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Water Management & Hydraulic Engineering

WMHE 2024

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10th – 14th September 2024, Štrbské Pleso, Slovakia

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Water Economy Planning on the River Treska Basin by Simulation Model

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1 Abstract

Water management planning is crucial for long-term economic, social and environmental stability in civilized societies. One can only make plans with stored water, i.e. water impounded in reservoirs, formed with construction of dams. The process of long-term water planning and management includes creation of new reservoirs, adding new water users to existing reservoirs, as well as improved management of the existing reservoirs. Such analyses are done for the river Treska basin, located in the western part of R.N. Macedonia. With total basin area of 2068 km^2 and average flow of Q=24,2 m^3/s, currently there are three existing dams with reservoirs – Kozjak, St. Petka and Matka – supplying water for power production, as well providing flood protection of the city of Skopje. During the water economy planning process, four new reservoirs are planned – Greshnica, Podvis, Makedonski brod and Kalugjerica - in order to suffice the lack of fresh drinking water for the analysed basin, as well as water for irrigation of agricultural land for the upcoming 20 years. In order to oversee the new planned scheme for the river Treska basin, simulation model is prepared with application of HEC ResSim software. The simulation modelling is carried out on river scale extent, by inclusion of the existing and planned dams with reservoirs. The output results of the simulation model point out that the basin has enough capacity to suffice the water demands for water supply and irrigation, and in addition, it provides increased power production from renewable energy sources, for the next 20 years.

Keywords: water economy planning, river scale, water demand, simulation model

2 Introduction

Planning the development of water economy systems at country level is a complex issue that implies a long-term planning, with optimal utilization of the available water resources, by taking into account the sustainability (providing possibility for future generations to also use the water resources) and integrality (complex systems solution that during the planning is optimized throughout compliance of the water economy interests and other parts of the spatial planning). In English, the closest term for the preparation of such a long-term plan is the so-called Water Master Plan. Within a document of this caliber, in the chosen scheme for the water management systems, the interests of the water economy sector and other users of the space - who usually have conflicting interests - should be harmonized.

Water economy planning precedes the implementation of water economy projects in the direction of achieving the most expedient development of human society and the use of water resources. In general, the goal of water economy planning is to enable the most effective use of water resources by meeting the anticipated short-term and long-term water needs [1].

From the water economy point of view, the only structures that ensure the temporal and spatial redistribution of water resources are water reservoirs, which are created by the construction of large dams. Storage of water is increasingly proving to be a necessary and key active measure to mitigate

spatial and temporal hydrological unevenness, to overcome asynchrony between available water and water demands, as well as to effectively reduce damage caused by extreme hydrological phenomena (droughts and floods).
In the paper, the water economy planning of the Treska River basin, in the Republic of North Macedonia, is outlined and described. The planning was done by applying a mathematical simulation model, with which the system's response to various hydrological and operational tasks is perceived.

3 Study area and input data

3.1 Treska River basin

The Treska River is a right tributary of the Vardar River, with a total catchment area up to the confluence in river Vardar of F = 1880 km^2. The mean annual measured flow before merging with river Vardar is Q = 23.34 m^3/s . Three dams with reservoirs were built in the Treska River basin - the Kozjak dam, St. Petka and Matka. According to water economy planning in the next 20 years, the Kalugjerica, Makedonski brod, Podvis and Greshnica reservoirs should be built in the Treska River basin. The reservoirs St. Petka and Matka represent single-purpose systems with a single purpose - power production. The Kozjak reservoir has two purposes - power production, and retention of flood wave of the Treska river. The Greshnica reservoir is planned for the power production and the provision of water for irrigation. The reservoirs Podvis, Kalugjerica and Makedonski Brod are planned for the production of electricity, provision of water for irrigation and water supply. In all reservoirs, in addition to the mentioned users, the mandatory environmental discharge is planned downstream of the dam, which is estimated at 17.5% of the average annual flow in the reservoir.
The location of all reservoirs in the Treska River basin is shown in Figure 1.
The Kozjak reservoir has the largest active storage of all reservoirs in the basin - planned and existing - with a total volume of V = 550·10^{6}m^3, of which 100·10^{6}m^3 are planned for retention space for mitigating the flood wave of the Treska river for the mean of protection of the city of Skopje in case of flood. Reservoir elevations, active storage volume and mean annual inflow for each reservoir in the basin are given in Table 1.

Table 1. Characteristic elevations of the reservoirs (Z_{nwl} – normal water elevation, Z_{max} – maximal water elevation, Z_{crest} – crest elevation), active volume (V) and average annual inflow (Q_{inflow}).

Status	Reservoir	Znwl	Zcrest	V	Q_{inflow}	Status	Reservoir	Znwl	Zmax	V	Q_{inflow}
		[masl]	[masl]	[10^6 m^3]	[m^3/s]			[masl]	[masl]	[10^6 m^3]	[m^3/s]
Existing	Kozjak	459	471.1	550	19.65	Planned	Greshnica	790	795	31.2	1.32
	St. Petka	357.3	366	1.10	20.65		Podvis	770	775	50.43	2.13
	Matka	315.5	318.4	3.55	20.85		Makedonski brod	560	565	3	10.11
							Kalugjerica	527	532	250	18.86

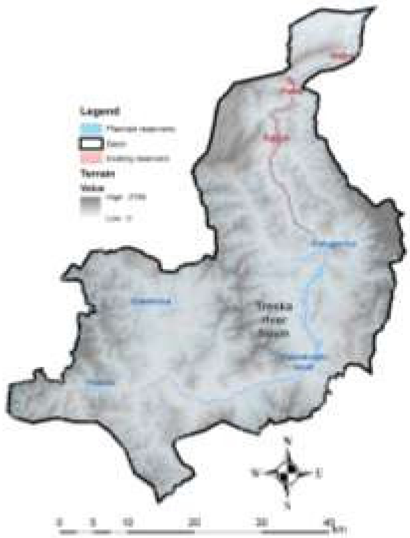


Figure 1. Overview of the catchment area of the Treska River basin with the planned and existing reservoirs. Map created with data from www.land.copernicus.eu.

