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I Integrated Water Resources Management

APPLICATION OF SIMULATION MODELS FOR MANAGEMENT OF COMPLEX WATER RESOURCES SYSTEM

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Abstract

The increasing water demands as well as unfavourable climate changes in the past decades have led to increased pressure to existing water resources systems worldwide and in our country. The priority is to maintain, manage and upgrade the existing water resources systems so they can successfully match the increased water demand for various purposes.

In the following paper, acknowledgments are commented obtained from simulation analysis of complex water resources system of cascade type, composed of existing two dams with reservoirs and planned water resources system with single dam and reservoir, as upgrade of the existing system, by application of simulation models. The input data are recorded hydrology time series of discharge for a period of 40 years, considered as sufficient amount of data to carry out reliable simulation analysis. In addition, the available data for the water demand are taken into consideration within the analysis.

Primary purpose of the existing two-reservoir water resources system is matching the water demand for water supply of the population and irrigation needs. In order to assess the state and capacity of the existing cascade water resources system, firstly, is prepared simulation model for such purpose. Based on the accomplished simulation experiment for the existing water resources system, another simulation model is prepared including the planned single water resources system. Namely, the simulation modeling and analysis run are carried out for both water resources systems – the existing and planned. The simulation models are prepared with application of HEC ResSim software, released by the USACE Army Corps of Engineers.

Keywords: complex water resources systems, simulation models, water demand, HEC ResSim.

1. Introduction

Scarcity of fresh water throughout the world as well as in RN Macedonia demands complex planning and management of available water resources. Mathematical models are created in order to comprehend the behaviour of complex water resources systems under different hydrology input as well as different operation policies applied to the system. Such analyses are done by simulation models, type of mathematical models that reproduce the behaviour of the system under certain hydrological input (inflows) and physical parameters of the system (1). Simulation model is a mathematical replica of the original system, describing the system with logical relations and mathematical equations (1). Namely, the model calculates output results of the system using the balance equation, having in consideration the input hydrographs, physical limitations of the system and the operation rules. The convenience of simulation models is the possibility of applying different input parameters, physical parameters or operation rules, and analysing the response of the system without implementing them on the real system, i.e. the simulation model is a simplified replica of the original system. Simulation models have been developed since mid 90's and are improved by the day – alongside digital technology development. Many software are available for the purpose of water resources simulation and analysis, such as MITSIM, WEAP, HEC ResSim, RIBASIM.

With application of simulation models, two different alternatives are analysed within the paper. The first alternative comprises of hydro system 'Lipkovo' and 'Glaznja', located in the north of RN Macedonia on river Lipkovska, north from the city of Kumanovo. The main purpose of this cascade hydro system is water supply for the city of Kumanovo and water for irrigation needs

The second alternative comprises of the hydro system 'Lipkovo' and 'Glaznja' upgraded with hydro system 'Slupchanka' wherefrom water is diverted to 'Lipkovo' in order to improve its water balance.

The goal of the analyses is to overview the capacity of the hydro system 'Lipkovo' and 'Glaznja', and the necessity of including hydro system 'Slupchanka' in order to fully suffice water needs in this region.

The first alternative represents the current state of the hydro system since ‘Lipkovo’ and ‘Glaznja’ are in operation, whereas ‘Slupchanka’ is in the process of commencement of the construction.

2. Case study

The analysed hydro systems are located in the north of RN Macedonia, close to the city of Kumanovo.

The hydro system ‘Lipkovo’ is comprised of two reservoirs with dams ‘Lipkovo’ and ‘Glaznja’ on river Lipkovska (Fig. 1). This configuration is alternative 1. ‘Lipkovo’ dam was built in 1958 as the downstream dam, whereas ‘Glaznja’ is located 5km upstream from ‘Lipkovo’ dam, built in 1972.

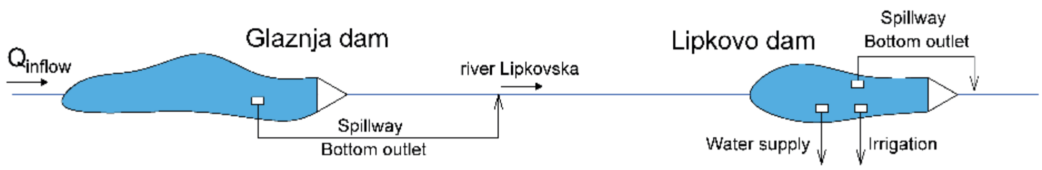

Figure 1. Layout of the cascade system ‘Lipkovo’

‘Lipkovo’ dam is concrete arch dam 40m high from the lowest point in the central cross section (Fig. 2), closing a reservoir with total volume capacity of $2{,}25 \times 10^6$ m^3. The normal operating water level in the reservoir is 478 masl, whereas the minimal operating water level is 468 masl. Water from ‘Lipkovo’ reservoir is used for water supply of the city of Kumanovo (approximately 200 l/s throughout the whole year), as well as irrigation of agricultural fields in total area of 2754 ha (currently 1300 ha are being actively irrigated).

