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The Effects of Underground Water Treatment Before and After the Modernization of the Water Treatment Plant

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ABSTRACT

The work concerns the effects of the treatment of groundwater contaminated with iron and manganese compounds taken from quaternary deposits. In the treatment process, a simple reagent-free technology based on aeration and rapid filtration processes was used. The article presents an analysis of the results of the quality of treated and abstracted water in the years 2008–2020. The period analyzed covers the modernization of the WTP, which was carried out in 2012. The purpose of modernization was to increase the efficiency of the WTP. After the modernization of the station, the efficiency of iron and manganese removal was found to be very high (99%), and the sequence of technological processes used was correct. The devices operated in the WTP work effectively by treating the water directed to the distribution system, which meets the Polish and EU quality requirements for water intended for human consumption.

Keywords: water treatment, underground water, iron, manganese, modernization of the WTP.

INTRODUCTION

Treatment of groundwater containing increased concentrations of iron and manganese compounds is a well-known process and is often described in the literature [Sawiniak et al., 2014; Jeż-Walkowiak et al., 2017; Olsińska, Brągiel, 2015; Siwiec et al., 2016; Gülay et al., 2018; Kvartenko et al., 2018; Shoiful et al., 2020]. However, in practice, it turns out that each groundwater may be different and require an individual approach of both the WTP designer and, later, its operator. This is especially important in the context of climate change, when water companies are required to adapt, protect existing water resources and look for alternative water sources [Gwoździej-Mazur et al., 2022]. Water and wastewater companies are sensitive to periods of high and low temperatures, as days with heavy rain may cause hydraulic overload of the sewage networks, while on hot days the demand for treated water increases significantly [Rak et al., 2021]. Low concentrations of iron and manganese in water are not harmful to health. However, excessive iron intake has negative health effects, including Kashin-Beck disease and an increased risk of heart disease. On the other hand, excess manganese contained in water can cause problems in the nervous system and cause carcinogenic effects [Kisło, Skoczko, 2017]. The iron and manganese compounds present in the water give it a metallic taste and smell. Iron and manganese can also damage equipment in homes. On the other hand, the deposits resulting from the oxidation of these compounds can block pipes and promote the growth of iron and manganese bacteria [Jeż-Walkowiak et al., 2010].

The process of removing iron and manganese from groundwater is based on their hydrolysis and oxidation to iron hydroxides (III) and manganese hydroxides (IV), which are insoluble in water. Initiating these processes requires intensive water aeration. Aeration removes some of the carbon dioxide and other gases from the water, such as hydrogen sulphide, and enriches the water with dissolved oxygen, which is usually very little in groundwater. The oxygen supplied to the water oxidizes the formed iron (II) and manganese (II) hydroxides to water-insoluble iron (III) and manganese (IV) hydroxides. Traditional groundwater treatment methods used are based on aeration and rapid filtration processes. In the case of low concentrations of iron and manganese, it is enough to use a one-stage filtration, in which the upper layer of the filter bed will retain iron and the lower layer of manganese. It should be added that catalytic filter beds are available on the market, containing manganese (IV) oxides, the use of which accelerates the oxidation of iron and manganese with a water pH acceptable in drinking water. These beds also have a much higher density than the quartz sand commonly used as filter fillers, allowing the use of the bottom layer of the bed for demanganization. In groundwater, organic compounds combined with iron can make groundwater treatment much more difficult. It is related to the fact that iron in humic compounds is more difficult to oxidize than $Fe(OH)_2$, because the organic substance must first be oxidized, and then oxidation of Fe(II) to Fe(III) takes place [Kłosok-Bazan, 2013; Krupińska, 2017].

Despite the fact that the above-mentioned technological processes are well known in engineering practice, it turns out that some groundwater requires the development of an individual iron and manganese removal technology based on predesign technological research [Szerzyna et al. 2016; Pruss et al. 2018, 2021].

As part of this study, the results of the quality of treated and abstracted water from 2008 to 2020 were analyzed. The period analyzed included the modernization of the WTP, which was carried out in 2012. The purpose of WTP modernization, due to the increase in demand for water, was to increase its efficiency. The study shows the impact of WTP modernization on the effects of applied treatment technology and the quality of the water delivered to the recipients.

