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THE OPTIMIZATION OPTIONS OF WATER SUPPLY SYSTEMS IN TERMS OF ENERGY CONSUMPTION

MOŽNOSTI OPTIMIZACIJE VODOVODNIH SISTEMOV Z VIDIKA PORABE ENERGIJE

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Keywords: heterogeneous water supply system, parameters of optimizations, energy consumption, economic indicators

Abstract

The provision of drinking water is a basic communal utility. Unfortunately, economic aspects cannot be ignored while ensuring the quality of healthy drinking water. Both the quality and the economics of the supply are influenced by numerous parameters that are determined by natural resources, technological processes, as well as by potential energy use within the water supply system. The optimization options of water supply systems in terms of energy consumption as well as in terms of other parameters are shown in the practical case of a heterogeneous water supply system in the municipality of Slovenska Bistrica.

Povzetek

Zagotavljanje pitne vode je ena od osnovnih komunalnih dejavnosti, pri čemer pri zagotavljanju kvalitetne zdrave pitne vode ne gre zanemariti tudi ekonomskih učinkov. Tako na kvaliteto kot na ekonomijo oskrbe vplivajo številni parametri, ki jih pogojujejo tako naravne danosti, tehnološki procesi, kot tudi potencialna energetska izraba znotraj vodovodnega sistema. Možnosti optimizacije vodovodnih sistemov glede na porabo energije kot tudi druge parametre so prikazane na praktičnem primeru heterogenega vodovodnega sistema oskrbe na območju občine Slovenska Bistrica.

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1 INTRODUCTION

Different types of water systems for the supply of drinking water exist due to geographical, climatic and other conditions. A quality water supply requires adequate quantities of drinking water. Even if consumption is reduced to the greatest extent practically possible, economic indicators cannot be ignored, even more so when they are dependent on legal requirements and the parameters dictated by the environment. Particular attention is given to energy consumption. The type, quality and quantity of water resources in a heterogeneous water supply system (the combination of natural sources, surface water supplies from the aquifers as well as the pumping stations from the wells) cover a number of parameters that dictate the necessary technology for the preparation of drinking water and of the entire supply system.

The heterogeneous water supply system under consideration in this paper is supplied from multiple water resources that are dependent on foreign energy as energy consumers. The water supply system is expanded with multiple water resources. Consequently, the economic use of energy and water is of crucial importance in their management. The main supply system connects eight water resources with very different characteristics, capacities and vulnerabilities.

2 THE STARTING POSITION OF WATER SUPPLY SYSTEM

2.1 General information about water resources, description and characteristics

Figure 1 shows the positional arrangement of water resources, water storage tanks and their capacities. It also shows the water supply network, which is intended for supplying the population with drinking water and the provision of fire safety.

