Design of groundwater protection zones in urban areas – limitations and challenges

Đulija Boreli-Zdravković, Vladimir Lukić, Nenad Milenković, Miloš Zorić, Dušan Đurić

Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Pinosava, Belgrade, Serbia
(corresponding author: djulija.boreli-zdravkovic@jcerni.rs)

Article history:
Received: September 9, 2022
Revision: September 14, 2022
Accepted: September 19, 2022

Abstract: Groundwater has long been used for water supply due to its good availability and quality. In urban areas, groundwater, as a source of drinking water for households, and commercial and industrial needs, has played a significant role in the development of cities. Due to the influence of anthropogenic activities, groundwater in urban areas can be polluted with a more substantial number of pollutants and in higher concentrations. In this context, the protection of sources comes to the fore, and the preservation of groundwater quality is carried out by a set of legal and technical measures implemented through the definition and maintenance of sanitary protection zones. Determining effective and adequate efforts to protect groundwater sources formed within or near urban areas must reconcile irreconcilable interests – preserving groundwater quality and the normal functioning and development of urban areas.

INTRODUCTION

In many cases, the water supply of large cities is related to sources on the river banks located within the urbanized parts of settlements. The consequence of that and the further expansion of urban and industrial zones is an increase in "pressure" on already formed groundwater sources. The protection of groundwater sources in Serbia is regulated by legal and technical measures defined in the Study on Sanitary Protection Zones [1]. In conditions where the land use in the broader area of the groundwater source is not specified, the separation and maintenance of sanitary protection zones are relatively simple. However, in the areas with an already defined land use (agriculture, urban zone, industrial zone), determining and maintaining the zones can be pretty complex and challenging in terms of harmonizing the interests of source protection and maintaining the function of the contents already present. Groundwater sources and their protection zones, which can occupy a significant area, are often threatened by both planned and unplanned development. It often happens that even after the adoption of protection zones, it is challenging to implement them fully. Through this paper, a review of the mentioned problem is given. Guidelines for separating sanitary protection zones around the world, as well as in the Republic of Serbia, were analyzed. Also, a description of significant water sources in urban areas was given, as well as a description of characteristic pollutants in urban areas. Description of experiences in separating and maintaining sanitary protection zones of water sources on the example of the Belgrade water source, with all the challenges designers faced when defining zones, has also been given. Since further urbanization is increasingly dynamic, the need for water is increasing, and defining and establishing sanitary protection zones is becoming a more significant challenge.

GROUNDWATER IN URBAN AREAS

The development of cities is, in many cases, linked to the river banks, which represent a significant resource in many aspects (water, food, transport, etc.). With the expansion of cities and the formation of modern urban areas, there was a significant increase in the demand for quality drinking water. In many cases, it was solved by abstracting groundwater from the rivers' alluvium on whose banks the city was formed. In this way, over time and with the development of towns, there was a conflict of interest in the further expansion and preservation of groundwater resources. Groundwater abstraction at a location close to the consumption area reduces the water supply system's investment, maintenance, and operation costs. In connection with this, it was necessary to find a balance between preserving the quality of groundwater resources and the expansion and development of cities. The potential impacts of urban areas on groundwater will be presented below.

The city is often compared to a living organism, which grows, develops, and within which numerous activities (city activities) take place, for which water is necessary. Available water sources are usually surface water and groundwater, although groundwater has a more stable and generally better quality and is, therefore, a more reliable source of water supply. Groundwater as a water source for households and commercial and industrial needs has contributed significantly to the development of cities.

A wide range of interactions with groundwater is present in urban areas. Some of the city's functions may have little impact, while others may be significant polluters and sources of waste. The influence of city activities on groundwater can be described as "pressures", and the most important ones can be singled out: housing (service water, sanitary and fire-fighting, waste water from different sources, etc.), green areas (use of pesticides and fertilizers in gardens, parks, etc.), manufacturing industry (wastewater from washing, cooling, etc.), recreation (playgrounds, golf courses, water sports, etc.), transport (hazardous waste) and commercial activities.

Pressures, i.e., sources of groundwater pollution can be point sources, such as leaking pipes, reservoirs, local spilling of dangerous substances on the ground surface, discharge of industrial wastewater and diffuse, due to the use of land in agriculture, washing from urban areas or leaking of sewage in the city area.

SELECTED EXAMPLES OF LARGE GROUNDWATER SOURCES IN URBAN AREAS

There are numerous examples around the world where groundwater sources and large urban areas coexist. Pressures on groundwater resources caused by urbanization will be shown in the example of four cities (Belgrade, Novi Sad, Budapest, and Vienna) that use groundwater for public water supply.

The total quantity of water used for the supply of Belgrade has been about 6000 l/s for the past ten years. Groundwater was formerly the exclusive resource for water supply and later became dominant. Today, groundwater covers about 40% of the total need for water (Figure 1) [2]. The Belgrade groundwater source, in terms of all its characteristics (capacity, size, number of water abstraction objects, location, consumption area, etc.), stands out in our country as the most important example of a source that is primarily located within the city core itself, on its border or its vicinity. It consists of 99 radial collector wells and about 50 tubular wells built in the alluvial sediments of the Sava River, which abstracts groundwater and transports it to three treatment plants. In the period from the formation of the source until today, the highest groundwater abstraction rate was about 7000 l/s. In today’s conditions, less than 2500 l/s of groundwater is abstracted from the aquifer formed in the Sava River alluvium. In addition to the mentioned aquifer, groundwater is also abstracted from the karst aquifer in the area of Ušće, with a total capacity of about 75 l/s.

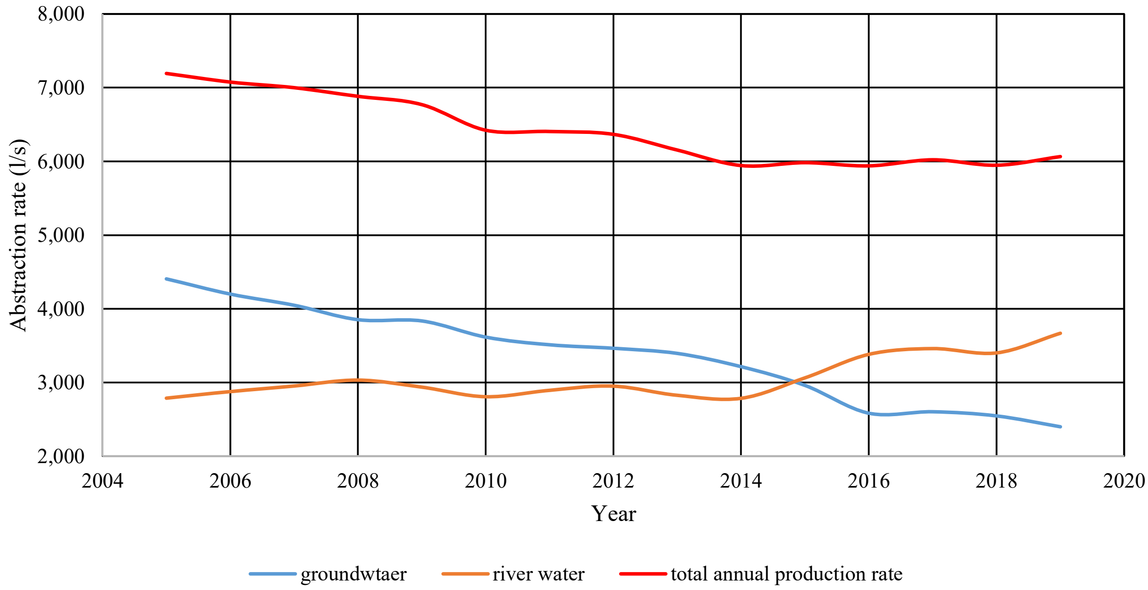

***Figure 1**. The ratio of collected groundwater and surface water for the water supply of Belgrade, for the period 2005-2019 [2]*

The water supply of Novi Sad, the second largest city in the Republic of Serbia, is achieved by abstracting groundwater at sources formed in the Danube River’s alluvium. These are the sources "Petrovaradinska ada" on the right bank of the Danube, while "Ratno ostrvo" and "Štrand" are on the left bank. Aquifers formed in sandy-gravelly sediments are tapped at all the sources. Groundwater from all sources is transported to the "Štrand" water treatment plant, where aeration, sand filtration, ozonation, activated carbon filtration, and disinfection are carried out.

