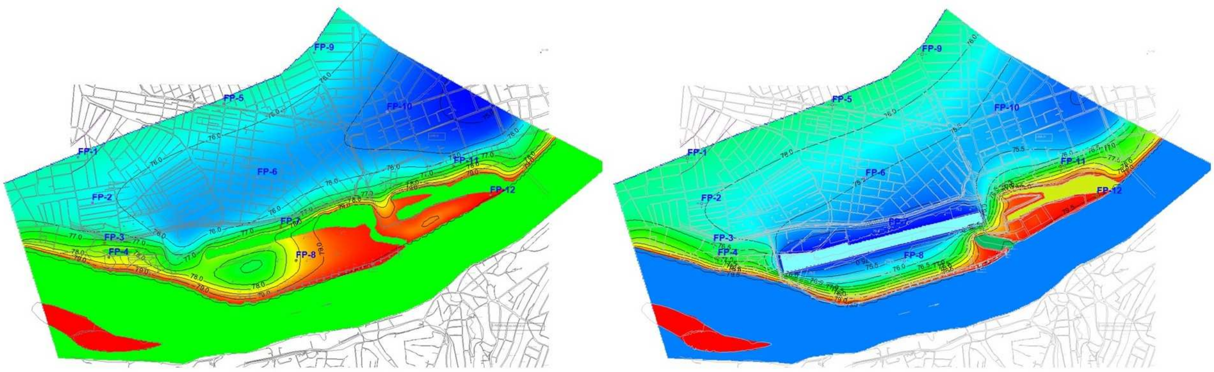

Figure 5. *Modeling results in the current (left) and designed conditions (right) for the hydrological conditions of April 2006*

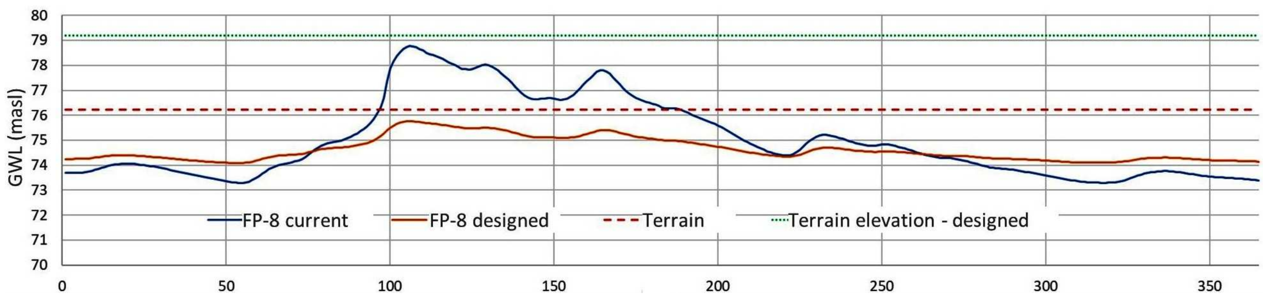

Figure 6. *The water table in the current and designed conditions in the central part of Kamenička Ada*

The model results indicate that the planned works on the hydrotechnical development of Kamenička Ada will not lead to a deterioration of the groundwater regime in the given area. The construction of the rowing trail, which will be "cut" into the water-bearing layer following the planning documents, will create a more stable groundwater regime, given that the trail will contribute to maintaining a constant level of groundwater in its wider zone. In this case, this means that in the period of high-water levels of the Danube River, the rowing trail will behave like a "drain". In other words, it will collect excess water in the area, which would otherwise occur, and thus prevent flooding of the terrain caused by high groundwater levels. On the other hand, in the period of low water levels of the Danube River, when the groundwater levels are also lower, the trail will fill the underground medium, which will make up for the deficit of water in the soil.

Of course, all of the above applies under regular maintenance of the rowing trail, that is, preservation of its hydraulic role in the groundwater regime. Considering that in the period of low water levels of the Danube River, and therefore low levels of groundwater, water from the rowing trail will infiltrate into the water-bearing layer, it will be necessary to compensate for the water deficit to maintain the elevation of the trail at the projected 74.5 masl.

Hydrodynamic computations carried out on the mathematical model of groundwater flow in the broader area of Kamenička Ada in Novi Sad have unequivocally shown that the planned changes in the area will not hurt the groundwater regime in the given area. Still, they will affect the formation of a more stable regime and the lowering of high levels of groundwater in the period of high-water levels of the Danube River. The results of the conducted hydrodynamic computations were part of the background documents of the General Urban Plan of the City of Novi Sad, which foresees the area's development.

Serbian-Chinese Industrial Park - SCIP

The project of the Serbian-Chinese Industrial Park "Mihajlo Pupin" (SCIP) envisages the construction of an industrial zone with an area of 320 ha in the broader area of Belgrade, at the left bank of the Danube River in the southwestern part of Pančevački Rit, north of the Northern Tangent Road (Figure 7a).

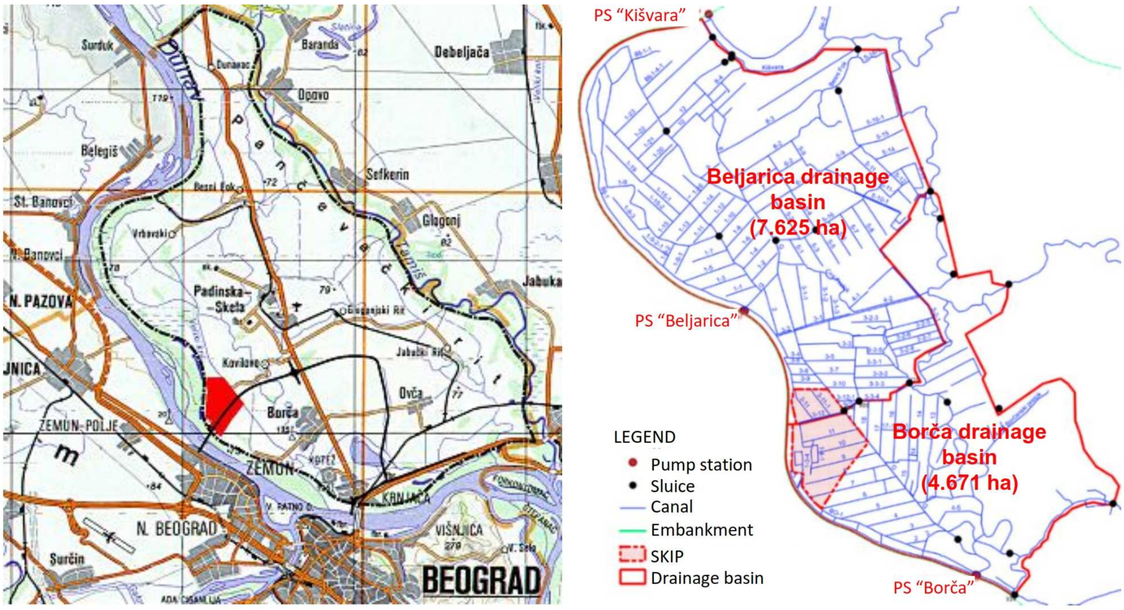

***Figure** 7. Position of SKIP: a) on the broader area; b) within the protection system against the harmful effects of water*