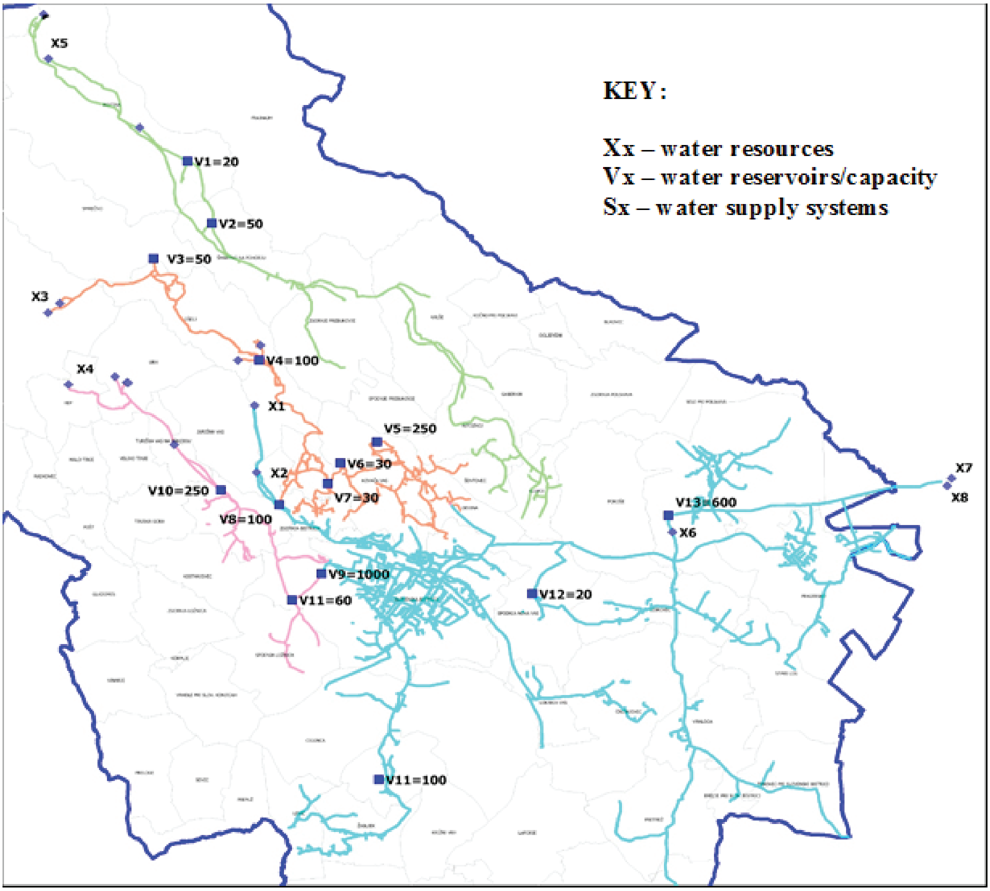


Figure 1: The positional scheme of water resources and water reservoirs

2.2 The characteristics and influential factors of individual water resources

X1 – water supply [494 MASL]: It is situated directly above the channel of the Bistrica River. The aquifer is located in the interstitial zone, which is composed of granodiorite. Its size is impossible to determine. On the average, about 18 l/s of groundwater are extracted from the water supply eight months of the year and 10 l/s of water during the summer months. The body of water from which the groundwater is extracted (together with the water supply) is threatened primarily by the point sources of pollution due to the insufficient thickness of unsaturated zone. The point sources of pollution are spillages and illegal dumping sites that might arise in the area of the water supply. Contamination could also be caused by the ingress of the nearby stream directly into the water supply. The deterioration of the water quality can be effectively avoided if the water protection zones are strictly complied with. The water supply is carried out by gravity; therefore, consumption is limited only to the maintenance of the quality of the water source and the preventive disinfection of the system with NaOCl. Reconstruction activities in the coming years would be limited to the reconstructions of construction works. The conditions for the reconstruction are the favourable location of the water source and the total energy use enabled by connecting the system to the central water supply system. On the water source itself, it is obligatory to provide disinfection of drinking water and to enable the residual effect of disinfection. The measurements of the production of the water resource, which are dependent on weather conditions and natural resources, should be performed [8] [9] [11].

X2 – water supply [381.9 MASL]: It is located on a stream of the Bistrica The body of water is the surface water of the stream and is almost entirely supplied from rainfall and to a lesser extent from the infiltration of groundwater from the thick layer of weathering that occurs above primary magmatic-metamorphic stones. The length of the stream from its source to the mouth is 18.8 km, and 10.8 km from the source to the water supply. The hydrographic area occupies a narrow part of the southern slopes of Pohorje around the valley with an area of 32.41 km². At the X2 water supply, a maximum of 50 l/s of water is extracted during the rainy season and 25 l/s during the dry season. The greater part of the stream's surface is the part of a protected area, which forms part of Natura 2000. In addition, the water source is considered a partly natural watercourse for the better part of its current. Due to the large water flow in the water body, the quantities of collected water are acceptable and do not affect the ecological status of the body of water itself. The body of water is largely compromised of the following conditions: the scattered point sources of pollution that are represented by the agricultural areas within the basin of the stream Bistrica, the point sources of pollution, which are found primarily in the wild dumping sites, and various buildings with unregulated sewers and other interventions that alter the natural sensitivity of the body of water. In order to be able to evaluate the threat parameters, it is necessary to implement an AOP procedure for the preparation of drinking water in the system itself. The procedure is energy consuming. Moreover, the preparation of water is the least economically viable due to the use of chemicals and the obligatory presence of the work force.

Two pumps with characteristics Q = 50 l/s, P = 45 kW, which are necessary for the cleaning of UF filters in the return washing of the biological films of membranes, should be installed in the system [8] [9] [11].

X3 – water supply [880 MASL]: The surrounding area is mostly overgrown with mixed forest. These areas are dominated by extensive agriculture and forestry. The body of water is located in weathered layers of igneous Pluto granodiorite. The surface of the body of water is estimated at 0.153 km²; the average thickness of the aquifer's weathered cover is several meters. The water from the water supply is extracted by using the dredged shaft. On average, about 2 l/s of groundwater is extracted from the water supply. The body of water from which the groundwater is extracted together with the water supply is threatened primarily by the point sources of pollution due to the insufficient thickness of the unsaturated zone. The point sources of pollution could be, for example, farms directly above the water supply or the fuel spillage on the road over the water supply as well as the unfavourable weather conditions. On the water source itself, it is obligatory to provide disinfection of drinking water and to enable the residual effect of disinfection. It is necessary to perform the measurements of the production of the water resource, which is dependent on weather conditions and natural resources. The water supplies X4 and X5 are under the same potential threat [8] [9] [11].

