Baseline and options for design of wastewater treatment plants as a part of large sewerage infrastructure: case study Veliko Selo (Belgrade Sewerage System)

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Abstract: For adequate dimensioning of wastewater treatment facilities, it is necessary to obtain and analyze the most reliable data on the quantity and quality of wastewater, with all necessary basic parameters for assessing the hydraulic and mass load of future process units and defining their capacity. To that end, the project of the construction of a collector system (interceptor) and a wastewater treatment plant for the Belgrade Central Sewerage System site included collection, systematization and analysis of existing data on the quantity and quality of wastewater, additional measurements of quantities and testing of wastewater quality, systematization and interpretation of the results, analysis of demographic data, assessment of future system load and the development of a mathematical models of the sewerage system using EPA SWMM package, as well as of transport of polluting substances in the natural recipients using RMA2/RMA4 through the SMS package. Final output is the baseline for the wastewater treatment plant of the Belgrade Central Sewerage System, as presented in this paper. The relevant legislation, focusing on two main outputs in terms of environmental protection of wastewater treatment – effluent and treated sludge, was analyzed individually, as well as considering interrelations between the provisions of legal documents. Four appropriate concepts for the wastewater treatment plant were singled out of a wider array of modern engineering solutions proven in practice, based on the analysis of legal and logistical constraints and pitfalls.

INTRODUCTION

For adequate design of wastewater treatment facilities, collection and analysis of the reliable data on quantity and quality of wastewater is a necessary prerequisite. According to [1] in this stage, the influent and effluent data are selected, and important parameters determined. Data cleaning, visualizing and transforming are part of this stage. The data are then available in a form that is compatible with a modeling technique. The integration of multiple databases or data integration is often required in data mining processes. The relationship between quality parameters can be analyzed by using the correlation coefficient, and data sample distribution for these parameters is analyzed. Further, time series models can be applied to the time series of selected influent quality parameters, the best models for each influent variable selected based on various statistics and the ability of the models to forecast future values in the time series [2]. The holistic perspective applied to evaluation of modern wastewater treatment plants (WWTPs), including not only effluent quality but also resource efficiency and recovery, global environmental impact and operational cost calls for assessment methods including both on- and off-site effects, using dynamic process models that include greenhouse gases, detailed energy models and operational cost – and life cycle assessment [3], needs a strong base in quality and quantity of influent data.

Although the sewage infrastructure in the City of Belgrade has mostly been built, the issue of wastewater evacuation and treatment is still not adequately resolved. Belgrade Sewerage System (BSS) is divided into five independent catchment areas, i.e., systems: Central, Batajnica, Banat, Ostružnica and Boleč. The largest of them is Belgrade Central Sewerage System (BCSS), which covers the area of about 85 % of the Belgrade Sewerage System, with about 1,250,000 inhabitants connected to the sewage infrastructure [4]. All wastewater is discharged without treatment into the Sava River and Danube River. For each of the aforementioned sewerage systems, a construction of wastewater treatment plant has been planned.

The concept of development of BCSS implies the construction of a collector system (INTERCEPTOR) and a wastewater treatment plant at the Veliko Selo site (WWTP "Veliko Selo"). The collector system (INTERCEPTOR) includes all collector sections (existing and the planned ones) of the main reception collector – Interceptor, with associated connecting and joint structures, as well as sewage pumping stations (SPSs) "Ušće Nova" and "Mostar" (Figure 1).

This concept has been confirmed more than once over the past 50 years through preparation of extensive technical and planning documentation. Major parts of the system were built during the period between 1980 and 2012, but different circumstances led to the fact that the system has not yet been completed and become operational. Since 2020s, efforts to finish the design and construction of the INTERCEPTOR and WWTP "Veliko Selo" have been intensified.

The major issues that had to be addressed regarding the WWTP design were to determine the baseline – wastewater quantity and quality as input data, as well as the legislative and logistical constraints (especially regarding the sludge quality and disposal, beside the effluent requirements) as the crucial factor for selection of the possible treatment options.

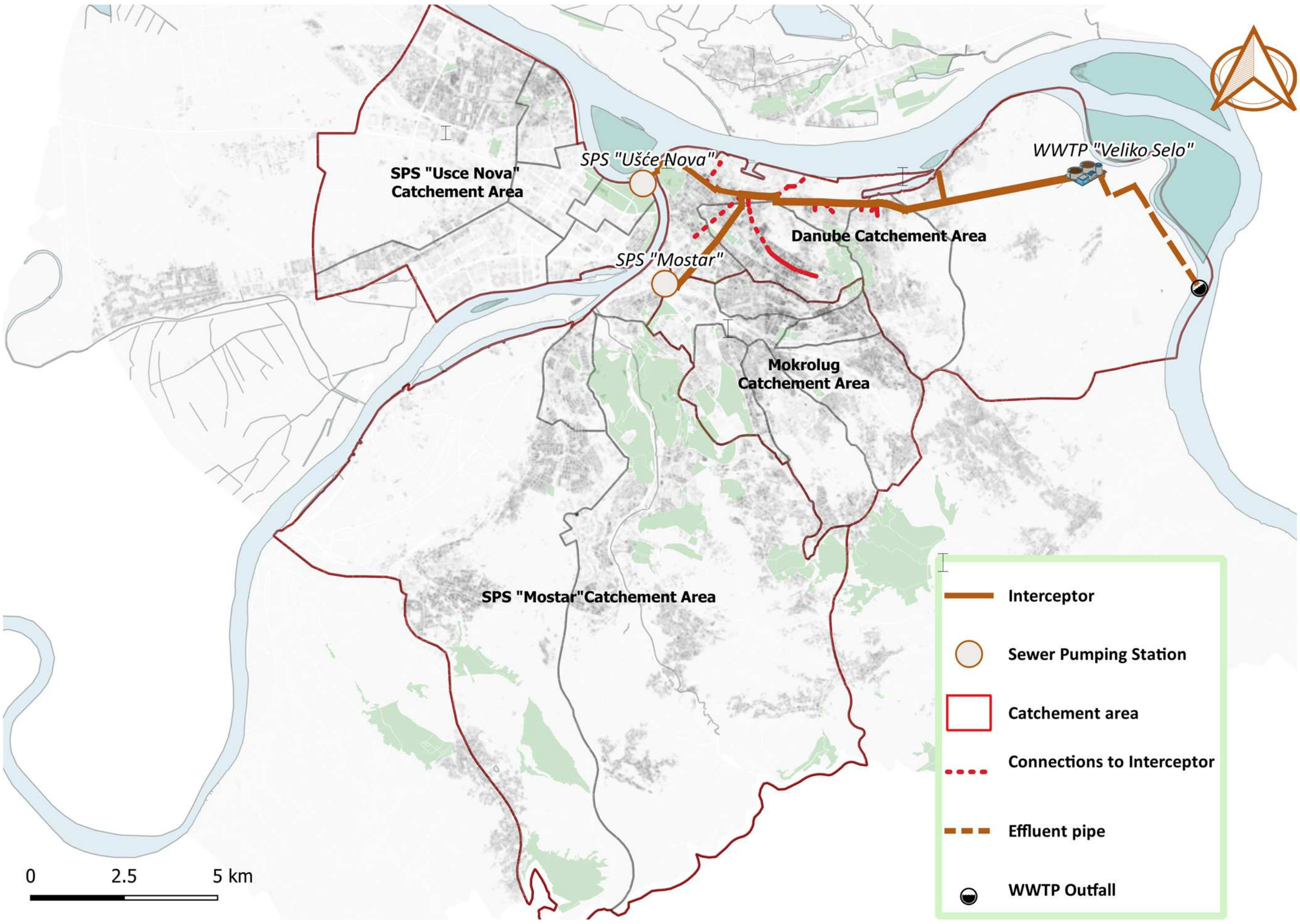

***Figure 1**. Catchment area of BCSS with its sub-catchments, Interceptor and WWTP Veliko Selo*

METHOD

Input data on wastewater quantity and quality

For adequate dimensioning of wastewater treatment facilities, it is necessary to have the most reliable data on the quantity and quality of wastewater, the basic parameters for assessing the hydraulic and mass load of future process units and defining their capacity.

Of particular importance is the availability of data based on which the optimal technological concept of wastewater treatment can be selected, such as: the mutual relationship between individual pollutants in wastewater, flow fluctuations on a daily and seasonal level, including the base wastewater flow and its seasonal variability, share and variability of atmospheric water and the like.

In accordance with the above, the field works and analysis of previous and newly obtained data on the quantity and quality of wastewater was performed, which included the following activities [4]:

- collection, systematization and analysis of existing data on the quantity and quality of wastewater of BCSS,
- additional measurements of quantities and testing of wastewater quality; systematization and interpretation of the results;
- analysis of demographic data;
- assessment of future system load;
- development of a mathematical model of the flow and transfer of polluting substances to the location of the WWTP "Veliko Selo",
- setting the baseline for the WWTP design.

The general goal was to determine the relevant categories of hydraulic load, such as: mean daily flow ($Q_{mean, d}$), maximum daily flow ($Q_{max.d}$), maximum hourly flow in dry weather ($Q_{max.h, dry}$), minimum hourly flow in dry weather ($Q_{min.h, dry}$), maximum hourly flow in rainy weather ($Q_{max.h, rain}$), as well as the determination of average, maximum and minimum values of key quality parameters (and mass balances of pollutants in wastewater, to serve as a basis for evaluating and defining the capacity and concept of the future WWTP "Veliko Selo". The data basis used comprised the following sources:

- results of regular laboratory analyses of wastewater quality, and campaigns of measuring the flow of wastewater at nine measuring spots (MSs) on the catchment BCSS (SPS "Karađorđe Sq.", SPS "Ušće", Sajam, Lasta, Dorćol, Istovarište, Ada Huja 1, Ada Huja 2 and Višnjica (Figure 2) in the period from 2010 to 2019 (PUC Belgrade Waterworks and Sewerage and Faculty of Civil Engineering in Belgrade), and the results of campaigns of measuring the flow of wastewater at the same MSs from 2007 to 2019,
- results of continuous flow measurements synchronous with the sampling of 24h composite samples for wastewater quality analyses, at three measuring points of BCSS ("Sajam", "Ušće", "Venizelosova St." – Figure 2) in the May-July 2021 period (Jaroslav Černi Water Institute - Belgrade).