Agricultural land intersected by melioration canals dominates the wider SCIP area. The lower parts of the wider alluvial area are located at elevations of 70 - 72.5 m above sea level, and until the end of the 19th century, they were almost constantly flooded. Significant land reclamation works were undertaken for the needs of stable agricultural production. The reconstruction and extension of the reclamation systems, as well as the protection line against flooding, were carried out on several occasions, especially for the needs of protection against the backwater of the Danube River caused by the operation of HPP "Đerdap 1". For this reason, today, there is a complex network of canals, natural watercourses, horizontal subsurface drainage, and pumping stations on the broader area, which are part of the Hydro Melioration System (HMS) "Pančevački Rit". The SCIP area encompasses parts of the drainage basins of pumping stations "Beljarica" (capacity of 3x1.6 m^3/s + 4x1.0 m^3/s, designed operating range of 67.80–68.50 masl) and "Borča" (capacity 2x2.0 m^3/s + 2x2.4 m^3/s, designed operating range of 68.00–69.00 masl), whose recipient is the Danube River (Figure 7 b). Maintaining the level in the supply channels of the pumping stations above the designed mode of operation is the main problem regarding protection from excessive internal water. Namely, it was observed that the pumping stations were loaded with water from the neighboring drainage basins and that the canal network is too long and poorly maintained, which affects the mode of operation of the pumping stations.

In the context of protecting the future SCIP urban complex from the harmful effects of water, particular attention needs to be paid to groundwater, bearing in mind, on the one hand, the requirements of the future industrial complex itself, and, on the other hand, the influences under which their regime is formed. The groundwater regime is under the dominant influence of the Danube River, especially in the peripheral parts next to the rivers, such as the SCIP zone, with the additional influence of the canal network and the operation of pumping stations. The impact of precipitation is prominent only in periods of high values. The conditions of recharge and discharge of the phreatic aquifer are a function of the filtration characteristics of the water-bearing layer, as well as the hydraulic connection of the river/aquifer or canal/aquifer. A shallow groundwater table characterizes the majority of Pančevački Rit, as detected on the broader SCIP zone (GWT at ground level or up to 1 m below the ground; Figure 8) and well P-405** within the scope of SCIP (Figure 9).

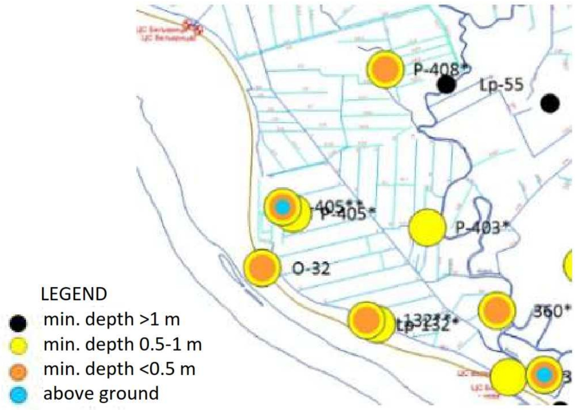

***Figure 8**. Registered minimum depths to the groundwater level on the broader SCIP zone*

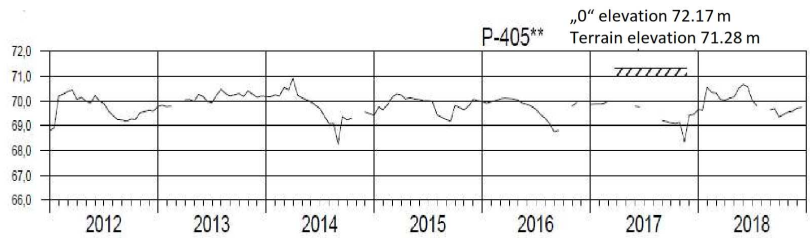

***Figure 9**. Oscillations of the water table at well P-405** in the scope of SCIP*

Given that groundwater regulation is based on a system of water structures that protect the entire Pančevački Rit from the harmful effects of water, water regulation for the needs of SCIP is considered in that broader context. A hydrodynamic model of the groundwater in the wider SCIP zone was created, namely from the minor bed of the Danube River in the east to the Vizelj canal in the west, and from PS "Borča" in the south, to PS "Beljarica" and further, in the north, with all the components that influence the groundwater regime.

As part of the mathematical model calibration process, the hydrodynamic computations resulted in representative aquifer parameters: filtration coefficients of the defined layer and hydraulic conductance at the contact river/aquifer or canal/aquifer. After the calibration process, the model was verified through the difference between the observed and computed values of water tables on control wells (Figure 10).

By comparing the computation results in the current and planned conditions, the changes in the groundwater regime that the development of the SCIP area would cause were considered. The land development of the area involves the conversion of agricultural land into construction land, with the backfilling of the secondary canals. In contrast, the channels of the first drainage line are retained. In this way, impermeable areas are also increased. The effects of different protection measures against elevated groundwater levels were also considered. A drainage norm (depth of water table) of 2.0 m was adopted as a criterion for protecting the industrial zone. However, considering that it is an industrial zone that has yet to be established and for which the conditions of construction and use of structures are defined in advance, a synthetic condition was checked that illustrates the levels that would be exceeded in the area of 20% of the time. As a reference time frame, the computation period of the model lasting 30 years (1987-2016) was adopted. For each of the planning scenarios (Figure 11 - Figure 17), a forecast of the depth of the water table with zones where water is registered above ground (blue) is given for two relevant conditions: (i) realized hydrometeorological conditions, condition: April 2006 (maximum level of the Danube River), (ii) synthetic condition: water tables, which for the conditions from the scenario are exceeded 20% of the time.

