Water treatment technology upgrade resulting from water quality changes in reservoirs

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Abstract: Due to the change in water quality in the reservoirs used for water supply purposes, as well as the poor condition of the potable water treatment plants, there is a need to improve the existing treatment processes to achieve the required efficiency and safety in the operation of the system. This paper describes the causes and issues in the operation of specific plants for processing potable water in Serbia and the applied technical solutions to improve the technological process of water treatment, with a particular focus on resolving the issue of water supply in the City of Užice, caused by the appearance of cyanobacteria in the Vrutci reservoir.

INTRODUCTION

The World Health Organization (WHO) classified access to water supply and potable water quality as primary indicators of the population's health status. The facts show that even though we live in the 21st century, a significant percentage of the people in Serbia still drink water that is not compliant with the quality standards, as evidenced by official data from the relevant institutions. According to data from the annual Report on the health suitability of potable water, in 2020, there were 107 public water supply systems in urban areas (68.6% of the total number of controlled ones) that delivered water to consumers complying with legal regulations (Institute for Public Health of Serbia "Dr. Milan Jovanović Batut").

According to data of the Statistical Office of the Republic of Serbia, in 2021, 687 million m^3 of water was used for public water supply. Of the total water collected, 64.2% was groundwater and source water, 25.8% was from watercourses, and 10.0% was from lakes and reservoirs.

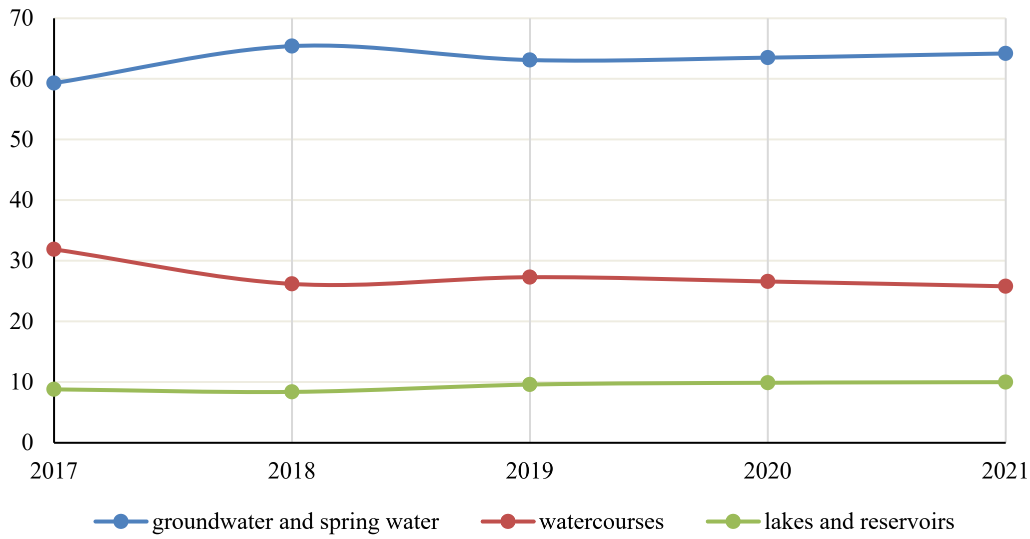

***Figure 1.** Share (%) of different water resources in the supply of potable water [1]*

The natural quality of groundwater on the territory of Serbia is quite uneven, which is a consequence of the different mineralogical-petrographic composition of water-bearing mediums, the genesis of groundwater and aquifers, the age of the water, different intensity of water exchange, etc. It ranges from water of an exceptional quality that does not require treatment to water that requires very complex treatment procedures before it can be used for public water supply. The lack of water at groundwater sources was solved by collecting and treating surface water, water intakes from watercourses, and constructing smaller and larger reservoirs to reach the required amounts of water in different hydrological conditions. A tabular presentation of the captured quantities of water by resource and by region of the RS is given in Table 1.

Table 1. *Share of captured water (in thousands of m^3) for 2021 by region of the Republic of Serbia [2]*

Type of captured waters	Total	From groundwater	From spring waters	From watercourses	From reservoirs
REPUBLIC OF SERBIA	686664 (p)	344601 (p)	96068 (p)	177319 (p)	68676 (p)
SERBIA - NORTH	368567 (p)	238609 (p)	8516 (p)	121442 (p)	0 (p)
Belgrade region	214018 (p)	92434 (p)	142 (p)	121442 (p)	0 (p)
Vojvodina region	154549 (p)	146175 (p)	8374 (p)	0 (p)	0 (p)
SERBIA - SOUTH	318097 (p)	105992 (p)	87552 (p)	55877 (p)	68676 (p)
Region of Šumadija and Western Serbia	175897 (p)	58307 (p)	40109 (p)	29795 (p)	47686 (p)
Region of Southern and Eastern Serbia	142200 (p)	47685 (p)	47443 (p)	26082 (p)	20990 (p)

(p) - previous data

Settlements in Vojvodina that are supplied with water from the basic water-bearing complex have significant problems regarding the quality of the water supplied to consumers due to the naturally high content of certain harmful substances (organic matter, arsenic, etc.). Local water supply sources often use groundwater from alluvial sediments through wells. The problems they face are, in the first place, related to susceptibility to pollution (absence of sanitary protection zones or non-compliance with prescribed measures, etc.) and the aging of wells at the source, manifested by a reduction in capacity. Certain cities/settlements in the Great Morava valley have significant problems with potable water quality due to high concentrations of nitrates in the aquifer.

Most of the reservoirs in Serbia used for water supply were built more than 30 years ago. Their condition in terms of water quality is not entirely satisfactory. Many reservoirs do not have a valid permit, the regulations on protection zones are often not followed, and the authority for the maintenance of the facilities used (water supply, flood protection, irrigation, etc.) is often unclear. The measures foreseen by reservoir designs, studies, and decisions on determining sanitary protection zones are partially implemented. Additionally, the infrastructure is worrying in many systems. Except for Ćelije, Gruža, and Barje, all reservoirs have significant maintenance problems [3]. In some of them, such as the Vrutci reservoir, which serves to supply water to Užice, the impaired quality of the lake water and outdated technology at its treatment plant have led to the suspension of water supply. Deterioration of water quality has also been registered in other reservoirs, which may, sooner or later, lead to a similar situation with the water supply of cities whose sources are these reservoirs.

WATER QUALITY IN RESERVOIRS IN SERBIA

The quality of water in reservoirs is a complex function of morphometry and characteristics of the catchment area, climate, hydrology, geology, morphology, land use, the purpose of reservoirs, as well as the features and structure of the ecosystem of the reservoir itself, that is, the physical, chemical, microbiological, and biological processes that take place in it. Bearing that in mind, the water quality differs significantly from one reservoir to another.