For the water needs distribution in the basin, according to the water economy planning, the following reservoirs are planned for water supply: Podvis, Makedonski brod and Kalugjerica. The average demand for water supply in the basin is V = 0.39 m^3/s. Since this is a water economy planning on long-term scale, the water needs are distributed throughout the planned reservoirs with percentage share, according to the size of their active volume, varying every month throughout the year, for 20 years ahead. The percentage share for each reservoir in the total water supply needs is given in Table 2. It can be noted that the largest amount for water supply is assigned on Kalugjerica reservoir since it is the largest planned reservoir in the basin, whereas reservoir Makedonski brod will be accounted for fulfilling a very small percentage of water supply demand.

Table 2. Percentage distribution of water supply needs by reservoirs, for the Treska River basin.

Reservoir	$V \cdot 10^6\ m^3$	P=V/V_sum
Podvis	50,430	0.166
Makedonski brod	3,000	0.010
Kalugjerica	250,000	0.824
V_sum=	303,430	

For fulfilling the demand of water for irrigation, the following reservoirs are planned: Greshnica, Makedonski Brod, Kalugjerica and Podvis. The total demand of water for irrigation per year is estimated at $7.88 \cdot 10^6\ m^3$/year, varying monthly from April through September each year. Since this is a water economy planning on long-term scale, the water needs are distributed throughout the planned reservoirs with percentage share, according to the size of their active volume, and the percentage share in the total irrigation needs is given in Table 3.

Table 3. Percentage distribution of irrigation needs by reservoirs, for the Treska River basin.

Reservoir	$V \cdot 10^6\ m^3$	P=V/V_sum
Greshnica	31.20	0.09
Podvis	50.43	0.15
Makedonski brod	3.00	0.01
Kalugjerica	250.00	0.75
V_sum=	334.63	

3.2 Reservoir Greshnica

The Greshnica reservoir is located near the village of Kjafa, on the border between the municipalities of Gostivar and Kichevo. The reservoir is planned, with active storage of $V = 31.20 \cdot 10^6 m^3$. The topographic properties of the reservoir (surface and volume curves) are shown in Figure 2. The total basin to the dam site is $F = 64.55\ km^2$. The estimated mean inflow in the reservoir is $Q = 1.32\ m^3/s$, and inflow hydrograph is shown in Figure 2.

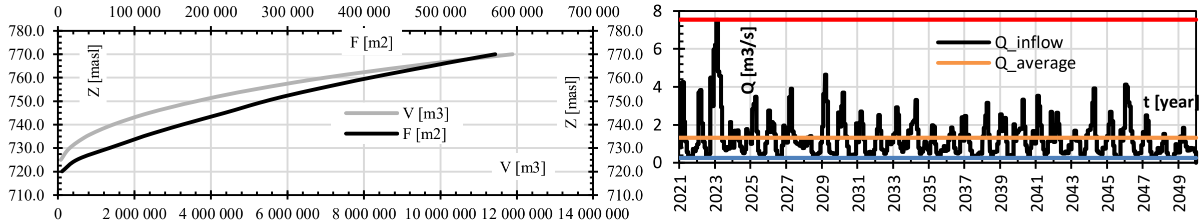


Figure 2. Topographic curves of Greshnica reservoir (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

3.3 Reservoir Podvis

The reservoir Podvis is located near the village of Podvis, west of the town of Kichevo. The reservoir is planned, with a live storage of $V = 50.43 \cdot 10^6 m^3$. The topographic properties of the reservoir are shown in Figure 3. The total basin to the dam site is $F = 117.23$ km^2. The estimated mean inflow in the reservoir is $Q = 2.13$ m^3/s, and inflow hydrograph is shown in Figure 3.

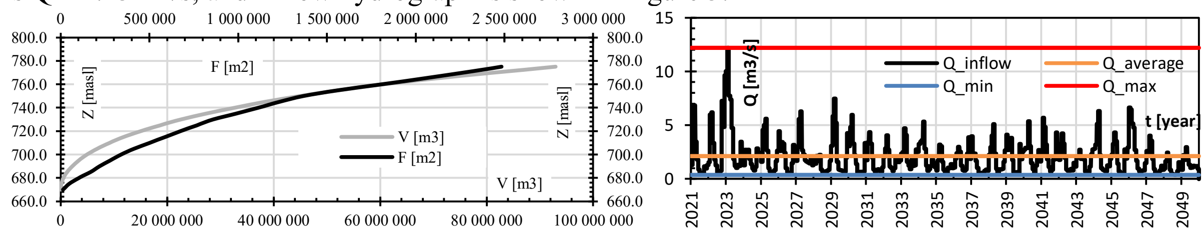


Figure 3. Topographic curves of Podvis reservoir (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

3.4 Reservoir Makedonski brod

The Makedonski Brod reservoir is located near the town of the same name. The reservoir is planned, with an active storage of $V = 3 \cdot 10^6$ m^3. The topographic properties of the reservoir are shown in Figure 4. The total basin to the dam site is $F = 886$ km^2. The estimated average inflow in the reservoir is $Q = 10.17$ m^3/s, and inflow hydrograph is shown in Figure 4.