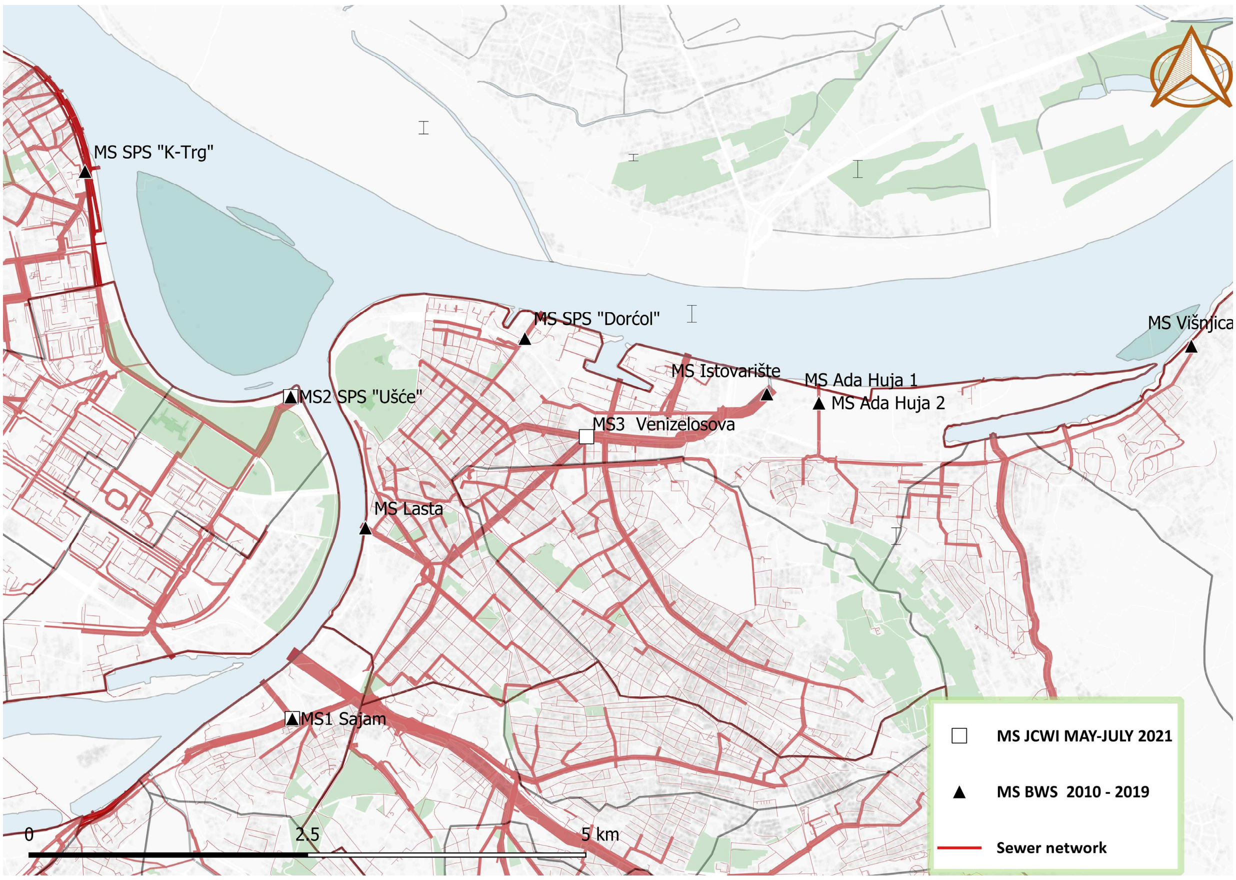

***Figure 2**. Measuring spots within BCSS*

Wastewater quantity, quality, and mass flows 2007 – 2019

As regards the wastewater quantity, data processing of recorded measurements from the 2007 – 2019 period was performed in order to obtain characteristic flows listed in the previous section [4].

Data processing of results of *in-situ* measurements and laboratory analyses of the wastewater samples was performed in order to obtain characteristic values of parameters of wastewater quality such as average, minimum and maximum value. Key parameters were biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN) as N and total phosphorus (TP) as P. In addition, quality parameters' values distribution was analyzed based on mass balance and probability functions:

- average based on mass balance – The mass balances were calculated and used to calculate the weighted average values of selected parameters of quality, by multiplying the mass flow for each period of synchronous flow measurement and sampling, with the duration of that period, summing those products, and dividing the sum with the cumulative flow during all periods (see table Table 1 – average values in parentheses). In addition to the mass balances for the samples taken synchronously with the flow measurement, the quarterly mass balances, as well as the mass balance based on the mean concentration and mean flow for the entire period from 2010 to 2019 were used to calculate average values of parameters of wastewater quality,
- most frequent value (and probability distribution of values) – the distribution of values of selected parameters of quality (BOD_5, COD, TN, TP and TSS) and probability mass function and the appropriate standard probability density function were calculated. Probability mass function was calculated by rounding the values to nearest 0.1, 1, or 10 mg increments (depending on the span of values of the given quality parameter) and determining the frequencies of occurrence of the increments. The Gumbel distribution provided the best match, and the frequencies for the increments were calculated by calculating probability for occurrence of any value within the increment. The mode (most frequent value) and scale parameter were determined based on the best match.

The available data on the flow of wastewater were compared with the data on the quality in order to single out the periods in which the sampling for determining the quality coincided with the flow measurement at the given measuring spot. In cases where there was a match, the mass flow (product of flow and concentration) was determined for parameters that are expressed through concentration in the following ways [4]:

- in the case of the current samples, for the mass flow calculation, the flow measured at the moment closest to the sampling moment, if the exact sampling time is known, was used. If the exact sampling time was not known, the mean flow for the period between 8:30 and 9:30 AM was used because most samples were taken at this time,
- in the case of 6-hour composite samples, mean flows for the corresponding 6-hour periods were used,
- in the case of 24-hour composite samples, the mean flow for the corresponding 24-hour period was used.

Wastewater quantity, quality, and mass flows, January-August 2021

Data processing of recorded measurements was performed in order to obtain following characteristic flows (with the same meaning as for the 2007 – 2019 period data processing). Data processing of results of *in-situ* measurements and laboratory analyses of the wastewater samples was performed in order to obtain characteristic values of parameters of wastewater quality such as average, minimum and maximum value. In addition, quality parameters' values distribution was analyzed based on mass balance and probability functions:

- average based on mass balance – the mass balances were used to calculate the weighted average values of selected parameters of quality, by summing the mass flow for each day of period of synchronous flow measurement and sampling, and dividing the sum with the cumulative flow during that period,
- most frequent value (and probability distribution of values) – probability mass function was calculated by rounding the values to nearest 0.5, 10, or 40 mg increments (the increments were several times bigger than for the 2010-2019 wastewater quality data, as the number of data points was up to 10 times smaller, so in order to obtain a frequency table the values had to rounded more), and determining the frequencies of occurrence of the increments. The Gumbel distribution again provided the best match, and the frequencies for the increments were calculated by calculating probability for occurring of any value within the increment. The mode (most frequent value) and scale parameter were determined based on the best match.

The mass flow (product of flow and concentration) for the period 19.05. – 18.07.2021 was determined for parameters that are expressed through concentration in the following way:

- for all 24-hour composite samples, the mean flow for the corresponding 24-hour period was used.

Flow and quality model of BCSS

Mathematical model was used to analyze the existing sewer network and hydraulic loads at BCSS, and to create projections of the quantities and quality of wastewater for the future period at WWTP "Veliko Selo". EPA SWMM software package was used for the development and implementation of mathematical model. Quality indicators of the Danube River transport were simulated by the RMA2/RMA4 through the SMS package.

General description

SWMM was developed between 1969 and 1971 by three groups: Metcalf and Eddy, Inc., the University of Florida, and Water Resources Engineers, Inc. It is widely used for analysis of quantity and quality problems related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. SWMM can generate hydrographs and (optionally) pollutographs (concentration vs. time) at any point along the collection system. Version 5.1.015 of the SWMM program, which was released in July 2020, was used for the implementation of the mathematical model [5].

Flow routing in channels and pipes in SWMM program is governed by the mass conservation equation (Equation (1)) and momentum conservation equation (Equation (2)) for gradually varied, unsteady flow (Saint Venant) equations. The user decides on the simplification level of the equations: the steady flow routing; the kinematic wave routing; or the full dynamic wave routing. In the transport compartment, SWMM solves the Saint-Venant equation using an explicit finite difference method and successive approximation [6]:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial H}{\partial x} + gAS_f = 0 \tag{2}$$

x is distance [m]; t is time (sec); A is flow cross-sectional area (m^2); Q is flow rate (l/s); H is hydraulic head of water in the conduit (Z + Y) (m), Z being a conduit invert elevation, Y a water depth; S_f is friction slope (-); and g is acceleration (m/s^2).

For the parts of BCSS where the sewage system is combined, sub-catchment areas and hydrological processes were simulated. Sub-catchments can be divided into impervious and pervious areas. Losses in impervious areas are only due to depression storage while in pervious areas infiltration may also be modeled through Horton, Green-Ampt or SCS Curve Number method. Surface runoff in pervious and impervious fractions is given by the Manning’s equation. SWMM also allows describing additional characteristics and processes within the study area, namely those related with subsurface water in groundwater aquifers and snowfall and snowmelt phenomena.