The "Ratno ostrvo" source is the largest of the three active sources listed, and it is used to supply water to the population and industry of Novi Sad and the surrounding settlements. It was formed in the inundation zone of the Danube River, downstream from the mouth of the Danube-Tisa-Danube (DTD) Canal, with a length of about 2 km. The source is located on the city's periphery; in the immediate vicinity, there are energy-industrial complexes (refinery and thermal power plant). The existing setup collects groundwater by operating nine radial collector wells. According to the statistical data of exploitation monitoring, about 60% of the consumption area's needs (~700 l/s) are met from this source.

The "Petrovaradinska ada" source is located on the right bank of the Danube River in Petrovaradin. Six radial collector wells and 8 tubular wells were built at the source. Currently, the source "Petrovaradinska ada" is the second largest, with average exploitation ranging from 300-400 l/s, depending on the needs of the consumption area. There is road and railway infrastructure in the vicinity of the source.

The "Štrand" source is located on the left bank of the Danube River, within the city core. This is the first source of organized public water supply in Novi Sad. It consists of 6 radial collector wells and 14 tubular wells. Due to constant bacteriological pollution, in mid-2009, the source stopped its continuous operation. Periodically, in short periods, individual wells are put into operation. Before that, the average capacity of the source was 50-270 l/s.

Budapest's water supply relies exclusively on the resources of the Danube, both in terms of groundwater and surface water. Today, the consumer area includes about 2.4 million users. Groundwater today is predominantly abstracted by wells built on two river islands, Szentendre (about 56 km^2) and Csepel (about 257 km^2). During the development of the sources, around 2600 wells and 3 galleries have been built on them to date. Today, nearly 750 wells are active at the aforementioned sources. The maximum capacity of the source is about 1 million m^3/day (approximately 11,500 l/s), while today, on average, almost half of that is collected [3]. Depending on local hydrogeological conditions, water abstraction structures consist of radial collector wells and dug and tubular wells. There are settlements and agricultural areas on both river islands near Budapest's urban core. The collected waters are treated at two treatment plants (oxidation with ozone and filtration on fast filters).

Vienna is predominantly (about 97%) supplied with drinking water from karst sources in the Alps. Also, in the city and the surrounding area, groundwater sources provide water in cases of increased consumption, as well as in matters of the possible reduced yield of the sources in the Alps. Sources in the city area were built at Danube Island, Lobau, and Nussdorf, as well as outside the city in the Moosbrunn settlement. The Moosbrunn water source, located southeast of Vienna, has two radial wells with a total capacity of about 750 l/s. Since 2006, the treatment of water contaminated with hydrocarbons has been carried out using advanced oxidation procedures (O_3/H_2O_2). The last opened source was on Danube Island (2015), where 8 radial collector wells were built. There is also a water treatment plant here, with a capacity of 500 l/s. There are waterways and road corridors in the vicinity of the source. The source of Lobau is located in the alluvium on the left bank of the Danube. Water is abstracted by wells (5), and the capacity of the source is about 1000 l/s. There is also a water treatment plant at this location. The wells are located in a forest area within the Donau-Auen National Park, and large oil warehouses are nearby. The Nussdorf source is located on the right bank of the Danube in the northern part of Vienna and serves as a backup source, with a capacity of about 1000 l/s. The water is abstracted by wells and then treated at the plant to drinkable quality.

SPECIFIC POLLUTANTS IN GROUNDWATER

Urbanization affects the quantity of groundwater by changing the ways of recharge and its quality by changing how land is used (industrial activity, development of utility infrastructure, agricultural activities, etc.). The degree of influence of industry and agriculture is related to the city's development, while pollution from sewage systems is characteristic of all urban areas. While sewage systems reduce the impact of wastewater on the groundwater, they certainly do not eliminate it. Groundwater contamination by sewage is the result not only of direct infiltration, that is, seepage from sewage systems, but also due to surface runoff and penetration of pollution in aquifers.

The primary pollutants that can get into groundwater are bacteria, viruses, and nitrogen compounds. City sewage can receive industrial wastewater previously purified or discharged without any treatment, which may contain heavy metals, organic compounds such as solvents, petroleum substances, and pesticides. Pollutants collected on various surfaces are washed away by rainwater runoff and can affect groundwater quality. This way, heavy metals (Pb, Zn, Cu, Cd, etc.), polyaromatic cyclic hydrocarbons (PAH), hydrocarbons from mineral oils, and others can enter the groundwater from urban areas. In contrast, nutrients can enter it from agricultural regions [4].

Municipal wastewater is characterized by high BOD (Biological Oxygen Demand), suspended solids, fecal bacteria, chlorides, and ammonia. Most of the organic carbon in the water can be attributed to carbohydrates, fats, proteins, amino acids, and volatile acids, but other organic molecules such as hormones, vitamins, chlorinated hydrocarbons, pesticides, and others can also be present in the water. Synthetic detergents are the primary source of inorganic compounds of phosphates, chlorides, sulfates, and boron. As for microorganisms, bacteria are the most common in wastewater. Over 100 different types of viruses have been registered in wastewater, the most being enteroviruses (Polio viruses, Coxsackie viruses, Echo viruses), which are characterized by poor removal efficiency at wastewater treatment plants, high resistance in the external environment, and long life in wastewater [5, 6, 7, 8].

Groundwater pollution originating from industry is related to the degree of industrial development of the city, the type of industry present, and the geological structure of the terrain, especially in terms of the capacity for natural attenuation. Groundwater contamination with heavy metals and organic solvents is widely present in industrialized countries. Table 1 shows the pollution indicators and their origin.

Table 1. *Potential indicators of anthropogenic impact (source: taken and adapted from Barrett et al., 1999) [9]*

Parameters	Precipitation	Geological medium	Agriculture	Sewage	Industry and economy
Main ions (Ca, Mg, K, Na, SO_4, Cl)	+	+	+	+	+
Nitrogen component (NO_3, NH_4, org. N)	+		+	+	+
B and PO_4		+		+	+
Other microcomponents (Br, Sr, F, CN)	+	+		+	+
Metals (Fe, Mn, microelements)		+		+	+
CFCs – chlorofluorocarbons	+			+	+
THMs				+	+
Bacteria of fecal origin				+	
Detergents				+	+
Industrial pollutants (hlorinated solvents, hydrocarbons…)				+	+
Microbiological				+	

You can often find areas where agricultural activity is present in urban areas. From the aspect of influence on the quality of groundwater, animal husbandry stands out. Farms can pose a serious threat to groundwater quality through the production of wastewater/sludge that can be discharged into nearby drainage canals and watercourses, disposed of on land, and infiltrated into the subsoil.

The survival and migration of microorganisms (bacteria and viruses) in the underground environment depend on the type of microorganism, the nature of the soil, and climatic conditions. Migration is controlled by variable factors such as moisture content, pH, salt type and concentration, soil composition and granulation, organic matter, and hydraulic conditions [10].

In recent years, the increased application of anthropogenic nanomaterials in various areas has resulted in increased production, resulting in their release into all parts of the environment. Among different nanoparticles, the production of carbon nanomaterials such as fullerenes, graphene, carbon nanotubes, and some metals and metal oxides such as silver, iron oxide, titanium dioxide, and zinc oxide are at the top. The risk of groundwater contamination with nanoparticles depends on their toxicity, fate, and transport behavior in the aquifer. Research has shown that the toxicity comes from the nanomaterial and the toxic compounds adsorbed on them.