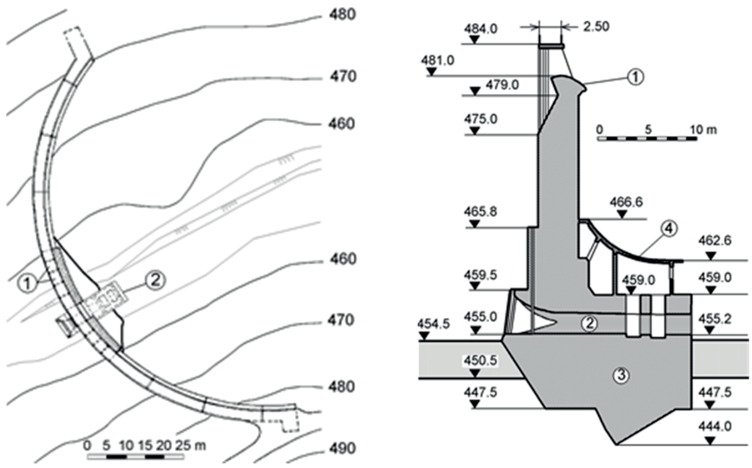

Figure 2. Layout and typical cross section of the arch dam ‘Lipkovo’

‘Glaznja’ dam is the highest concrete arch dam in RN Macedonia, 80m high, built 5km upstream from ‘Lipkovo’ reservoir (Fig. 3). ‘Glaznja’ reservoir has total volume capacity of 22×10^6 m^3 ($\times10$ times larger than ‘Lipkovo’ reservoir) where the main water management is conducted for this hydro system. The normal operating water level in the reservoir is 588 masl, whereas the minimal operating water level is 547,6 masl. Water from this reservoir is directly released into ‘Lipkovska’ river i.e. in the downstream ‘Lipkovo’ reservoir.

The hydro system ‘Lipkovo – Slupchanka’ is comprised of the previously described and built dams with reservoirs ‘Lipkovo’ and ‘Glaznja’, upgraded with dam and reservoir ‘Slupchanka’. Water from ‘Slupchanka’ reservoir will be diverted to ‘Lipkovo’ reservoir in order to improve its water balance and provide more reliable water supply flow (Fig. 4). This configuration, is hereafter, alternative 2. The connection between ‘Slupchanka’ and ‘Lipkovo’ is a pipeline. This pipeline is modelled as a ‘diverted outlet’ with assigned release of 0,2 m^3/s at all times during the simulation analysis, hence, other physical characteristics of the pipeline are not of paramount importance to the model.

‘Slupchanka’ dam is located approximately 2 km upstream from the village ‘Slupchane’ – village in the region of Kumanovo city (Fig. 5). The dam is at stage of construction commencement, by prepared technical documentation at level of Basic Design, and it is planned as a concrete face rockfill dam, with height of 54m (2). The topographic curves for dam Slupchanka are displayed on Fig. 6.

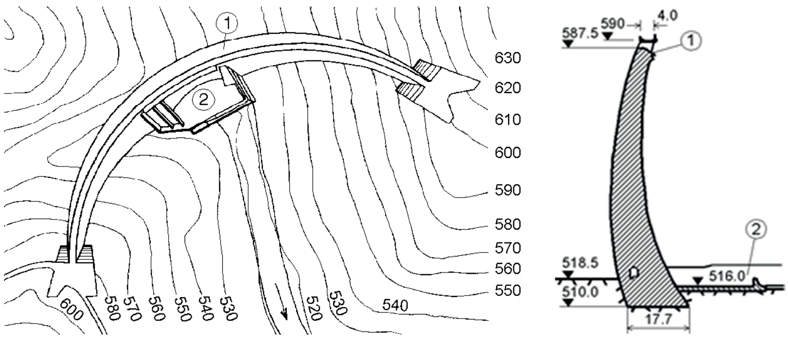

Figure 3. Layout and typical cross section of the arch dam ‘Glaznja’