Simplification of mathematical model and model development

For practical reasons, the mathematical model of BCSS has been simplified to the main structures in the network [4]. The simplification of a database is a common procedure in the practice of hydraulic modeling, and there are several justified reasons for this:

- The information generated by the detailed model of hydraulic condition in local networks is of limited accuracy,
- The detailed simulation of local networks (without detailed calibration) does not generate significant improvement of results in the main pipelines that are of interest in the general analysis of the functioning of large networks, such as the BSS network,
- Difficulties with the simulation model increase progressively with the size of the model in terms of the number of pipes and nodes.

A simplification of the sewerage network is achieved through the following methods:

- By eliminating secondary local networks, and connecting local sub-catchments to the final upstream manhole of the simplified network,

- By eliminating manholes along the pipeline, which remain in the simplified model, and connecting two pipes into one, unless it means a significant change in the configuration of the model. In this case, too, the sub-catchments and other hydraulic loads connected to the manhole that is being eliminated are reconnected to the nearest upstream or downstream manhole left after the simplification process.

During the development of the BCSS simulation model, the BCSS was divided into three independent units (sub-models) [4]:

- Model of the catchment area MS Sajam – "Sajam" covers the catchment area of the measuring point, within which the quantities and quality of wastewater were measured. Contains 219 nodes, 4 wet wells, 3 pumping stations, 222 pipelines and 1 outflow. The total length of the presented sewerage network is 37.5 km,
- Model of the catchment area MS Ušće – "Ušće" – The entire sewer network and structures of these sub-model are a single functional unit and a completely independent sewerage system, with the final downstream point at SPS "Ušće" and the outflow of wastewater at the Sava and Danube confluence. Model covers the catchment area of the MS Ušće The model of the sewerage network contains 93 nodes, 4 wet wells, 4 pumping stations, 91 pipelines and 1 outflow. The total length of the covered sewerage network is 21.9 km,
- Model of the catchment area MS Venizelosova St – "Terazije Tunnel" - The model of the sewerage network contains 84 nodes, 1 wet well, 1 pumping station, 82 pipelines and 2 outfalls. The total length of the presented sewerage network is 10.07 km.

Input hydrographs of the model are the result of simulations conducted in sub-models Sajam, Ušće, and Terazije tunnel.

The results of the simulations performed in sub-models MS Sajam, MS Ušće, and MS Terazije tunnel are the input hydrographs for the Model of the future system (SPS "Ušće Nova" – Interceptor – WWTP "Veliko Selo"). On this specially developed model, the existing hydraulic load is mapped to the future sewerage system and carried to the location of the WWTP "Veliko Selo". Input parameters for the model simulations were based on hydraulic loads applied to precisely defined network nodes in the form of various hydrographs. The future system model represents how the Central Sewerage System will function after the Interceptor and WWTP "Veliko Selo" are constructed and fully operational. The model of the sewerage network of the future system contains 170 nodes, 3 wet wells, 3 pumping stations, 167 pipelines, 2 overflows and 3 outlets. The total length of the presented sewerage network is 29.49 km [4].

River Quality Model

The mixing of effluent and river water, i.e. potential impact of the effluent on the Danube River quality indicators was simulated by the RMA2/RMA4 models tandem. The RMA2 model is a hydrodynamic model based on flat flow equations in the shallow domain (depth-averaged Navier-Stokes equations). The model assumes a hydrostatic distribution of pressures in the vertical direction and as such is suitable for simulating mixing in zones at a greater and intermediate distance from the initial dilution zone. Spatial discretization of the computational domain is on the network of finite elements, which enables the definition of bathymetry in high spatial resolution. The RMA4 model is a transport model, which calculates transport equations based on the flow solution obtained by simulating the RMA2 hydrodynamic model.

Legislative framework regarding wastewater treatment in the Republic of Serbia

The relevant legislation, focusing on two main "products" of wastewater treatment – effluent and treated sludge in terms of environmental protection, was analyzed individually, as well as considering interrelations between the provisions of legal documents.

Effluent quality legislative framework in the Republic of Serbia

The Law on Waters ("Official Gazette of the RS", No. 30/2010, 93/2012, 101/2016, 95/2018 and 95/2018 – anth. law) prescribes that wastewater, prior to its discharge into the recipient, must be treated to a level that corresponds to emission limit values of pollutants in waters (defined within the Regulation on Emission Limit Values of Pollutants in Waters and Deadlines for their Achievement ("Off. Gazette of the RS", No. 67/2011, 48/2012 and 01/2016)), or to a level that would not jeopardize environmental quality standards (quality indicators) of the recipient (defined within the Regulation on Limit Values of Pollutants in Surface and Ground Waters and Sediment and Deadlines for their Achievement ("Official Gazette of RS", No. 50/2012), whichever is more stringent.

The analyses were performed taking into consideration that the Danube River is the recipient of the WWTP "Veliko Selo" effluent.

Sewage sludge land use and landfill legislative framework in the Republic of Serbia

In the Republic of Serbia there is a lack of legislative framework related to land use (agricultural reuse, "landscaping", recultivation, etc.) of the sewage sludge (sludge from WWTP), while the relevant legislation for consideration of sludge disposal at landfills is the Law on Waste Management ("Official Gazette of RS", No. 36/2009, 88/2010, 14/2016 and 95/2018) and related by-law documents, including Rulebook on Categories, Testing and Classification of Waste ("Official Gazette of RS", No. 56/2010, 93/2019 and 39/2021).

The legislation on waste management recognizes sludge from the wastewater treatment plants and assigns it a waste index number "19 08 05". Article 10 of the Rulebook on Categories, Testing and Classification of Waste prescribes that prior to its disposal, the waste should be tested (analysed) in accordance with the List of parameters which is given as Annex 10 of the Rulebook. The List contains over 40 parameters.

The only legal document which has addressed the issue of potential sewage sludge land use is Regulation on Emission Limit Values of Pollutants in Waters and Deadlines for their Achievement ("Off. Gazette of the RS", No. 67/2011, 48/2012 and 01/2016), at the end of which, unrelated to the rest of the content of this legal document, the Table 7 of Chapter III has been given, with "Emission limit values for residues from municipal wastewater treatment", containing "limit values" (in mg/kg of "residue") for 8 heavy metals and 5 other parameters (13 in total) for: 1) Use in agriculture and 2) For other purposes, such as: covering landfills, improving the landscape (filling of depressions), improving the quality of soil on which agricultural crops will not be grown and cattle will not be grazed for at least one year, etc. This Table could be considered as a sort of excerpt from Directive 86/278/EEC, with mostly stringent values and without specifying some important characteristics of "residues" (moisture content, etc.).

Beside the fact that the sewage sludge disposal on landfills is addressed by the Law, while the sewage sludge land use is addressed only by by-law document, most evident discrepancy is that for the purposes of sludge disposal at a regulated landfill, the analysis of more than 40 parameters is required, while for agricultural and other uses, only 13 of them should be analyzed, which is highly contradictory.

RESULTS

Wastewater quantity and quality input data analyses

The results of processing of 2007 – 2019 and January-August 2021 periods data on wastewater quantity were utilized to calculate mean daily flow, maximum daily flow, maximum hourly flow in dry weather, minimum hourly flow in dry weather, and maximum hourly flow in rainy weather. The results of processing of 2010 – 2019 and May-July 2021 periods data on wastewater quality were used to calculate average, minimum, and maximum values of parameters of wastewater quality, as well as the mode (most frequent value) and scale parameter based on the best match with the Gumbel distribution.

Wastewater quantity, quality and mass flows, 2007 – 2019

Characteristic flows based on processing data of the flow measurements from this period are presented in Table 1.

Table 1. *Characteristic flows based on data processing of recorded measurements, 2007 – 2019 period*

		MS								
Conditions	Flows (l/s)	Sajam	Ušće	Lasta	Dorćol	Istovarište	Ada Huja 1	Ada Huja	Višnjica	SPS"K.Sq"
Dry	$Q_{avg.d}$	1,480	667	280	152	530	35	28	177	305
	$Q_{max.d}$	1,764	732	303	167	600	40	34	203	
	$Q_{max.h}$	2,247	939	437	239	771	51	47	240	
	$Q_{min.h}$	531	303	143	89	238	16	15	61	
Rainy	$Q_{max.h}$	3,989	1,336	2,405		5,890	273	227	380	

The final output of data processing of records of wastewater quality analyses and flow measurements in 2010 – 2019 period were the average, minimum, and maximum values of parameters of wastewater quality, as well as the mode (most frequent value) and scale parameter based on the best match with the Gumbel distribution.

***Table 2**. Number of samples analysed for 9 measuring spots, 2010 – 2019 period*

		No. of samples									
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1.	MS Ušće	221	131	98	74	92	86	33	25	51	60
2.	MS Sajam	104	211	113	61	52	37	45	26	42	60
3.	MS Višnjica	142	96	59	70	54	31	20	18	10	24
4.	MS Lasta	51	127	61	59	26	2	19	20		32
5.	MS Istovarište	159	65	57	29	21	16	29	22	13	39
6.	MS Dorćol	174	94	53	58	90	75	40	20	72	44
7.	MS Ada Huja 1	114	56	84	34	23	32	24	18	15	12
8.	MS Ada Huja 2	78	112	125	40	23	32	24	18	15	12
9.	MS SPS Karađorđe Sq.		14	74	56		32	29	16	18	36