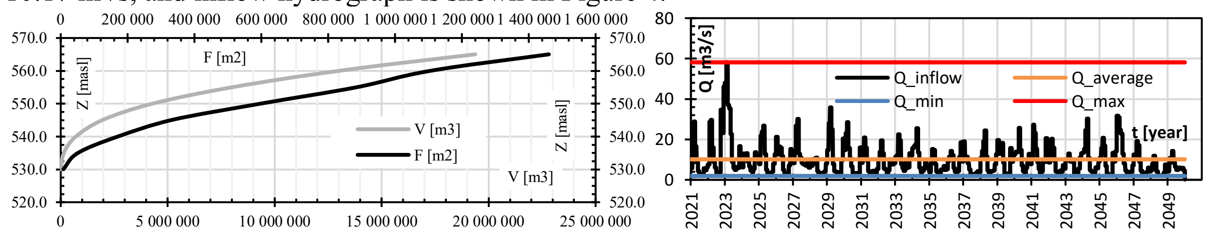


Figure 4. Topographic curves of reservoir Makedonski brod (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

3.5 Kalugjerica Reservoir

The Kalugjerica reservoir is located upstream of the existing Kozjak reservoir. The reservoir is planned, with an active storage of $V = 250 \cdot 10^6 m^3$. The topographic properties of the reservoir are shown in Figure 5. Total basin to the dam site is $F = 1605$ km^2. The estimated mean inflow in the reservoir is $Q = 18.86$ m^3/s, and inflow hydrograph is shown in Figure 5.

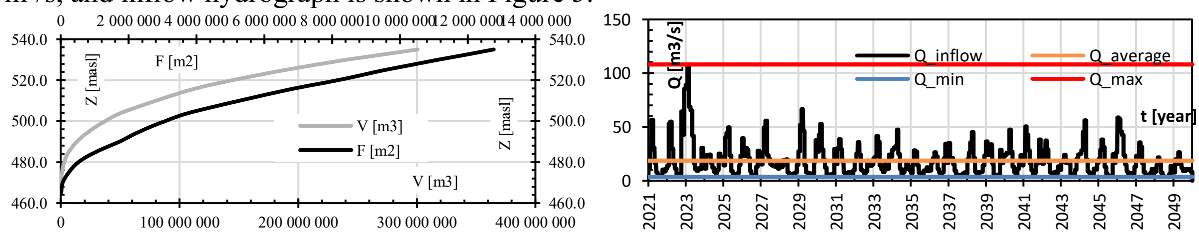


Figure 5. Topographic curves of Kalugjerica reservoir (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

3.6 Kozjak reservoir

The Kozjak reservoir is an existing reservoir on Treska river, formed with the construction of Kozjak dam in 2004. The primary purpose of Kozjak reservoir is retention of flood wave of Treska river in the retention space of the reservoir of $V = 100 \cdot 10^6$ m^3. In addition to retention of the flood wave, the reservoir is also planned for the production of electricity. For this purpose, the Kozjak HPP was constructed downstream of the dam with an installed capacity of $Q = 100$ m^3/s and an installed power of $P = 82$ MW. The active storage of the reservoir is $V = 550 \cdot 10^6$m^3. The topographic properties of the reservoir are shown in Figure 6. The estimated mean inflow in the reservoir is $Q_{av} = 19.65$ m^3/s, and inflow hydrograph is shown in Figure 6.

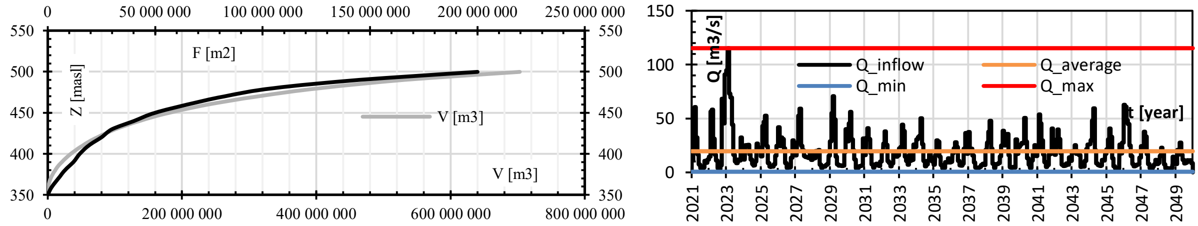


Figure 6. Topographic curves of Kozjak reservoir (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

3.7 Reservoir St. Petka

The reservoir St. Petka is an existing reservoir located downstream of the Kozjak reservoir, formed with the construction of the dam St. Petka in 2012. The primary purpose of the reservoir is the production of electricity. The installed capacity of the hydropower plant is $Q = 100$ m^3/s and $P = 36.4$ MW. The active volume of the reservoir is $V = 1.1 \cdot 10^6$m^3. The topographic properties of the reservoir are shown in Figure 7. The estimated mean inflow in the reservoir is $Q = 20.65$ m^3/s, and inflow hydrograph is shown in Figure 7.

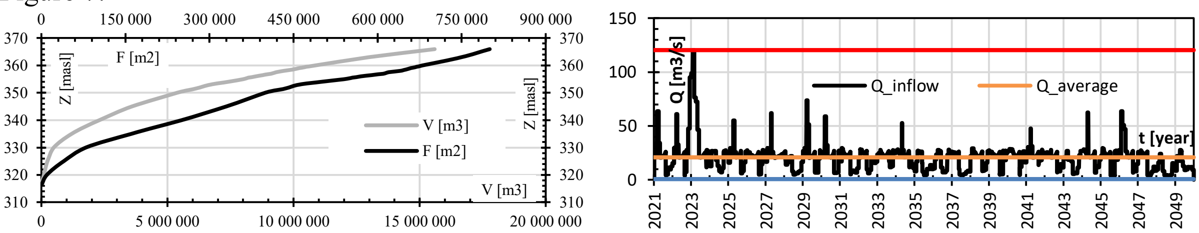


Figure 7. Topographic curves of reservoir St. Petka (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

3.8 Matka reservoir

The Matka reservoir is an existing reservoir that was created with the construction of the Matka dam, built back in 1938. It is the first dam built in R. Macedonia. The primary purpose of the reservoir is the production of electricity. The installed capacity of the hydropower plant, after the construction of the new machine building, is $Q = 42$ m^3/s and $P = 9.6$ MW. The active volume of the reservoir is $V = 3.55 \cdot 10^6$m^3. The topographic properties of the reservoir are shown in Figure 8. The estimated mean inflow in the reservoir is $Q = 20.85$ m^3/s, and inflow hydrograph is shown in Figure 8.