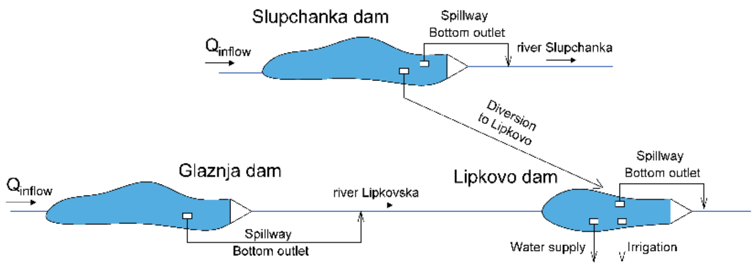

Figure 4. Layout of the cascade system ‘Lipkovo – Slupchanka’

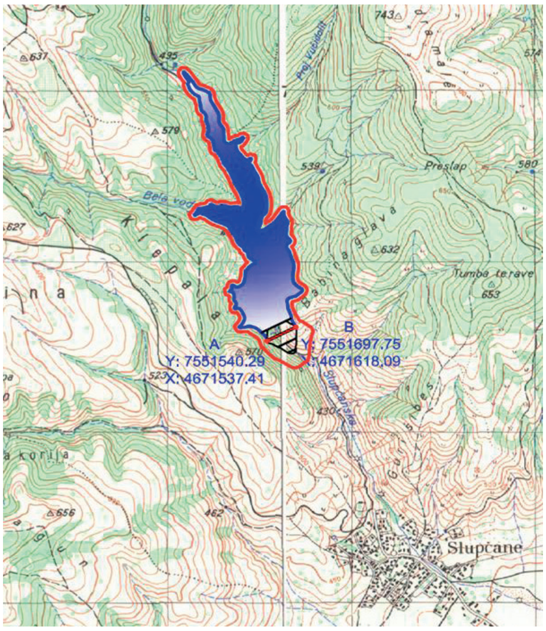

Figure 5. Location of ‘Slupchanka’ dam (2)

The normal operating level in the reservoir is 491 masl, and the minimal operating level is 468 masl. Total reservoir volume capacity is $2{,}89\times10^{6}$ m^3.

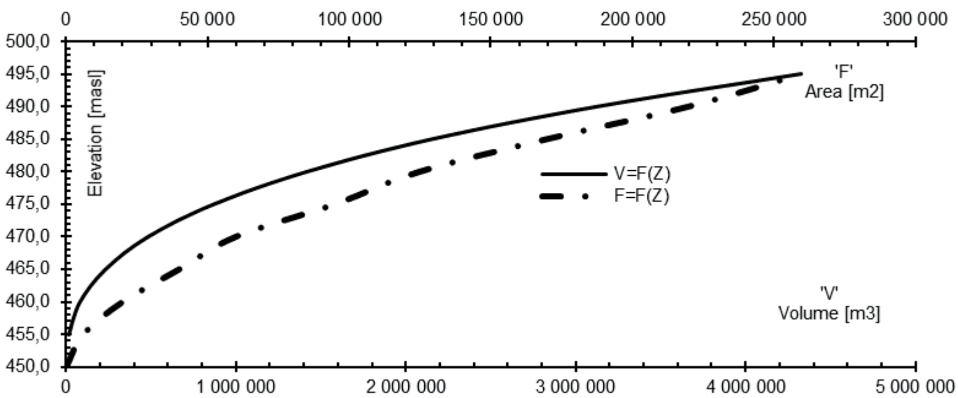

Figure 6. Topographic curves for reservoir ‘Slupchanka’ (2)

3. Simulation model

Simulation model is applied to perform the analyses of the complex water resources system. More precisely, the model was created by HEC ResSim software, that offers the possibilities for simulation analysis of complex water resources systems. The software consists of three basic modules: (1) Watershed setup, (2) Reservoir network, and (3) Simulation module (3). In the first module, the model is set up and relationships between the elements is defined. In the second module, physical parameters of the elements and operation rules for the whole systems are defined. In the third, defined configurations are called upon and analyses are conducted, with an overview of the results (4).

Two simulation models are analysed. Alternative 1 is comprised of 'Lipkovo' and 'Glaznja' reservoirs, whereas alternative 2 is comprised of 'Lipkovo', 'Glaznja' and 'Slupchanka' reservoirs.