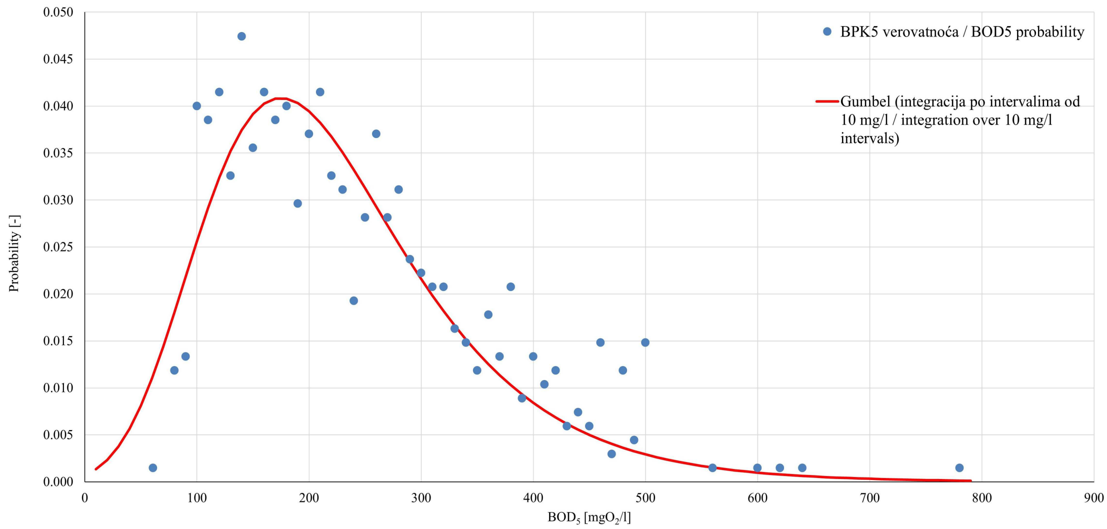

***Figure 3**. Probability mass function for BOD_5 at MS Sajam (2010 – 2019) calculated by rounding the values to 10 mg increments and determining the frequencies of occurrence of the increments. The Gumbel distribution of BOD_5 is shown by red curve. Mode (i.e., location parameter μ) is 180 mg/l, scale parameter β is 90 mg/l, and standard deviation is 115 mg/l*

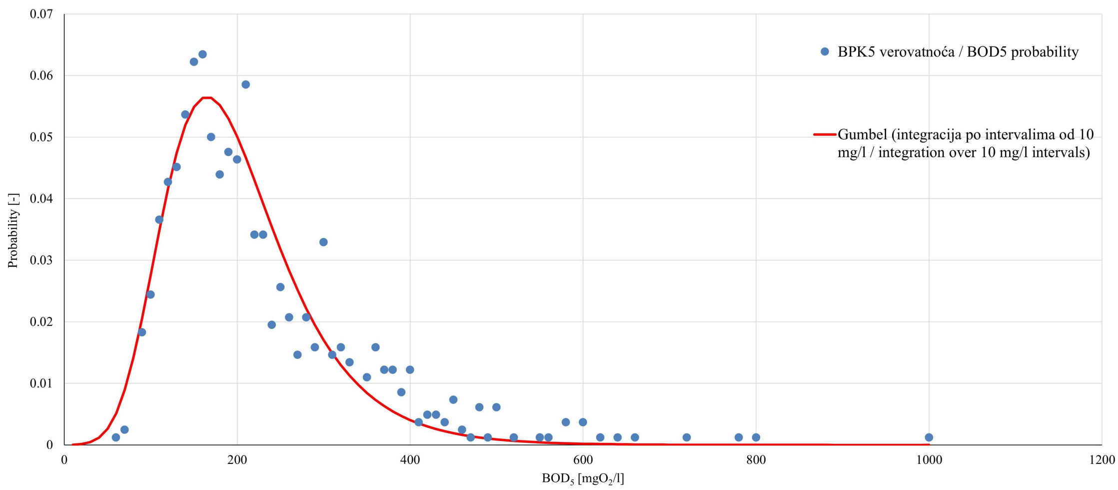

***Figure 4**. Probability mass function for BOD_5 at MS Ušće (2010 – 2019) calculated by rounding the values to 10 mg increments and determining the frequencies of occurrence of the increments. The Gumbel distribution of BOD_5 is shown by red curve. Mode (i.e., location parameter μ) is 250 mg/l, scale parameter β is 110 mg/l, and standard deviation is 141 mg/l*

***Table 3**. Minimum, maximum, and average values of selected parameters (BOD_5, COD, TSS, TN, TP) for 9 measuring spots, 2010 – 2019 period. Values within parentheses are mass averages calculated as cumulative mass flow divided by cumulative flow for synchronous flow measurements, while values within brackets are the modes. Average values for the combined flow were calculated as combined mass flows of all MSs (products of average flow and average value of the parameter) divided by combined average flows of all MSs*

MS	BOD_5			COD			TSS			TN			TP		
(avg.flow)	min	max	avg	min	max	avg	min	max	avg	min	max	avg	min	max	avg
MS Sajam (1480 l/s)	61	780	240 (239)	85	1952	361 (325)	1.0	8,141	200 (228)	4	129	31	1	12	4 (5)
MS Ušće (667 l/s)	60	1000	224 [170]	105	2077	348	1.0	15,103	257	2	240	42	1	24	5
MS Lasta (280 l/s)	75	500	195 (282)	67	849	296 (419)	2	3,016	165 (148)	2	137	28 (39)	0.2	58	6 (13)
MS Dorćol (152 l/s)	15	495	147	62	970	239.5	0	3,310	107	1	145	25	1	25	5
MS Istovarište (530 l/s)	68	480	173	87	1323	268	2	3,374	142	5	150	31	1	22	7
MS Ada Huja 1 (35 l/s)	75	2600	182	85	6481	285	2	17,106	309	3	181	24	0.1	9	3
MS Ada Huja 2 (28 l/s)	20	470	157	91	1993	255	1	1,686	191	0.5	182	22	1	20	5
MS Višnjica (177 l/s)	73	650	212 (268)	101	1144	316 (369)	0.0	6,826	228 (122)	6	424	36 (69)	3	15	7 (6)
MS SPS Karađorđe Sq.	85	460	215	104	726	323	4	2,062	165	8	202	40	2	13	7
Total (3649 l/s)			215			328			195			33			5

Calculations of number of population equivalents (PEs) from mass flows (calculated as products of average flows and average values of BOD_5 and COD) and standard specific productions of those parameters are presented in Table 4. The number of PEs were extrapolated in proportion to the ratio between the official number of sewer system users in the entire BCSS and within the catchments of all MSs.

***Table 4**. Calculated BCSS PEs based on BOD_5 and COD mass flows and standard specific production of BOD_5 and COD for the 2010 – 2019 period*

Measuring spot (MS)	Catchment area (ha)	Number of sewer system users*)	PE calculated based on BOD_5 (60g/d/PE) 2010-2019	PE calculated based on COD (120g/d/PE) 2010-2019
MS Sajam	7276.9	518,224	511,084	384,410
MS Lasta	112.8	23,041	78,700	59,581
MS Ušće	2,997.8	224,980	215,097	166,963
MS Dorćol	92.0	17,284	32,150	26,216
MS Istovarište	1,225.7	164,653	131,752	102,211
MS Ada Huja 1	43.2	4,620	9,179	7,172
MS Ada Huja 2	104.4	3,075	5,202	4,226
MS Višnjica	115.6	68,000	53,969	40,231
MS SPS "Karađorđe Sq."	381.7	62,857	94,544	71,022
Sum of MSs	12,350.1	1,086,734	1,131,667	862,032
BCSS	29,900.0	1,113,510	**1,154,762***	879,624*

*) projection in proportion to Sum of MS/BCSS

Wastewater quantity, quality and mass flows, January-August 2021 period

Characteristic flows based on processing data of the flow measurements from this period are presented in Table 5.

Table 5. *Characteristic flows based on data processing of recorded measurements, January-August 2021 period*

Conditions	Flows	MS Sajam (17.4. – 15.8.2021)	MS Ušće (15.1.– 15.8.2021)	MS Venizelosova St. (18.3. –15.8.2021)
Dry	$Q_{sr.d}$ (m^3/d)	98,385	54,683	13,930
	$Q_{sr.d}$ (l/s)	1,139	633	161
	$Q_{max.d}$ (m^3/d)	133,833	70,263	15,980
	$Q_{max.d}$ (l/s)	1,549	813	185
	$Q_{max.h}$ (l/s)	2,199	1,138	289
	$Q_{min.h}$ (l/s)	287	217	88
Rainy	$Q_{max.h}$ (l/s)	6,210	1,717	3,097

The final output of data processing of records of wastewater quality analyses and flow measurements in May-July 2021 period were the average, minimum, and maximum values of parameters of wastewater quality, as well as the mode (most frequent value) and scale parameter based on the best match with the Gumbel distribution.

Compared to the 2010-2019 period 40 mg increments were used, bigger than 10 mg ones for the 2010-2019 wastewater quality data, as the number of data points was up to 10 times smaller, and to obtain a frequency table the values had to be rounded more. Nevertheless, the Gumbel distribution again proved to be the best match for the data.

In addition to the key parameters, the table with the average concentration of heavy metals is presented, for which the wastewaters were also analysed. The concentrations of heavy metals are of key significance for the calculations regarding the quality of sludge after the final treatment, whether it is a dehydrated sludge or ash.

Table 6. *Minimum, maximum, and average values of BOD_5, COD, TSS, TN (as N), TP (as P) for 3 measuring spots, May-July 2021 period. Values within parentheses are mass averages calculated as cumulative mass flow divided by cumulative flow during the period of synchronized measurements and sampling, values within brackets are the modes. Average values for the combined flow were calculated as combined cumulative mass flows of all MSs divided by combined cumulative flows of all MSs during the same period*

MS	BOD_5			COD			TSS			TN			TP		
(avg.flow during synchronous sampling)	min	max	avg	min	max	avg	min	max	avg	min	max	avg	min	max	avg
MS Sajam (1257 l/s)	149	898	305 (294) [250]	254	1349	552 (537)	95	664	227 (215)	28	60	42 (44)	3	16	8 (8)
MS Ušće (696 l/s)	86	834	304 (329) [250]	231	1125	542 (574)	43	547.2	223 (225)	35	64.8	50 (52)	3	15	8 (9)
MS Venizelosova St. (186 l/s)	84	802	249 (264) [210]	168	1126	437 (469)	42	678.4	194 (184)	17	64.8	37 (39)	2	13	6 (6)
Total (2135 l/s)			293			527			209			45			8

***Table** 7. Average values of concentrations of heavy metals for 3 measuring spots, May-July 2021 period (ones listed in Rulebook on Categories, Testing and Classification of Waste ("Official Gazette of RS", No. 56/2010, 93/2019 and 39/2021) and Regulation on Emission Limit Values of Pollutants in Waters and Deadlines for their Achievement ("Off. Gazette of the RS", No. 67/2011, 48/2012, 01/2016) are marked by bold font)*

	As (µg/l)	**Ba (µg/l)**	Bi (µg/l)	**Cd (µg/l)**	Co (µg/l)	**Cr (µg/l)**	Cu (µg/l)	Mn (µg/l)	Fe (µg/l)	**Mo (µg/l)**	**Ni (µg/l)**	**Pb (µg/l)**	Sn (µg/l)	**V (µg/l)**	**Zn (µg/l)**	**Hg (µg/l)**
	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.	avg.
MS Sajam	<10	86.3	<25	<2	<2	26.3	46.1	117.5	2,553	15.7	11.8	14.1	<10	<5	183.8	<1
MS Ušće	<10	82.2	<25	<2	<2	21.0	35.9	57.0	1,184	14.6	8.9	9.2	<10	<5	143.8	<1
MS Venizelosova St.	<10	73.9	<25	<2	<2	25.5	38.4	56.9	1,385	24.7	10.3	9.2	<10	<5	147.1	<1

The results of the statistical analysis on the probability distribution show that the distribution is skewed in comparison with normal distribution. The most frequent value is not the same as mean value which should be taken into consideration in the design process.