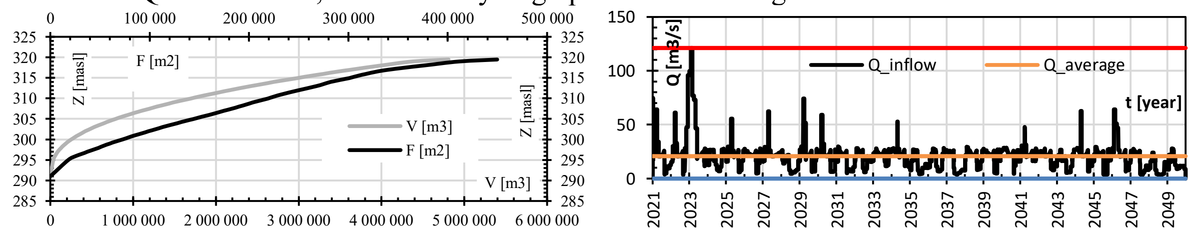


Figure 8. Topographic curves of Matka reservoir (graph on the left) and inflow hydrograph in the reservoir (graph on the right).

4 Simulation model

For the study of the water economy planning in the Treska River basin, a mathematical simulation model was developed in the HEC ResSim software.
HEC-ResSim is a software used to model complex water resources planning and management for multidimensional and multipurpose systems, in order to meet the demands of the water users. With the help of the software, it is possible to model reservoirs for flood defense, water supply for population and industry, power production, as well as combinations of operational policies and prioritizing multiple water users according to the demands [2].
Before developing the watershed model, it is necessary to define: (1) inflow hydrograph in each reservoir, (2) physical properties of the reservoir, (3) water demands, and (4) operational rules for system operation. In addition to the mentioned steps, in the models it is important to define the placement of the reservoirs and their mathematical connection in order to carry out successful analyses. Namely, the discharge from the upstream reservoir should appear as inflow in the downstream reservoir. Such interactions are defined based on Figure 9, where the calculation scheme for the complex water resources system for Treska River basin is displayed.
The hydrographs of inflows in each reservoir are formed according to the measured inflows in gauging stations Kicevo, Makedonski Brod, Zdunje and St. Bogorodica. Each inflow hydrograph for the modeled reservoirs are shown in Figures 2 through 8.
Water demand for water supply and irrigation are defined according to the percentage distribution, given in Table 2 and Table 3. In all reservoirs, in addition to the mentioned water needs, the mandatory environmental discharge is planned downstream of the dam, which is estimated at 17.5% of the average annual inflow in the reservoir.

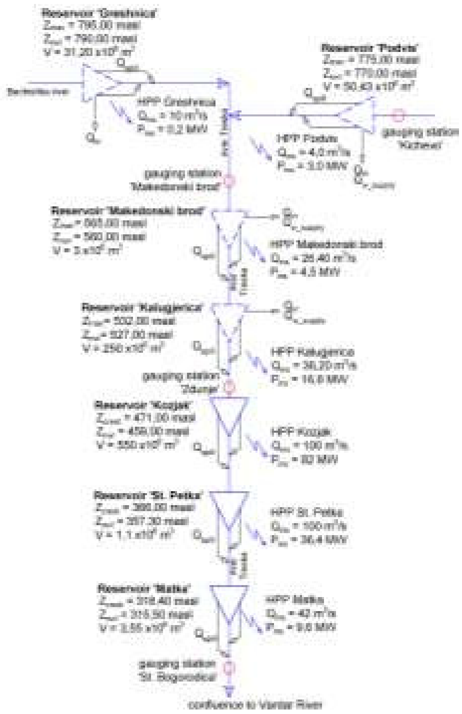


Figure 9. Calculation scheme of the complex water economy system of the Treska River basin.

5 Output results and discussion

As follows, results are shown obtained with the simulation model of Treska River basin.

5.1 Output results for the planned reservoirs

In case of Greshnica reservoir, it can be seen that throughout the entire simulation period the reservoir is full

(Figure 10), and irrigation demand and required environmental flow are almost completely meet (Figure 11-12). The average annual power production through the hydropower plant is E=1.03 GWh /year (Figure 13).

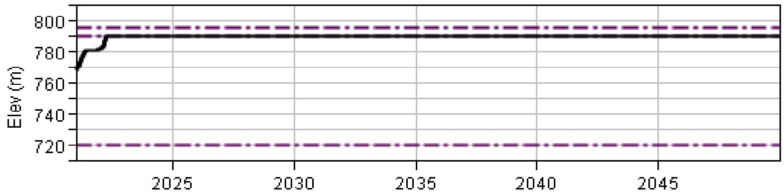


Figure 10. Fluctuation of water level in Greshnica reservoir.

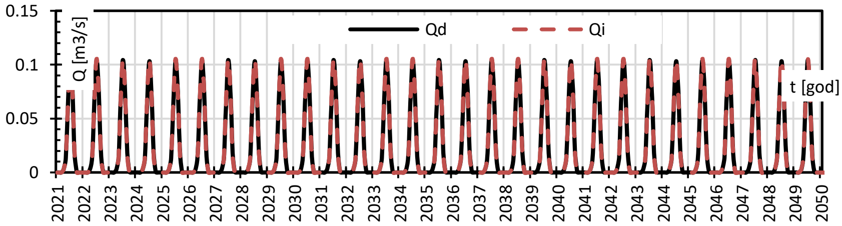


Figure 11. Comparative display of irrigation demand (Q_i) and delivered water (Q_d) from Greshnica reservoir.