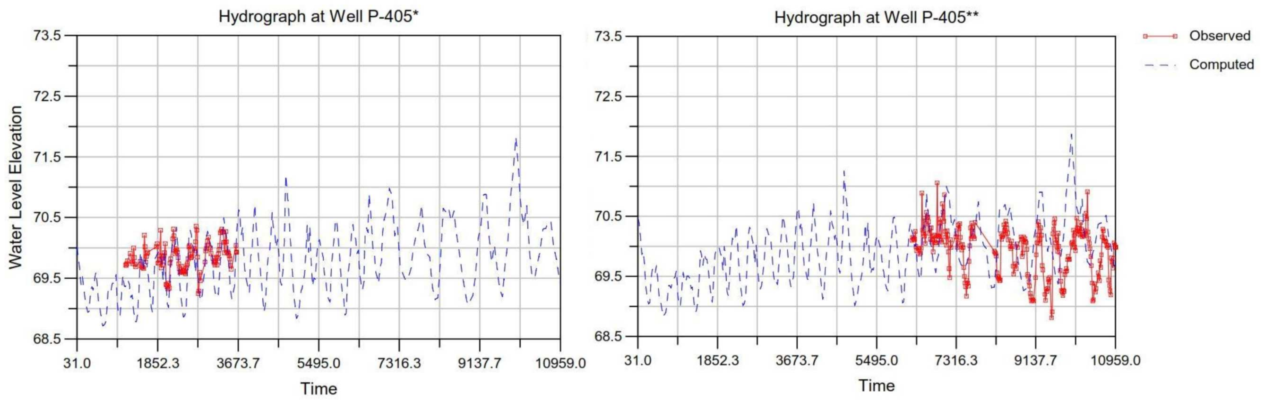

Figure 10. *Observed and computed values of water tables on wells P-405* and P-405** in the scope of SCIP*

Currently, groundwater levels in the SCIP area and the surrounding land are generally shallower than 1 m. In certain hydrological conditions, water can also appear on the ground (Figure 11). Under usual hydrological conditions, the backfilling of canals within the borders of SCIP does not cause deterioration of conditions within the boundaries of SCIP and on neighboring land. However, some deterioration may occur outside the SCIP boundaries due to Danube levels with an exceedance probability of less than 1%, such as those recorded in April 2006 (Figure 12).

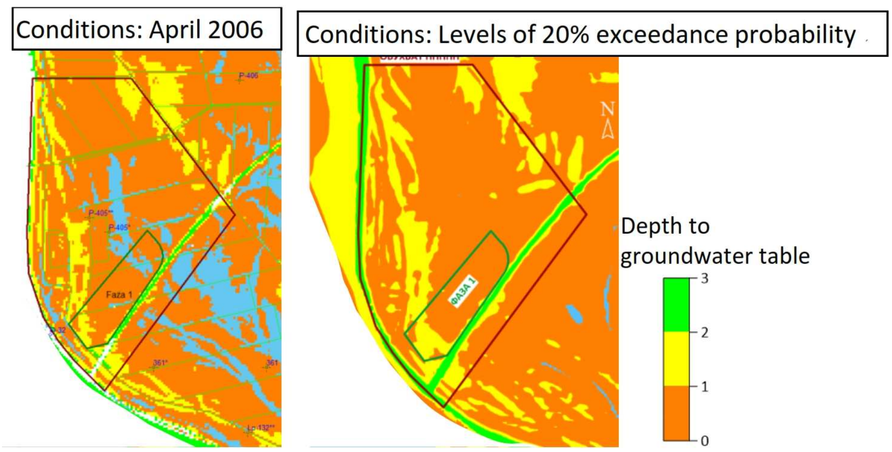

Figure 11. *Scenario 1: Current conditions*

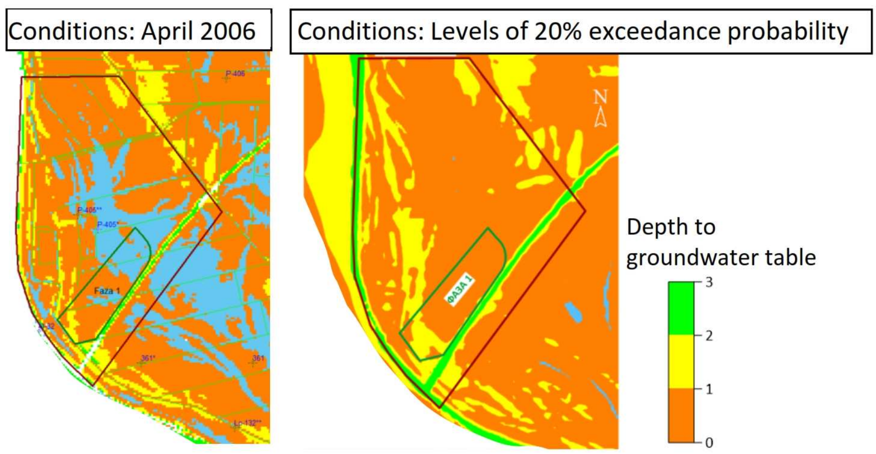

Figure 12. *Scenario 2A: Secondary backfilled canals within the SCIP area*

The results of the simulations indicate that the revitalization of HMS "Pančevački Rit" and operation in the designed mode would significantly impact maintaining a favorable groundwater regime in the peripheral zones of SCIP. On the other hand, due to the backfilling of the secondary canal network, the groundwater levels in the central part of the SCIP area would generally remain shallower than 1.0 m (Figure 13).

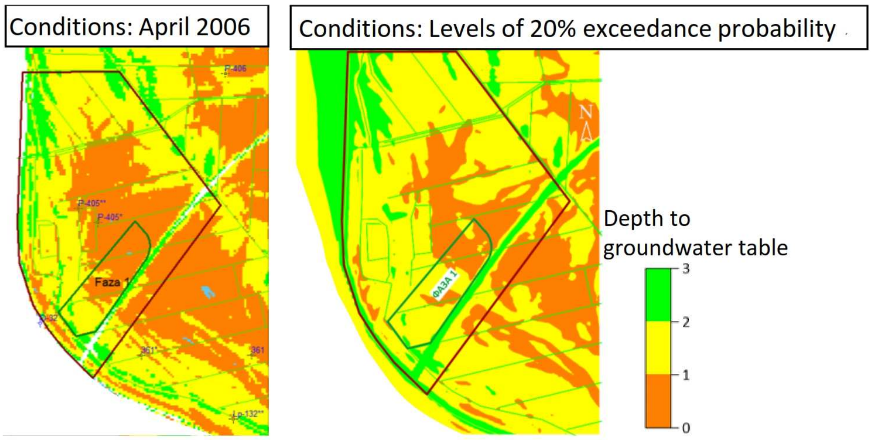

Figure 13. *Scenario 2B: Secondary backfilled canals within the SCIP area; HMS "Pančevački Rit" revitalized*

The results of the simulations indicate that it is possible to achieve a satisfactory fulfillment of the protection criteria against a high-water table. However, the application of measures according to this scenario does not have sufficient efficiency for the drainage of precipitation, i.e., preventing the retention of excess stormwater on the heavy clayey soil typical for this part of Pančevački Rit (Figure 14).