Numerous reservoirs are over 50 years old, while the catchment area is dominated by agricultural regions and settlements where the issues of wastewater treatment and municipal waste disposal have not been resolved. This greatly affects the state and quality of the water in the reservoir and, therefore, the treatment at the water treatment plants. Unregulated torrential flows of the main tributaries can introduce a significant quantity of suspended solids, nutrients, and metals (Mn, Fe, etc.), as well as microbiological pollution of anthropogenic and animal origin, pesticides, and other pollutants. In terms of potable water quality, from the physicochemical parameters, the following parameters most often deviate pH value, turbidity, color, organic matter, ammonia, nitrites, iron, manganese, nickel, etc. It has been demonstrated in practice that modern technological processes can be used to treat the water from the reservoirs to potable quality, regardless of their water quality.

The primary issue in the engineering practice of potable water treatment, whose sources are reservoirs and lakes, is the occurrence of algal blooms. In recent decades, these phenomena have become more frequent and widespread, resulting from eutrophication - the aging of reservoirs. This naturally slow process, accelerated by harmful anthropogenic influences, is further intensified by climate change (higher temperatures, extreme rains, longer dry periods). The results of the monitoring of the quality of reservoirs, carried out by the Environmental Protection Agency, indicate that the processes of eutrophication of reservoirs have advanced, resulting in a large number of reservoirs used for water supply having a weak or poor ecological potential [4]. An increase in nutrients leads to increased productivity of aquatic ecosystems, which can lead to an excessive increase in algal biomass or macrophytic vegetation. Although phytoplankton has a crucial role in aquatic ecosystems, as the primary producer of organic matter in water, its excessive accumulation can seriously affect water quality, especially if anaerobic conditions are created. As a result, there is an increased content of suspended solids in water, concentrations of ammonia, nitrite, metals, hydrogen sulfide, methane, and humic acids [5]. Phytoplankton species differ in the ecological, morphological, and physiological characteristics that allow them to survive and reproduce. They can strongly influence the potable water treatment process by producing secondary metabolites. Algae, as a part of suspended particles in water, can cause the destabilization of flocs and negative affect the sedimentation process, which results in a greater intake of algal biomass on sand filters, a reduction in the efficiency of the filter, and the need for more frequent washing of the filter, which, as a direct consequence, increases the production costs of potable water. Algae can lead to organoleptically unacceptable water quality (color, unpleasant taste, and odor - geosmin, methylisoborneol). They can also be a source of substances that are harmful to the health of consumers (various cyanotoxins, etc.). The finding of algae and zooplankton in the final water indicates that the potable water treatment process is compromised and risky in terms of the penetration of other microorganisms, including pathogens.

In recent decades, at the global level, the spread of "blooming" of cyanobacteria has been noticed in many lakes and reservoirs [5]. Cyanobacteria are potentially toxic organisms, as they can produce a wide range of toxins, the impact of which varies from neurotoxicity and hepatotoxicity to mild irritation [6]. Of the cyanobacterial species recorded so far, between 50% and 75% exhibit toxicity and have been recorded on every continent. However, it should be noted that not every bloom of a particular species is toxic [3]. A bloom's toxicity depends on the ratio of toxic to non-toxic strains present in a specific bloom. Future climate change scenarios predict rising temperatures, increased vertical stratification of aquatic ecosystems, and changes in seasonal and interannual weather patterns (including droughts, storms, and floods). The prevailing opinion in the literature is that climate change will be a catalyst for the further expansion of cyanobacterial blooms on a global scale and that current water management strategies must be adapted to the ecological effects of global warming [7]. The magnitude of the problem today is indicated by the estimated damage caused by eutrophication in the United States of America (USA) alone amounts to approximately 2.2 billion USD per year. Climate change is expected to contribute to water quality degradation due to higher water temperatures, reduced dissolved oxygen concentrations, and thus reduced capacity for self-purification. Due to more frequent floods and droughts due to climate change, there are other risks of water pollution and contamination with pathogens caused by floods or higher concentrations of pollutants in dry periods.

WHO has provided guidelines for assessing the risk to the population's health in relation to the registered number of cyanobacteria cells in water used for water supply purposes. According to these guidelines, a population of cyanobacteria < 2,000 cells/ml, i.e., a concentration of chlorophyll in water up to 1 µg/l represents a low risk, from 2,000 to < 100,000 cells/ml – moderate to high, and over 100,000 cells/ml or 50 µg/l of chlorophyll a represents a high risk [8]. In some reservoirs in the Republic of Serbia, over 100,000 cells/ml were registered, representing a high risk due to a potential breakthrough through the water treatment system or the cause of its failure due to a high biomass load. This phenomenon was noted in the reservoirs Vrutci, Ćelije, Garaši, and Gruža [4]. The Gruža reservoir, used for Kragujevac's water supply, suffers from a large anthropogenic impact. High levels of nutrients significantly impact the appearance of cyano-blooming in this reservoir [3]. The intensive expansion of cyanobacteria (mainly the *Aphanizomenon flosaquae* species) and blooming phenomena observed during the summer period of the last few decades indicate the eutrophic status of the reservoir [9]. A selective water intake was implemented with inlets on three levels to improve raw water quality at the WTP Gruža. A system for hypolimnetic diffuse aeration was installed in the water intake zone (at 50 m and 150 m).

The primary role of the Garaši and Bukulja reservoirs is the water supply of Aranđelovac. Physic-chemical and algological research carried out in these reservoirs indicates a deterioration of water quality and the need for interventions to reduce the trophic state of the reservoirs. According to the results of research carried out so far, the reservoirs belong to mesotrophic-eutrophic reservoirs. Algological research carried out from 2004 to 2011 found that fire algae dominated phytoplankton, but cyanobacteria were always subdominant. A mass cyanobacteria bloom was established in 2006 (*Planktothrix agardii, Aphanizomenon flos-aquae, Microcystis aeruginosa,* and *Anabaena affinis*). The highest intensity of blooming was in 2016 of the species *Planktothrix agardhii* [4], and it appeared sporadically along the coast in 2018 and 2019. According to PUC "Bukulja" data, algae and toxins were not registered in potable water samples. The Ćelije reservoir faced quality-related problems very early, given that untreated municipal and industrial wastewater flows into it. The first incident of cyano-blooming was recorded as early as 1988. It has been repeated several times, the last time in 2003 (*Microcystis aeruginosa, Aphanizomenon flos-aquae*, *Anabaena circinalis*). Problems with water quality caused the improvement of the treatment technology at the "Majdevo" plant and the associated operating laboratories.

Apart from the ones mentioned, blooming incidents were also registered at other reservoirs. The Bovan reservoir, from which potable water is supplied to Aleksinac, had blooming episodes in the last 20 years, and biomass peaks from the phylum *Pyrrophyta - Ceratium hirundinella* (2001) and from the phylum *Cyanobacteria* (2006). Also, according to the estimated abundance in the RHMS Report from 2009, the algal community is dominated by *Ceratium hirundinella*. Various studies have concluded that *Ceratium hyrundinella* (Dinoflagellata) is a frequent constituent of freshwater lakes and reservoirs and is found in many trophic states. In deep stratified lakes, it typically co-dominates with *Microcystis aeruginosa* (a toxic cyanobacterium) during the summer months, with populations typically exceeding 10^3 cells/ml.