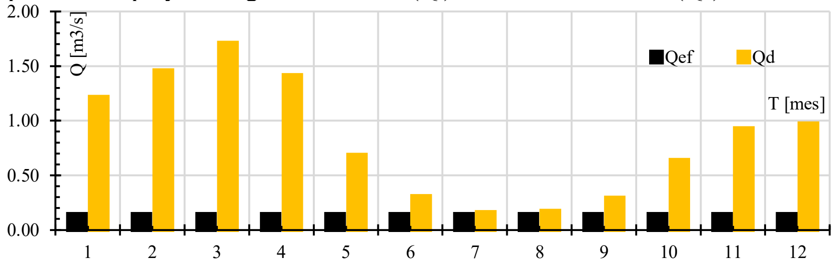


Figure 12. Comparative display of required environmental flow (Q_{ef}) and delivered water (Q_d) from Greshnica reservoir.

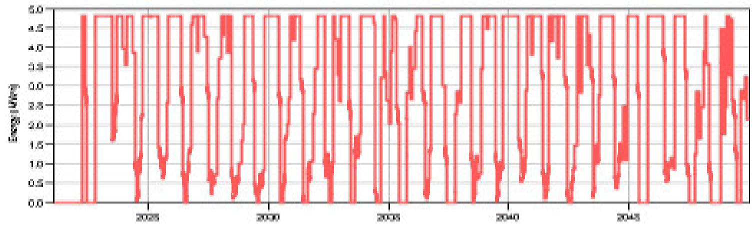


Figure 13. Power production from HPP Greshnica, average annual production E= 1.03 GWh/year.

In case of Podvis reservoir, it can be seen that throughout the entire simulation period, the reservoir is full (Figure 14), the water supply and irrigation demands are fully met (Figure 15 and 16) as well as the required environmental flow (Figure 17). The average annual power production is E = 13.55 GWh /year (Figure 18).

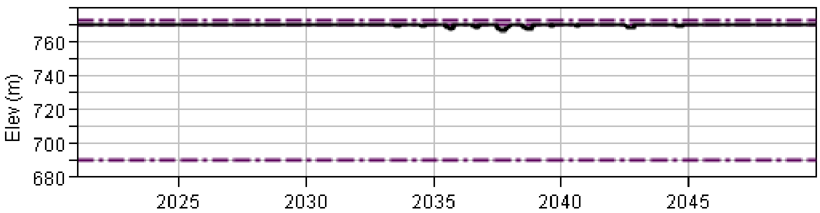


Figure 14. Fluctuation of water level in reservoir Podvis.

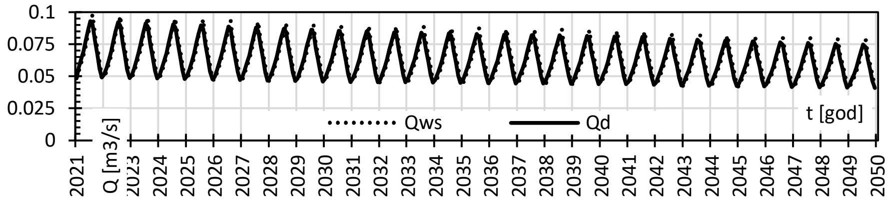


Figure 15. Comparative display of water supply demand (Q_{ws}) and delivered water (Q_d) from Podvis reservoir.

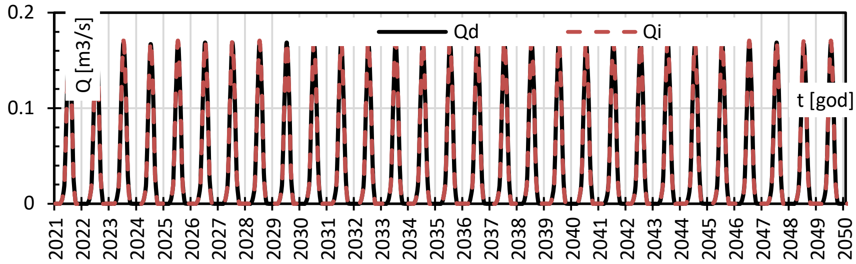


Figure 16. Comparative display of irrigation demand (Q_i) and delivered water (Q_d) from Podvis reservoir.

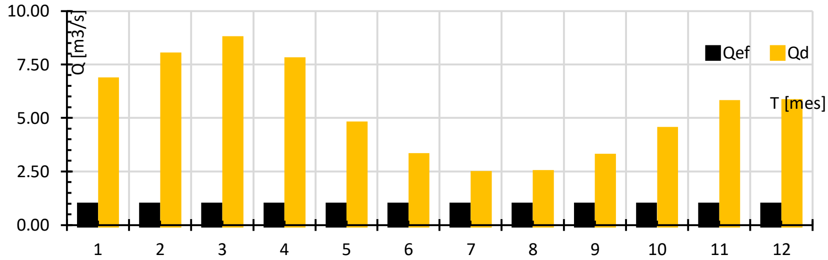


Figure 17. Comparative display of required environmental flow (Q_{ef}) and delivered water (Q_d) from Podvis reservoir.