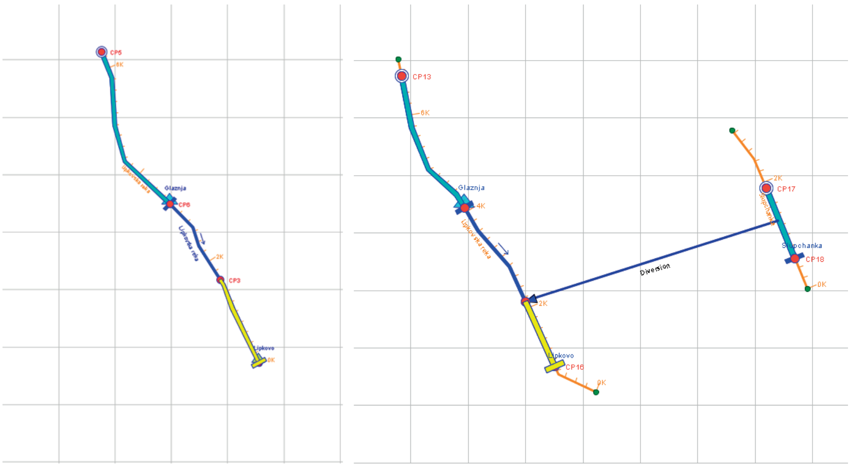

Figure 7. Display of schematics for simulation models for alternative 1 (left) and alternative 2 (right)

As input parameters, gauged flow hydrographs of Lipkovska and Slupchanka river are entered. Both hydrographs are over 40-years long (measured data from 1961 to 2000) and are used with the presumtion that in future similar dry and wet periods will repeat – as gauged in the 40-year timeline. Reservoir parameters are defined through Volume-Surface curves, whereas physical parameters of the apprutenant structures are entered through their maximal capacity curves. The time step of simulation run is 1 Day, common for analyses of this type.

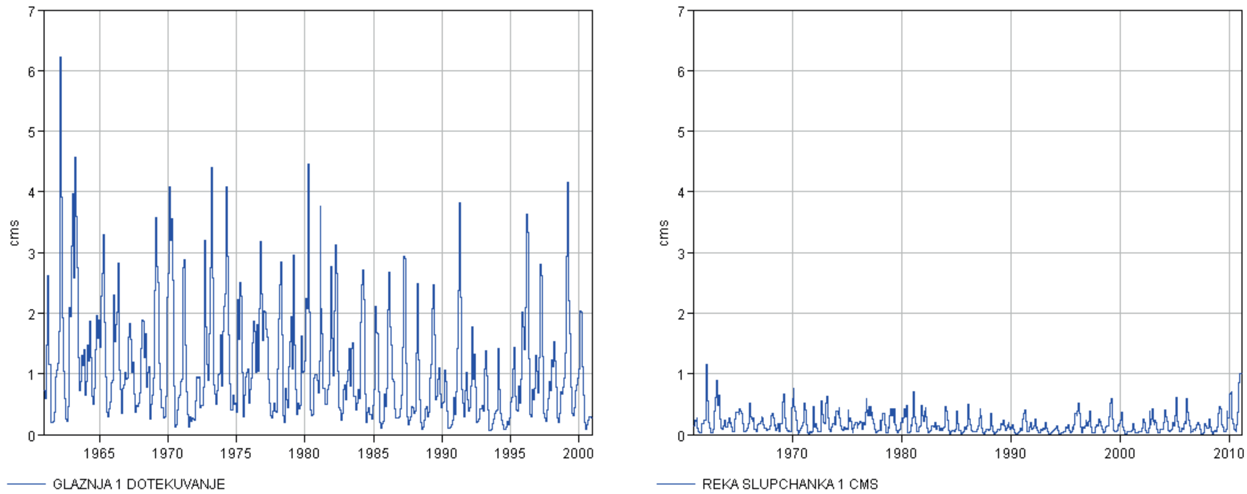

Figure 8. Hydrographs of inflow at 'Glaznja' and 'Slupchanka' reservoirs

Water supply and irrigation needs are entered as average monthly needs, derived from reference data (5).

Table 1. Monthly water needs for the city of Kumanovo

Q_{aver} [m³/s]	January	February	March	April	May	June	July	August	September	October	November	December
	0.260	0.220	0.230	0.230	0.250	0.260	0.270	0.260	0.240	0.230	0.220	0.200

Table 2. Monthly irrigation needs.