Algological research of the Sjenica, Zlatar, and Radoinja reservoirs until 2003 revealed that their characteristic periodical bloom was caused mainly by the species *Planktothrix rubescens* (Cyanobacteria), with a trophic status within the limits of meso-eutrophy [10,11]. Tests of the reservoir show that *Oscillatoria rubescens* has been appearing since 1989 in the Sjenica reservoir. Recent tests indicate that the Sjenica reservoir is under significant pressure from nutrient and organic pollution, which arrives via the Uvac River and the main tributaries of the reservoir, with the most significant load at the entrance to the reservoir. Eutrophication in the Sjenica reservoir also results in the appearance of filamentous formations at the plant in Priboj, which is supplied with water primarily from the downstream Radoinje reservoir, where the remains of algae lead to the rapid clogging of the filter fields, the deterioration of the raw water quality, which all together requires additional activities at the plant and increases water treatment costs.

The development of analytical instrumental technologies and new knowledge about the harmful effects of certain substances on human health has to lead to changes in the legal regulations regarding the requirements for the quality of potable water supplied to consumers. Due to the unknowns and lack of data on the mechanisms of toxic effects related to cyanobacteria, and in terms of prevention and precaution, WHO issued guidelines for only one cyanotoxin, microcystin-LR (1 µg/L), which is the most toxic cyanotoxin discovered so far. The Global Water Research Coalition (London, 2009) recently issued international guidelines on toxic cyanobacteria and water supply. In June 2015, the US Environmental Protection Agency (US EPA) published guidelines for public water supply systems regarding managing the risks of cyanotoxins in potable water [12].

EXISTING STATE OF WATER TREATMENT PLANTS AND THE NEED FOR IMPROVEMENT OF TECHNOLOGICAL PROCESSES

Problems in the operation of water treatment plants (WTP)

Water treatment plants from reservoirs built in the 1980s in Serbia mostly had similar treatment technology that achieved excellent results for the water quality at that time. Problems in operation and achieving the effects of these facilities began with the gradual worsening of the water quality in the reservoirs, primarily caused by the processes of "aging". The recognized causes of problems in the operation of the plants were of crucial importance for the subsequent selection of solutions to improve the existing water treatment processes. Table 2 gives a comparative overview of existing technological treatment procedures at select water treatment plants in Serbia that use water from reservoirs as raw material, and where the first step is very often pre-disinfection with chlorine in the raw water pipeline.

Table 2. *Comparative overview of the original technological treatment procedures on selected WTPs in Serbia*

Plant	Capacity	Pre-treatment	Main treatment	Disinfection
WTP "Bukulja" Aranđelovac	300 l/s	Cascade aeration and circular coagulator "Passavant" (dosing of Al-sulphate and polyelectrolyte together with sedimentation)	Filtration in closed self-cleaning steel filters	Chlorine gas
WTP "Majdevo" Kruševac	500 l/s	Dosing of Al-sulphate and polyelectrolytes in the distribution chamber and sedimentation in the pulsator	Ozonation and filtration on open concrete sand gravity filters	Chlorine gas
WTP "Bresje" Aleksinac	300 l/s	Dosing of Al-sulphate and polyelectrolyte, sedimentation on a lamella clarifier (with honeycomb lamellae)	Filtration on open concrete sand gravity filters	Chlorine gas
WTP "Petar Antonijević" Užice	400 l/s	Dosing of Al-sulphate and polyelectrolytes in the distribution chamber and sedimentation in the pulsator	Filtration on open concrete sand gravity filters	Chlorine gas
WTP "Mihajlovac" Priboj	275 l/s	Dosing of Al-sulphate and polyelectrolytes, hydraulic type of flocculation, and sedimentation in a lamella clarifier	Filtration on open concrete sand gravity filters	Chlorine gas

After more than two decades of operation, problems began to appear in the operation of these plants, and they could be overcome by changing the doses of chemicals and experienced plant management. Over time, raw water quality changed significantly, the existing processing technology was less and less adequate, and the equipment became worn out. Below is a brief overview of the recognized problems and operational difficulties encountered by the mentioned plants.

Table 3. *Overview of recognized problems in the operation of the plants in the period since 2000*

<table>
<tr><th>Plant</th><th>Pre-treatment</th><th>Main treatment</th><th>Disinfection</th><th>Other</th></tr>
<tr><td>WTP "Bukulja" Aranđelovac</td><td>Inadequate dosing of chemicals</td><td>Absence of the oxidation process
Inefficient operation and very poor condition of the filters</td><td rowspan="5">An outdated method of disinfection</td><td rowspan="5">Obsolescence of all equipment
Lack y of wastewater and sludge treatment
Insufficient equipment/absence of adequate equipment for monitoring and monitoring water quality
Lack of measuring and regulating equipment
Lack of modern automation and management</td></tr>
<tr><td>WTP "Majdevo" Kruševac</td><td>Absence of coagulation and flocculation processes Inadequate operation of the pulsator (works like a regular clarifier)</td><td>Deterioration of the sludge discharge system</td></tr>
<tr><td>WTP "Bresje" Aleksinac</td><td>Inadequate dosing of chemicals</td><td>Absence of the oxidation process</td></tr>
<tr><td>WTP "Petar Antonijević" Užice</td><td>Absence of coagulation and flocculation processes Inadequate operation of the pulsator (works like a regular clarifier)</td><td>Absence of the oxidation process</td></tr>
<tr><td>WTP "Mihajlovac" Priboj</td><td>Absence of coagulation and flocculation processes</td><td>Absence of the oxidation process</td></tr>
</table>

Common to the mentioned plants was the lack of adequate preparation of water during the clarification process (insufficient time for the reaction to take place, inadequate place and method of dosing chemicals), i.e., the absence of effective coagulation and flocculation, as well as treatment of technological wastewater and sludge. Unlike the other plants, only WTP "Majdevo" had an ozonation process, which contributed to the plant successfully overcoming the challenges in terms of quality deterioration in the raw water in the Ćelije reservoir. Based on the experience gained from the example of WTP "Majdevo," it was concluded that the main disadvantage of other plants is the absence of the oxidation process, which would reduce the load on the filters and increase the treatment efficiency. In addition to the mentioned shortcomings, deterioration of most of the equipment at all the plants was registered due to decades of exploitation. In particular, the lack of adequate equipment for monitoring the effects of purification, tracking, and monitoring the quality of raw and treated water is particularly noteworthy, primarily because of the lack of biological laboratories at production plants.