X4 – water supply [880 MASL]: It is located on the eastern slopes of Pohorje. Its body of water is located in the thick weathered layer, which can be found above the metamorphic-magmatic rocks of Pohorje. The aquifer's surface is estimated at 857,400 m² (0.8 km²); the average thickness of the aquifer's weathered cover is several tens of meters. In the rainy season, approximately 2.5 l/s of water is covered by the water supply whereas in dry periods up to 1.5 l/s of water is [8] [9] [11].

X5 – water supply [1289, 5 MASL]: On the eastern slopes of Pohorje, this water supply is located in the thick weathered layer, which is found above the metamorphic-magmatic rocks of Pohorje. The aquifer�s surface is estimated at 1.1 km², the average thickness of the aquifer�s weathered cover amounts to a several tens of meters. In the water supply, there is a maximum of 3 l/s of groundwater included [8] [9] [11].

X6 – borehole (deep well) [289.1 MASL]: It is located at the crest of the hill. The water is extracted from the Pliocene aquifer. The plio-quarternary regional aquifer occupies the eastern fringes of Pohorje between Maribor and Slovenska Bistrica, where it continues over the region of Dravinjske gorice and reaches the west all the way up to Ptujska gora. In the central part, it is covered by gravelly clay layers of the Drava River and its tributaries. The estimated area of the body of water is 1.1 km², the average thickness is around 40 m, and its volume is thus about 44,403,000 m³. Preferred pumping quantities are up to 22 l/s. The microbiological water source is not compromised due to the thickness of the impermeable layer and due to the permeability of the earth layers in the aquifer zone. The bigger problem is the concentration of iron and manganese, which have the geological origin in the aquifer zone itself. The production of drinking water according to AOP processes should be anticipated. Allowed concentrations could be provided with regular flushing and cleaning of wells as well as by mixing the water from different supply systems. The replacement of existing pumps with three pumps with following characteristics of Q = 150 m³/h, p = 4-10 bar, N = 37 kW, 380V is anticipated. The movement of the measuring point on the TP is also anticipated. The tariff billing system would thus be lowered by one degree, and extraction characteristics would be adjusted to the period of reduced energy consumption in order to avoid the conical consumption of electricity[8] [9] [11].

X7 – borehole (surface well) [246.2 MASL]: Located at the top gravel terrace on the Drava field, this body of water occupies large areas, and it is impossible to define it locally. It is composed of three aquifers. On the regional level, it occupies the eastern fringes of Pohorje all the way up to Ptujska gora. In the central part, it is covered by gravelly clay layers of the Drava River and its tributaries. Its area is estimated at 429.3 km², with its depth sometimes exceeding 1000 m. The estimated total abstraction from wells is about 80 l/s of water. The body of water from which together with the water supply the groundwater is extracted is threatened due to the fact that it lies relatively shallow under the surface and is separated from the surface by a permeable layer and only locally by a thick layer of clay. It is threatened by agriculture, industry, septic tanks and un-repaired gravel pits. The borehole is heavily contaminated with triazine pesticides, nitrates and herbicides. It is necessary to ensure the disinfection of drinking water and provide adequate amounts of water from the deeper layers of the aquifer. Two pumps with characteristics Q = 43 l/sec, H = 90 m, P = 50 kW are built into the system [8] [9] [11].

X8 – borehole (deep well) [246.2 MASL]: Located at the highest gravel terrace in the Drava field, this plio-quarternary regional aquifer occupies the eastern fringes of Pohorje all the way up to Ptujska gora. In the central part, it is covered by gravelly clay layers of the Drava River and its tributaries. The estimated area of the body of water is 2.5 km², the average thickness is around 54 m, and its volume is thus about 121,655,250 m³. The recommended pumping quantities from the wells are 28 l/s. The water source is under the same threat as X6. Two-pumps with characteristics Q = 15 l/s and H = 100 m, P = 37 kW-X8 should be fitted into the system [8] [9] [11].

2.3 The required quality of water resources

The requirements concerning the content of the parameters in drinking water are determined by the Rules on Drinking Water (The Official Gazette of the Republic of Slovenia, no. 19/04, as amended). Table 1 lists the most basic parameters in terms of the specific characteristics of individual water resources, which limit their direct use without prior preparation [4] [16].