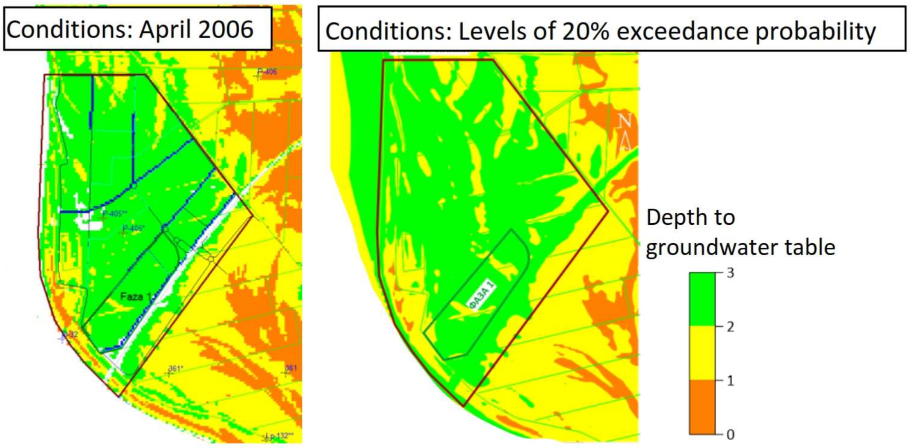

Figure 14. *Scenario 3: Secondary backfilled canals within the SCIP area; HMS "Pančevački Rit" revitalized; local drainage system (series of drainage wells) on the lowest terrains*

Backfilling the terrain can reduce the negative impacts of a high-water table in the conditions that currently exist in the area. By backfilling at an elevation of 71.5 m above sea level, the protection criterion cannot be met, so it is necessary to provide adequate drainage of the area thus formed or to increase the elevation of the backfill (Figure 15). By backfilling in combination with ensuring the operation of the surrounding HMS "Pančevački Rit" in the designed mode, partial fulfillment of the criteria can be achieved (Figure 16). By backfilling the terrain to an elevation of 71.5 m above sea level, in combination with the construction of a local drainage system, a partial fulfillment of the criteria can be achieved somewhat better than in Scenario 5 (Figure 17).

The negative impacts of high groundwater levels in the broader area of SCIP can be eliminated by developing the land intended for urbanization. By forming a backfilled layer, it is possible to avoid stormwater retention on the ground. Adequate protection of the area from groundwater can be achieved by: (i) backfilling to an elevation of 72.5 masl within the boundaries of SCIP, which enables independence from the operation of the existing drainage HMS "Pančevački Rit", without the need to build a local drainage system and without the costs of its maintenance and management; (ii) replacing materials and approximately maintaining the current terrain elevations within the boundaries of SCIP, along with the revitalization of HMS "Pančevački Rit" and the construction of a local drainage system for the needs of SCIP users; (iii) backfilling to an elevation of 71.5 masl within the boundaries of SCIP, with the revitalization of HMS "Pančevački Rit"; (iv) backfilling to an elevation of 71.5 masl within the boundaries of SCIP, with the construction of a local drainage system for the needs of SCIP users.

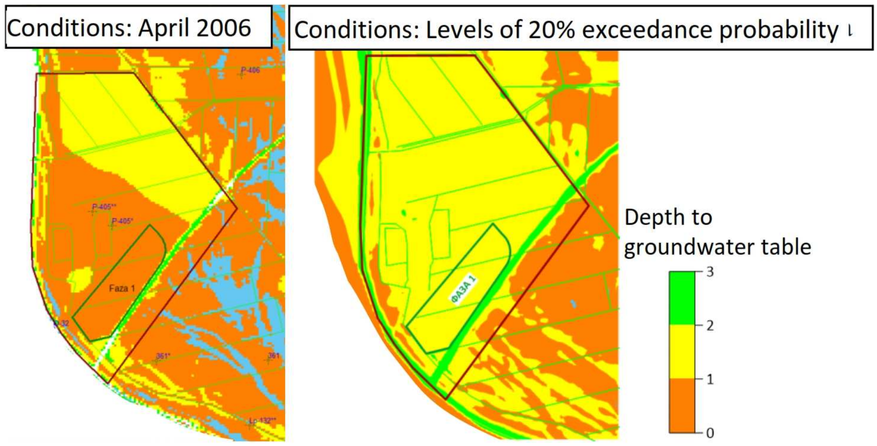

***Figure 15**. Scenario 4: Secondary backfilled canals within the SCIP area; terrain backfilled to an elevation of 71.5 masl*

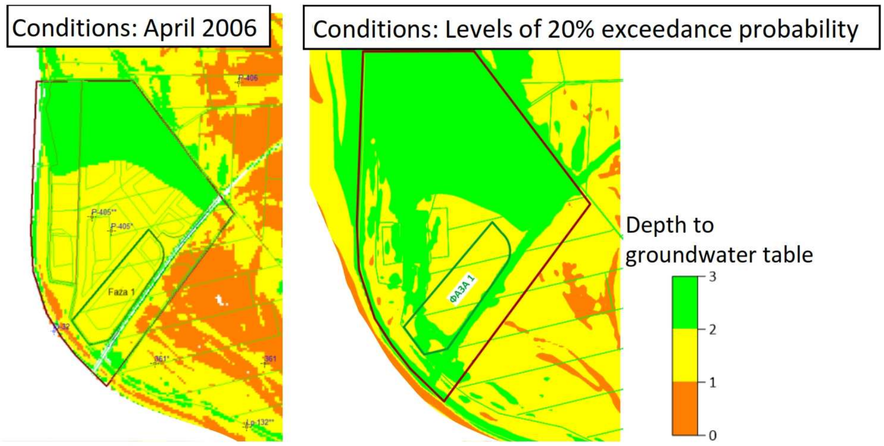

***Figure 16**. Scenario 5: Secondary backfilled canals within the SCIP area; HMS "Pančevački Rit" revitalized; terrain backfilled to an elevation of 71.5 masl*

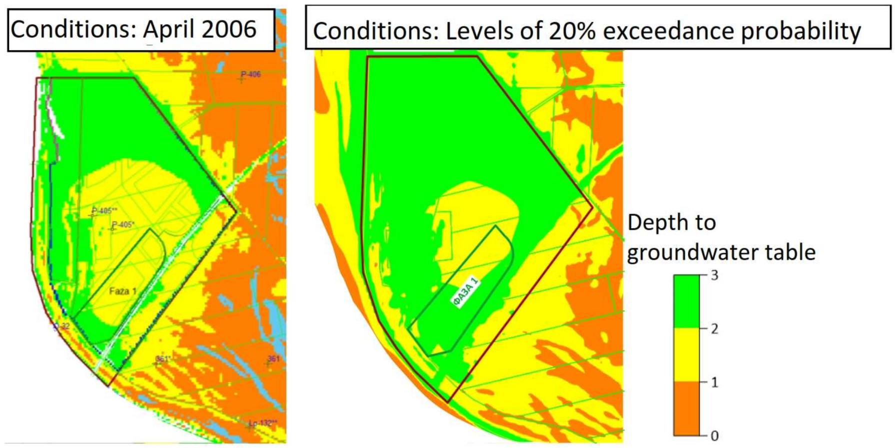

***Figure 17**. Scenario 6: Secondary backfilled canals within the SCIP area; terrain backfilled to an elevation of 71.5 masl; the local drainage system (strings of drainage wells) along the SKIP perimeter*