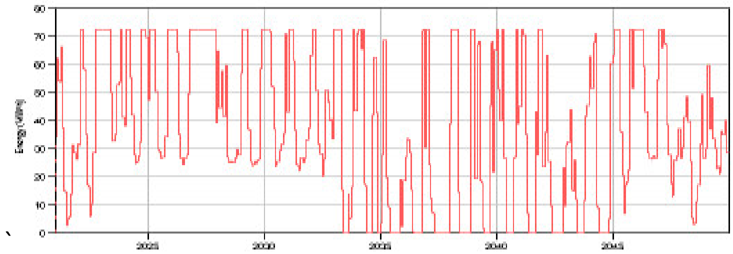


Figure 18. Power production from HPP Podvis, average annual production E = 13.55 GWh/year.

For Makedonski Brod reservoir, it can be seen that throughout the entire simulation period the level in the reservoir periodically varies (Figure 19), and the water supply and irrigation demands are met (Figure 20 and 21) as well and the required environmental flow (Figure 22). The average annual power production is E = 8.59 GWh /year (Figure 23).

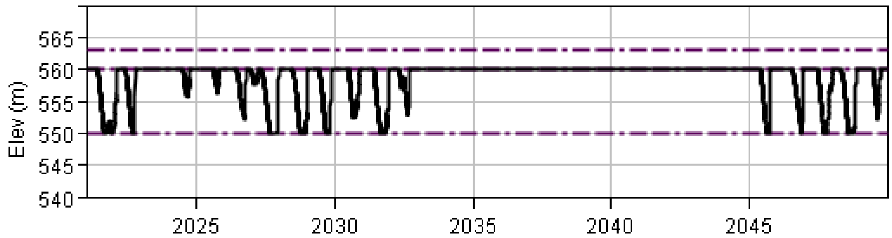


Figure 19. Water level fluctuation in the Makedonski Brod reservoir.

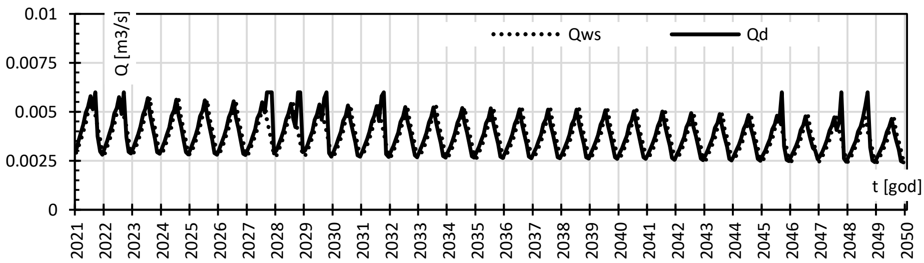


Figure 20. Comparative display of water supply demand (Q_{ws}) and delivered water (Q_d) from Makedonski Brod reservoir.

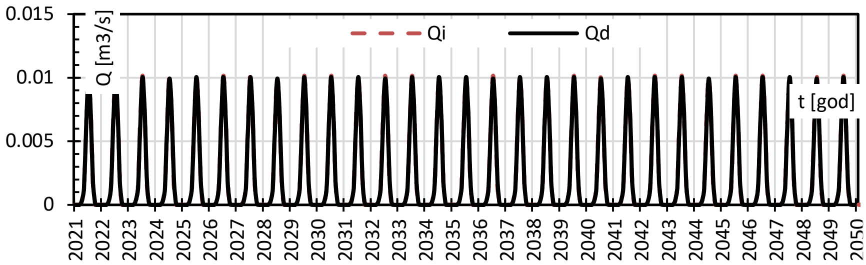


Figure 21. Comparative display of irrigation demand (Q_i) and delivered water (Q_d) from Makedonski Brod reservoir.

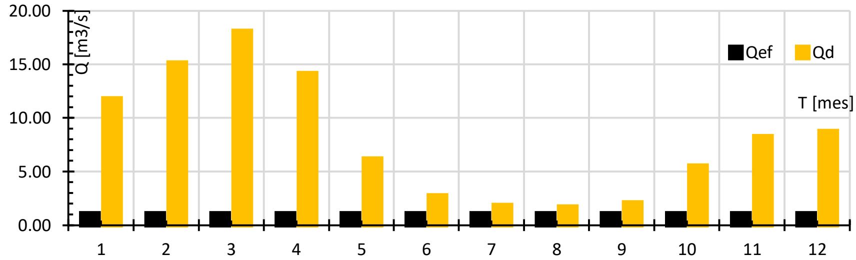


Figure 22. Comparative display of required environmental flow (Q_{ef}) and delivered water (Q_d) from Makedonski Brod reservoir.

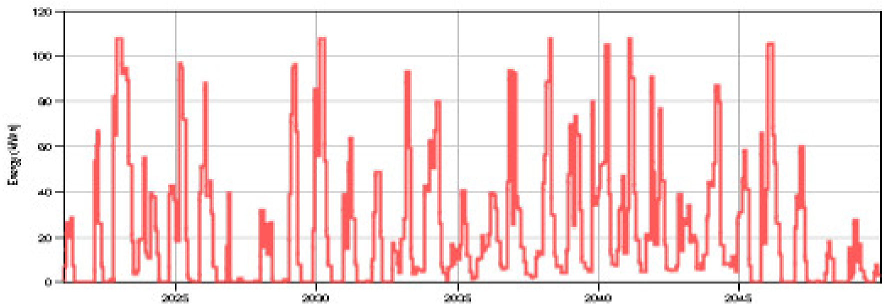


Figure 23. Power production from HPP Makedonski Brod , average annual production E= 8.59 GWh/year.

At Kalugjerica reservoir, it can be seen that throughout the simulation period the level in the reservoir is completely at normal water level (Figure 24) and the water supply and irrigation demands are fully met (Figure 25-26) as well and the required environmental flow (Figure 27). The average annual power production is E= 44.46 GWh /year (Figure 28).