2.4 The list of possible contaminants regarding the characteristics of water resources

Table 1: *The list of the most distinctive contaminants according to the characteristics of the water source and the level of threat*

Possible contamination	**The description of the contamination**	**Limit values**	**Threats to the water source**
Coliform bacteria	The group of bacteria that can be found both in the human and animal waste and in the environment.	0/100 ml	X1, X2, X3, X4, X5, X7
Escherichia coli	The bacteria are the indicator of pollution by faeces.	0/100 ml	X1, X2, X3, X4, X5, X7
Enterococci	The bacteria are the cause of an older faecal contamination.	0/100 ml	X1, X2, X3, X4, X5, X7
Clostridium sporogenes	Sporogenes present in the surface waters.	0/100 ml	X2
Triazine pesticides	Atrazine is an organic herbicide used in agriculture for weed control.	0.1 μg/l	X7
Herbicides	Metolachlor is an herbicide used in agriculture.	0.1 μg/l	X7
Nitrates / nitrites	Nitrates (NO_3) and nitrites (NO2) occur when the fertilizers are applied.	50 mg/l/ 0.50 mg/l	X7
Mn	It primarily represents an aesthetic problem.	50 μg/l	X6, X8
Fe	The presence of iron in the water affects its flavour, colour and aroma.	200 μg/l	X6, X8

The table shows that the source X7 is the critical source of the drinking water supply since its quality of drinking water is questionable in almost all points of potential contaminants. Nevertheless, it has a massive advantage over the other water sources due to the capacity of the production of the water resource. Precisely due to the assessment of the risk level in the process of optimizing the system, the idea of replacing the water source or of protecting its qualities has arisen.

3 OPTIMIZATION OF THE WATER SUPPLY SYSTEM

3.1 The organisation chart of the state of development of the water supply system

Due to the lack of water capacities and the inadequate hydraulic design of the water supply network, it is necessary to approach the hydraulic improvement of the entire system effectively and meaningfully as well as to ensure the quality of drinking water in accordance with the legislation currently in force. The system of improving the overall water supply network would take place in phases. The system of energy improvement is to be divided into four phases.

Figure 2 shows the estimated construction of the energy-efficient water system in phases and describes the activities that would be needed to ensure the optimal operation of the water supply system, which directly affects the economically justified price of water services for users.