Registered appearances of pollutants on the example of Belgrade and Novi Sad

Novi Sad and Belgrade (which also uses treated surface water) use groundwater from the alluvial sources of the Danube and Sava rivers, respectively. The sources are located in urban areas or their immediate vicinity. The water quality of the Sava and Danube rivers has a dominant influence on the water quality of the resources used in the water supply system of these cities. Both rivers are international, and the quality of these watercourses is formed outside the borders of the administrative areas of these two cities. Still, the pressures registered in these cities cannot be ignored. Along its entire stretch and in the zone of the constructed wells, the Sava River receives more than ten municipal wastewater discharges, several streams, and stormwater effluents. Additionally, considering that the water-abstraction objects of the Novi Sad water supply system are located on the bank, downstream from the city wastewater outlet and the DTD Canal, there is a risk of aquifer pollution by specific pollutants present in the Danube River. To a lesser extent, these sources are supplied with water from the hinterland "attacked" by human activities. In the backcountry of these sources, there are residential areas (with accompanying infrastructure), industrial zones, and agricultural areas. During the research carried out in 2009/2010, in the groundwater of the "Ratno ostrvo" source, mineral oils were registered in concentrations above those permitted by the Regulation on potable water [11]. The presence of benzene, toluene, xylene, and chloroform was occasionally registered [12]. At the "Štrand" source, microbiological pollution was registered, and the presence of mineral oils, chlorinated ethenes, and chloroform probably originated from sewage [13]. The presence of mineral oils, chlorinated alkanes, ethene (vinyl chloride), and occasionally BTEX compounds in low concentrations was registered in the Ranney wells of the "Petrovaradinska ada" source [14].

The analysis of parameters and indicators of anthropogenic influences carried out on water samples from Ranney wells of the "Belgrade water source" showed that in the zones close to residential areas, an increase in these parameters was registered, with the fact that the values found did not exceed the stipulated norms for potable water. It was observed that the quality of groundwater in the urban area (Novi Beograd and Ušće) is worse than the water quality in other parts of the source area. This refers to the presence of ammonium ions and the appearance of elevated chlorides, sodium, and potassium levels. The high content of solvents, trichloroethylene, and tetrachlorethylene was registered in the water of Novi Beograd wells Rb-21 and RB-23 and piezometers in the surrounding area. In the piezometers in Surčinsko Polje, the influence of the melioration canals and the present farms is evident. Regarding the content of pesticides, the area of Ada Ciganlija turned out to be the most unfavorable location, which may be a consequence of the model of utilization (golf courses, maintenance of embankments, other grassy fields, etc.). The maximum recorded values were registered in well RB-12-2, 0.93 μg/l for mecoprop (MCPP) and 0.32 μg/l for MCPA, above the permitted concentration in potable water of 0.1 μg/l [15].

In the last 10 years, the testing of specific compounds, such as endocrine-disrupting compounds (EDCs), pharmaceutically active compounds (PhACs), and personal care products (PCPs), has begun in surface waters and groundwaters, which represents a water supply resource. All the listed compounds are found in wastewaters that reach surface waters and, through them, also reach groundwaters of alluvial sources. Monitoring of concentration levels and frequency of occurrence of pharmaceuticals in surface waters and groundwaters was carried out in the period between 2009-2015. A total of 25 pharmaceuticals and metabolites were analyzed in 184 surface and groundwater samples, of which 61 were surface water samples and 123 were groundwater samples. A total of 10 pharmaceuticals were detected in surface waters, while 8 pharmaceuticals were found in groundwater [16]. Previous tests of the river bank filtration process indicate a significant degree of filtration and removal of pollutants. The measured concentrations of these compounds in water samples from Ranney wells are several times lower than in surface water.

PRINCIPLES OF GROUNDWATER SOURCE PROTECTION

International experiences in defining sanitary protection zones of potable water sources

Determining sanitary protection zones of public water supply at the global level differs in methodological approaches and ways of delineation. Also, in some countries, the determination of the zones was established at the national level, while in a certain number of countries, this problem was transferred to the regional or even local level. Considering the great diversity in the approaches to defining sanitary protection zones, the following criteria can generally be adopted, i.e., determining the zones on several levels [17]:

- Well protection zone, that is, the immediate protection zone. This is the zone near a well or another water-abstraction structure. The goal is to prevent the sudden penetration of pollutants or damage to the well structure.
- Inner protection zone: this zone should provide enough time to reduce the content of pathogenic microorganisms to an acceptable level.
- Outer protection zone: the size of this zone should provide enough time for the dilution and attenuation of slowly decomposing materials to an acceptable level. In some cases, when defining this zone, the time needed to determine the permanent intake of pollutants and take remedial measures should also be considered.

- Catchment zone, a further, much wider zone that in some cases includes the entire groundwater catchment of the source area, from which all water finally reaches the point of capture. The goal is to avoid long-term quality deterioration.

Based on the previously presented criteria for determining sanitary protection zones, the countries worldwide that defined the formation of the zones decided to allocate 2 to 4 groundwater source protection zones.

Generally, as criteria for defining the zones, either the physical distance from water collecting structures and/or the travel time of pollution to them, for which there is a significant reduction in the activity of chemical and microbiological indicators or their complete removal, are adopted. When defining the mentioned criteria, the geological-hydrogeological characteristics of the source were also considered, i.e., primarily the type of porosity of the aquifer (intergranular, karst-fracture type of porosity...), considering the different behavior of pollutants in porous environments. Considering all the specificities of different types of sources and aquifers, criteria were defined for allocating sanitary protection zones of groundwater sources. In addition to the mentioned criteria for determining the zones, socio-economic parameters should be considered.

An overview of the criteria for defining sanitary protection zones of groundwater sources is given in Table 2.

According to the data presented, it is possible to conclude that the separation of zones differs significantly from country to country, which is logical considering the diversity of local geological and hydrogeological characteristics. Generally, a certain distance from the object (fence) defines the immediate zone of sanitary protection (Zone I), which prevents access and directly endangers groundwater quality through the water abstraction object. Approaches to distinguishing other zones are significantly different from country to country.

The separation of sanitary protection zones based on the mentioned criteria is relatively simple in areas where the land use has not been previously defined (new groundwater sources). However, problems can occur with existing sources where the land use has already been established (agriculture, industry, urbanized area). In these cases, it is necessary to reconcile the conflicting interests of groundwater quality protection and the interests of existing users of the given area. Under the given circumstances, complex analyses of groundwater flow conditions, potential pollutants that may appear in a given area following its purpose, physical and chemical characteristics of pollutants, and their behavior in groundwater are performed. Based on the analyses, zones of sanitary protection are defined in such a way as to try to preserve the quality of groundwater, as well as not violate the interests of the users of the area

Defining Sanitary Protection Zones in the Republic of Serbia - legal basis

Groundwater protection in the Republic of Serbia is institutionally divided between several ministries. The Ministry of Agriculture, Forestry and Water Management, the Ministry of Environmental Protection, and the Ministry of Health are all partially responsible for protecting and preserving groundwater quality. Each of the ministries mentioned above carries out activities from its domain of action to maintain groundwater quality and protect groundwater sources.

The main law in the field of water is undoubtedly the Law on Water (Official Gazette of the RS, No. 30/10, 93/12, and 101/16) [18], which is primarily harmonized with the EU Water Framework Directive (WFD). Article 73 of the Law obliges the Republic of Serbia to identify water bodies of surface and groundwater (through public water management companies) that are used or may be suitable for human use in the future. Identified water bodies that are used or can be used, under Article 73 of the Law, must be protected from intentional or accidental pollution and other influences that may adversely affect the yield of the source and the quality of the water.

Protecting water sources for public water supply is under the authority of the Ministry of Health. The definition of sanitary protection zones of the public water supply source is carried out through several legal and technical procedures.

The first step in establishing sanitary protection zones is preparing the Study on sanitary protection zones. The determination of protection zones and the preparation of the Study itself and its content are defined within the Rulebook on the method of determining sanitary protection zones of water supply sources from 2008 [1].