METHODOLOGY

Characteristics of the water treatment plant

The analyzed Water Treatment Plant is located in a small town, inhabited by about 25 000 people. Water is drawn from the Quaternary seams. Currently, there are five wells along the shoreline of the nearby lake. In 2012, the Water Treatment Plant was modernized, as a result of which its capacity increased to Q = 360 m^3/h. The treated water directed to the water supply network meets the parameters specified in the applicable Regulation of the Minister of Health on the quality of water intended for human consumption [RMH, 2017].

Water taken from existing deep water intakes for the purpose of its aeration and degassing is supplied to cascade aerators, in which the forced air flow is countercurrent to the water flowing through the device. The aerated water flows into the reaction chamber, which is located directly below them. In the reaction chamber, the water is thoroughly mixed with the dissolved oxygen supplied during the aeration process and kept there for about 7.5 minutes. The water from the reaction chamber is subjected to a two-stage filtration.

The first filtration stage consists of three open filters with a two-layer anthracite-quartz bed. The total height of the fltration bed is 1.1 m (0.3 m anthracite with grain diameter d = 1.4–2.5 mm and 0.8 m quartz sand, d = 0.8–1.4 mm). The previously precipitated iron (III) hydroxide is retained in the first stage filters. The water then flows to the three single-layer second-stage filters filled with quartz sand, where the manganese removal process takes place. The total height of the second stage fltration bed is 0.8 m quartz sand with grain diameter d = 0.8–1.4 mm. Through second-degree filtration, oxidized manganese compounds are removed from treated water. The maximum filtration speed at the WTP does not exceed 5.0 m/h.

The filters are backwashed in 3 stages: with air at an intensity of 60 m^3/m^2h, with a water-air mixture (air 35–60 m^3/m^2h and water 7–15 m^3/m^2h); water with an intensity of 30 m^3/m^2h. The filter backwash frequency is determined on the basis of measuring the pressure losses of the filter beds, both in the case of 1st- and 2nd-degree filters. Backwashing is initiated when the pressure loss in the bed exceeds 2.0 m. For first-degree filters, backwash is performed at least once a week, while for second-degree filters, backwash is performed at least once every two weeks. For the time to backwash the filter, the capacity of the station is reduced so that the filtration speed does not exceed 5.0 m/h.

The last process on the technological line at the water treatment plant analyzed is emergency water disinfection with sodium hypochlorite at a maximum dose of 1.0 g Cl_2/m^3. There are two points to introduce the disinfectant in the technological line. The first step is to introduce sodium hypochlorite into the treated water after second degree filtration, in front of the additional treated water tank. The second place where sodium hypochlorite is dosed is a point after the additional clean water tank, in front of the main treated water tank. The process is to be used only in an emergency, because disinfection is not provided during normal operation of the station, due to the satisfactory composition of the raw water in terms of bacteriology. The treated water is directed to the additional or main clean water tank and then flows to the water supply network.

RESULTS

The quality of the groundwater intake pumped into the WTP in the years before and after the modernization of the WTP

Excess iron and manganese concentrations were found in the abstracted water, as well as increased values of parameters such as turbidity and color. However, in terms of bacteriology, water does not raise objections.

The average values of the parameters tested for untreated water in 2008–2020 are presented in Figure 1.

The average iron concentration is 2.814 ± 0.9065 mFe/l, so it is much higher than the value determined in RMH, which is 0.2 mFe/l. The average manganese concentration for 2008–2020 is 0.232 ± 0.0621 mMn/l, which significantly exceeds the limit of 0.05 mMn/l specified by the Regulation of the Minister of Health. The deviation from the high mean value for all results for both iron and manganese is very small, indicating that both metals practically always exceeded the RMH requirements. The mean turbidity of the 12 years analyzed was 23.93 ± 9.731 NTU. It should be noted that, in the case of turbidity, even the minimum value of the considered years exceeds the recommended value. In the case of the color of the abstracted water, elevated values are also found. The mean value for the color is 20 ± 15.97 mPt/l. All other parameters analyzed in the abstracted water meet the requirements for drinking water in the current Regulation of the Minister of Health [RMH, 2017].

In the case of the raw water analyzed, the presence of no coliform bacteria, Escherichia coli, and enterococci was never detected during the control monitoring from all the years analyzed. This means that the water taken in bacteriological terms is safe for consumers. Furthermore, the drained water has an average hardness of 260 $mgCaCO_3$/l and is not corrosive.