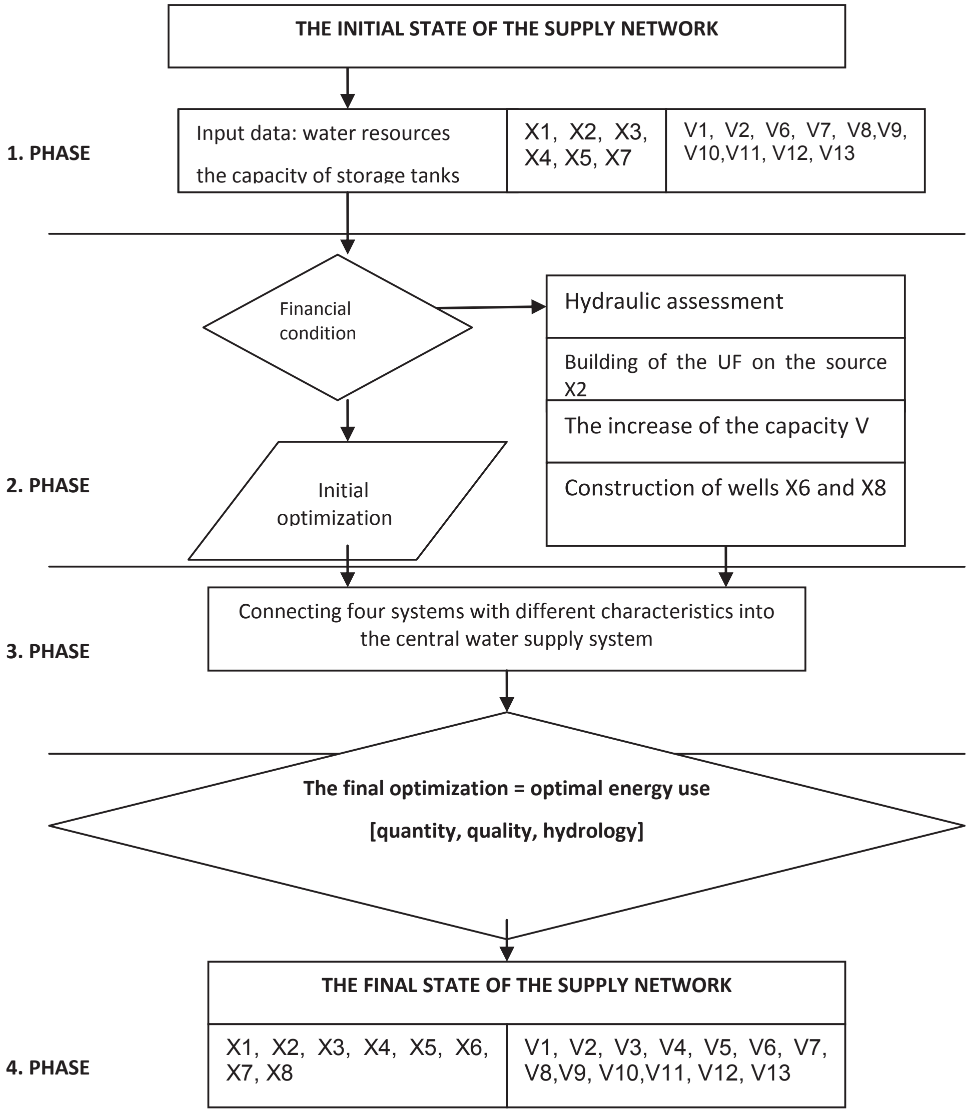


Figure 2: *The organization chart of the phased processes of work*

3.2 The phases of the optimization process

Phase 1: A thorough review of the system was made and the water quality at a particular water source determined. The primary task of the first phase was the determination to provide sufficient quantities of water resources at the relevant quality level and the selection of the cleaning procedures for the existing water resources given the available technical options and resources. The procedures were prepared on the theoretical basis of the review and the assessment of the existing water supply system and on the basis of the evaluation of conditions and opportunities for the modernization of the system in accordance with the boundary conditions of the quantitative status of water resources, the required quality of water by the user and optimal energy state of the water-supply areas [14] [15].

Phase 2: This phase is divided into four steps. In the first step, the calculation of the hydraulic assessment of the stability and functioning of the water supply system was made. Based on the results, the possibilities for the reconstruction of infrastructure and the purifying of the drinking water by advanced methods were verified. The possibilities of water regulation in terms of energy efficiency by upgrading water storage tanks were examined.

The second step required the construction of deep wells, X6 and X8, which provides the quality and the quantitative boundary condition(mixing of water from wells X6 and X8 with other individual water resources X2, X7) which can also meet the quality conditions if there is appropriate mixing of water.

The third step was achieving the condition of water quality, taking into account the given characteristics of the water source X2 and the available technology. The ultrafiltration procedure enabled doing so. The ultrafiltration technique is membrane filtration-driven by the external differential pressure. In addition to the differential pressure, differences in concentration occur during the process. In the case of electrically charged particles, an electric field also occurs. The membranes shown in Figure 3 are hollow tubes with an internal diameter of approximately 0.8 mm and a porous wall. The pore size is about 20 nm (0.020 micrometres), which means that it may retain bacteria (6 log grades) and viruses (4 log grades). Membrane tubes are grouped into membrane elements which are inserted into the pressure tube [12] [13] [17] [20].

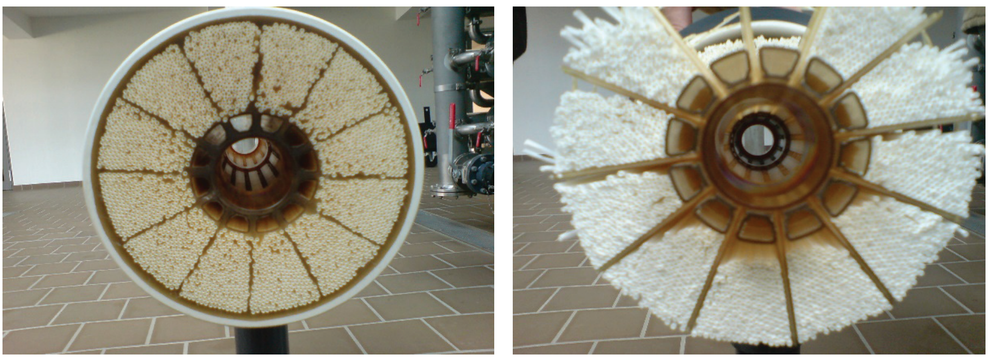


Figure 3: *The picture of the membrane module*

The forth step of Phase 2 of the system's optimization process is the assessment of the available capacities of water reservoirs forming part of the individual water supply system. The capacities of water reservoirs do not currently meet the needs for the retention of sufficient quantities of drinking water in terms of the inflows, fire water and the availability of water resources. As a result, the individual systems suffer significant losses of the water already extracted from the system. In the course of the phased construction and the optimization of the water supply system, the construction works for increasing water storage tanks in accordance with Table 2, for the individual water supply systems are being done [5].

***Table 2:** The capacity of water reservoirs in individual systems*

Water supply system	**The existing capacity of the water reservoirs**	**The expected capacity of water reservoirs**
S1	1800 m³	4700 m³
S2	460 m³	460 m³
S3	70 m³	270 m³
S4	310 m³	310 m³

The need for the integration of individual systems into a single water supply system is, therefore, the inevitable task of the stakeholders responsible for the management and maintenance of the water supply system. Their task should be to establish an energy-efficient system in order to minimize losses of the water extracted from the system.