The important result of the statistical analysis is that the results of wastewater quality analyses that were performed during the 2010 – 2019 period by the PUC Belgrade Waterworks and Sewerage lab, and the results of wastewater quality analyses that were performed during the May-July 2021 period by the Jaroslav Černi Water Institute lab have the same probability distribution. This is a significant confirmation that the results of the wastewater quality analyses from those two periods are reliable and comparable.

The characteristic values of the key parameters are generally slightly higher in the May-July 2021 period, which could be explained in several possible ways, for example by the big difference between the duration of the two periods, or by the changes in the sewerage system during the 2010 – 2021 period etc. No correction was introduced in either data set as the cause of the differences could not be determined with certainty, so the data were used as such in the calculations for the baseline determination.

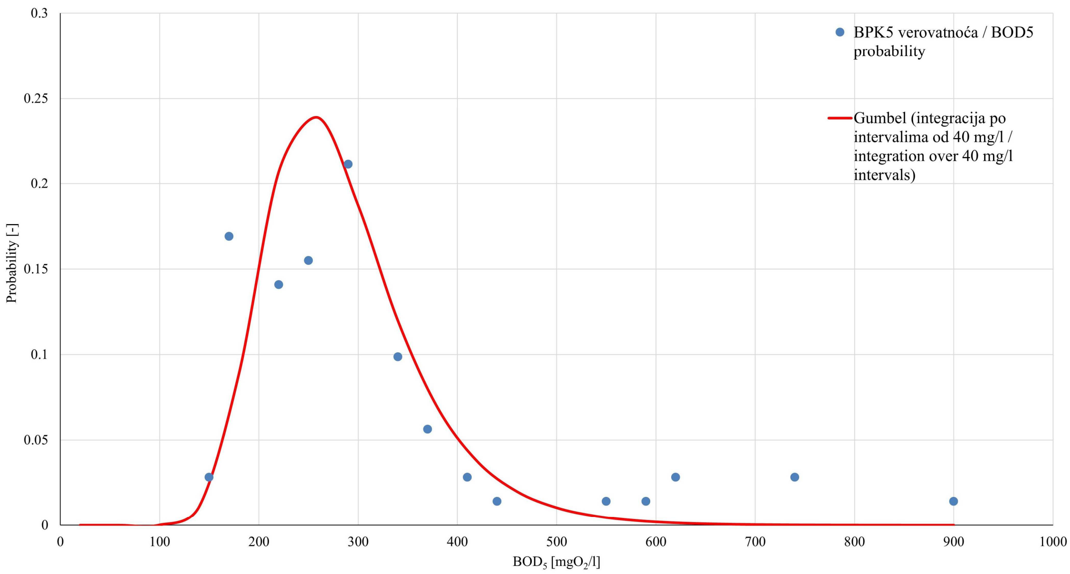

***Figure 5**. Probability mass function for BOD_5 at MS Sajam (May-July 2021) calculated by rounding the values to 10 mg increments and determining the frequencies of occurrence of the increments. The Gumbel distribution of BOD_5 is shown by red curve. Mode is 250 mg/l, scale parameter β is 60 mg/l, standard deviation is 76.9 mg/l*

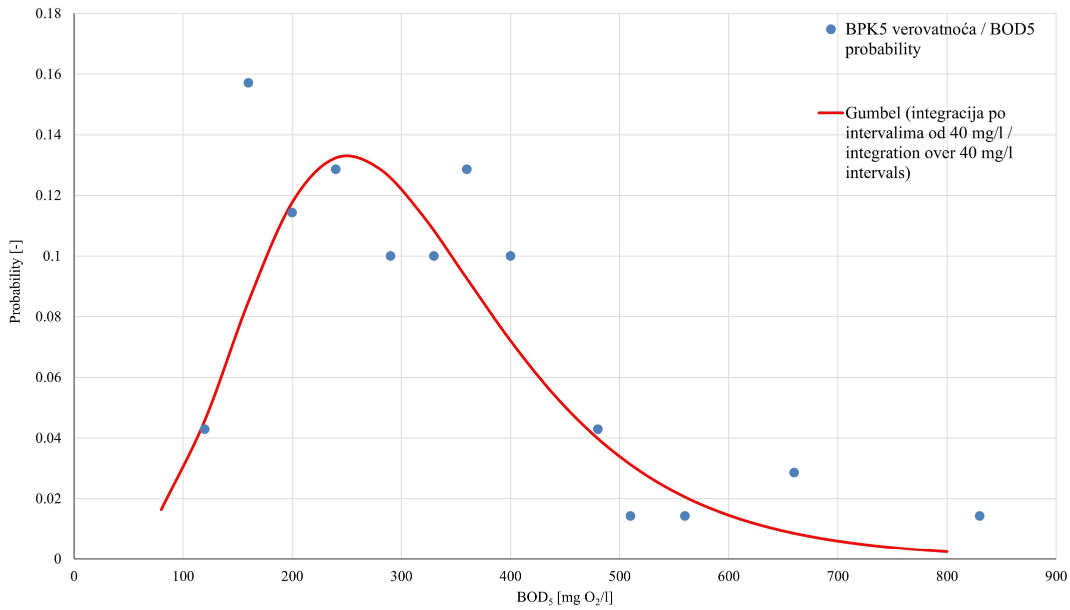

Figure 6. *Probability mass function for BOD_5 at MS Ušće (May-July 2021) calculated by rounding the values to 40 mg increments and determining the frequencies of occurrence of the increments. The Gumbel distribution of BOD_5 is shown by red curve*

Calculations of number of PEs from mass flows (calculated as average of all daily mass flows of BOD_5 and COD during the period at each MS) and standard specific productions of those parameters are presented in Table 8.

Table 8. *Calculated BCSS PEs based on BOD_5 and COD mass flows and standard specific production of BOD_5 and COD for the May-July 2021 campaign*

Measuring spot (MS)	Catchment area (ha)	Number of sewer system users*)	PE calculated based on BOD_5 (60g/d) 19.5.-16.7. 2022	PE calculated based on COD (120g/d) 19.5.-16.7. 2022
MS Sajam	7,276.9	518,224	502,154	458,783
MS Ušće	2,997.8	224,980	318,064	277,645
MS Venizelosova St.	521.0	105,000	67,712	60,331
Sum of MSs	10,759.7	848,204	887,930	796,759
BCSS	29,900.0	1,113,510	**1,256,203***	1,127,218*

* projection in proportion to Sum MS/BCSS

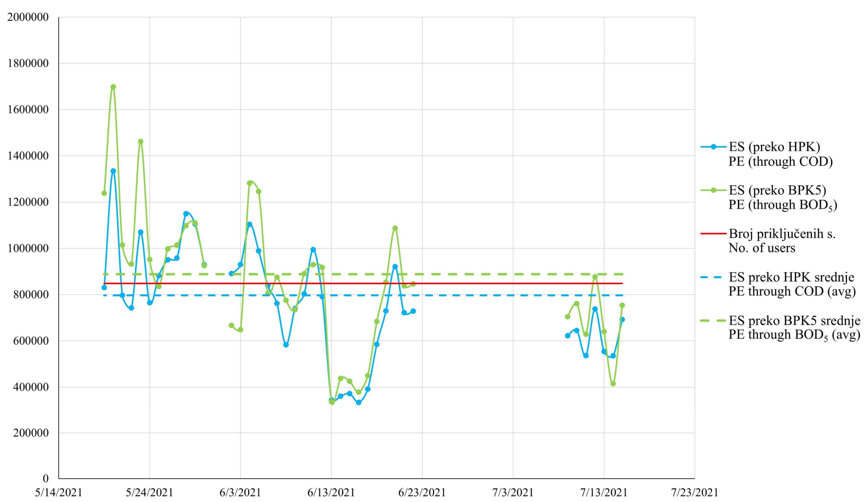

Figure 7. *The combined number of PEs based on combined mass flows and standard specific production of BOD_5 and COD (green and blue curves, respectively), and corresponding averages over the entire period (green and blue dashed lines)*

Flow and quality model of BCSS

Models of the catchment areas and sewerage systems connected to MS Sajam, MS Ušće and MS Venizelosova St. are the sub-models described in the Method section. The results of the simulations performed in sub-models MS Sajam, MS Ušće, and MS Terazije tunnel are the input hydrographs for the model of the future system.

The simulation results are presented as a 24-hour time series of the simulated network flow at selected locations. When it was possible, simulated and measured outcomes were compared. The fundamental finding is that the simulations results of hydraulic models are quite similar to the observed time series. The simulation results for the MS Ušće sub-model as example shows a good match with measured flows – Figure 8. The computed time series generated on the WWTP "Veliko Selo" profile are therefore a credible basis for the prediction of hydraulic load on the plant.