Applied solutions to improve the treatment process

By analyzing the existing technological processes of treatment, the condition of the facilities, and the equipment in relation to changes in the quality of raw water, solutions were proposed for improving technological lines at the mentioned water treatment plants and their modernization. Improved technological procedures, application, and treatment efficiency provide further guidelines for solving problems at other plants with similar operational problems. When deciding on the manner to improve the treatment technology, in addition to ensuring the required quantity of water, what is primarily taken into account is that the quality of the water from the plant meets the criteria outlined in the Regulation on potable water [13]. Table 4 shows the adopted technological solutions for improving water treatment per the system's real needs and requirements.

***Table* 4.** *Adopted solutions for the improvement of technological treatment procedures*

<table>
<tr><th>Plant</th><th>Pre-treatment</th><th>Main treatment</th><th>Disinfection</th><th>Other</th></tr>
<tr><td>WTP "Bukulja" Aranđelovac</td><td>A modern system for the preparation and dosing of chemicals</td><td>The new processing unit for ozone oxidation
New filtration system</td><td>Disinfection using a UV system and a system for obtaining a NaOCl solution by electrolysis</td><td rowspan="5">Lagoons for wastewater and sludge treatment
Modernization and replacement of outdated equipment
New equipment for management and monitoring</td></tr>
<tr><td>WTP "Majdevo" Kruševac (capacity increased to 1000 l/s)</td><td>Correction of pH by introducing CO_2
Pre-disinfection with ClO_2
A modern system for the preparation and dosing of chemicals
New processing unit for coagulation and flocculation
Repurposing of the existing pulsators into lamella clarifiers</td><td>Modernization of ozonation equipment
Reconstruction of existing filters</td><td>Disinfection using a UV system and a system for preparing a NaOCl solution by electrolysis</td></tr>
<tr><td>WTP "Bresje" Aleksinac</td><td>Pre-disinfection / pre-oxidation with ClO_2 at the water intake at the dam
A modern system for the preparation and dosing of chemicals</td><td>The new processing unit for ozone oxidation
Reconstruction of the filter by introducing a specific double bottom system</td><td></td></tr>
<tr><td>WTP "Petar Antonijević" Užice (capacity increased to 500 l/s)</td><td>Pre-disinfection with ClO_2
A modern system for the preparation and dosing of chemicals
New processing unit for coagulation and flocculation
Repurposing of the existing pulsators into lamella clarifiers</td><td>The new processing unit for ozone oxidation
Reconstruction of existing filters
New processing unit filters with granulated activated carbon (GAC)</td><td>A new way of disinfection by applying ClO_2</td></tr>
<tr><td>WTP "Mihajlovac" Priboj</td><td>New processing unit for coagulation and flocculation
Reconstruction of the existing lamella clarifier</td><td>The new processing unit for ozone oxidation
Reconstruction of existing filters</td><td>A new way of disinfection using a system for the preparation of a NaOCl solution by electrolysis</td></tr>
</table>

Considering the significant eutrophication problem and the occurrence of biological indicators in the reservoirs, the ozonation process is necessary as part of the treatment. Before applying ozone, a good pre-treatment is required, which includes pre-disinfection/oxidation and coagulation and flocculation with chemical dosing. The filters at the plants are a crucial system for water treatment, so it is planned to proceed with the reconstruction of the existing filter units and, where necessary, with the introduction of a new filtration method. Applying an additional level of filtration on activated carbon filters contributes to better efficiency and safety in water treatment technology, so this step is always a good solution. The final disinfection of water ensures the presence of the required residual disinfectant in the network for consumers. For these purposes, the introduction of new technologies for generating sodium hypochlorite (NaOCl) or chlorine dioxide (ClO_2) solutions on site is foreseen. After the introduction of new technological units and the reconstruction of the existing ones, outstanding work effects and water quality were obtained by the Regulation, which was confirmed by official analyses of the quality of water distributed to consumers by competent public health institutes that perform monitoring under legal regulations (WTP "Majdevo," WTP "Bresje," WTP "Petar Antonijević," WTP "Bukulja," etc.).

SOLVING THE PROBLEM OF WATER SUPPLY DUE TO ALGAE "BLOOMING" - THE EXAMPLE OF THE CITY OF UŽICE

Deterioration of water quality in the Vrutci reservoir and problems with water supply

At the end of 2013 and the beginning of 2014, there were severe problems with the quality of water in the Vrutci reservoir, as a result of which, the entire city and the surrounding settlements were left without high-quality drinking water because the water treatment plant was not able to meet the required level of water quality with the existing technological treatment process. The Government of the Republic of Serbia immediately formed an expert team tasked with developing a long-term remediation program for water quality from the Vrutci reservoir and the Terms of Reference for the reconstruction of the existing plant for the treatment of potable water. The Terms of Reference provided an initial, optimal proposal for water treatment technology so that the existing facilities of the plant could be used to the maximum extent and maximum efficiency and flexibility during operation could be ensured.

The raw water of the Vrutci reservoir is characterized by elevated values of turbidity and color, as well as a high content of organic matter, manganese, ammonium ions, and occasionally iron and nitrates. The content of these parameters in raw water was measured within the following limits: color 0.6-35 °Pt-Co, turbidity 0.4-16 NTU, pH 6.7-8.4, oxidability 7.5-28 mg/l, nitrates <GD ~13 mgN/l, iron <0.01-0,47 mg/l, manganese <0.01-3.6 mg/l (average ~ 0.1mg/l), ammonium ion <GD-0.7 mgN/l and TOC 3-9.2 mgC/l. In addition, a problem was noted with the appearance of cyanobacteria - species *Planktothrix rubescens*, as well as nematodes in raw water that is captured for the needs of the population's water supply and industry. *Planktothrix rubescens* belongs to the planktonic, freshwater species that appear in mesotrophic and eutrophic large lakes and stagnant waters.