Phase 3: The essence of the hydraulic improvements and assessment of the geographical terrain is the functional interconnection of water supply systems into the central water supply system. After reviewing the elevation angles and the geographical terrain shown in Table 3, it is obvious that the interconnection of all four systems is possible and with this measure the quantitative exchange of water is provided even in spite of unfavourable hydrological deficits, [10].

Table 3: The geographic relief of the connections of the water supply system

Water supply system	**Definition V/n.v.**						**The connection option**
S1		**V8**	345.4	**V12**	307		YES
		V9	328	**V13**	298.5		
S2	**V3**	853.1	**V5**	467.3	**V7**	470.6	YES
	V4	651.6	**V6**	463.1			
S3		**V1**	907.5	**V2**	842.6		YES
S4		**V10**	543.5	**V11**	319.2		YES

Phase 4: The final optimization of the water supply system is planned as well as the ensuring of the control and the functioning of the system with the use of a numerical model based on the quantities, required quality of the water sources, and weather conditions. The control and the functioning of the system is ensured with the introduction of on-line measuring of the quality of water sources as well as with the upgrading and optimizing the telemetric management of the water supply telemetry system to such a degree that with minimum energy consumption, the optimal quality of drinking water would be provided in accordance with the current hydrologic conditions. From the perspective of optimization, the possibility of producing one's own energy is considered. The energy would be used for providing illumination and for the ability to provide one's own energy for the purposes of providing

quality condition of surface water sources. The construction of a small hydropower plant under the given conditions should be incorporated into the supply system [1][2].

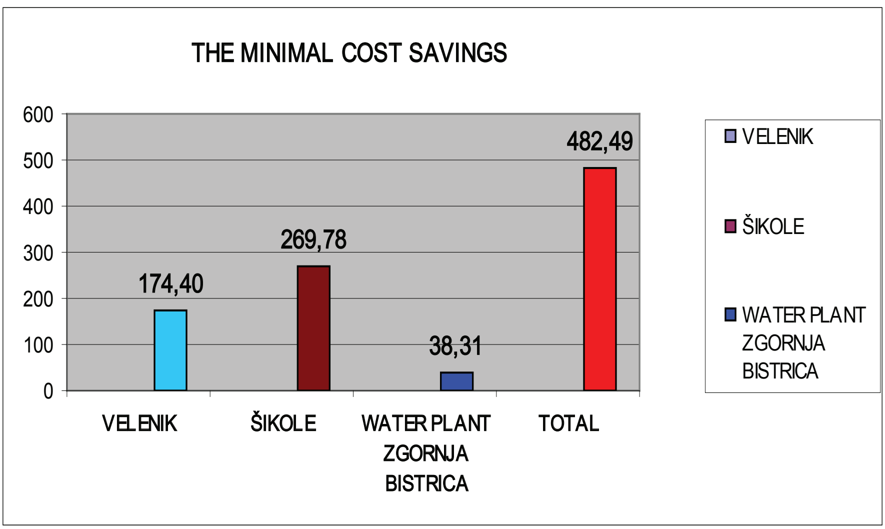
4 THE INFLUENCE OF SPECIFIC INDIVIDUAL PARAMETERS ON THE OPTIMIZATION

4.1 The optimization of the system in terms of energy consumption

All water sources are replenished in good operating conditions of the water storage capacity of 1700 m³. With the completion of the works in the process of the construction of water supply facilities as part of the cohesion project for the construction of the water supply system for drinking water and with the increase of the capacity of water storage tanks from 1800 m³ to 4700 m³, as well as with the introduction of the basic pumping conditions in a lower tariff system and by avoiding peak energy consumptions, there would be a significant reduction in power consumption achieved; simultaneously, the tariff system for the energy consumption would be modified. By modifying the energy consumption, the monthly savings would be equal to the amount shown in the following table, at least in the case of more favourable operating conditions even up to one third of the calculated and displayed amount due to the conical charge of the energy consumption [3] [7].

Table 4: *Possible energy savings in energy consumable water resources*

VELENIK			**174.40 €**
64	4.02497	257.60	
64	3.09094	197.82	
64	1.79098	114.62	
0	1.79098	0,00	
ŠIKOLE			**269.78 €**
99	4.02497	398.47	
99	3.09094	306.00	
99	1.79098	177.31	
0	1.79098	0,00	
WATER PLANT ZGORNJA BISTRICA			**38.31 €**
22	4.83229	106.31	
22	3.09094	68.00	
		TOTAL	**482.49 €**
		TOTAL/12	**5,789.84 €**