Resolving the issue of drainage without backfilling/replacing the material cannot achieve the desired effects due to the unfavorable characteristics of the soil and pronounced local depressions, the leveling of which is necessary for future land repurposing, as well as the positive effects of backfilling: (a) the backfilled layer of dredge sand represents a kind of retention for receiving part of the precipitation (reduction of surface runoff), which is more pronounced on natural terrain; (b) the level of protection against a high water table (case of drainage system failure) is greater since the natural terrain is located below the water table of the Danube River most of the time. Based on the presented technical observations and taking into account the financial indicators (investment and exploitation costs of individual and combined technical measures, reduced to a time plane of 30 years), it is recommended to backfill the area in question to an elevation of 72.5 masl as a sustainable measure of protection against excess surface water and groundwater.

"Makiško Polje"

Peripheral areas of cities are suitable places for forming residential businesses and recreational-tourist zones. This is how the initiative to create an urban zone, i.e., a residential-business complex, on the part of Makiško Polje on the territory of Belgrade, came about. Particular significance is given to the urbanization of this area by the reserved location for the construction of the Depot and terminal Line 1 of the Belgrade Subway. The selected part of Makiško Polje, with a total area of about 680 ha, belongs to the territory of the city municipality of Čukarica and is located on the right bank of the Sava River. The area is limited by bypassing the E-75 highway, the Sava highway (direction Belgrade-Obrenovac), Andy Warhol Street and Milorad Jovanović Street, and the "Makiš" marshaling yard complex.

Flooding of the Sava River has continually endangered significant coastal areas. Makiško Polje is protected from external waters by a continuous embankment line built from Ada Ciganlija to Ostružnica. For protection against internal waters, a drainage system was built, whose main canal ends with the "Veliki Makiš" pumping station, with a capacity of 4.0 m^3/s, to pump excess water from the area into the recipient - the Sava River.

In the zone of Makiško Polje, there is also a Belgrade groundwater source along the Sava River. It consists of wells of public utility Belgrade Waterworks and Sewerage (BWS) that capture groundwater for the water supply of the population of Belgrade. The system consists of 19 Ranney wells along the river, 17 tube wells within the area, a large number of observation wells – piezometers (Figure 18), and the water treatment plant "Bele Vode".

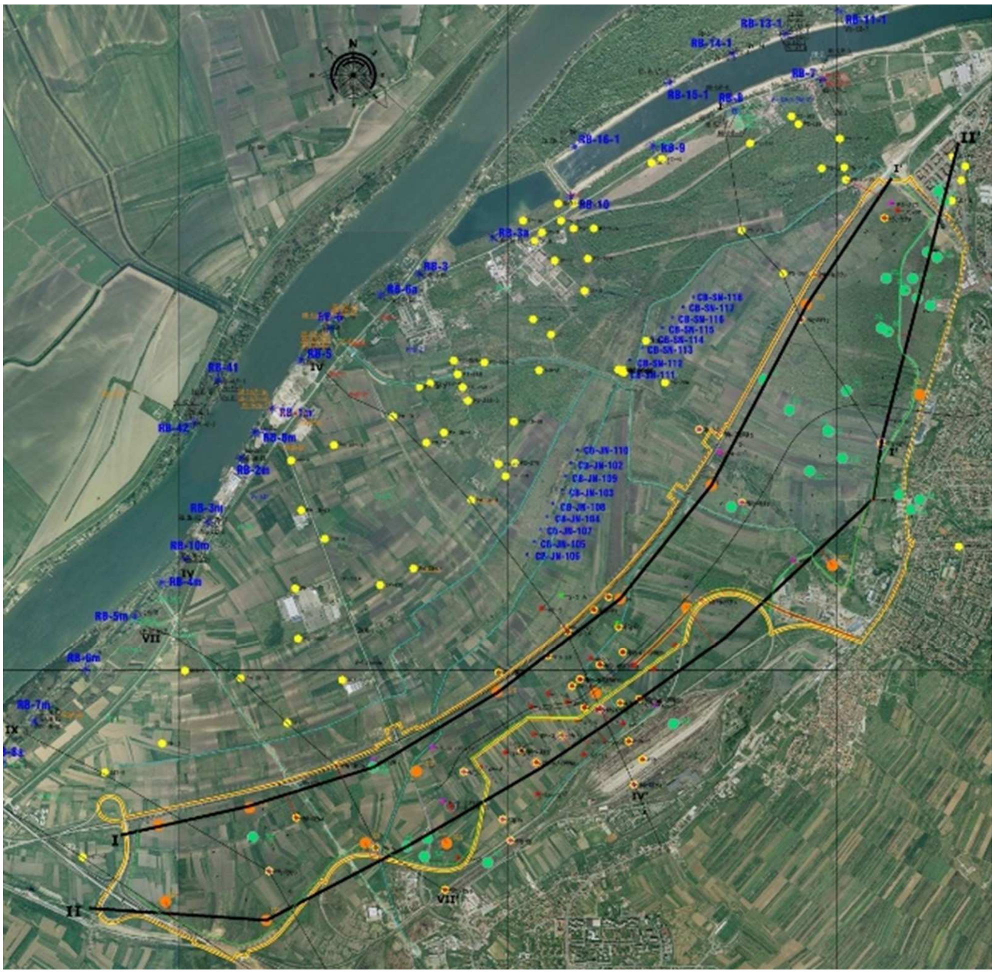

Figure 18. *Locations of the existing structures (wells, piezometers, drills) in Makiško Polje*

Storm or sanitary sewer system does not exist in the area, given that it is predominantly agricultural land and there are no settlements. So far, stormwater has been collected by existing canals.

The available potentials of the considered area and, above all, the current situation (urbanization, industry, traffic, agriculture, environment) impose the need for special consideration of water management issues related to protection against harmful effects of water and water protection. The General Design analyzed hydrotechnical measures (regulation of existing canals, existence of wells of BWS, collection and treatment of wastewater, etc.), which play a significant role in the development and protection of this part of the Makiško Polje area.

It is possible to apply appropriate measures depending on the selected concept and criteria for the protection and development of the areas and specific conditions in the area (hydrogeological, geomorphological, hydrological, soil, etc.).