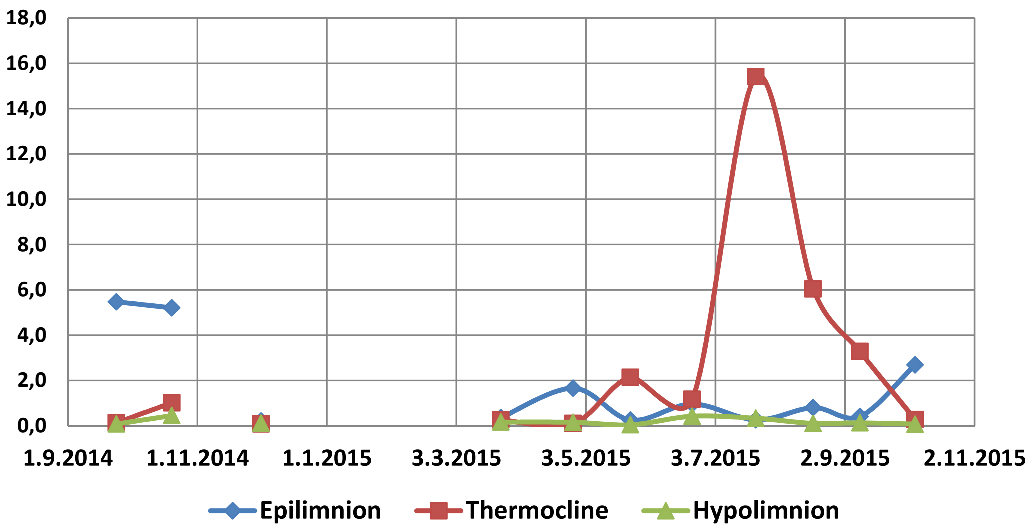

***Figure 2.** Phytoplankton biomass in Lake Vrutci (mg/l)* [6]

They color the water red during the blooming period and often bloom under the ice in winter, coloring the water red (Figure 3). Studies of Planktothrix species have shown that they contain the highest concentration of microcystins per gram of dry weight. P. rubescens probably settled in Lake Vrutci in the period between 2009 and 2011, when there was a significant increase in the internal load in the conditions of a change in the water discharge regime from the reservoir or the occurrence of intense anaerobic conditions at the bottom of the reservoir for some other reasons. Due to the worsening of the reservoir's water quality, the treated water quality occasionally deviated from the values allowed by the Regulation. The reason for the bacteriological unsuitability was most often the presence of aerobic mesophilic bacteria, as well as bacteria of coliform origin, while the most common cause of physic-chemical unfitness was the increased share of potassium permanganate, i.e., the percentage of organic substances. Increased turbidity and residual chlorine concentration were occasionally registered.

Figure 3. *The appearance of the reservoir due to cyanobacteria*

Emergency measures for the removal of cyanobacteria

To quickly intervene to reduce the content of cyanobacteria at the plant and in the distribution network, immediate and short-term chlorine dioxide dosing was started in January 2014. Based on the water analyses obtained during the emergency intervention on January 6 and 7, 2014, the diagrams show chlorine dioxide doses and the content of Planktothrix rubescens cells by processing stages.

On the first day, a high dose of chlorine dioxide of 1 mg/l was applied to reduce cyanobacteria's content in the water supply system urgently.

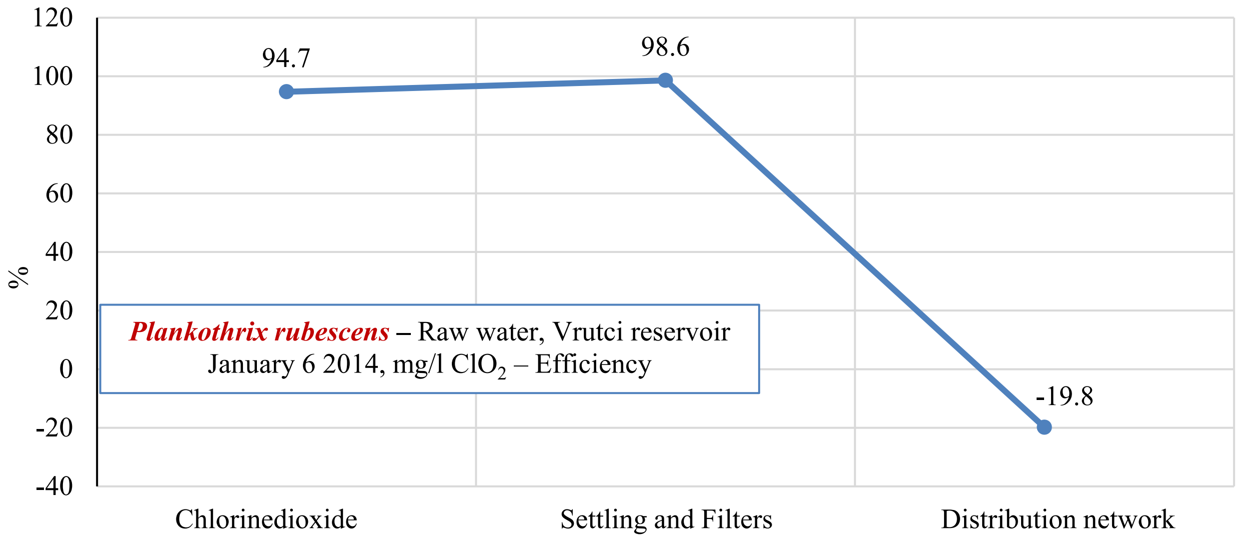

Figure 4. *The degree of removal of cyanobacteria - in the water treatment phase with a dose of 1.0 mg/l ClO_2 [14]*

On the second day, the dose was reduced three times to 0.3 mg/l, considering that according to the Regulation on potable water, 0.4 mg/l of chlorine dioxide is allowed in the water distributed to consumers. It can be concluded that even with a smaller dose of ClO_2, significant effects were achieved that enabled Užice to temporarily switch to an alternative water intake from the Sušičko Vrelo reservoir until the modernization of the water treatment plant is completed.

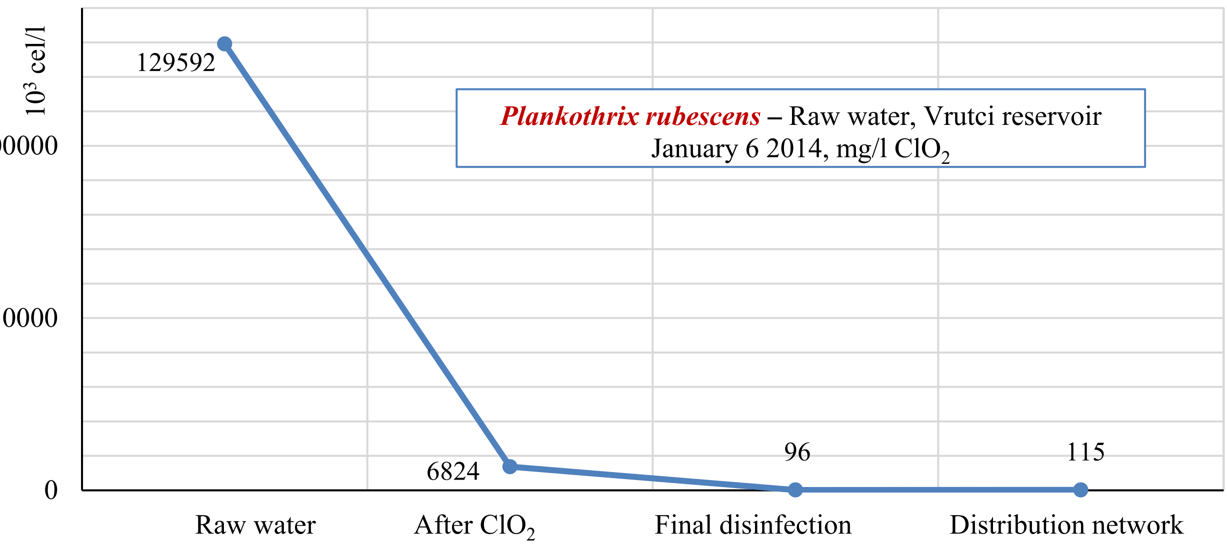

Figure 5. *The degree of removal of cyanobacteria - in the water treatment phase with a dose of 0.3 mg/l* ClO_2 *[14]*