The Study in question defines the zones of sanitary protection of groundwater sources concerning the type of porosity of the aquifer, the protection of the aquifer by the overlying stratum, and the groundwater flow conditions. In addition, the Study defines measures for preventing groundwater pollution and the necessary monitoring network and frequency. Based on the type of porosity, aquifers are classified into aquifers with intergranular porosity and aquifers with karst porosity. The confined and unconfined conditions are distinguished based on the flow conditions.

***Table 2**. Criteria for defining sanitary protection zones (Source: Krešić et al. (2006) taken and adapted from Dimkić et al., 2012) [17]*

Country	Well/source	Inner protection zone	Outer protection zone	Catchment area
Austria	Immediate protection zone	Protection zone : 60 days	Zone I of preventive protection, total feeding area	Zone I of preventive protection: the area for which observation is carried out
Belgium (Walloon region)	Zone I of water supply structures 10 m	IIa 24 h or more, > 25 in the karst includes all priority infiltration sites associated with the source, IIb: 50 days in pressurized aquifers, free-level aquifers Sand : IIa +100 m, gravel Iia + 500 m, Karst Iia +100 m	III: Observation zone, that is, catchment area	
Germany	Zone I: a fenced area of at least 10 m around the water collecting structures	Zone II: travel time of 50 days	Zone III: Catchment area of the well or source, it can be divided into zones IIIa and IIIb if the length of the zone exceeds 2 km	
Netherlands	Catchment of one or more wells: 60 days or >30m for porous or karst aquifers (restriction: only activities related to water supply are allowed)		Protected area: a) 10 years; b) 25 years, karst aquifer; a) 2 km; b) feeding zone; (restrictions: unacceptable - transport and storage of hazardous materials, industry, waste disposal, construction, military activities, intensive agricultural production, mining, wastewater discharge)	
Croatia	Ia: immediate source area, Ib: immediate catchment area	IIIa: 24h Highly restricted zone III: limit 1-10 days and control zone	IV: 10 - 50 days – limited protection zone, special protection zone, zone of water reserves	
Ireland	IA: 0-10 m	IB: 10 - 300 m	IC: 300 - 1000 m	
Italy	Each local government is responsible for drafting regulations			
Malta	Expropriated land in the immediate vicinity of the well	500 m or more		
New Zealand	Zone I: fenced area with a diameter of 5 m or more from the well, at least 30 m (in zones where this can be achieved in a rational way)	Zone II: Travel time from 1 year to the well (based on the decline in microorganism activity along the stream) to a maximum distance of 2.5 km with conservative parameter variability. If there is no information about the direction of groundwater movement, the zone will be defined as an area with a radius of 2.5 km from the axis of the well. For aquifers where there is a slight decrease of activity of microorganisms over long flow lengths (such as karst aquifers), Zone 2 is equated with Zone 3		Zone III: catchment area of a well with a conservative tolerance for parameter variability. In the case where there is no data on the direction of groundwater flow for Zone III, the entire catchment area is adopted. Incidentally, where a large number of wells capture groundwater from the same aquifer, it may be more pragmatic for Zone III to adopt the complete catchment area
Portugal		Highly permeable medium: 20 -25 m. Poorly permeable medium :10 - 20 m. Zones with impermeable or poorly permeable upper strata with a thickness of > 50 m: 5 - 10 m	Poorly permeable medium: 100 - 200 m. Zones with impermeable or poorly permeable upper strata with a thickness of >50 m: 20 m	
Slovakia	10 -50 m	50 days or > 50 m	Catchment area	
Spain	Immediate protection zone - 24 h	II: 50 days (porous medium), 100 days (karst)	I year	Remote protection zone
Turkey	I: 50 m (porous medium), 100 m (karst)	II: 50 -250 m (porous medium), 100 - 500 m (karst)	III: Recharge zone	Catchment area

To define the zones of sanitary protection, the distance criteria from the water abstraction object in meters were adopted, as well as the travel time of the tracer to the water abstraction object in days, depending on the type of porosity and flow conditions. An overview of the determination of sanitary protection zones depending on the geological and hydrogeological conditions and hydrodynamic characteristics is given in Table 3.

***Table 3**. Boundaries of sanitary protection zones of groundwater sources in the Republic of Serbia [1]*

	Zone I (immediate zone of sanitary protection)	**Zone II (narrow zone of sanitary protection)**	**Zone III (wider zone of sanitary protection)**
Intergranular type of porosity/unconfined/with an overlying stratum[1]	A fenced area of at least 10 m from the water collecting structure in which a permanent employee resides; A fenced area of at least 3 m around the water collecting structure if it is not occupied by a permanent employee	Travel time to the water abstraction object of at least 50 days	Travel time to the water abstraction object of at least 200 days
Intergranular type of porosity/confined/ with an overlying stratum[1]		A minimum of 50 m from the water abstraction object	A minimum of 500 m from the water abstracting object
Karst type of porosity/unconfined/with an overlying stratum[1]		Travel time to the abstraction object of at least 1 day + fencing[2]	The entire catchment area
Karst type of porosity/confined/with an overlying stratum[1]		A minimum of 500 m from the water abstraction object + fencing[2]	At least 1000 m from the water abstraction object in the direction of the water flow

Legend: Overlying stratum[1] – an upper protective layer that contributes to reducing the impact of pollutants from the ground surface, Fencing[2] – With aquifers in porous karst-fracture type of mediums, the sinks, sinkholes, faults and other karst forms within Zone II are fenced off.

When the Study on sanitary protection zones for a specific source is being developed, a series of legal procedures for its implementation follows. In the first step, the Ministry of Health of the Republic of Serbia, i.e., the Provincial Secretariat for Health, Social Policy and Demography of AP Vojvodina, must consent to the Elaborate (Decision on the determination of Sanitary Protection Zones). After that, the local government on whose territory the source in question is located adopts the Study, incorporates the defined zones into the urban plans, and defines the limits within the distinguished zones.

As mentioned, establishing sanitary protection zones in an area that does not already have a specific purpose is not an issue. Potential issues can arise regarding defining the existing water source zones in urbanized areas. In those cases, there may be a mismatch between the purpose and the manner of using the current contents and the preservation of the source. Irresponsible behavior and deliberate violation of the established measures can create a particular problem. Figure 2 shows an example of an apparent collision of the existing infrastructure and contents and a violation of the prescribed actions within the defined protection zones.

In cases where there is existing infrastructure in the defined sanitary protection zones, groundwater quality is protected by adhering to the measures and applying legal-technical regulations to prevent intentional or accidental groundwater pollution. There is undoubtedly a need to implement strict penalties to avoid the deliberate introduction of pollutants into groundwater.

***Figure 2.** Existing outlet manhole of the sewerage pumping station (left); illegal landfill within the defined sanitary protection zone of the "Petrovaradinska ada" source in Novi Sad [14] (right)*

APPROACHES APPLIED IN DEFINING SANITARY PROTECTION ZONES OF THE BELGRADE WATER SOURCE

The area of the "Belgrade water source" and its surroundings is characterized by a diversity of the geological structure of the terrain, which also indicates the existence of different hydrogeological properties of the rocks. Geological structure, porosity, and tectonic processes that have occurred result in the presence of different types of aquifers. For the water supply of Belgrade with groundwater, the intergranular aquifer is predominantly used, which is formed in alluvial sediments. At the same time, a small part is collected from karst (karst - fracture) aquifers.

Within the alluvial deposits of the Sava River, aquifers were formed in sediments of the intergranular porosity (with moderate and reduced water permeability) under confined conditions. Since the Sava River deposited layers of coarse-grained and fine-grained material in several phases (polycyclic shifts) in its geological history, it was noted that the alluvial aquifers (or aquifers) could locally be very different from one another, both in terms of permeability and yield, due to the existence of multiple cycles of deposition of sandy-gravel layers, which alternate with clayey-silty interlayers, as evidenced by the different capacities of the existing wells.