Due to the quality of abstracted water, the technology of its treatment will aim to reduce the turbidity, color, and concentration of iron and manganese. In the graphs in Figures 2–5. presents the key parameters for the technology in the water taken in each quarter in the years before and after the modernization of the WTP.

In Figure 2 presents a diagram showing the concentration of manganese in raw water in 2008–2011, that is, before the modernization of the station and after the modernization, i.e., in 2012–2020.

In the presented diagram (Figure 2) it can be seen that the manganese concentration in the water collected during the years 2008–2020 significantly exceeds the permissible value, which is represented by a continuous red line. Monitoring of the quality control of raw water confirmed too high manganese concentrations in raw water. The highest concentration of manganese in abstracted water was recorded in the fourth quarter of 2011.

Figure 1. Average values of the tested parameters of untreated water in 2008–2020

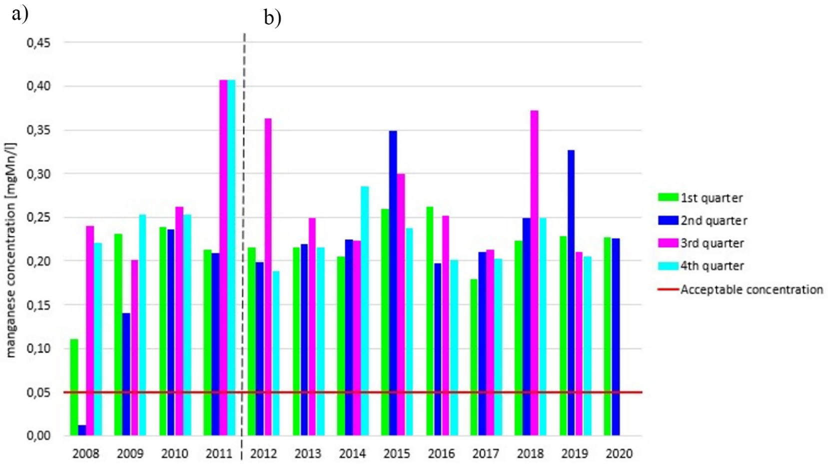

Figure 2. Manganese concentration in untreated water in 2008–2011; a) before the modernization of the WTP, and b) in the years 2012–2020 – after the modernization of the WTP

At that time, the manganese concentration in raw water was 0.407 mg Mn/l, more than eight times the limit value in drinking water. When comparing the quality of the water before and after the modernization of the WTP, it was observed that over the years analyzed the manganese concentration did not change, it always exceeds the limit value in water intended for human consumption [RMH, 2017].

Figure 3 shows the changes in iron concentration in raw water in the years before and after the modernization of the station.

Diagram (Figure 3) clearly shows that the concentration of iron in untreated water significantly exceeds the legally permitted value in almost all monitoring monitoring carried out since 2008. The highest iron concentration in raw water was recorded in the first quarter of 2017, at 5.289 mgFe/l.

In Figure 3 presents changes in turbidity in the water collected in the years before and after the modernization of the station.

The graph (Figure 4) shows that the turbidity in the groundwater of the analyzed intake significantly exceeds the recommended requirements. In the years before the modernization, slightly lower NTU values for turbidity are observed than in the years after the modernization; however, in all the years under consideration, the values significantly exceed the recommendations of the RMH. The highest value, equal to 55.1 NTU, was recorded in the fourth quarter of 2014. However, the lowest value, equal to 2.57 NTU, was observed in the first quarter of 2010. Such a high turbidity in the abstracted water could be caused by the presence of high concentrations of iron and manganese compounds.