The general concept of water management in the area of Makiško Polje rests on the implementation of critical activities, namely: (1) land development by backfilling and protection against high groundwater levels, (2) protection against flooding and stormwater, and (3) collecting wastewater.

Protection against high groundwater levels implies either (a) backfilling, i.e., artificially raising endangered areas to elevations that will ensure that freely formed groundwater levels are not higher than the required elevation, or (b) draining endangered areas, i.e., lowering groundwater levels to the desired level or (c) a combined method - backfilling with simultaneous drainage of areas.

Protection against flooding and stormwater entails using the existing canal network and pumping station, construction of new pumping stations, peripheral canals and collectors, formation of floodways, etc. Wastewater collecting, which refers to land development and the construction of a sewage system that transports wastewater to the wastewater treatment plant, enables the application of legal regulations in the field of environmental protection, thus respecting the modern solutions in this area.

This paper focuses on protecting the area from high groundwater levels, for which a mathematical groundwater model was created and calibrated. The area covered by the mathematical model is somewhat wider than the area of interest to include all the boundary conditions and simulate all the elements that affect the groundwater regime. Hydrodynamic computations were carried out for the current conditions in the area, as well as in the case of the implemented proposed land development measures. The results are shown in the form of isolines of groundwater levels in the area of Makiško Polje for current conditions in the area, that is, without the application of specific hydrotechnical measures for different hydrological conditions of the Sava River, or water levels with a probability of occurrence of 50% and 10%. Through hydrodynamic computations, the impact of the operation of BWS wells of the Belgrade groundwater source on the protection of the area from elevated groundwater levels was examined (Figure 19-Figure 21).

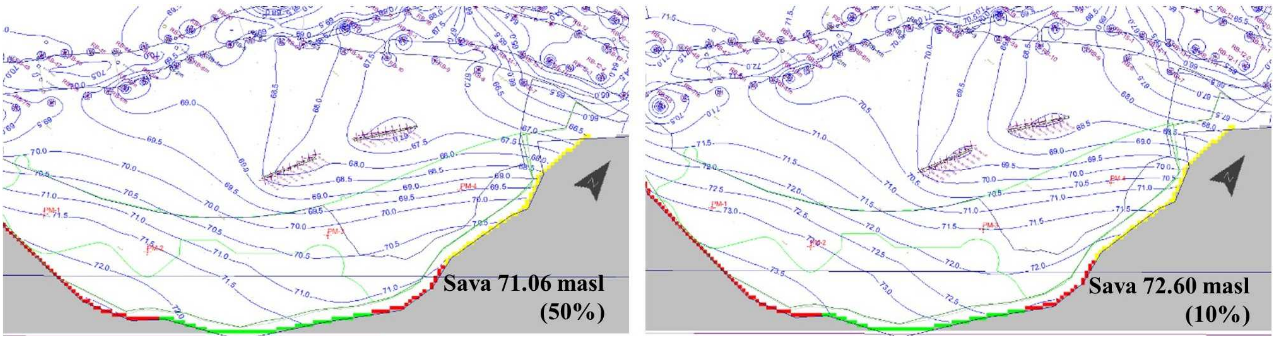

***Figure 19**. Groundwater regime in current conditions at the current operation of BWS wells (523 l/s)*

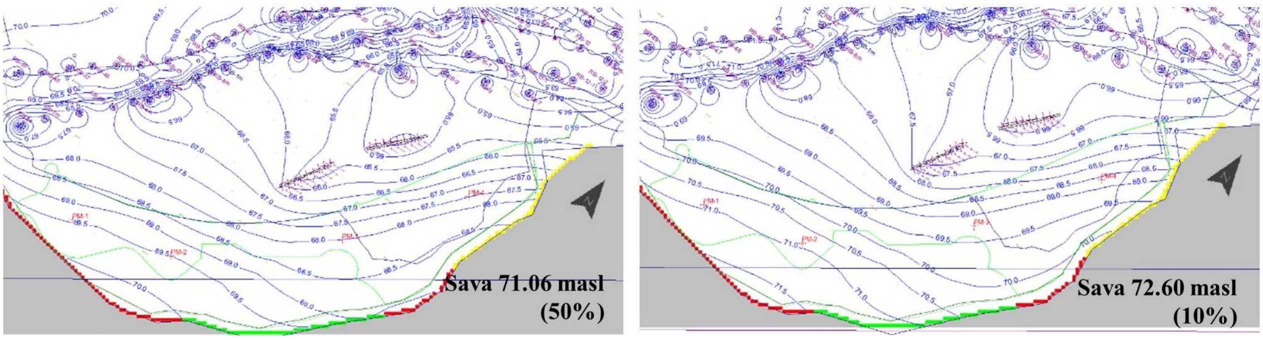

***Figure 20**. Groundwater regime in current conditions at the maximum operation of BWS wells (1,140 l/s)*

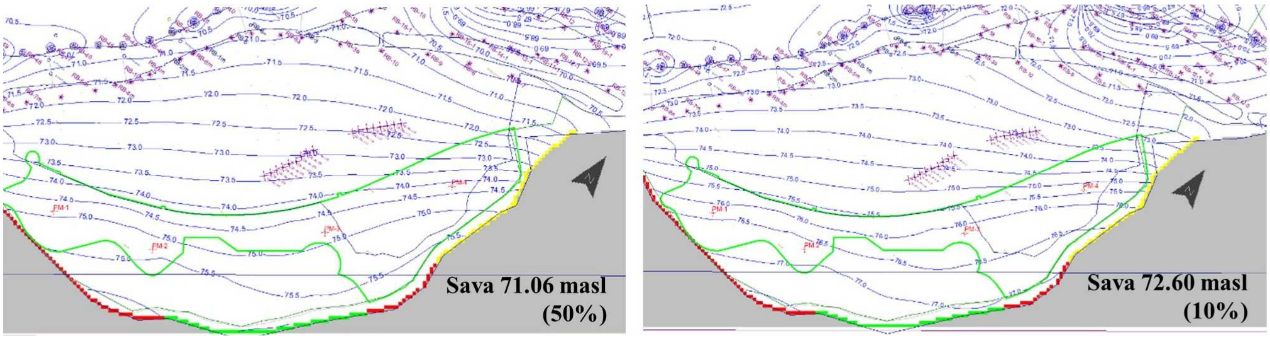

***Figure 21**. Groundwater regime in current conditions without operation of BWS wells*

The results of the performed computations indicate that the most unfavorable scenarios are those in which there is no effect of BWS wells in the area (it is excluded), regardless of the water level of the Sava River. The piezometric heads ranged from 73.0 masl to almost 76.0 masl in these scenarios. The groundwater level would be near or above the ground in these cases. This conclusion is logical, given that the water intake structures (wells with horizontal drains) located along the river represent drainage, that is, a system that protects the coast in the hinterland from the high levels of the Sava River. On the other hand, from the aspect of coastal protection from high water levels of the Sava River, the most favorable scenarios are when the wells of the Belgrade groundwater source operate at maximum capacity and when water tables range from 67.5 masl to 70.0 masl. Bearing the above-mentioned in mind, from an engineering and economic point of view, it is justified to maintain the existing groundwater source in Makiško Polje, invest in it, keep it and expand its capacity. In this way, a double benefit is achieved, the City of Belgrade receives additional quantities of high-quality drinking water, and on the other hand, the coast and the existing facilities located in the zones of interest of the Makiško Polje are protected.