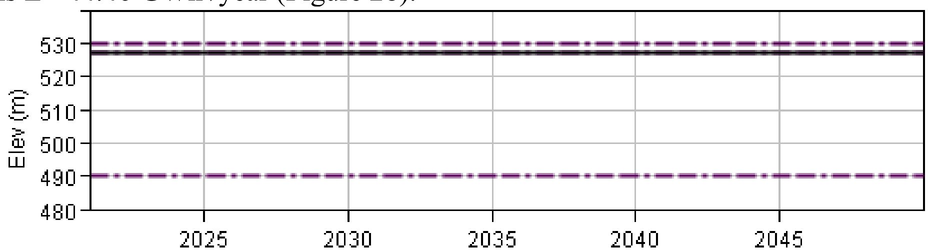


Figure 24. Water level fluctuation in Kalugjerica reservoir.

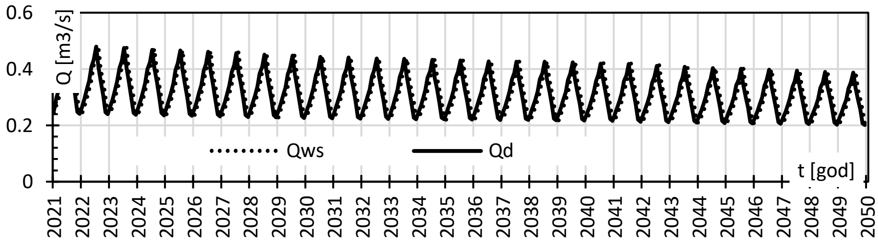


Figure 25. Comparative display of water supply demand (Q_{ws}) and delivered water (Q_d) from Kalugjerica reservoir.

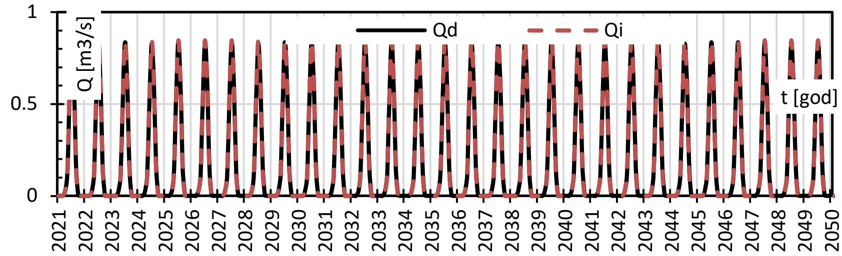
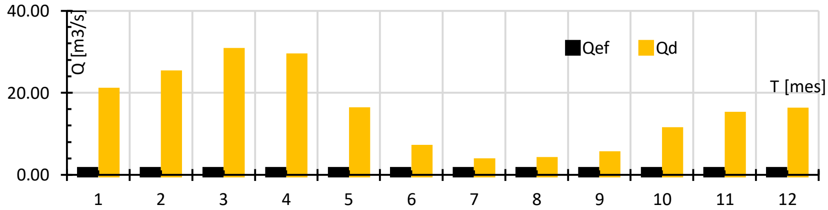


Figure 26. Comparative display of irrigation demand (Q_i) and delivered water (Q_d) from Makedonski Brod reservoir.



Attachment 27. Comparative display of required environmental flow (Q_{ef}) and delivered water (Q_d) from Kalugjerica reservoir.

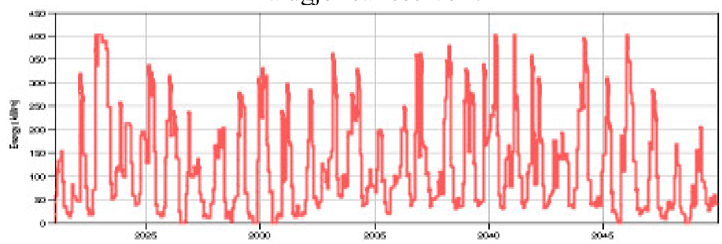


Figure 28. Power production from HPP Kalugjerica, average annual production E= 44.46 GWh/year.

5.2 Results for the existing reservoirs

The modeled existing reservoirs – Kozjak, St. Petka and Matka have been analyzed from the aspect of power production.

At Kozjak reservoir, during the simulation period the reservoir level is varying (Figure 29) in accordance with the set operational policy for power production. Namely, in the time period of analysis of 20 years in the simulation model, the average annual power production in HPP Kozjak is 80.21 GWh/year (Figure 30). According to the Reports on the work of ESM - the company that manages this hydropower plant, the average power production in the past 18 years, for the period from 2004 to 2021, is 123.62 GWh, with 44.3 GWh/year as minimal production in 2004, and 250.9 GWh/year as maximal production in 2010 [3].

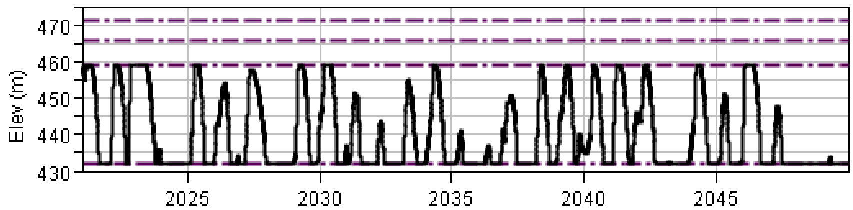


Figure 29. Water level fluctuation in Kozjak reservoir.

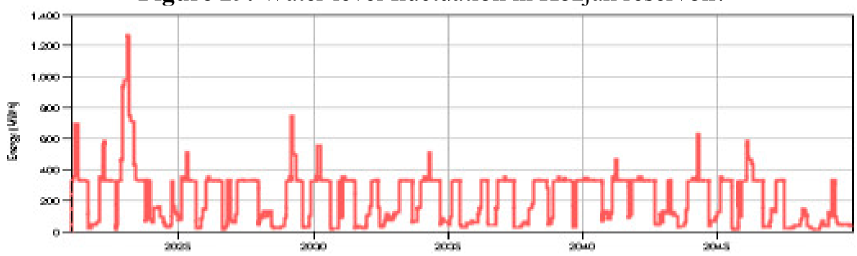


Figure 30. Power production from HPP Kozjak, average annual production E = 80.21 GWh/year.