Foreign experiences regarding the removal of cyanobacteria and cyanotoxins from the water

World practice regarding the appearance of cyanobacteria and how to remove them has shown that, in most cases, cyanotoxins are cell-bound (intracellular). Thus, any physical particle separation process that removes cyanobacterial cells without damaging them is an effective barrier to cyanotoxins, especially microcystins. Pre-oxidation is often applied to improve other processes, such as the effects of coagulation. Hence, it is essential to keep in mind the potential risks of cell lysis and cyanotoxin release. The effects of cyanobacteria oxidation were obtained based on the analyses carried out with different doses. The percentage of cyanobacteria oxidation depends on the dose of chlorine and the type of cyanobacteria registered in the water. With chlorine doses of 2-3 mg/l, a high degree of oxidation is obtained, over 90%, while with doses of over 4 mg/l, that percentage goes up to 100% for certain types of cyanobacteria. Other compounds were tested for these purposes, such as ozone, chlorine dioxide, potassium permanganate, etc. The application of ozone shows a high percentage of oxidation for all examined species of cyanobacteria with doses up to 5 mg/l, which is expected. The application of potassium permanganate gives different effects in relation to the species present. Applied doses of 1-2 mg/l and a specific reaction time provide a 100% oxidation effect on *Microcystis st*. Additionally, the dosing of 1 mg/l of chlorine dioxide with a particular time for the rejection of the reaction gives an oxidation effect of 100% for the same type of cyanobacteria. The obtained effects of the application of different oxidizing agents show a high degree of oxidation of different types of cyanobacteria with the application of adequate time for the reaction to take place, with the best effects being achieved on the cyanobacteria *Microcystis st* [15, 16].

Conventional treatment for removing cyanobacteria from water involves coagulation and flocculation, followed by clarification and rapid filtration. Coagulation and flocculation are processes that group suspended particles with the help of chemical coagulants, such as various aluminum and iron salts, synthetic organic polymers, or a combination of inorganic and organic coagulants.

In the clarification process, coagulated particles (flocs) are separated from the water by sedimentation, dissolved air flotation (DAF), or up-flow clarification processes. Two common alternatives to the conventional process are direct filtration, where there is no clarification step, and contact filtration, where the flocculation and clarification steps are eliminated. While the coagulation process is ineffective at removing dissolved (extracellular) cyanotoxins, it is very effective at eliminating intracellular cyanotoxins.

Morphological characteristics of cells, especially their size, shape, and surface characteristics, can influence the effectiveness of coagulants used to remove cyanobacteria. Some studies have shown that removal efficiency increases with cell size, with spherical cells having greater removal efficiency than elongated cells. Consequently, microscopic examination of cyanobacteria – even without identifying the species – can help optimize the efficiency of coagulation and flocculation processes. Some practical experience suggests that another indicator of coagulant dose might be cell surface area: smaller cells would require a higher dose than larger cells at equivalent biovolume. Inconsistent findings indicate that the effectiveness of coagulation depends on the type of cyanobacteria and the water quality, and doses and coagulants vary from case to case, depending on the applied treatment processes. After coagulation, the formed flocs must be removed from the water, mainly by sedimentation. Dissolved air flotation (DAF), a process in which air bubbles introduced at the bottom of the chamber push flocs to the surface, is particularly effective for removing cyanobacteria. Cyanobacteria that cause eutrophication contain gas vacuoles responsible for their rise to the water surface [17], which is why clarification is more efficient with flotation rather than sedimentation. However, DAF cannot be applied to all waters loaded with cyanobacteria. Generally, only colored waters of low turbidity are subject to flotation processes [15]. Some tests have shown satisfactory results using PAC as a coagulant. The efficiency in removing cyanotoxins depends on the type of cyanotoxin, the type of PAC, its dose, dosing site, contact time, and DOC content.

It is expected that after clarification, the water is sent to filtration, where different materials are used as filter filling, including sand, anthracite, and activated carbon. Although the filtration process effectively removes remaining flocs, individual cells and/or filaments may break through and be present in the filtered water. Most cyanobacterial cells and filaments are 2 µm or bigger in size; therefore, membranes with a pore size smaller than this, such as microfiltration (MF) and ultrafiltration (UF), will remove cells. As coagulation is applied as a membrane pre-treatment, the presence of cyanobacteria will likely lead to a rapid increase in transmembrane pressure and affect the purification process. MF and UF are ineffective in removing soluble cyanotoxins because the pore diameters are larger than these molecules. On the other hand, the pore size of membranes in nanofiltration (NF) and reverse osmosis (RO) is smaller than cyanotoxin molecules. The rejection of various toxins by these membranes depends on the molecular weight cutoff (MVCO) and membrane surface chemistry, the relationship between these factors, and the size and chemical characteristics (such as polarity, charge, and hydrophilicity) of the toxins.

Granular activated carbon is used as filter filling in place of conventional mediums for rapid filtration or, more commonly, as a final step in final water quality treatment. GAC is highly effective in removing microcystins, saxitoxins, and anatoxins. However, continuous dissolved organic matter adsorption reduces the GAC filter's adsorption capacity for cyanotoxins and consequently reduces its service life. GAC will remove cyanotoxins below the detection limit in most cases, but after a few months of operation, there is usually a significant breakthrough. A combined process, where ozonation precedes filtration with activated carbon, has proven to be highly effective because cyanotoxins are susceptible to ozonation. GAC can remove all oxidation by-products.

Presentation of the technical solution for improving the technological process of water treatment at WTP "Petar Antonijević"

With a detailed analysis and a comprehensive approach, a solution was adopted to improve the existing water treatment technology at the plant to solve the problem in the long term and so that the plant could supply water under the Regulation on potable water. During the development of the treatment concept at WTP "Petar Antonijević," particular attention was paid to the removal of cyanobacteria for the most part through primary treatment, sedimentation, i.e., clarification with the correct selection of chemical doses, and then, as an improvement of technology, the ozone block, and GAC filters were introduced, which guarantee the safety of the system's operation to remove cyanotoxins. The plant's capacity has remained unchanged in terms of technology and equals 400 l/s, while the possible hydraulic capacity is 500 l/s.

The adopted technology for treating water to drinking quality is presented below [14]:

- pre-disinfection of lake water (ClO_2/Cl_2),
- a complete line for coagulation and flocculation in the new facility with chemical dosing of adequate coagulants and flocculants (Al-sulphate / poly aluminum chloride and polyelectrolytes),
- sedimentation in existing clarifiers with their reconstruction into lamella clarifiers to improve the efficiency of settling well-prepared particles previously in the coagulation and flocculation processes,
- the ozonation process in the new facility, which is a vital part of the treatment process,
- filtration on rapid, open sand filters with their complete reconstruction, along with the washing system,
- filtration on activated carbon filters (GAC filters) in the new facility,
- final water disinfection (ClO_2/Cl_2),
- treatment of technological wastewater in the clarifier – a lagoon in the new facility,
- modern automation and management,
- auxiliary facilities.