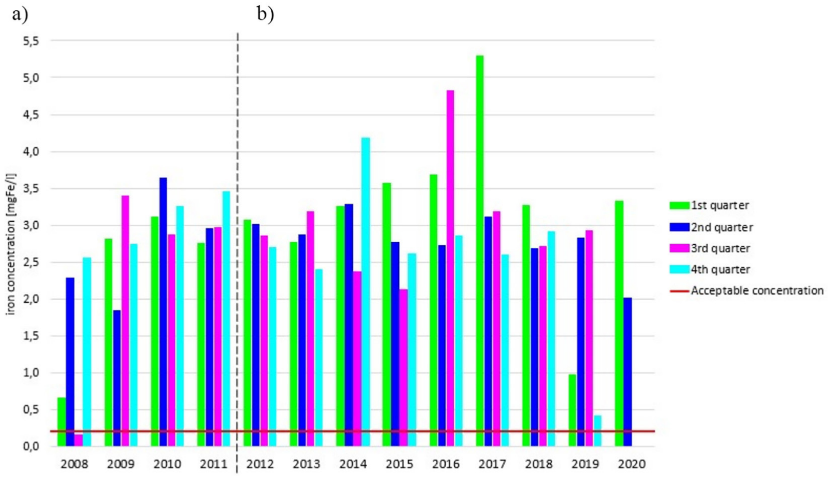

Figure 3. Iron concentration in untreated water in 2008–2011; a) before the modernization of the WTP, and in the years 2012–2020; b) after the modernization of the WTP

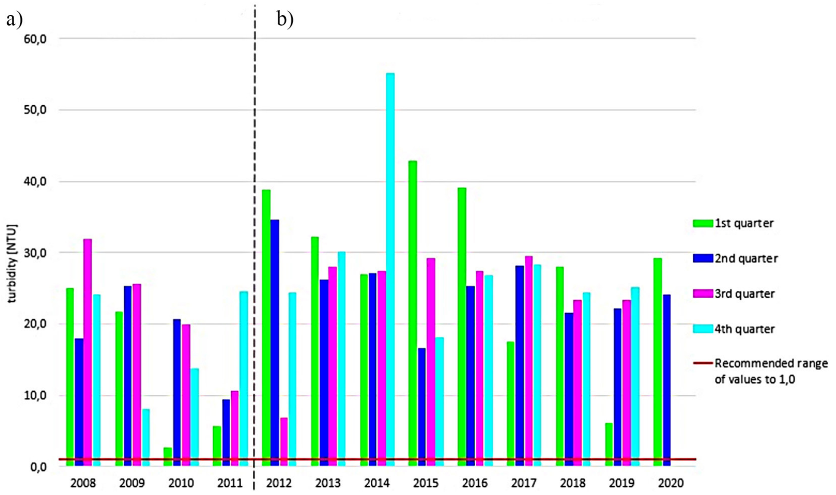

Figure 4. Turbidity in untreated water in 2008–2011; a) before the modernization of the WTP, and in the years 2012–2020; b) after the modernization of the WTP

In Figure 5. shows the color in raw water in the years before and after the modernization of the station.

The graph (Figure 5) clearly shows that sometimes the color of the water was equal to the acceptable value for the consumer (15 mg Pt/l), and sometimes these values were even lower. However, color exceedances have been observed among many raw water control monitoring performed since 2008. The highest value was recorded in the first and second quarters of 2009; then the water color was 70 mg Pt/l. As in the case of turbidity, the increase in color is a result of the presence of high concentrations of iron and manganese in the abstracted water. Both the color and the turbidity are of mainly organoleptic significance, hence the Regulation of the Minister of Health states that both parameters must be acceptable to consumers and without abnormal changes.

The quality of treated water in the years before and after the modernization of the WTP

Control monitoring of treated water quality in 2008–2015 was carried out once a quarter. Usually, treated water samples were taken for water quality analyzes at four measurement points in the city. Since 2016, control monitoring of the quality of treated water has been carried out based on 2 to 5 samples of treated water once a month.

In Table 1 presents the minimum, maximum and average values, as well as standard deviations for the tested parameters of the quality of treated

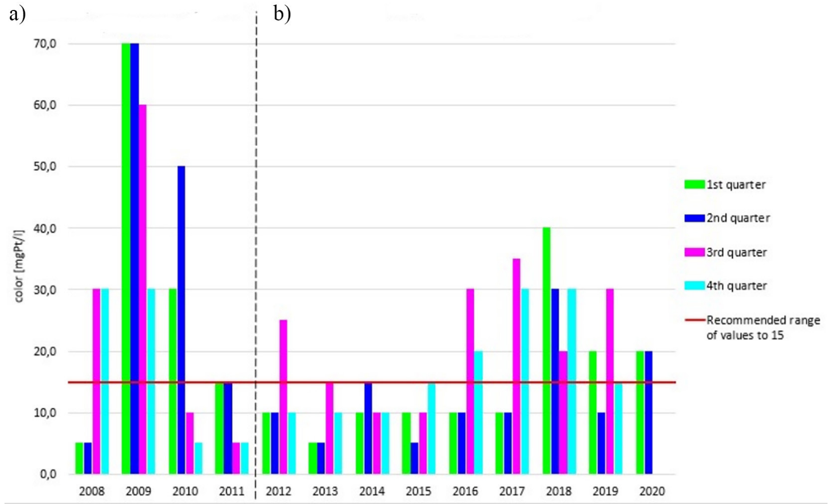

Figure 5. The color of untreated water in 2008–2011; a) before the modernization of the WTP, and in the years 2012–2020; b) after the modernization of the WTP