At St. Petka reservoir, during the simulation period the reservoir level is varying (Figure 31) in accordance with the set operational policy for power production. The average annual power production in HPP St. Petka, according to the simulation model, is 45.85 GWh/year (Figure 32). According to the Reports on the work of ESM, the average power production in the past 10 years, for the period from 2012 to 2021, is 45.4 GWh, with 12.2 GWh /year as minimal production in 2012, and 75.8 GWh /year as maximal in 2015.
At Matka reservoir, during the simulation period the reservoir level is varying (Figure 33) in accordance with the set operational policy for power production. The average annual power production in HPP Matka, according to the simulation model, amounts to 24.21 GWh /year (Figure 34). According to data from EVN - the company that manages this hydropower plant, the average annual power production is 30 GWh /year.

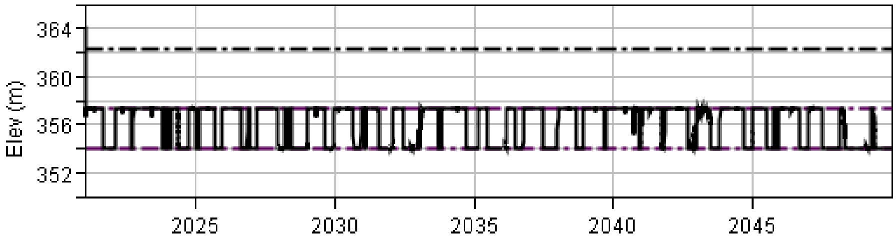


Figure 31. Fluctuation of water level in reservoir St. Petka.

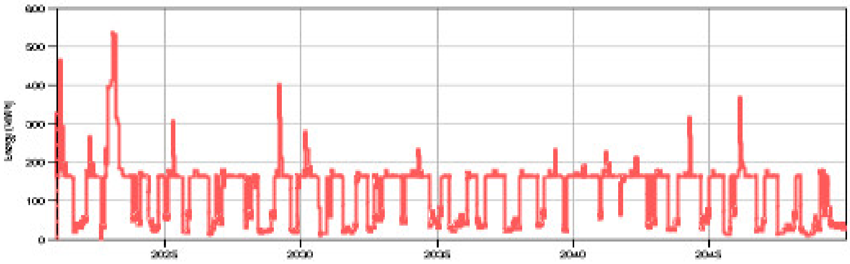


Figure 32. Power production from HPP St. Petka, average annual production E= 45.85 GWh/year.

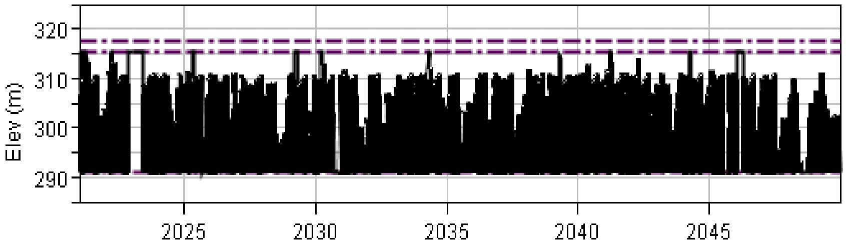


Figure 33. Water level fluctuation in Matka reservoir.

Figure 34. Power production from HPP Matka, average annual production E=24.21 GWh/year.

6 Conclusions

In order to analyze the adopted scheme for development of the Treska River basin with construction of new dams with reservoirs, a simulation analysis is conducted in HEC ResSim software. Three existing reservoirs are included in the model – Kozjak, St. Petka and Matka, and four newly planned reservoirs are included – Greshnica, Podvis, Makedonski Brod and Kalugjerica. All reservoirs are modeled for fulfilling a certain demand – water supply, irrigation needs and/or power generation. The goal of the analyses is to oversee the response of the reservoirs in the basin while maximal demands are required, with gauged hydrographs assigned as inflow for each reservoir, for a simulation period of 20 years and time step of the analyses of 1 day.

Based on the conducted simulation analysis of the complex water economy system for the Treska basin with the given hydrological parameters, operational management policy and the comparative analysis of the output results with the water needs, we single out the following conclusions:

1) The water level in the reservoirs is kept partially constant, with small variations in the active storage zone, with the exception of the reservoirs Kozjak, St. Petka and Matka, where a significant variation of the water level is observed in the active storage zone in correlation with applied operational policy based on the criterion for maximizing of the power production.
2) The ecological criterion (providing environmentally guaranteed flow) is met (or exceeded) in all reservoirs.
3) The water supply demands are met in all reservoirs, where the abovementioned purpose is foreseen.
4) The irrigation demands are met in all reservoirs, where the abovementioned purpose is foreseen.
5) The power production is correlated with the available amount of water (water level in reservoir and hydraulic head), according to the specified operational policy which gives priority of meeting the other water demands (water supply and irrigation). The average annual power production at basin level (as the sum of the average annual production of the individual planned HPPs within the basin, obtained by the simulation analysis) is estimated at 67.63 GWh /year. The cumulative average annual power production at the basin level (as the sum of the average annual production of the planned and existing HPPs within the basin) is estimated at 217.90 GWh/year. Basically, with construction of the new four reservoirs – Greshnica, Podvis, Makedonski Brod and Kalugjerica, additional 67,63 GWh will be generated for the electricity grid as a renewable energy.

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