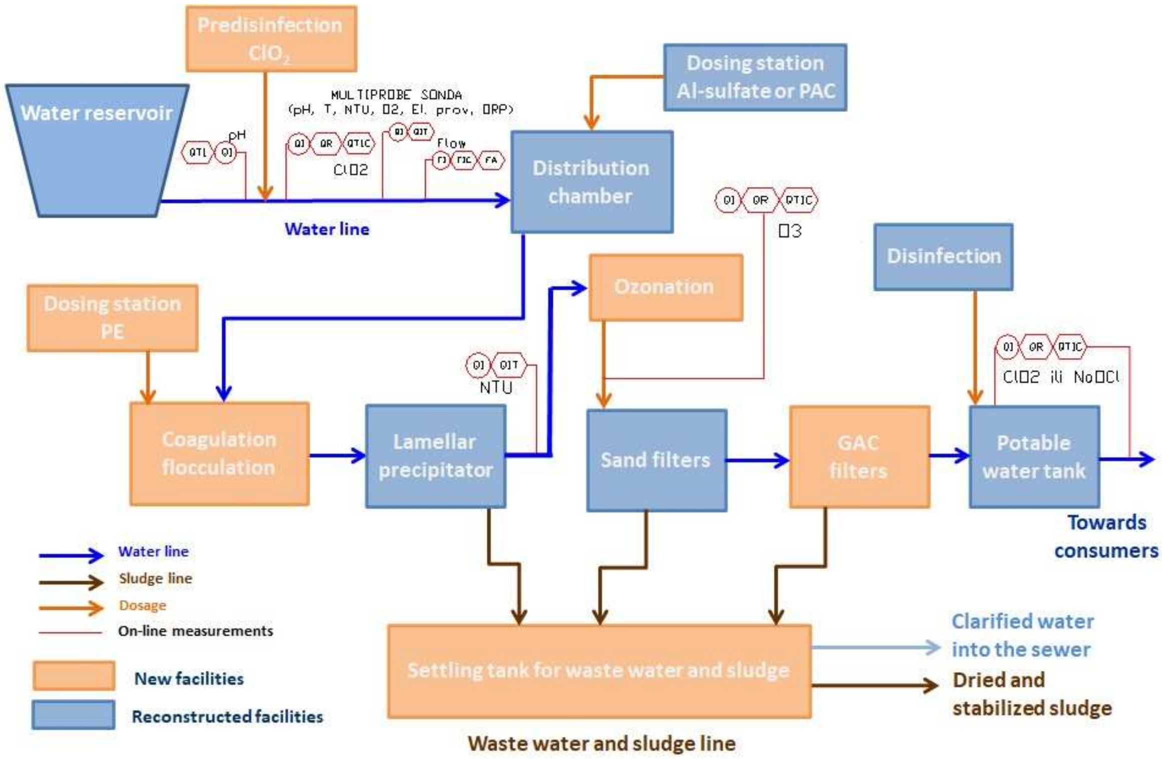

Figure 6. *WTP "Petar Antonijević" – diagram*

Based on the hydraulic calculation, the new structures were integrated with the existing ones so that the water flows by gravity without pumping. Pre-disinfection with chlorine dioxide has proven useful and more advanced than chlorine gas, given that ClO_2 is effective as a disinfectant and an oxidant in water treatment. Around the world, chlorine gas is being increasingly abandoned and replaced with a NaOCl solution, chlorine dioxide, or some other adequate disinfectant, primarily due to the safety of handling such systems. In the event of a higher content of cyanobacteria in the water, doses are carefully determined so that the cells are not lysed, and cyanotoxins are released.

The water from the reservoir is brought to the first structure at the plant - the distribution chamber (coagulation), which ensures water intake from the dam and where the clarification process begins with the coagulation process. Aluminum sulfate or poly aluminum chloride is dosed in the distribution chamber as a coagulant. After that, the water enters the flocculation chambers, a new facility at the plant. Flocculation takes place in three stages, i.e., in three chambers, so each one has a different retention time, depending on the level of flocculation, as well as different mixing speeds in the chambers. Accordingly, the facility was designed to have two independent lines, each with a maximum capacity of 250 l/s. Each line has three chambers each, which are equipped with suitable mixers for gentle mixing over the entire surface and depth of the chamber.

Figure 7. *Coagulation and flocculation facility*

The first formation of flocs is carried out in the first stage of flocculation, where a retention time of approx. 3 min is provided. The flocculant or polyelectrolyte is dosed in the first flocculation stage, accelerating the formed flocs' growth. In the second stage of flocculation, with the correct selection of the mixing gradient, the flocculation process continues, where a retention time of approx. 6 min is provided, while in the third stage it is completed when the particles are ready for the sedimentation process (retention time of approx. 18 min). At the water outlet from the flocculation facility, two DN 800 pipelines are provided, in which the water speed is approximately 0.5 m/s, to ensure the preservation of flocs formed in the flocculator to the lamella clarifier.

To improve the sedimentation process, the existing pulsators were reconstructed to become lamellar clarifiers. Therefore, the existing pipes for draining water from clarifiers were dismantled, and instead of them, plate lamellae and collection channels for draining clarified water were installed. The area available for settling has been significantly increased by inserting many separation cells (water/sludge) or lamellae into the facility. Counter current lamellar sedimentation uses the most straightforward and reliable flow hydraulics, while plate lamellae with a distance of 80 mm are the most efficient. The primary function of the clarification process (coagulation, flocculation, and sedimentation) is to remove cyanobacteria from the water mechanically, that is, by forming stable flocs heavy enough to settle as sludge. The efficiency of this part of the process is critical. It depends on the correct dosage of the coagulant and the flocculant, as well as on the concentrations of the prepared chemical solutions.

After settling, the water is taken to ozonation, a vital part of the treatment technology. Ozone is a powerful oxidizing agent that quickly reacts with most inorganic and organic compounds, microorganisms, and viruses in water, without giving the water any odor or taste. Ozone primarily removes microcystins if they are released into the water after the decomposition of cyanobacteria. A new facility for ozonation was built, consisting of two levels: on the first level, there are chambers for the introduction of ozone and the ozonation process, while on the second level, there is equipment for the production and destruction of excess ozone. The essential characteristics of the ozone block (ozonation chamber) and equipment are 2 parallel lines of 250 l/s each (with 2 chambers per line), a contact time of approx. 20 min, maximum ozone dose of 1.5/2.0 gr/m^3. Two ozone generators with a capacity of 3.6 kgO_3/h and two catalytic ozone destructors (catalytic with overheating) were installed in the machine hall. Liquid oxygen is used for ozone production. The liquid oxygen gasification station is located in an open area, along an internal road, in front of the plant. When choosing the location of the liquid oxygen station, attention was paid to making sure that all the other facilities were at a proper distance from the station. The storage tank is placed on its concrete foundation, and the rest of the equipment is on the plateau of the station. For the production of ozone to be carried out successfully, water for cooling the ozone generator was also provided from the tank for a domestic water supply of 8 m^3/h.