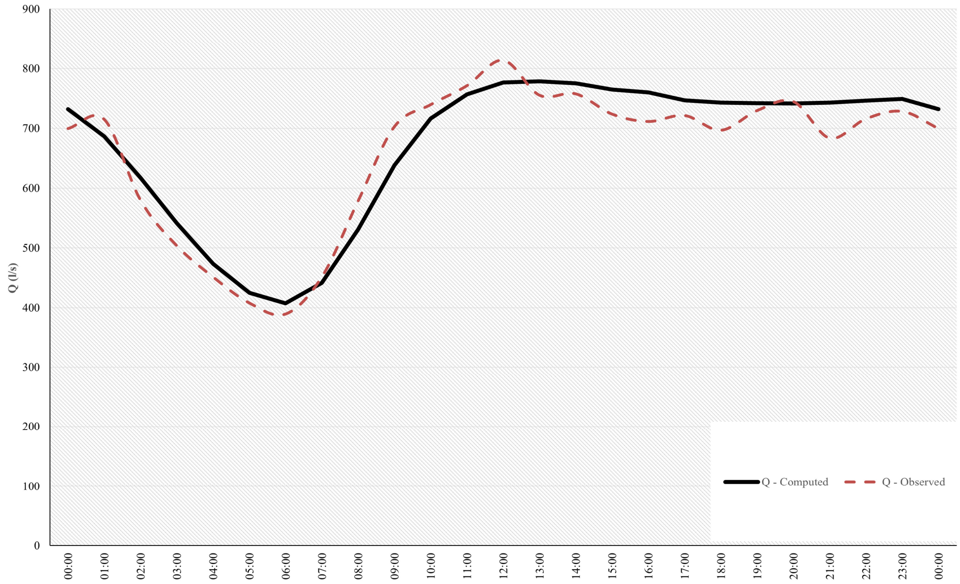

Figure 8. *The dashed line shows the observed flow at the MS Ušće on a typical dry weather day, whereas the black line represents the flow predicted by the mathematical model. All metrics indicate that the estimated hydrograph is quite similar to the observed hydrograph*

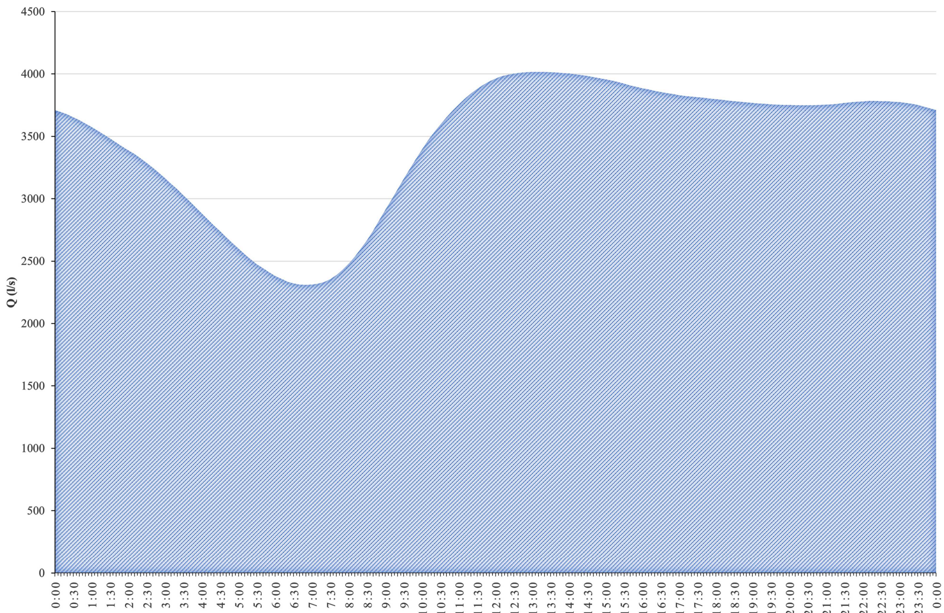

Figure 9. *Calculated hydrograph at the location of the future WWTP "Veliko Selo" for the existing quantities of wastewater from the Central Sewerage System (average day)*

WWTP concept

Water line concept

The level of wastewater treatment that should be reached at WWTP "Veliko Selo" was determined on the basis of legislation requirements and the results of applied RMA2/RMA4 models for simulation of the mixing zone downstream of the effluent. Effluent quality should comply with the emission limit values, from the Regulation on Emission Limit Values of Pollutants in Waters and Deadlines for their Achievement ("Off. Gazette of the RS", No. 67/2011, 48/2012 and 01/2016) as shown in Table 9. The influence of wastewater treatment on the natural recipients is twofold – the raw wastewater discharge at all outlet points is discontinued, and effluent discharge downstream from Belgrade is introduced. The marked positive effects of the cessation of the detrimental influence of raw wastewater discharge can be easily inferred from Figures 10 and 11, and the simultaneous very limited negative effects of the WWTP effluent discharge are illustrated in Figure 12 [7].

The elimination of the negative impact of wastewater outlets Sajam, Lasta, SPS Ušće and SPS Karađorđe Sq. on Sava River, that are clearly observed on the Figure 10, is perhaps the most significant positive efect of Interceptor and the WWTP on the environment will be the discontinuation of the discharge of untreated water into the Sava River which is, due to the much lower discharge, markedly more sensitive than the Danube River.

Having in mind all previously listed effects, it is clear that the discharge of effluent of stipulated quality (Table 9) would not jeopardize quality indicators of the recipient even for the Danube low waters.

***Table 9**. The upper limit values of the key parameters of quality of WWTP effluent as stipulated in the legislation*

Parameters	Unit	Limit value	Lowest % of reduction
COD	mg/l	125	75
BOD_5	mg/l	25	70-90
SS	mg/l	35	90
Ntot	mg/l	10	80
Ptot	mg/l	1	80

***Figure 10**. Wastewater discharges from BCSS (current state) into the Sava and the Danube Rivers upstream from the confluence (average wastewater flow, low waters, dry period)*

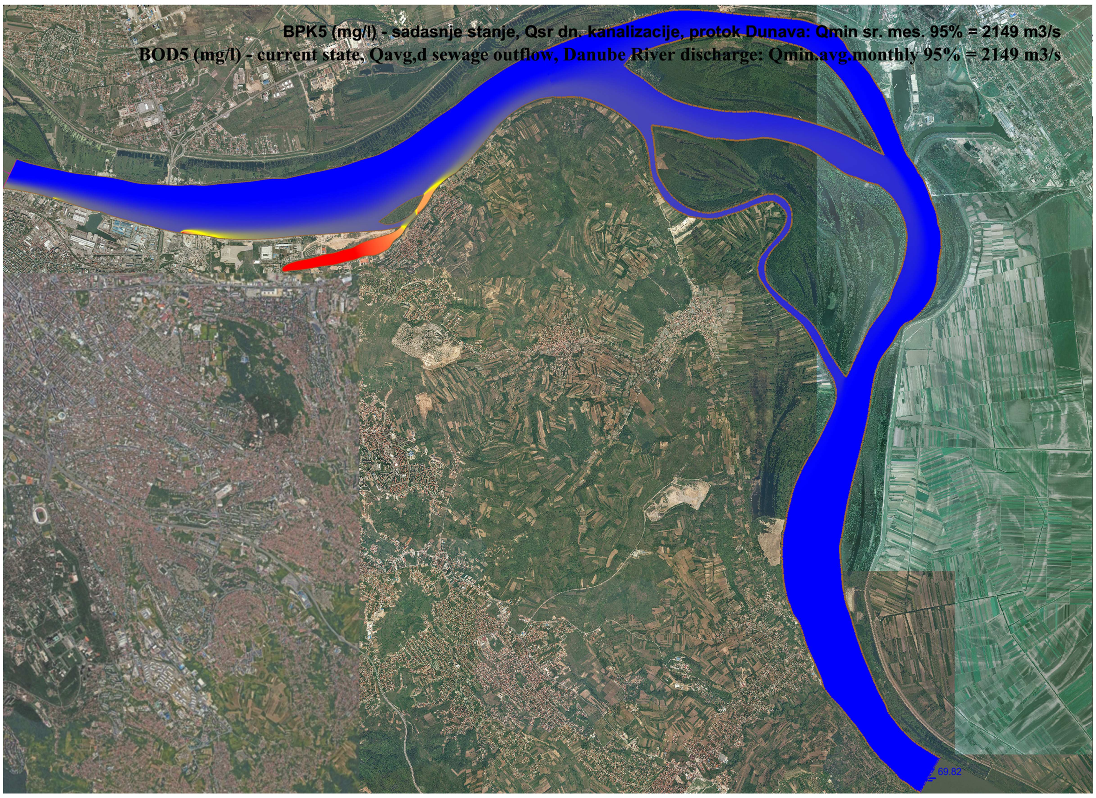

***Figure 11**. Wastewater discharges from BCSS (current state) into the Danube River downstream from the confluence (average wastewater flow, low waters, dry period)*