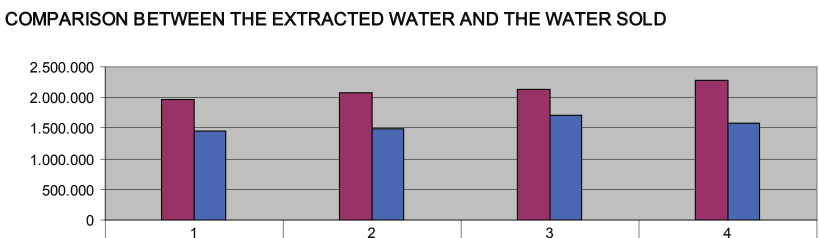


4.2 The influence of disruptions in the water supply system on the optimization

The hydraulic connection of water supply systems into a single supply system would completely prevent the water loss in the system. Providing hydro-geologically favourable conditions, in the case of the connection of the system, the maximum allowed limit of the utilization of water resources with the lowest operating costs would be reached. Together with that and with the complementing of the quantities of less favourable water resources in terms of energy use, a system of optimal functioning in terms of technical and financial characteristics would be established. The possibility of connection was already defined in Table 3 and geographically shown in Figure 7. By connecting water systems, the losses of the already extracted water in the system would be reduced since, with the increase of water storage tanks and with the telemetric balance of water extraction, the surpluses of the already extracted water in the water distribution network would be intercepted.

The significant disruptions in the operation of the water system are mainly caused by exceeding allowed values for the parameters of drinking water quality at a specific water source, regarding the characteristics of the water source. Moreover, the disruptions in the system of drinking water supply can easily occur due to unforeseen events in the course of eliminating the defects in the water supply system. These kinds of disruptions are short-term and they affect the losses in the system only to a lesser extent. The greatest losses in the water supply system occur when there are undetected hidden defects in the distribution system of drinking water supply and unauthorized water abstraction from the system. These problems should be solved in phases, but not in the course of this project. Table 5 shows the problems of quantitative losses of water from the water supply system in question [2] [10] [17].

Table 5: *Water losses in the system*



YEAR	2010	2011	2012	2013
The quantity of the extracted water	1.962.749	2.075.816	2.131.840	2.272.956
The quantity of the water sold	1.446.669	1.493.006	1.710.245	1.583.721
LOSSES	26%	28%	20%	30%

4.3 The impact of the specific costs on the optimization

Depending on the characteristics, operating and maintenance conditions and energy use, the price of a cubic metre of water can be easily determined for the individual water sources. Table 6 shows the calculation of the price of water per cubic meter depending on the individual characteristics of the water source. According to the on-line measurement of the quality of the water sources, and according to the available quantities and specific costs, the optimal regulation of water supply is planed [19].

***Table 6:** The average price of water based on the characteristics of the water source*

The name of the drinking water source	The amount of the water abstracted 2014	The energy consump-tion	The work costs	The cost of chemi-cals	Other costs	Total costs	Price per unit	Price per unit
X1	551,129	1,500 €	30,000 €	4,000 €	5,000 €	40,500 €	0.0735 €	0.0955 €
X2	355,854	17,000 €	110,000 €	28,000 €	25,000 €	180,000 €	0.5058 €	0.6576 €
X3	115,484	2,636 €	20,000 €	2,000 €	8,000 €	32,636 €	0.2826 €	0.3674 €
X4	69,107	830 €	18,000 €	4,000 €	8,000 €	30,830 €	0.4461 €	0.5800 €
X5	168,750	100 €	36,000 €	2,000 €	12,000 €	50,100 €	0.2969 €	0.3860 €
X6	132,132	11,600 €	21,000 €	2,000 €	12,000 €	46,600 €	0.3527 €	0.4585 €
X7, X8	445,632	30,000 €	42,000 €	5,000 €	20,000 €	97,000 €	0.2177 €	0.2830 €
							Average price:	0,4040 €

In terms of quantity, in accordance with Table 6, it is, therefore, reasonable to exploit the water source with the lowest economic value, as shown in Figure 4, and the highest level of quality and production of the water source, as shown in Figure 5.