From the aspect of groundwater protection, one of the key roles is played by the protective top layer with its hydrogeological and hydrodynamic characteristics (the protective role is attached to all sediments in the overlying stratum of the water-bearing complex whose hydraulic conductivity is $k<1x10^{-7}$ m/s). In the "Belgrade groundwater source" area, the overlying stratum of the water-bearing complex is composed of flood facies sediments, represented by fine-grained clastites (silty-clayey sediments). The thickness of the layer is different and ranges from 0 to 13 m, indicating the turbulent genesis of the youngest deposits. The groundwater vulnerability map (Figure 3) shows that most of urban area is characterized by medium and high vulnerability. With further urbanization, the pressure on the source is constantly increasing.

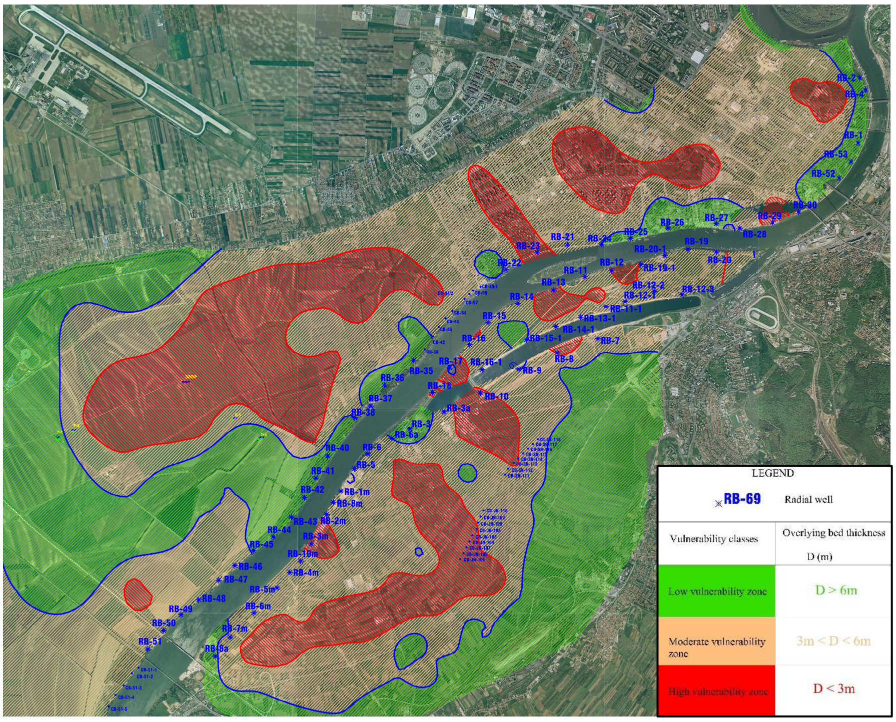

***Figure 3**. Groundwater vulnerability map of the urban area of the "Belgrade groundwater source" [20]*

Configuration of the Belgrade groundwater source and aquifer recharge conditions

The construction of wells on the banks of rivers and lakes has long been recognized as a way of efficient and successful use of groundwater. This method of abstracting groundwater is known as coastal filtration or bank filtration. The method uses the positive effects of the porous medium to remove numerous pollutants present in the surface water during the flow of water from the river bed to the abstraction wells. This positive effect is achieved predominantly due to filtration, adsorption, oxidation-reduction reaction, and biodegradation. The capacity of self-purification depends mainly on the flow rate, retention time, oxidation-reduction and pH conditions, the length of the travelled path, i.e., the type of sediments in which it exists, and the hydraulic characteristics of the aquifer.

The beginning of radial collector wells use, built on the banks of the Sava River, is related to the increase in needs and expansion of the Belgrade water supply system. From 1953 until today, a total of 99 such wells were built, from the mouth of the Sava River to 53 km of the left and 15.5 km of the right bank (with smaller zones without abstraction wells). In addition to radial collector wells, the Belgrade groundwater system consists of 17 vertical wells in Makiš far from the Sava, 29 wells on the left bank of the inundation of the Sava River, and 3 deep drilled wells that abstract water from karst aquifers.

Dominant recharge of the wells is due to the infiltration of water from the Sava River into the aquifer. The recharge conditions are not ideal" [19] due to the layering of aquifer sediments, the Sava Riverbed's geometry, and the radial wells' position. This means that in a significant part of the source, even though the wells are on the banks of the Sava River and the Sava Lake, the capacity of the aquifer to achieve the mentioned self-purification effects is present (which was confirmed through analyses of the physic-chemical characteristics of the raw groundwater at the treatment plants).

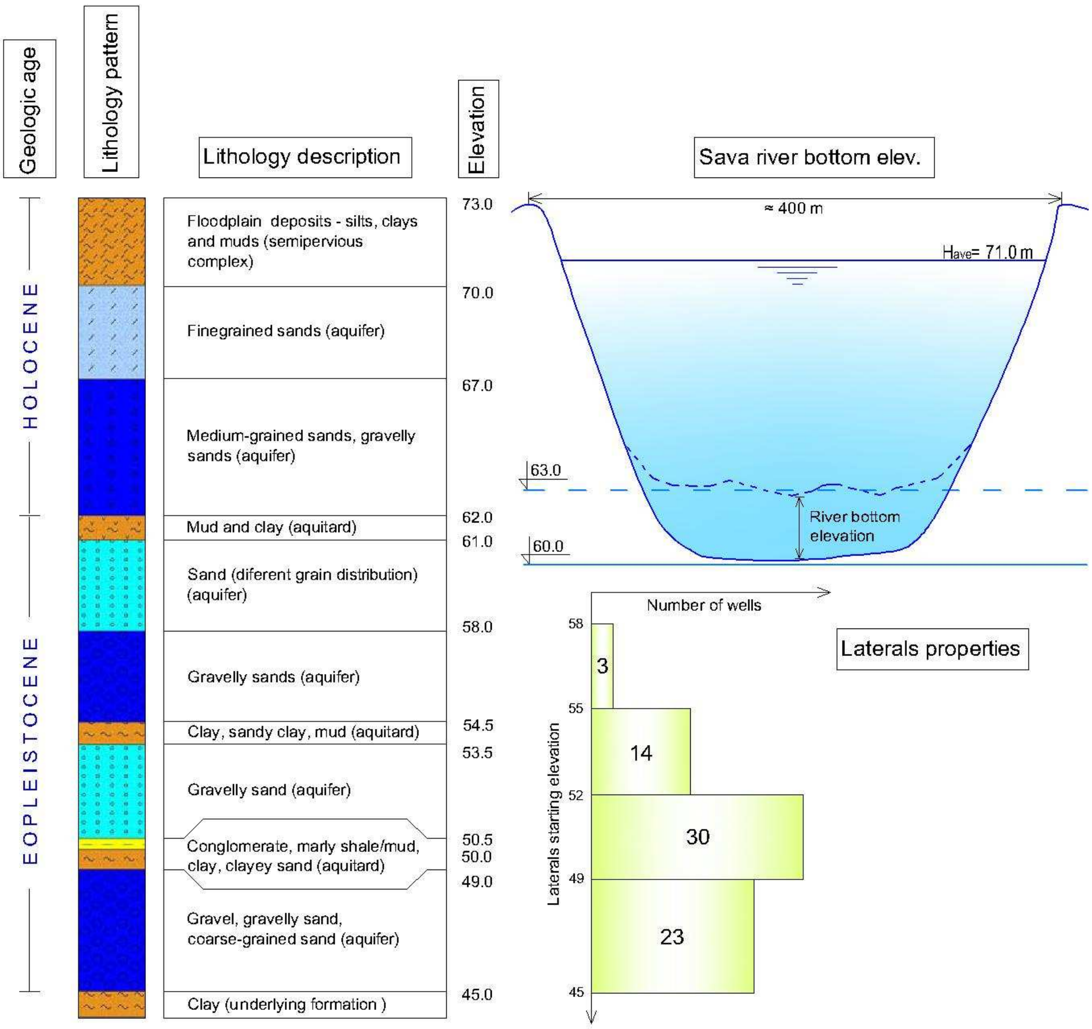

***Figure 4**. Altitude relationships of the RB drain zone, hydrogeological characteristics and geometry of the Save riverbed - part of the source downstream from the Ostružnica Bridge (according to Boreli Dj. and Slimak T.) [15]*

Part of the water abstracted by the wells also comes from the direction of the hinterland. The quantification of this inflow is not simple and requires detailed field measurements that are usually unavailable. By using the data on the total mineralization of the abstracted water, as well as the characteristics of the river water and the water of the hinterland of different sectors of the source, the approximate ratios of the participation of the waters of the Sava River and water from the backcountry in the total amount of abstracted groundwater were calculated. These inflows were also checked on the hydrodynamic models (Table 4). The presented data is a clear indicator that the preservation of the water quality of the Sava River is the most important for the protection of well water quality, but also that the influence of the hinterland is certainly not negligible.