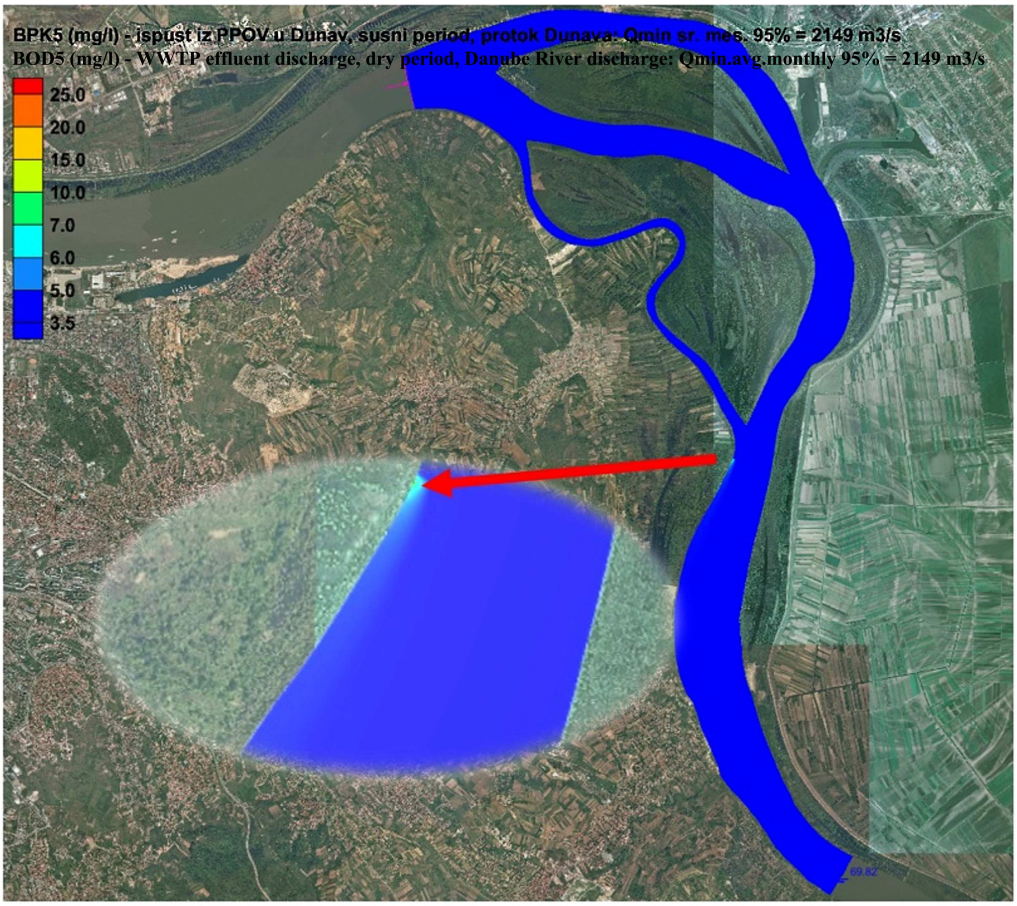

***Figure 12**. Effluent discharge from WWTP "Veliko Selo" into the Danube River (average effluent flow, low waters, dry period)*

Required effluent quality could be achieved by any of the advanced biological processes, based on activated sludge, along with preliminary and primary treatment prior to biological stage. A_2O – an advanced biological process from the group of conventional activated sludge (CAS) processes, is suggested as the most appropriate for WWTP "Veliko Selo" (Figure 13).

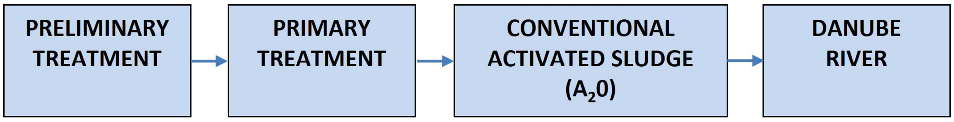

Figure 13. *Process flow diagram for WWTP "Veliko Selo" water line*

Sludge line options

While there are no uncertainties regarding the final destination of WWTP "Veliko Selo" effluent, for final sludge treatment and disposal there are several possibilities.

Preliminary selection of possible final sludge treatment technologies was based on legislation requirements and constraints.

Taking into consideration legal requirements and gaps that were pointed out in the Method section, WWTP capacity and other technical and logistical specificities, incineration on site [8] and co-incineration in cement or thermal power plants have been given priority as the two alternatives for final sludge treatment. Both of the alternatives have their advantages and disadvantages, which should be elaborated within techno-economic analysis. The same conclusion was reached in some earlier comprehensive analyses (e.g. [9]).

Whether the incineration will take place on WWTP "Veliko Selo" site, or at another plant (cement or thermal power), prior to its final treatment, sludge can be subjected to a hydrothermal carbonization process, resulting in transformation into "biochar" or "biocoal", a very interesting product that can be used as a fuel substitute [10].

Before final treatment, sludge (both primary and surplus) should be thickened, digested, dewatered and dried or carbonized, as shown in Figure 14.

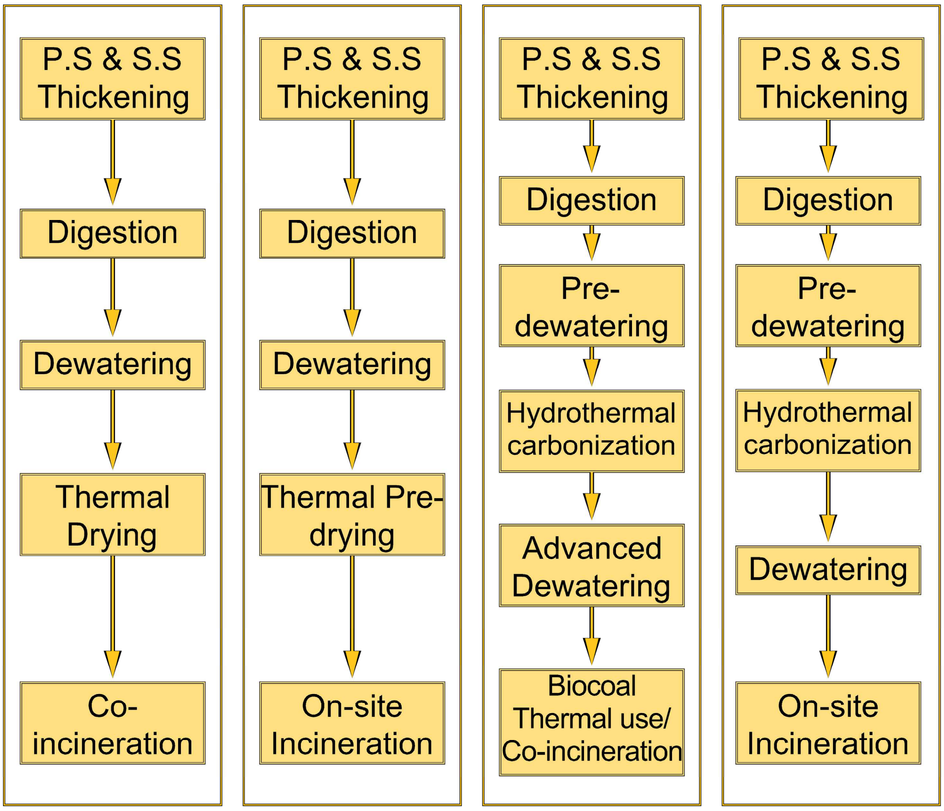

Figure 14. *Sludge treatment alternatives*

WWTP "Veliko Selo" concepts

For complete WWTP "Veliko Selo" the same water line is taken as preceding all four sludge line options, combined forming the following appropriate WWTP "Veliko Selo" concepts [10], as shown in Figures 15-18.