Table 1. The quality of treated water before and after the modernization of the WTP

Parameter	Unit	The quality of treated water in 2008–2011					The quality of treated water in 2012–2020					Permissible parameter values, according to the 2017 Regulation of the Minister of Health
		Number of analyzes	Min. value.	Max. value	Average value	Standard deviation	Number of analyzes	Min. value	Max. value	Average value	Standard deviation	
pH	-	63	7.35	8.27	7.68	0.2451	247	7.10	8.03	7.58	0.1222	6.5–9.5
Electric conductance	μS/cm	63	411.0	680.0	528.8	32.5	247	338.0	630.0	531.8	20.14	< 2500
Aluminium$^{1)}$	mg/l	47	0.010	0.022	0.011	0.0021	-	-	-	-	-	< 0.2
Manganese	mg/l	63	0.004	0.039	0.005	0.0047	243	0.0001	0.0220	0.0019	0.0028	< 0.05
Iron	mg/l	61	0.060	0.200	0.071	0.0269	245	0.001	0.180	0.019	0.0208	< 0.2
Turbidity	NTU	61	0.01	0.63	0.12	0.1183	245	0.01	0.70	0.22	0.0862	Accepted by consumers. Recommended range to 1.0
Color	mgPt/l	63	5.0	10.0	5.1	0.6299	247	5.0	15.0	5.5	1.602	Accepted by consumers. Recommended range to 15.0
Smell	TON	63	1.00	1.00	1.00	0.00	24	1.0	1.0	1.0	0.00	Accepted by consumers. (1–5)
Taste	TFN	63	1.00	2.00	1.02	0.1260	24	1.0	1.0	1.0	0.00	Accepted by consumers. (1–8)
Ammonium $^{2)}$	mg/l	63	0.05	0.16	0.06	0.0234	140	0.05	0.45	0.07	0.0403	< 0.5
Nitrates $^{1)}$	mg/l	47	0.50	4.50	1.40	1.452	-	-	-	-	-	< 50
Coliform bacteria	NPL/100ml	63	0.00	0.00	0.00	0.00	247	0.00	3.00	0.02	0.2290	0
Escherichia Coli	NPL/100ml	63	0.00	0.00	0.00	0.00	247	0.00	0.00	0.00	0.00	0
Enterococci $^{1)}$	NPL/100ml	47	0.00	0.00	0.00	0.00	-	-	-	-	-	0
Total content of Ca and Mg $^{3)}$	mgCaCO$_3$/l	-	-	-	-	-	231	53.0	393.0	257.9	42.97	60–500

Note: $^{1)}$determined until – 2010; $^{2)}$determined until – 2017; $^{3)}$determined since – 2013.

water from the years before the modernization of the WTP (2008–2011) and the years after the modernization of the WTP (2012–2020)

EFFECTS OF WATER TREATMENT BEFORE AND AFTER THE MODERNIZATION OF THE WTP

Based on the results summarized in Table 2 it can be concluded that the efficiency of water treatment, both before and after the modernization of the WTP, is very high. During the modernization of the station, the technological system was not interfered with; only the equipment existing at the WTP was modernized. However, after the modernization of the station, a slight increase in the efficiency of removing iron and manganese from the taken off water was observed. In the case of reducing the turbidity and color after modernization, the efficiency obtained was similar to that obtained in the years before modernization.

The obtained results can be compared with the data available in the literature. For example, at the pilot plant for the treatment of groundwater contaminated with iron and manganese compounds [Pruss et al., 2018], as a result of the technological processes carried out, analogous to the analyzed WTP, a manganese removal efficiency of 99% was obtained, that is, the same as that obtained in the WTP after modernization. In the case of iron removal, the effects of water treatment are also very similar, since the average iron removal efficiency after modernization at the analyzed water treatment plant is 99.0%, while in the above publication the efficiency of 99.7% was obtained. A greater difference was observed for turbidity and color. The pilot station enables the reduction of turbidity in 64%, while in the analyzed WTP the efficiency is as high as 99%. At the analyzed WTP, it is also possible to obtain a better color reduction efficiency, which amounts to 72%, while in the case of the tested pilot station, the efficiency was only 42%. Undoubtedly, it was related to the quality of the treated water.