Table 4. *Assessment of the share of hinterland water in the total captured groundwater at radial collector wells by sector in 2011 [20]*

Source area	Number of wells	Sum of well abstraction Q (l/s)	Q (l/s) inflow from the hinterland	% share of hinterland water
Ušće	5	347.4	127.7	36.8%
Marina and NB blocks	10	626.4	173.9	27.8%
Jocina Ada	4	221.7	41.6	18.8%
Donje Polje	12	438.7	55.6	12.7%
Upstream from the Ostružnica Bridge	29	908.0	122.5	13.5%
Ada Ciganlija	20	813.0		
Makiš	19	772.0	191.1	24.8%

Capacities of parts of the source by selected sectors

Radial collector wells are equipped with pumps with frequency regulators and operate at the set level. The amount of water abstracted by each of the wells is not directly measured but determined indirectly (through the power with which the pump aggregates work, through summary flow meters on the raw water system, and occasional systematic measurements on the wells). The use of wells is not constant throughout the year, so the "capacity of the sector" shown here is defined as the sum of the registered intakes of individual wells during the detailed measurement campaigns, which are usually realized in the period of low water or twice a year (data from PUC Belgrade Waterworks and Sewerage).

The “sector capacity” change is given for several sectional states from 2005 to 2019. The sectors are separated according to the differences in land use in the hinterland. In addition to the observed quantities of groundwater collection, the diagram also shows the exploitation that corresponds to the state of the source with the projected construction of new drains on many existing wells (the exploitation used in the development of the Elaborate on sanitary protection zones of Belgrade, SPZs). The registered well capacities ranged from 4500 to 2900 l/s in the last 15 years. The exploitation (Figure 5) amounts to about 5300 l/s, and this exploitation quantity was, in fact, the relevant one for defining the boundaries of the sanitary protection zones within the study.

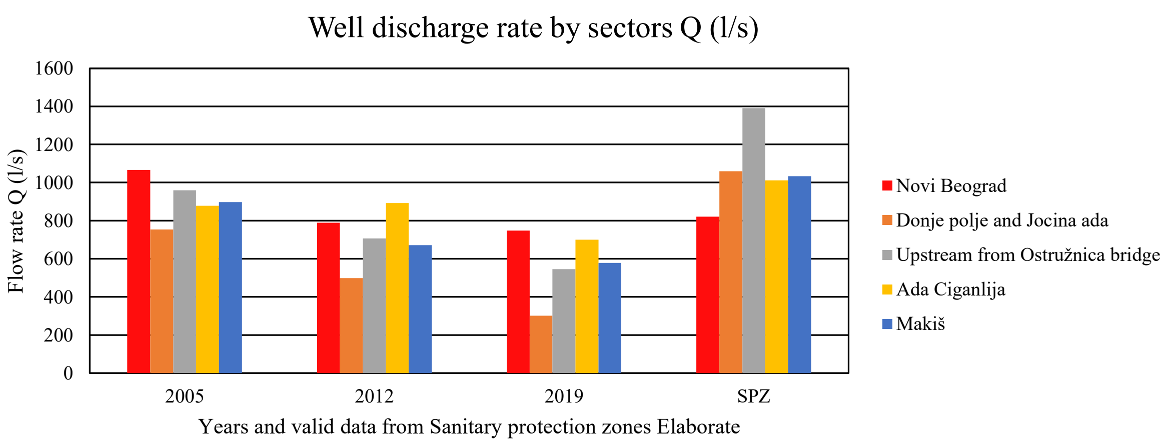

Figure 5. *The capacities of the wells of the Belgrade water source by sectors [2]*

Applied principles of determining sanitary protection zones of the Belgrade water source

Protecting resources, that is, the preservation of natural characteristics is ensured through applying appropriate measures and restrictions. The level of protection is achieved and the state of groundwater quality is monitored. Restrictions related to the protection zones of the source must be practical and in line with the needs and possible effects of the protection they achieve, which depend on the characteristics of the source, i.e., configuration, aquifer recharge conditions, capacity, the importance of the source, natural protection, existing and necessary monitoring, etc. The protection of the long linear series of wells built on the banks of the Sava River and the Sava Lake and the recharge conditions has two essential characteristics:

- protection must be carried out in a significant area of the zone between the river and the wells, as well as in the hinterland of the wells
- the risk of disruption of the overall quality of the abstracted groundwater due to pollution in the hinterland is relatively low, given the almost independent recharge zones (from the hinterland) of individual wells.

Immediate protection zone (Zone I)

Physical separation (fencing) of the immediate zone was not proposed, considering that the installation of a fence is usually impossible (due to existing embankments, local roads, promenades, etc.), except for a small number of wells where it was accomplished. The physical protection of the wells is achieved through a security system at the level of the structure itself (locking and anti-burglar alarms). The immediate zone of sanitary protection, which includes the above-ground and underground part of the radial collector well, was proposed at 60 m from the object and would visually be separated from the rest of the area by planting low vegetation.

***Figure 6**. An example of a well on the Makiš coast [20]*

Narrow protection zone (Zone II)

The boundaries of the narrow protection zone were defined based on the following most important criteria:

- requirements defined by the Rulebook on the method of determining and maintaining sanitary protection zones of water supply sources (Official Gazette of the RS, No. 92/08) [1],
- hydrogeological characteristics, micro and macro heterogeneity,
- source development plans, structure utilization plans (renovation or maintenance of radial collector wells),
- the current conditions in the area and in the surroundings,
- the results of monitoring the water quality on objects, indicators of anthropogenic influences,
- the available fund of relevant information in the immediate zone of the objects and in the surrounding area (number, quality, spatial arrangement of hydrogeological investigation works and monitoring results),
- results of hydrodynamic calculations and the assessment of the degree of reliability of the results, the wells recharge regime from the direction of the river and the hinterland,
- global risk assessment, that is, the results of the calculation of the impact of dispersion on the output quality of water in the well for the hypothetical appearance of a pollutant at the border of the zones (transport with dispersion effects for hydrodynamic conditions registered in the hinterland of individual wells - representative of the sector).
- the necessary aquifer monitoring regime (levels, abstraction and quality of groundwater),
- the general vulnerability assessment of the analyzed aquifer,
- the response of the aquifer to registered accidents in the area (if there were any).

In addition to the water travel time, when defining the border of the protection zone, the criterion of a minimum distance of 500 m to 560 m from radial collector wells was adopted for the upstream sector. This sector of the source has less relevant data outside the immediate zone of the water-collecting structures. The distance criterion was introduced because of the microheterogeneity that characterizes the Quaternary aquifer. The eventual existence of zones of higher permeability at one of the locations, which could not be registered due to a smaller fund of investigation works (a considerable amount of information, but still incomplete in some parts), would not significantly reduce the level of protection on such a long stretch of water flow, considering the self-purifying potential of the aquifer.

In the narrow protection zone, protection measures representing restrictions and additional protection measures were prescribed, which essentially increases the cost of using the area with strict control over the implementation of the specified conditions. These measures were defined for a large group of existing users/activities recorded through a specially implemented cadaster of users.