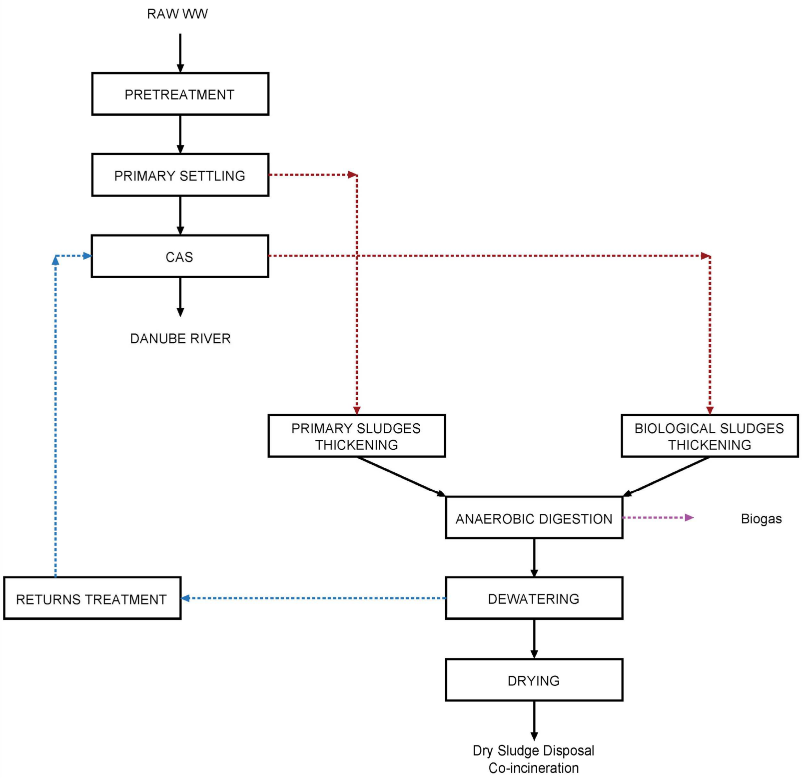

***Figure 15**. Process flow diagram for WWTP "Veliko Selo" Concept 1*

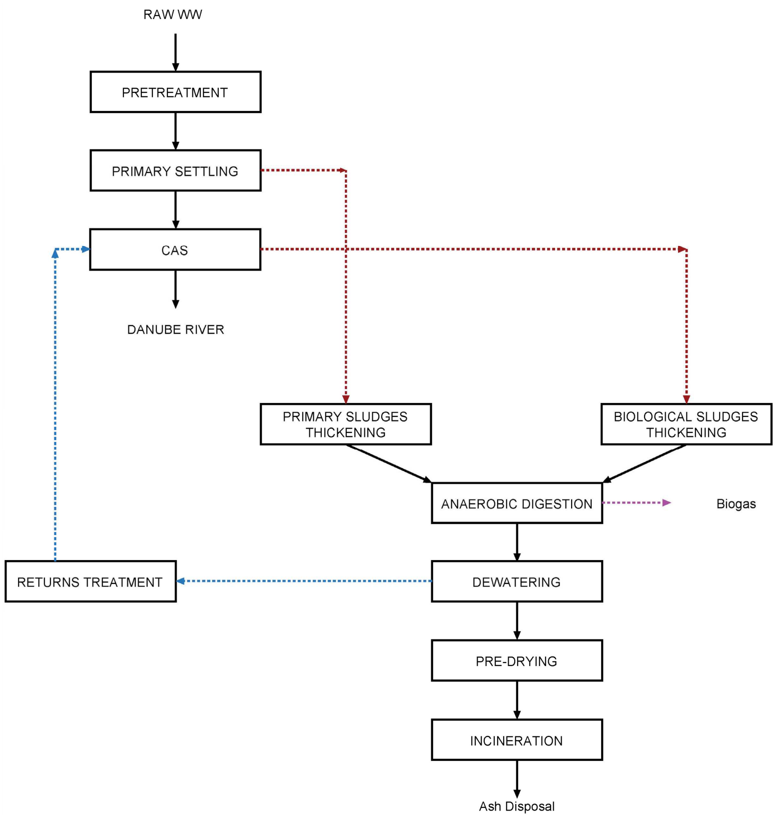

***Figure 16**. Process flow diagram for WWTP "Veliko Selo" Concept 2*

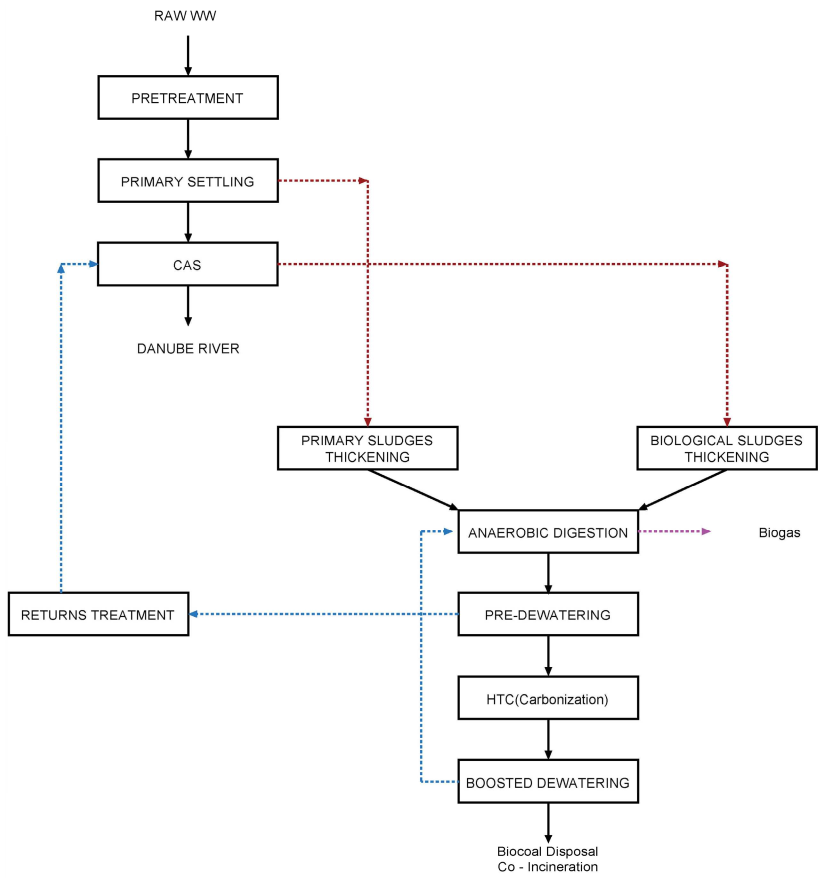

***Figure 17**. Process flow diagram for WWTP "Veliko Selo" Concept 3*

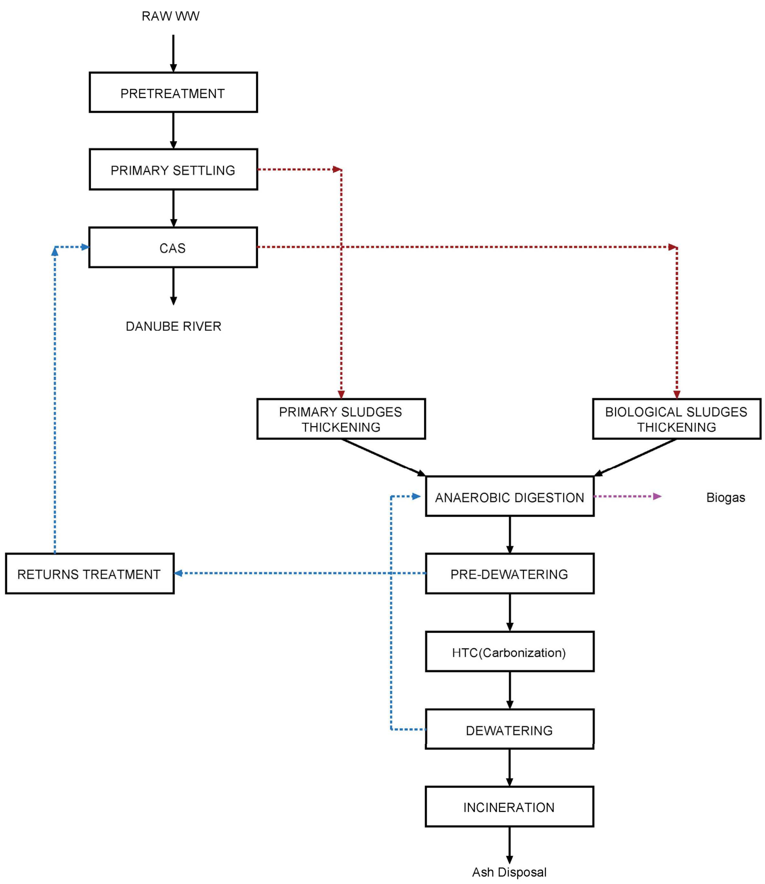

***Figure 18**. Process flow diagram for WWTP "Veliko Selo" Concept 4*

DISCUSION

Baseline wastewater quantity and quality

Baseline quantity, based on 2007 – 2019 and January-August 2021 periods data analyses, and flow and quality model of BCSS

Based on all completed analyses and collected data on the quantity of wastewater of BCSS, as well as the conclusions derived from the outputs of mathematical modeling calibrated to the measured flows [4], hydraulic load overview table has been created – Table 10.

***Table 10**. The characteristic flows of wastewater in the BCSS relevant for the preliminary and primary treatment [4]*

Parameter	Unit	2021
Average daily flow, $Q_{sr.d}$	m^3/d	302,400
Average daily flow, $Q_{sr.d}$	m^3/s	3.50
Average diurnal hourly flow (ADHF), (ADHF=ADF/18)	m^3/h	16,800
Maximum daily flow, $Q_{max.d,dry}$	m^3/d	345,600
Maximum daily flow, $Q_{max.d,dry}$	m^3/s	4.00
Maximum dry weather hourly flow, $Q_{max.h, dry}$	m^3/h	20,448
Maximum dry weather hourly flow, $Q_{max.h, dry}$	m^3/s	5.68
Minimum dry weather hourly flow, $Q_{min.h, dry}$	m^3/h	8,500
Maximum rainy weather daily flow, $Q_{max.d,rain}$	m^3/d	1,270,080
Maximum rainy weather hourly flow, $Q_{max.h, d.wet}$	m^3/h	46,584
Maximum rainy weather hourly flow, $Q_{max.h, d.wet}$	m^3/s	12.94

Baseline quality, based on 2010 – 2019 and May-July 2021 periods

The final results of the analyses of wastewater quality data and resulting baseline data are shown in Table 11. The baseline Interceptor averages were calculated from 2010 – 2019 and May-July 2021 mass flow averages in proportion to combined flows over the two periods. The minimums and maximums were set based on minimums and maximums from both periods, for MS Sajam and MS Ušće as the most important outlets making up 50% of flow. For TSS the minimum and maximum values were extracted from May-July 2021 period data, as the 2010 – 2019 maximum values were too high.

***Table 11**. The characteristic values of the key parameters of quality of combined wastewater of the sewage system of the central area in Belgrade [4]*

Parameter	Unit	2010 – 2021		
		avg	min	max
Biochemical oxygen demand, BOD_5	mg/l	244	60	1000
Chemical oxygen demand, COD	mg/l	402	85	2100
Total suspended solids, TSS	mg/l	200	40	700
Total nitrogen, TN	mgN/l	38	3	240
Total phosphorus, TP	mgP/l	6	1	25

WWTP "Veliko Selo" concepts elaboration

The four appropriate concepts for the WWTP "Veliko Selo" that were preselected out of a wider array of modern, engineering solutions proven in practice, based on the analysis of legal and logistical constraints and pitfalls will be further subjected to the techno-economic analysis.

CONCLUSIONS

For determination of baseline and preselection of appropriate concepts for WWTP "Veliko Selo" design different methods have been applied, as presented in the paper. Baseline and proposed concepts should serve as a basis for WWTP final concept selection and its dimensioning. For the purposes of selection an optimal WWTP "Veliko Selo" concept, a detailed techno-economic analysis should be conducted, respecting the methodological approach on the basis of which the categories that are considered as waste are ever more seen as a resource, i.e., the possibility of establishing a system that serves the implementation of a circular economy, the principles of which are based precisely on the use of waste and production residues as raw materials.

Following sequence of steps in determination of baseline and WWTP concept is highly recommended:

- Collection of all available data on the quantity and quality of wastewater and basic processing, with all necessary basic parameters for assessing the hydraulic and mass load of future process units and defining their capacity.
- Analysis of the collected data regarding reliability, and statistical analysis,
- Performing a new quantity and quality measurements, sampling and laboratory analyses campaign,
- Analysis of the newly collected data, comparison with the previous data, statistical analysis,
- Defining the baseline for wastewater quantity and quality,
- Analysis of legislation regarding the wastewater, sludge reuse, sludge and other waste disposal,
- Choosing appropriate WWTP concepts based on the analysis of legal and logistical constraints and pitfalls, from the wider array of modern, practically proven engineering solutions.

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CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

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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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