Table 2. Average efficiency of underground water treatment before and after the modernization of the WTP

Parameter	Unit	Average values for raw water	Average values of treated water in 2008–2011	Average efficiency of water treatment before modernization [%]	Average values of treated water in 2012–2020	Average efficiency of water treatment after modernization [%]
Manganese	mg/l	0.232 ±0.0621	0.005 ±0.0047	98.0	0.0026 ±0.0028	99.0
Iron	mg/l	2.814 ±0.9065	0.075 ±0.0269	97.0	0.021 ±0.0208	99.0
Turbidity	NTU	23.96 ±9.731	0.14 ±0.1183	99.0	0.23 ±0.0862	99.0
Color	mgPt/l	20.0 ±15.97	5.1 ±0.6299	75.0	5.5 ±1.602	72.0

In the pilot technological investigation, groundwater was treated, characterized by the presence of iron in combination with humic compounds, which are difficult to remove in a typical reagent-free technology based on the aeration and filtration process.

Another example is the WTP for the city of Słupsk [Pruss P. and Pruss A., 2010], which was modernized in 2010. Underground water from municipal intakes in the city of Słupsk is classified as water of good quality. Characterized by an increased concentration of iron, manganese and color, it could therefore be effectively treated with a simple reagent-free technology based on natural aeration and rapid filtration processes. As a result of the aeration process and rapid filtration, satisfactory effects of reducing the iron concentration to values below 0.03 mg Fe/l were obtained; manganese up to 0.031 mg Mn/l and colors up to 5 mg Pt/l.

The next example is the modernization of WTP Leśna in Zabrze [Sawiniak et al., 2014]. The water collected from the deep wells was characterized by an increased iron content of 0.4 mg Fe/l and a manganese content of 0.25 mg Mn/l. The technical and operational problems of the pressure filters operating in the WTP made it necessary to modernize it. Modernization was preceded by technological research. After the modernization of the WTP, the iron and manganese removal process from the water was highly effective. Iron concentration after the treatment process ranged from 0.01 to 0.032 mg Fe/l, while manganese concentration did not exceed 0.020 mg Mn/l. Additionally, after the modernization of the station, the organoleptic properties of the treated water were improved, financial savings were achieved due to the reduction of chemicals dispensed into the water, the energy consumption was reduced, and the filtration cycle was extended.

Another example is the treatment of difficult water in Seroczyna [Reczek et al., 2015]. The water captured there is not of good quality; it is characterized by a low pH and an increased concentration of iron, manganese, and nickel. It is definitely corrosive (high concentration of aggressive carbon dioxide and low alkalinity). Filtration through activated quartz sand allowed to effectively (96%) reduce the manganese concentration from 0.25 mg Mn/l in the collected water to a value below 0.01 mg Mn/l in the treated water.

CONCLUSIONS

The modernization of the WTP carried out in 2012 was related to the increase in water demand and did not change the existing water treatment technology.

In the technological processes carried out at the WTP, efforts are made to reduce the concentration of iron, manganese, and the turbidity and color. The concentration of iron in the abstracted water is on average 2.814 ± 0.9 mg/l every 14 times the limit value of 0.2 mg Fe/l, while the average manganese concentration is on average 0.232 ± 0.06 mg/l, which is almost 5 times the limit value of 0.05 mg Mn/l. The increase in turbidity and color is caused by high concentrations of iron and manganese in the intake water. Therefore, these parameters may be lowered along with the removal of excess of these metal compounds from the water.

It was found that the classic treatment technology used in the WTP is undoubtedly an effective technology. The water treated at the analyzed Water Treatment Plant, both before modernization (2008–2011) and after modernization (2012–2020), meets the requirements for water intended for human consumption and is safe for consumers.

The modernization of the WTP carried out in 2012 made it possible to increase the efficiency of the WTP and had a positive effect on the water treatment process, as the average efficiency of iron and manganese removal from groundwater increased to 99%.

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