Two technical measures are foreseen for hydrotechnical development of part of Makiško Polje and to protect it against excessive water and groundwater, depending on whether the BWS wells are in operation. If the wells are in operation, the suggested measure is to backfill the terrain to a minimum elevation of 74.0 masl. Suppose the BWS wells are not in operation, in addition to backfilling to an elevation of 74.0 masl. In that case, it is necessary to build a so-called "drainage curtain" in the form of wells along the boundary of the area, i.e., in the hinterland. The proposed measures are simulated as forecast hydrodynamic computations on the formed mathematical model (Figure 22 - Figure 24).

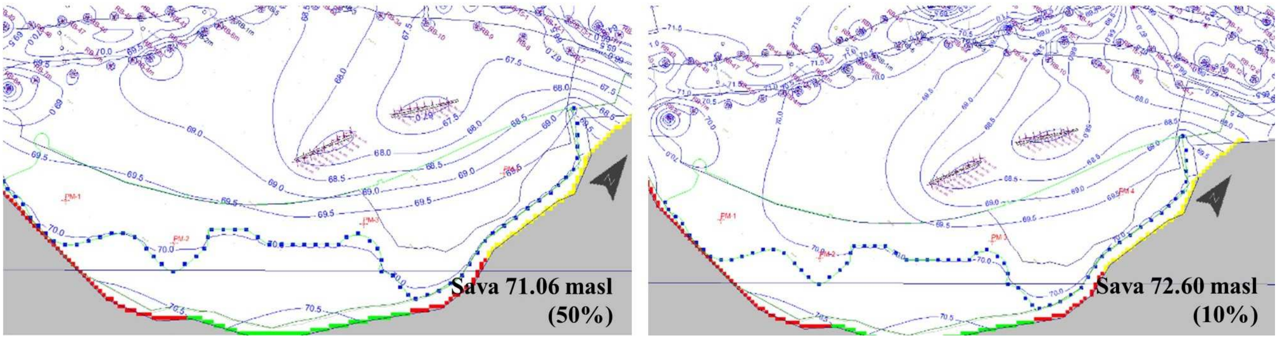

***Figure 22**. Groundwater regime in designed conditions (backfilling to an elevation of 74.00 masl and a drainage curtain - blue dots as wells in the hinterland), at the current operation of BWS wells (523 l/s)*

The results of the computations carried out in designed conditions also indicate that the most unfavorable scenarios are those in which the BWS wells are inactive, regardless of the water level of the Sava River. In these scenarios, the piezometric heads ranged from 70.0 to 70.5 m above sea level, which are maintained thanks to the drainage system operation on the southern border of the area in question. When the BWS wells in the Makiško Polje area operate at the maximum registered capacity, the piezometric heads range from 69.0 to 69.9 masl for different water levels of the Sava River. In such circumstances, the operation of the planned drainage system, i.e., drainage curtain, is not necessary because the condition that the groundwater levels should be at a depth greater than 3.0 m are met with backfilling to an elevation of 74.0 masl.

For the reception of water collected by the drainage system, i.e., the drainage curtain, and for the reception of drainage water from the backfilled terrain in the coverage area, it is necessary to build a recipient - a marginal drainage canal. Such a system would protect the area from high groundwater levels that may hurt the planned infrastructure and activities.

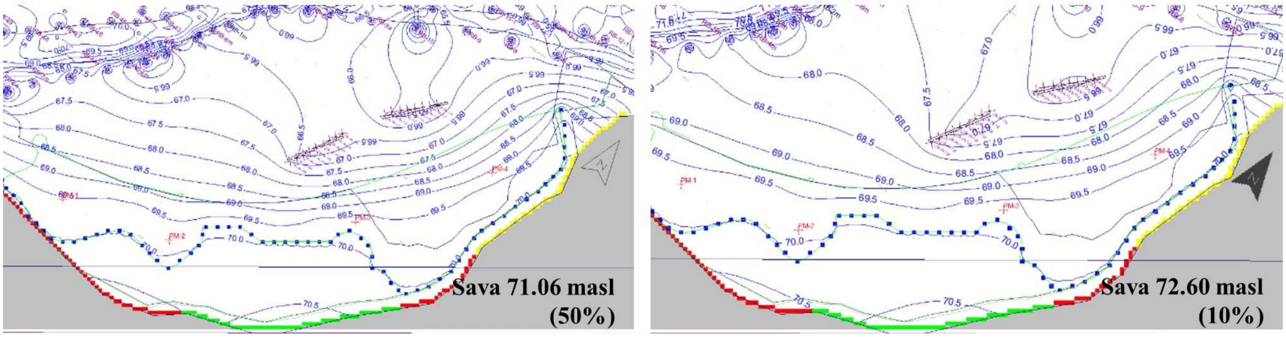

Figure 23. *Groundwater regime in designed conditions (backfilling to an elevation of 74.00 masl and a drainage curtain - blue dots as wells in the hinterland), at the maximum operation of BWS wells (1,140 l/s)*

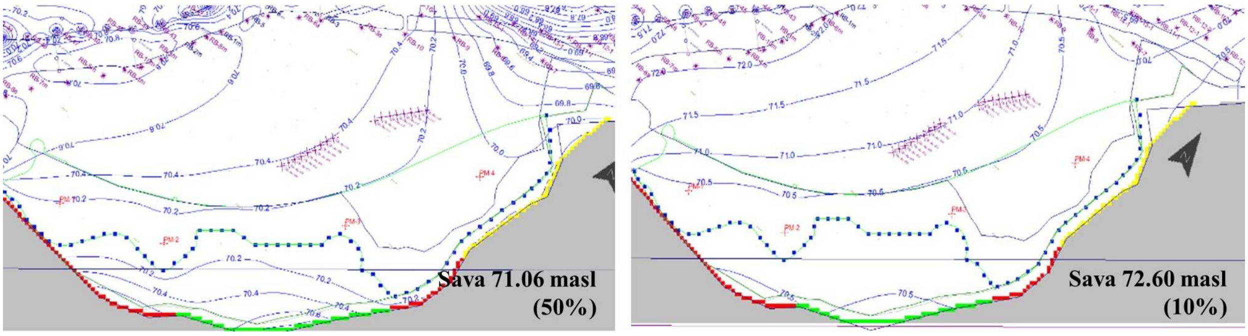

Figure 24. *Groundwater regime in designed conditions (backfilling to an elevation of 74.00 masl and a drainage curtain - blue dots as wells in the hinterland), without the operation of BWS wells*

The simulation results of different conditions indicate that the negative impact of high groundwater levels can be annulled by applying the proposed technical solutions. In other words, for the future urban environment within Makiško Polje, it is possible (with appropriate technical solutions, primarily by backfilling the terrain to an elevation of 74.00 masl) to satisfy the criterion that the level of groundwater with a 10% probability of occurrence should be at a depth greater than 3.0 m.