Q_{aver} [m^3/s]	January	February	March	April	May	June	July	August	September	October	November	December
	0.000	0.000	0.290	0.290	0.290	0.290	0.290	0.290	0.000	0.000	0.000	0.000

In HEC ResSim it is mandatory to divide the reservoir in different zones. Each zone has its one, specific characteristics and rules that apply only for the zone itself. When creating a basic model, three zones are automatically generated: (1) Flood Control zone, (2) Conservation zone, and (3) Inactive zone. Flood control zone is normally the zone above normal operating water level, when the elevation in the reservoir rises above the normal level and spills out. Conservation zone is the zone where all operation rules are applied, such as rules for irrigation, water supply or whatever the purpose of the reservoir is. Basically, the volume of water in the conservation zone is the avaialble water, that will be managed. Conservation zone is located between Flood control and the Inactive zone. Below the Inactive zone no rules can be applied since this water levels are considered to be below the physical capacities of the outflow structures. In Table 3, all three different zones and elevations for each reservoir is shown, as modelled in both alternatives.

Table 3. Definition of elevatios for zones at the reservoirs for alternative 1 and 2

Reservoir / Zone [masl]	Glaznja	Lipkovo	Slupchanka
Flood control	590,00	482,80	495,00
Conservation	588,00	481,00	493,00
Inactive	547,60	468,00	468,00

4. Results and discussions

Two models are prepared for the capacity analyses, one for alternative 1 and second for alternative 2. Results on reservoir water level fluctuation and delivered water is commented as follows.

4.1. Alternative 1 – hydro system 'Lipkovo'

For alternative 1, a simulation run was carried out for hydro system 'Lipkovo' comprised of both 'Lipkovo' as downstream and 'Glaznja' as upstream reservoir, for a simulation period from 1961 to 2000. The main purpose of this hydro system is delivering water quantities for water supply for the city of Kumanovo and for irrigation of the region. By analysing the output results for alternative 1, it can be noticed significant oscilation of the water level for reservoir Glaznja (Fig. 9), especially in the period of low water from 1988–-1996. There is also variation of the input flow and output flow from the Glaznja reservoir (Fig. 10), acording to overall reservoir capcacity. The average controlled release towards 'Lipkovo' reservoir is Q_{aver}=1,1 m^3/s.

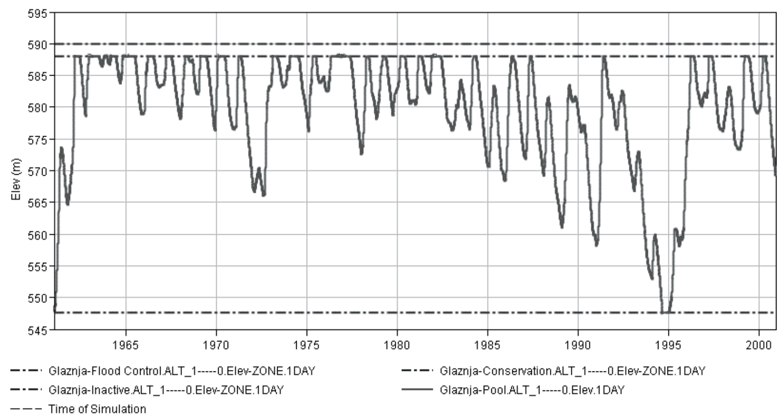

Figure 9. Water level fluctuations in 'Glaznja' reservoir during the analyses period, for alternative 1

By analysing the output results for alternative 1 in case of Lipkovo reservoir, there is some oscilation of the water level (Fig. 11) typical for the period of low water from 1988-1996. There is also variation of the input flow and output flow from the Lipkovo reservoir (Fig. 12), acording to overall reservoir capcacity. The average controlled release from Lipkovo reservoir is 1,09 m^3/s – much of which is due to spillway overflow.