***Figure 8**: Ozonation facility – ozone generators*

After ozonation, the water is transported to reconstructed open concrete sand filters. The filters are rapid gravity filters with a constant level and filtration speed with sand filling. Under the sand filters, there is a clean water tank with an inviolable volume of water that is not disinfected for washing the filters, as well as a significantly larger tank area with disinfected water for distribution to the city's water supply network. The sand filter filling is washed with water and air using pumps and blowers and replaced with new, modern equipment.

After the sand filters, the water is transported to the new gravity filters with activated carbon, which are used for the treatment of drinking water as the last technological unit of the plant for the treatment of potable water, in the case of the highest contamination of raw water, primarily the removal of cyanotoxins after ozonation. GAC filters consist of 8 filter fields and a filter gallery (each field approx. 30 m^2). By filtering water through a layer of activated carbon, all possible residual particles and undesirable organic and inorganic compounds are removed while improving the taste and smell of drinking water and the appearance of microcystins. The GAC filters are washed with pumps and compressors that have also been installed for sand filters. Water is transported to the filters via overflow canals, which enables an even distribution of water and load on the filters. The operation of the filters can be managed from the command-and-control center of the plant itself or the consoles. In addition to the automatic operation of the filters, it is planned to allow the filters to be washed manually, with direct insight from the operator about the manner and quality of cleaning each filter.

Figure 9*: GAC filter facility*

After filtration, the water is disinfected to ensure the microbiological integrity of the water at all points in the distribution network. At the WTP, the final disinfection was done with chlorine gas. Given that all the dangers and adverse effects of storing chlorine gas for humans and their environment are known, alternative solutions for substituting it were analyzed. Based on the elaboration and presentation of alternative solutions, as well as the consideration of advantages and disadvantages, an alternative way of final disinfection of water with chlorine dioxide, which is obtained on-site in a safe manner from two powdered chemicals, was proposed. The intended optimal dose of chlorine dioxide is 0,2 mg/l, and dosing is performed at the entrance to both chambers of the clean water tank based on the data obtained from the flow meter. In contrast, corrective disinfection is completed according to the residual. After disinfection, the water is ready for distribution to consumers in Užice.

After treatment, a certain amount of wastewater and sludge is produced and evacuated to lagoons that receive water from washing filters and sludge from the clarifier. When cleaning the filters, a large quantity of dirty water is produced in a relatively short time, based on which the lagoon was designed with two independent chambers (working and spare), each with a volume of 660 m^3. Clarified water from the chamber is discharged into the drainage channel through openings on the partition wall with a diameter of 2 cm. The discharge of the clarified water takes about 4-5 hours, ensuring the necessary retention time and sedimentation of the sludge. This means that clarified water is gradually discharged into the sewer through the openings in the quantity of about 15 l/s, the quality of which corresponds to the TLV prescribed by the Regulation on discharge into sewers. Periodic cleaning of the chambers is envisioned after reaching the set level of sludge in the chamber, after which it is switched off. After dehydration, the sludge is removed and taken to a landfill, which makes the lagoon chamber functional again.

The physicochemical laboratory was supplemented with additional equipment. At the same time, the biological and microbiological laboratory was also completely equipped with adequate laboratory equipment to monitor the water quality in the reservoir and through all stages of treatment.

An essential improvement in the water treatment process is rehabilitating the raw water intake at the dam at levels of 587.70 masl, 600.00 masl, and 612.00 masl, which enables selective water intake depending on the water quality in the reservoir. In this way, the load on the treatment plant is reduced, especially in terms of the content of ammonium ions, iron, manganese, and algae. The introduction of online monitoring by installing multiparameter probes on individual shutters in the collecting structure that perform automatic measurements of selected quality parameters (O_2, pH, electrical conductivity, chlorophyll) would further improve plant management.

Achieved treatment effects

During the execution of the works and after the completion of the construction, the adjustment of the dosing of chemicals, the speed of the mixers during flocculation and ozonation, filter washing parameters, and so on began. During the trial operation of the system, floc tests and system tests were carried out to adjust the operation of the entire plant as quickly as possible, first in a temporary mode for supplying water from Sušičko Vrelo and then from the Vrutci reservoir.

In cooperation with the operating laboratory at the WTP, optimal doses of chemicals were determined by floc tests, which were also applied to actual conditions. The optimal doses for the test period during winter conditions ranged from 15 to 35 mg/l of 10% Al-sulphate solution and from 0.2 to 0.3 mg/l of 0.2% polyelectrolyte solution. The mixing speeds were adjusted so that in the first stage, the speed of the mixer is 6 rpm, in the second stage, it is 3 rpm, while in the third stage, it is 1.5 rpm. In such conditions, excellent flocs are created, which, in the continuation of the process, can very easily settle in the lamella clarifier. During the trial period, optimal doses were established, which in conditions of lower loads, when raw water has lower concentrations of organic matter, amount to about 0.5 – 0.8 mg/l, that is, in conditions of higher water loads ($KMnO_4$ consumption over 20 mg/l), they can go up to 1.5 mg/l. Since the plant was put into operation in 2018/2019, it has given excellent results, and the treated water has complied with the Regulation of potable water. The WTP achieves the required purification effects after each part of the process (coagulation and flocculation, sedimentation, ozonation, sand filters, GAC filters, and disinfection) and represents a modern, stable and reliable system.

CONCLUSION

A significant number of artificial reservoirs in Serbia face a problem regarding water quality which manifests itself in the form of increased concentrations of specific quality parameters (nutrients, heavy metals, pesticides, etc.). A significant issue is the increasingly frequent appearance of algal blooms (cyanobacteria). The changes above in the water quality in the reservoirs negatively affect, limit, or prevent the use of these water resources for their intended purposes (example of the Vrutci reservoir).

Reservoirs intended for water supply are not given enough attention regarding protecting, monitoring, and managing water quality. In the coming period, it is necessary to develop and improve monitoring programs to meet users' needs, primarily utility companies dealing with water treatment and distribution. Also, it is essential to develop and implement prognostic water quality models to manage reservoirs.

Along with the abovementioned activities, it is necessary to continuously invest in improving processing technology at potable water treatment plants. Applying modern treatment processes with maximum use of existing technological units is essential. Based on previous experience in the reconstruction and extension of the plant, it has been shown that the application of the ozonation process is a vital part of the treatment technology in conditions of deteriorated water quality in reservoirs. Introducing new chemicals in the process of clarification and disinfection with filtration on activated carbon provides additional efficiency and reliability of the plant's operation.

Bearing in mind the possible negative consequences for the population's health, it is necessary to pay much more attention to this problem in the coming period, which is why competent institutions and relevant teams of experts must develop strategic documents with the dynamics of implementation.

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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

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