CONCLUSION

This paper emphasizes the necessity of conducting thorough hydrotechnical analyses as the basis of the integrated water management concept at the inception phase of spatial planning. Careful planning of water structures is necessary to enhance the resilience of new urban zones, but also to adopt an acceptable management plan through the definition of trade-off points, which are an integral part of any sustainability project [13].

Groundwater modeling in presented case studies was used to prioritize investment plans and the best management strategy. Groundwater models were used to assess (i) groundwater flow (and management) in current conditions and (ii) the application of (different) technical measure(s) that would assure adequate protection of the area of interest. Simulation results were a base for modelers and designers to choose satisfying measures, i.e., the technical solution which provides sufficient protection from high groundwater levels.

As previously stated, groundwater models represent just one part or step in our approach toward achieving integrated water management. The necessary task is to establish a monitoring and management system that makes the project sustainable in future exploitation. For managing and later maintenance of the proposed hydrotechnical system, each project envisages the formation of a unique data management center that assembles and analyses data from various sources (from the newly planned monitoring network), distributes (processed) data to different end users in the area, and issues recommendations and warnings for upcoming situations that may cause direct or indirect damage to some users.

REFERENCES

[1] Korah, P.I. (2021). Smart urban development strategies in Africa? An analysis of multiple rationalities for Accra's City Extension Project. In: Kim, H.M., Sabri, S., Kent, A. (Eds). Smart Cities for Technological and Social Innovation (p. 157-180). London: Academic Press.

[2] Yeh, A.G.O., Li, X. (1998). The sustainable land development model for rapid growth areas using GIS. International *Journal of Geographical Information Science*, 12(2), 169-189.

[3] Bansal, N., Mukherjee, M., Gairola, A. (2017). Smart Cities and Disaster Resilience. In: Seta, F., Sen, J., Biswas, A., Khare, A. (Eds). From poverty, and inequality to Smart City (p. 109-122). Singapore: Springer.

[4] El-Kholei, A.O. (2019). Risks, hazards, and disasters: can a smart city be resilient? In: Visvizi, A., Lytras, M.D. (Eds). Smart Cities: Issues and Challenges (p. 125-146). Cambridge: Elsevier.

[5] IPCC (2007). Summary for Policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller H.L. (Eds). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

[6] Kurochkina, V. (2020). Urban water bodies as the basis for the functioning of public spaces. Proceedings of the International Scientific and Practical Conference "Environmental Risks and Safety in Mechanical Engineering" (ERSME-2020), E3S Web Conf., 217, 02005.

[7] Koutsoyiannis, D., Karavokiros, G., Efstratiadis, A., Mamassis, N., Koukouvinos, A., Christofides, A. (2003). A decision support system for the management of the water resource system of Athens. *Physics and Chemistry of the Earth*, 28 (14–15), 599-609.

[8] Le Page, M., Fakir, Y., Aouissi, J. (2020). Modeling for integrated water resources management in the Mediterranean region. In: Zribi, M., Brocca, L., Tramblay, Y., Molle, F. (Eds). Water Resources in the Mediterranean Region (p. 157-190). Amsterdam: Elsevier.

[9] Walker S. (2000). The value of hydrometric information in water resources management and flood control. *Meteorological Applications*, 7, 387–397.

[10] Turner, R.J., Mansour, M.M., Dearden, R., Dochartaigh B.É.Ó., Hughes A. G. (2015). Improved understanding of groundwater flow in complex superficial deposits using three-dimensional geological-framework and groundwater models: an example from Glasgow, Scotland (UK). *Hydrogeology Journal*, 23, 493–506.

[11] McDonald, M.G., Harbaugh, A.W. (1984). A modular three-dimensional finite-difference ground-water flow model: Open-File Report 83–875. Denver: US Geological Survey.

[12] Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G. (2000). MODFLOW-2000, The U.S. Geological Survey modular ground-water model - User guide to modularization concepts and the ground-water flow process: Open-File Report 00–92. Denver: US Geological Survey.

[13] de Magalhaes, R.F., de Moura Ferreira Danilevicz, A., Palazzo, J. (2019). Managing trade-offs in complex scenarios: A decision-making tool for sustainability projects. *Journal of Cleaner Production*, 212, 447-460.

Editors

Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference in the Honour of 75 Years of the

Jaroslav Černi Water Institute

October 19-20, 2022, Belgrade, Serbia

EDITORS
Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
in the Honour of 75 Years of the

Jaroslav Černi Water Institute

October 19-20 2022, Belgrade, Serbia

Publisher

Jaroslav Černi Water Institute
Jaroslava Černog 80, 11226 Belgrade, Serbia
www. jcerni.rs, office@jcerni.rs

For the Publisher

Prof. dr Dejan Divac, Director General

Editors

Prof. dr Dejan Divac
dr Nikola Milivojević
Prof. dr Srđan Kostić

Cover page design

Tanja Jeremić

Printing

M&G Marketing, Belgrade

Circulation

1000 copies

PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

CONTENTS

HYDROINFORMATICS SYSTEMS IN WATER MANAGEMENT

WATER AND UNDERGROUND STRUCTURES

WATER QUALITY MANAGEMENT

CIP - Каталогизација у публикацији - Народна библиотека Србије, Београд

556(082)
626/628(082)

INTERNATIONAL Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute (2022 ; Belgrade)
Contemporary Water Management : challenges and research directions :
proceedings of the International Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute, October, 19-20, 2022, Belgrade, Serbia / editors Dejan Divac, Nikola Milivojević, Srđan Kostić. - Belgrade : Jaroslav Černi Water Institute, 2022 (Belgrade : M&G Marketing). - 430 str. : ilustr. ; 30 cm

Tiraž 1.000. - Bibliografija uz svaki rad.

ISBN 978-86-82565-55-0

a) Хидрологија - Зборници b) Хидротехника - Зборници

COBISS.SR-ID 76403977

9 788682 565550