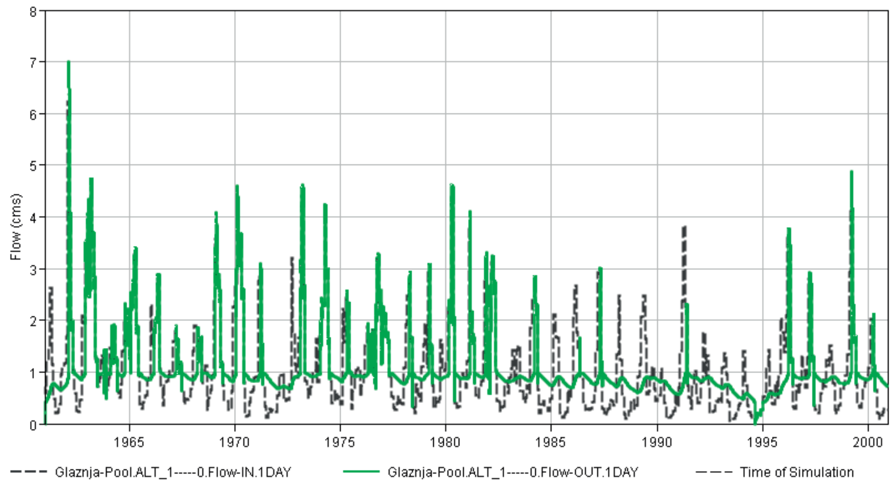

Figure 10. Inflow and outflow hydrographs for 'Glaznja' reservoir

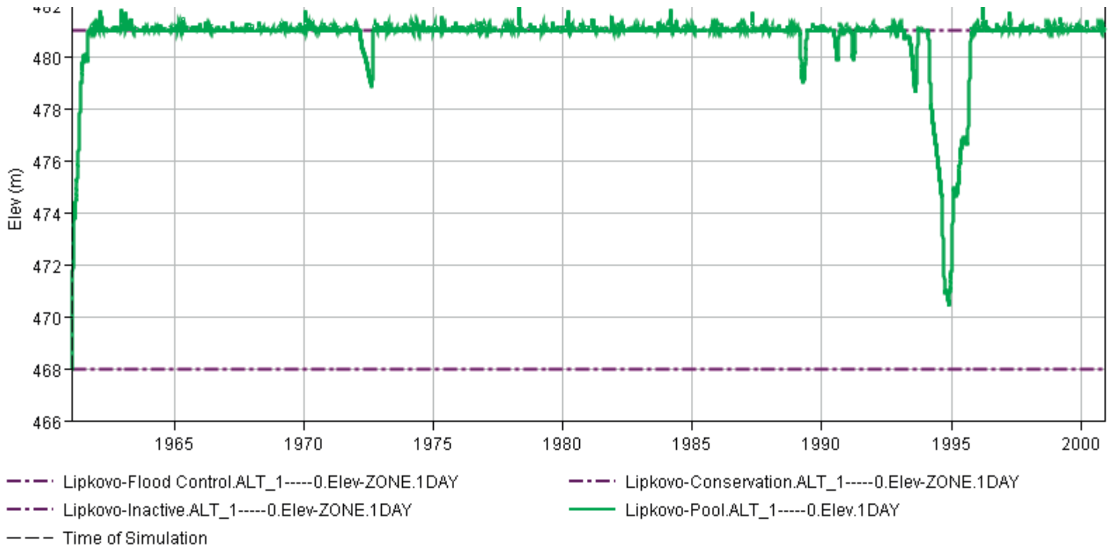

Figure 11. Water level fluctuations in 'Lipkovo' reservoirs during the analyses period, for alternative 1