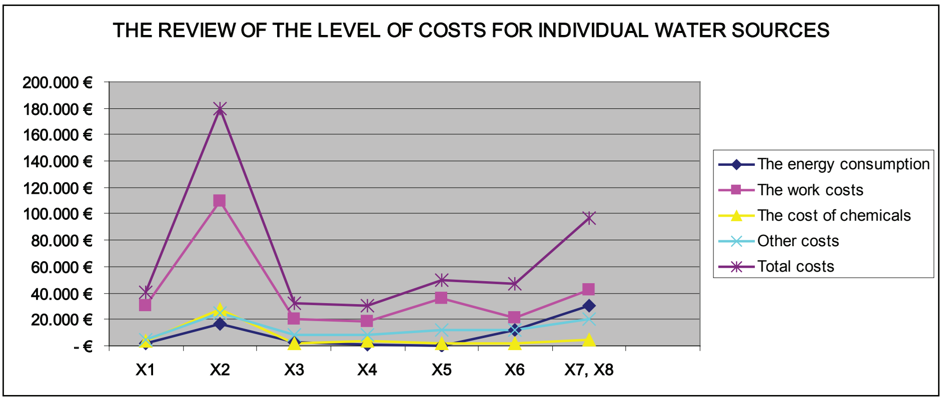


***Figure 4:** The assessment of the costs for the individual water sources*

***Figure 5**: The comparison of the costs and the production of the water source*

4.4 The influence of the capacity of water sources on the optimization

The quantities of the abstracted water in the water supply system are dependent on the technical characteristics of the individual water source, the need for the quantities of extracted water and the natural features of the available capacities of the water source. The allowed quantities of drinking water extracted from the system are noted in the water-related licenses based on the calculated and measured values of the available capacities of the individual aquifer taking into account the ecological minimum of the aquifer's area. Table 7 gives an overview of the quantities of the water in the water supply system which are lower than the permitted levels in water licenses, which is why the optimization is wide open, [18].

Table 7: *The capacity of water sources and the amount of the extracted water*

The name of the drinking water source	The amount of the withdrawal of VD [m³]	The amount of the extracted water, 2011	The amount of the extracted water, 2012	The amount of the extracted water, 2013	The amount of the extracted water, 2014
X1	580,000	203,539	343,122	367,172	551,129
X2	1,350,000	742,639	785,375	625,891	355,854
X3	137,000	44,910	61,666	92,329	115,484
X4	103,500	49,857	52,252	75,548	69,107
X5	170,000	33,023	38,050	113,612	168,750
X6	300,000	237,488	180,144	116,244	132,132
X7	1,396,719	292,340	302,920	280,120	249,870
X8		243,790	212,440	182,090	157,970

Figure 6 shows the trend of the optimal utilization of water sources in accordance with the required boundary conditions of quality, quantity and price. After the connections of the water supply systems are made in accordance with the proposed final state shown in Figure 7, the highest level of optimization of the system would be reached.

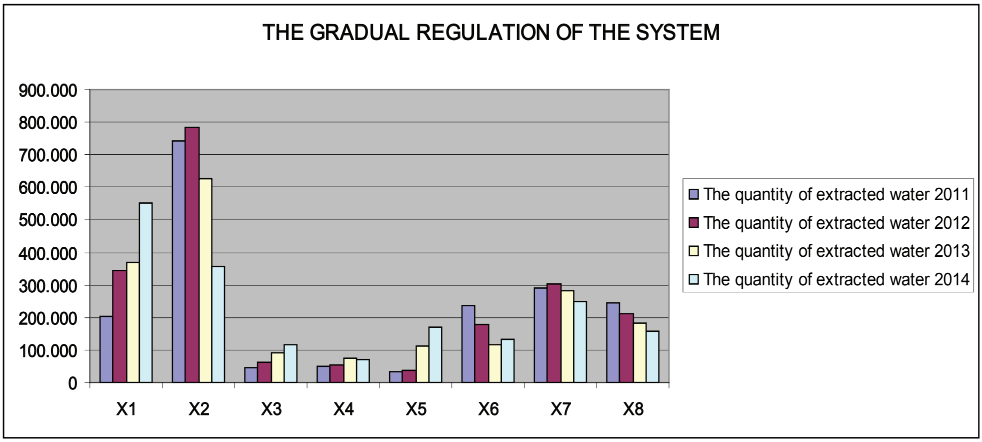


***Figure 6**: The trend of the utilization of water resources*

5 CONCLUSION

Since the economic exploitation of water resources represents savings in the consumption of the capacities of water resources for an entire generation and thus reduced energy consumption, it is more than reasonable to perform the optimization of the entire water supply system, taking into account all the given aspects.

Figure 7 shows the final state of the water supply system after all four phases of the optimization are performed. In the case that the capacities of storage tanks are upgraded and with them associated improvements of the hydraulic system made, providing the favourable hydrological conditions and the possibility of the quantitative utilization of water sources of the gravitational system as well as the water refilling from the unfavourable water sources in terms of energy consumption but simultaneously quantitatively independent of the hydrological conditions, the telemetric monitoring of the system status could be reached. The level of monitoring would be such that it would provide the highest possible rational supply with drinking water in terms of quantity, quality and price to satisfied customers.

The potential energy utilization of water sources within the water supply system and online control with the use of an appropriate numerical model simulation of the entire water supply system, which is currently under preparation, contributes to the optimal use of water resources and to the required energy consumption.

Figure 7: *The final state of the water supply system*

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