The position of the narrower protection zone's boundary for restoring many wells (the largest expected exploitation at the restored source in the future) is defined in the following range of water travel time through the aquifer (Table 5).

Table 5*. Criteria for adopted groundwater travel times when separating Zone II of the Belgrade water source by sector [20]*

Sector	Travel time in years	Sector	Travel time in years
Novi Beograd and Ušće	0.5 to 1 year	Ada Ciganlija	1.5 years
Donje Polje and Jocina Ada	2 to 7 years	Makiško Polje-tubular wells	1.5 years
Upstream of the Ostružnica Bridge	0.5 to 3 years	Makiško Polje RB	1.5 to 5 years

It is noted that the adopted travel times are far greater than the minimum prescribed by the Regulation (50 days). The shortest adopted water travel time proposed from the border of Zone II is 0.5 years (180 days). Considering the current level of development of the area in the hinterland of the source, the boundaries of the protection zone in the sector of Novi Beograd and Ušće have entered the existing urban area.

Wider zone of sanitary protection (Zone III)

The wider protection zone of the source includes the area where the construction and activity of built structures and the performance of other activities, which can cause a change in the water's natural composition, are predominantly monitored. When defining the boundaries of the wider protection zone, the following criteria were used:

- requirements defined by the Rulebook on the method of determining and maintaining sanitary protection zones of water supply sources (Official Gazette of the RS, No. 92/08) [1],
- natural hydrogeological and geomorphological boundaries,
- the existing level of area utilization and pressures that have been registered,
- the existing urban plans and their degree of development,
- the possibility of transferring negative impacts from the wider to the narrower and immediate protection zones through surface flows,
- the uniqueness of the surface water and groundwater sources based on one watercourse – the Sava River.

The wider protection zone includes the entire area of the Sava River valley, up to its terraces on the left bank of the upstream sector, that is, older sediments in the area downstream from the Ostružnica Bridge. The Sava watercourse and flood flow are an integral part of the broader zone of groundwater and surface water sources protection.

The wider protection zone also includes the area of the Veliko Ratno Ostrvo, which was considered by earlier technical documentation as a potential source area. Still, the project was not implemented due to the problem of preserving the natural conditions of the habitat (related to plant species and birds).

CHALLENGES IN DEFINING AND IMPLEMENTING SANITARY PROTECTION ZONES OF THE BELGRADE WATER SOURCE

Recognized challenges

When defining the sanitary protection zones, the following challenges were recognized:

- The inappropriateness of the co-existence of certain existing users and the required level of protection of the source in the established zones. The most extreme example is the railway yard in Makiš, which was in a narrower protection zone.

- Pronounced differences in the actual potential impacts of the user depending on their position within the defined zone. For example, the narrow area extends from 60 m from the wells to an average distance of 500 m or more from the water intake. Prescribed conditions had to be uniform within one zone regardless of local differences. That is why in certain parts, these conditions are too strict.
- Adjusting the borders of the sanitary protection zones to the development plans and use of the source. These plans are a dynamic category and subject to significant changes. For example, an infiltration system was previously planned in Makiš and Donje Polje (in the 1970s and 1980s). During the 1990s, the future infiltration source was moved further from the city and designed in the Zidine sector.
- The issue of illegal and legal users within the zones. Due to the prohibition of any land development (according to the Regulation from 1986), the area of the former narrow protection zone remained dominated by agricultural activity, land development was not planned (nor carried out), and most of the pre-existing and later constructed objects use septic tanks. The pressure on this area was constantly growing, and illegal and legal buildings and landfills were built, which were sometimes utterly incompatible with the purpose of water supply. To make matters worse, the attack on this area starts from the most attractive locations, that is, from the riverbank where the water supply objects are located: wells and water intakes on the Sava River.

All the challenges, in the conditions of the existence of protection zones formed in 1986, as well as poor building practice but also tolerating illegal structures near the wells, created unease with the public (and some experts as well) about any changes of protection zones boundaries, regardless of their justification.

Specifics when defining the sanitary protection zones of the Belgrade water source

The proposed measures and limitations were defined for 6 large groups of activities and over 85 types of facilities or activities. The selected groups of activities are: urban planning and construction works, municipal activities, industrial activities, agriculture and forestry, traffic and transport, sports, recreation, and tourism.

***Figure** 7. An example of the environment of the RB-1m wells, right bank of the Sava River [20]*

The list of activities was harmonized with with the Regulation and with the present users who reside in the proposed protection zones, as well as with the planned or desired purposes of certain parts of the defined area of the zones. For each of the listed activities, an expert opinion was given on the possibility and conditions of residing in certain protection zones of the Belgrade water source. For purposes that were not listed, procedures that needed to be implemented were explicitly suggested.

All the activities are classified into five categories, namely:

P – Prohibited – prohibited regardless of the application of protective measures.

NR – Not recommended – it requires the application of the standard, additional, and location-specific protection measures; most often, it refers to an activity already present as a detected activity at a site within the same zone. The necessary, locally specific measures are defined by a particular study of the risks of building the structure.

AA – Allowed, with the application of standard technical measures and additional protection measures resulting from a detailed analysis of the micro-location and characteristics of the planned structures.

A – Allowed, with standard technical protection measures.

P-AA – It is prohibited to create new and implement additional protection measures for existing ones (for example, this category includes golf courses and tracks for auto-moto races in a narrower protection zone in the area of sports and recreation activities).

Potential issues during the implementation of defined sanitary protection zones

Regarding the protection of water sources, the GUP (General Urban Plan) of the City of Belgrade (Official Gazette of the City of Belgrade No. 11/2016) [21] provides a graphic presentation of the zones and states: The protection of water sources is carried out under:

- Rulebook on the method of determining and maintaining sanitary protection zones of water supply sources (Official Gazette of the RS, No. 92/08) [1];
- Decision on sanitary protection zones on the administrative territory of the City of Belgrade for sources of groundwater and surface water that serve the purpose of water supply of the City of Belgrade (Ministry of Health, No. 530-01-48/2014-10 dated August 1, 2014) [22]; and
- Decision on the termination of the validity of certain decisions of the City Committee for Health, Labor and Social Policy and the City Committee for Health (Official Gazette of the City of Belgrade, No. 84/14) [23].

This means that in the GUP itself, which is a public document, citizens cannot get acquainted with the prescribed measures for protecting water supply sources, which certainly does not contribute to transparency regarding the application of measures.

At the request of individual investors, due to city needs or plans at the level of the Republic (SPSPA), during the development of plans, conditions are requested from competent institutions PUC BWS, the Secretariat for Environmental Protection, etc. PUC BWS has elaborated and supplemented the proposed measures and restrictions defined in the Elaborate in their conditions. Issues can arise when it is necessary to carry out additional local field investigation works and analyses, which should, through appropriate calculations, provide a hydrotechnical basis for planning purposes. On the other hand, the funds needed to carry out the necessary research often exceed the budget of the plans.

Therefore, it happens that in the zone that was defined as narrower in 1987 in the old Decision on zones, and which has remained the more limited zone of sanitary protection of sources in the new Decision from 2014, in the course of only 6 years, the number of users has increased and, therefore, the risk to the quality of groundwater. The example of the Makiško Polje zone between the Sava highway and the Sava River illustrates this perfectly.