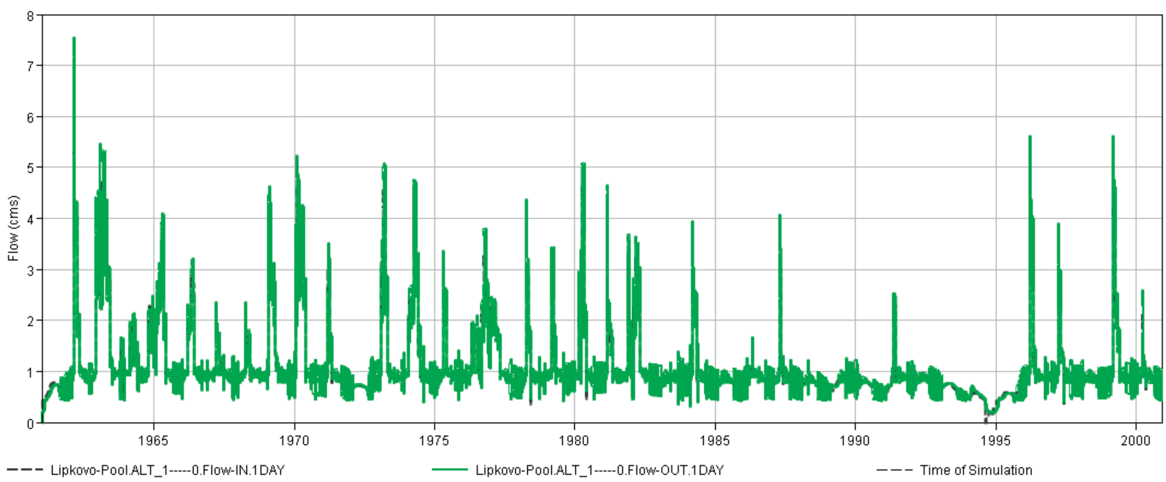

Figure 12. Inflow and outflow hydrographs for 'Lipkovo' reservoir

On Fig. 13 are displayed output values from reservoir Lipkovo for water supply, irrigation and environmental discharge, as well and spillway overflow. The environmental flow in the operation scenario is set as priority and it is matched during the full analysis period. The water supply and irrigation discharge are mainly matching the specified water demands. However, there is overflow from reservoir Lipkovo, that is minimized by the applied operation policy.

According to the results, with average release of 1,1 m^3/s from 'Glaznja' reservoir and set tandem operation with 'Lipkovo', covering the target water needs is in range between 69% (January) to 100% for most of the other period during the year (Figure 14, left), whereas 88% to 95% of the irrigation needs are covered during the vegetation period with this operation policy (Figure 14, right). Both water supply as primary, and irrigation as secondary water purposes are meeting the specified water demands according to the output results from alternative 1. It should be noted that the analyses are conducted with water needs for irrigation taken into consideration as average delivered water dervied from 10-years long recorded data. The current irrigated fields using water from this hydro system are approximately 50% of the planned agricultural land for irrigation.