***Figure 8**. 2015 - Layout of the area of the narrower protection zone (between the Sava highway and the Sava River) in the stage of development of the GUP, which includes new boundaries of the zones (red line-narrower zone; green line-wider zone) (source: Google - state in 2015)*

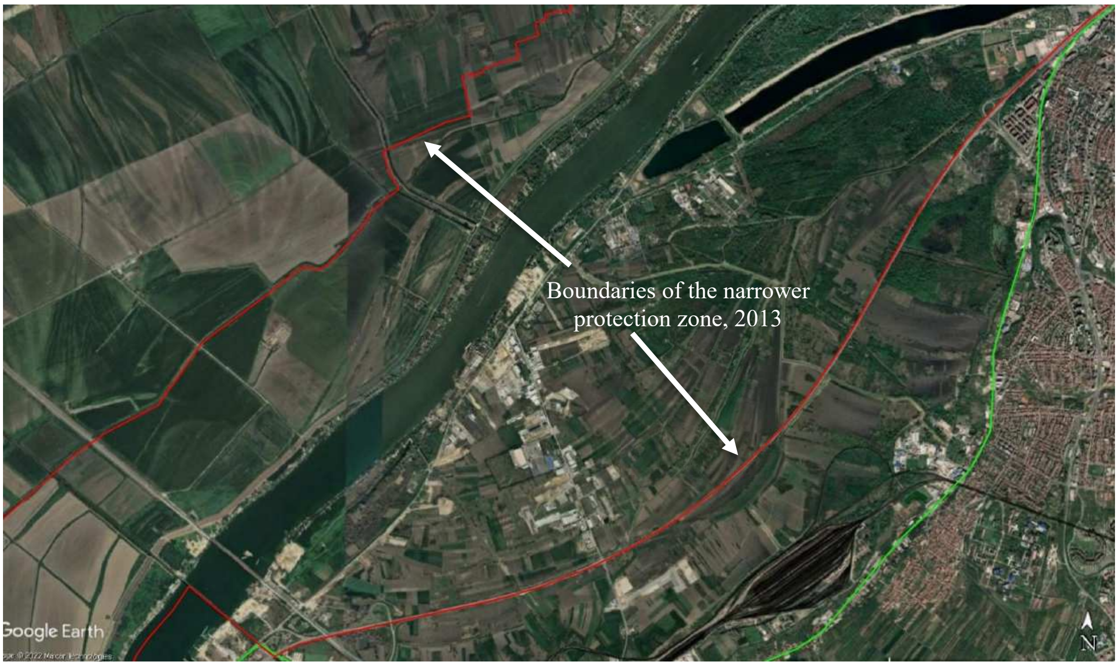

Figure 9. *2021 - Layout of the area of the narrower protection zone (between the Sava highway and the Sava River), 6 years after their determination (red line-narrower zone; green line-wider zone) (source: Google - state 2021)*

CONCLUDING REMARKS AND RECOMMENDATIONS

The definition of sanitary protection zones, their maintenance, and the implementation of measures defined within the Elaborate on protection zones, in the conditions of co-existence of groundwater sources and urban contents, is a big challenge that requires the coordination of all the participants in this process, from designers, planners, operators of sources, to the competent inspection services. The problems when defining the zones in such cases are reflected in how to reconcile the conflicting interests of preserving groundwater quality and the development and functioning of urban areas.

When defining sanitary protection zones under given conditions, in addition to the guidelines provided in the Regulation, hydrogeological characteristics, source development plans, current conditions, results of groundwater quality monitoring of the surroundings, results of hydrodynamic calculations, risk assessment, vulnerability assessments, and any possible reaction of aquifers to accidental pollution, must also be considered. Particular attention must be paid to the existing users of the area whose existence within the zone of sanitary protection is inappropriate. Forming an adequate monitoring program in the given location is necessary based on their potential influence.

Bearing this in mind, as well as the fact that in such cases, it is not possible to completely exclude the potential impact of urban areas on groundwater, the preservation of groundwater quality is reduced to strict compliance with measures within the defined sanitary protection zones and an adequate monitoring program that should allow enough time for reacting in the event of the appearance of pollutants in groundwater in the water source area. To that end, it is necessary to acquaint the public (users of the area) with the defined zones of sanitary protection of the source, as well as with the restrictions within the zones, to try to reduce the risk of possible (accidental or intentional) disruption to the quality of groundwater through the education of the population.

REFERENCES

[1] Rulebook on the method of determining and maintaining sanitary protection zones of water supply sources (2008). Official Gazette of RS 90/2008.

[2] Jaroslav Černi Water Institute. (2010). *Preliminary feasibility study with the general design of the Belgrade water system.*

[3] Nagy-Kovács, Z., Davidesz, J., Czihat-Mártonné, K., Till, G., Fleit E., Grischek, T. (2019). Water Quality Changes during Riverbank Filtration in Budapest, Hungary, *Water 2019*, 11, 302.

[4] Rajaković-Ognjanović, V., Đukić, A., Lekić, B., Ljubisavljević, D. (2013). Rainwater management, *Water and sanitary technology*, 43(2), 55-62.

[5] Gholipour S, Ghalhari MR, Nikaeen M, Rabbani D, Pakzad P, Miranzadeh MB. (2022). Occurrence of viruses in sewage sludge: A systematic review. *Science of the Total Environment*.

[6] Black, E.K., Finch, G.R. (1993). Detection and occurrence of waterborne bacterial and viral pathogens. *Research Journal of the Water Pollution Control Federation*, 63(4), 730-735.

[7] WHO Scientific Group on Human Viruses in Water Wastewater and Soil & World Health Organization. (1979). Human viruses in water, wastewater and soil: report of a WHO scientific group [meeting held in Geneva from 23 to 27 October 1978]. World Health Organization.

[8] Vivier, J.C. Ehlers, M.M. Grabow, W.O.K. (2004). Detection of enteroviruses in treated drinking water, *Water Research,* 38, 2699–2705.

[9] Barrett, M.H. (2005). Chapter 2 "Characteristics of urban groundwater" in „*Urban groundwater pollution, IAH International Contributions to Hydrogeology 24“,* David N.Lerner (Ed.), Taylor & Francis e-Library.

[10] Yates, M.V., Yates, S.R., Gerba, C.P. (1988). Modeling microbial fate in the subsurface environment. *Critical Reviews in Environmental Science and Technology,* 17(4), p 307-344.

[11] Rulebook on the Hygienic Safety of Drinking Water. (2019). Official Herald of the FRY, No. 42/98 and Official Gazette of the Republic of Serbia. No. 28 2019.

[12] Jaroslav Černi Water Institute. (2010). *Elaborate on sanitary protection zones of the "Ratno ostrvo" source in Novi Sad.*

[13] Jaroslav Černi Water Institute. (2010). *Elaborate on the sanitary protection zones of the source and processing complex "Strand" in Novi Sad – innovation*.

[14] Jaroslav Černi Water Institute. (2010). *Elaborate on sanitary protection zones of the "Petrovaradinska ada" source in Novi Sad*.

[15] Jaroslav Černi Water Institute. (2011). *Study of the Belgrade groundwater source - state and directions of development - I to IV phases*.

[16] Kovačević, S. (2017). Analysis of the self-purifying potential of groundwater for the removal of pharmaceuticals using the method of river coastal filtration. Doctoral dissertation, University of Novi Sad, Faculty of Technical Sciences. (in Serbian).

[17] Dimkić, M., H.J. Brauch, M., Kavanaugh, M. (2012). Groundwater management in large river basins. IWA Publishing, London, UK.

[18] Law on Waters. (2016). Official Gazette of Republic of Serbia Nº 30/10, 93/12, 101/16.

[19] Jaroslav Černi Water Institute. (1984). *A study of the impact of the Đerdap on the decline of the yield of the Belgrade Groundwater Source*.

[20] Jaroslav Černi Water Institute. (2013). *Elaborate on sanitary protection zones of underground and surface water sources used for water supply in Belgrade*.

[21] General Urban Plan of City of Belgrade. (2016) Official Gazette of City of Belgrade 11/2016.

[22] Ministry of Health of the Republic of Serbia, ref. 530-01-48/2014-10. (1 August 2014). Decision of the Sanitary Protection Zones Determination at the Administrative City Territory for the Underground and Surface Water Sources Used for Water Supply to the City of Belgrade.

[23] Decision on the termination of the validity of certain decisions of the City Committee for Health, Labour and Social Policy and the City Committee for Health. (2014). Official Gazette of the City of Belgrade, No. 84/14.

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

„J.ЧЕРНИ"

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