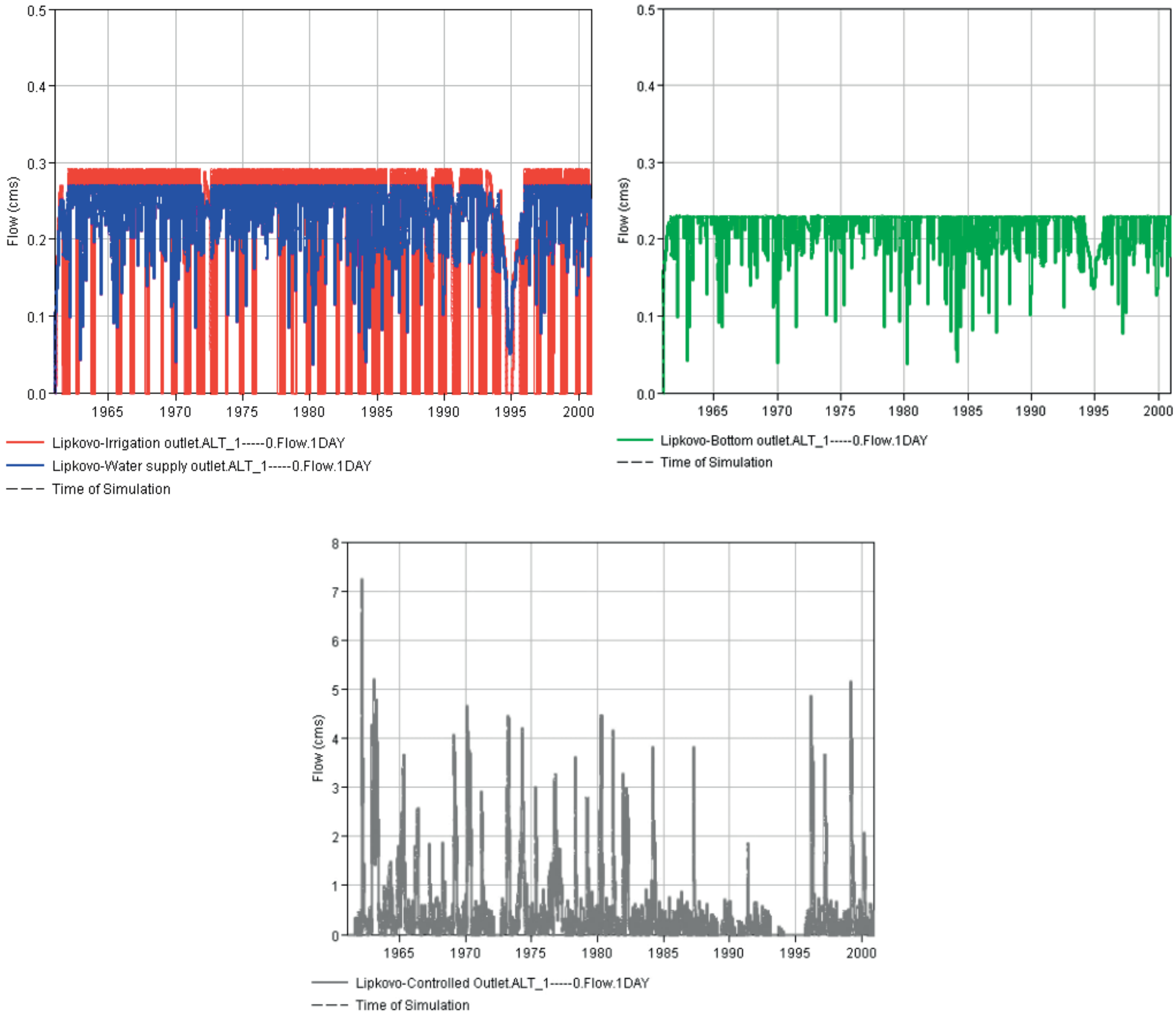

Figure 13. Releases from 'Lipkovo' reservoir for water supply, irrigation, (upper left), spillway release (upper right) and environmental flow (bottom) during the whole simulation period for alternative 1

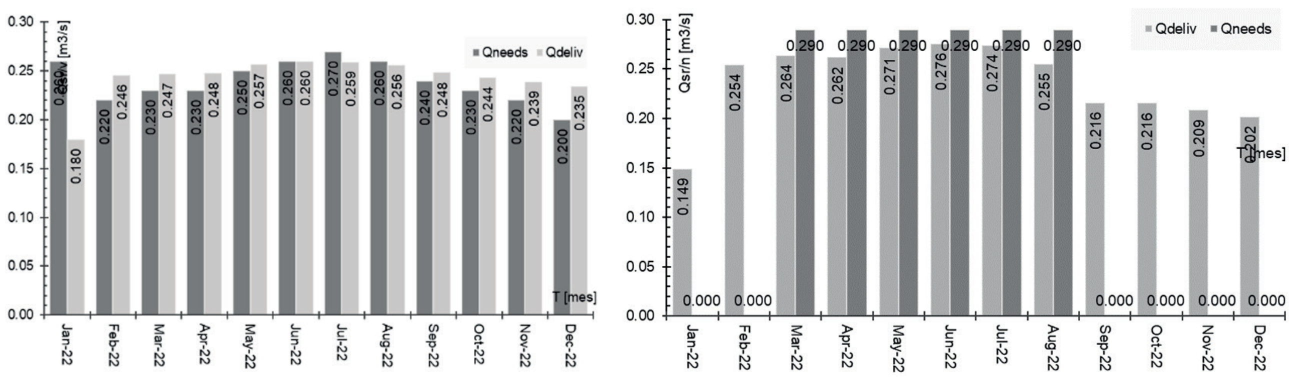

Figure 14. Water demands and delivered water in m^3/s for water supply (left) and irrigation (right), results from alternative 1

4.2. Alternative 2 – hydro system 'Lipkovo' with 'Slupchanka'

As planned in the Water master plan from 1973, as addition to the 'Lipkovo' hydro system another dam with reservoir is planned – hydro system 'Slupchanka'. The following alternative – alternative 2 is an upgraded alternative. The main purpose of 'Slupchanka' hydro system is to improve water balance of the 'Lipkovo' hydro system and provide water when increased demands of water – for both irrigation and water supply. For alternative 2, a simulation run was conducted for hydro system 'Lipkovo' and 'Slupchanka' comprised of both 'Lipkovo' as downstream and 'Glaznja' as upstream reservoir, as well as 'Slupchanka' reservoir with water deviation to 'Lipkovo' reservoir, for a simulation period from 1961 to 2000. 'Slupchanka' reservoir is located on a different watershed than 'Lipkovo' and 'Glaznja', and water from this hydro system is planned to be deviated to 'Lipkovo' reservoir through a deviation canal, with approximately 0,2 m^3/s of water to be transferred to 'Lipkovo' reservoir.

By analysing the output results for alternative 2, it can be noticed significant oscilation of the water level for reservoir Slupchanka (Fig. 15), specially in the low water periods from 1988–1996, where the water level is approximaltey at elevation of dead storage. On average, according to the applied operation policies and tandem operation of all reservoirs, a discharge of 0,17 m^3/s is conveyed to reservoir 'Lipkovo' reservoir 'Slupchanka' through the water conveyor (Fig. 16). Controlled release from 'Lipkovo' reservoir is increased compared to alternative 1, to 1,23 m^3/s. The average controlled release from 'Glaznja' remains the same as in alternative 1, by value of 1,10 m^3/s.

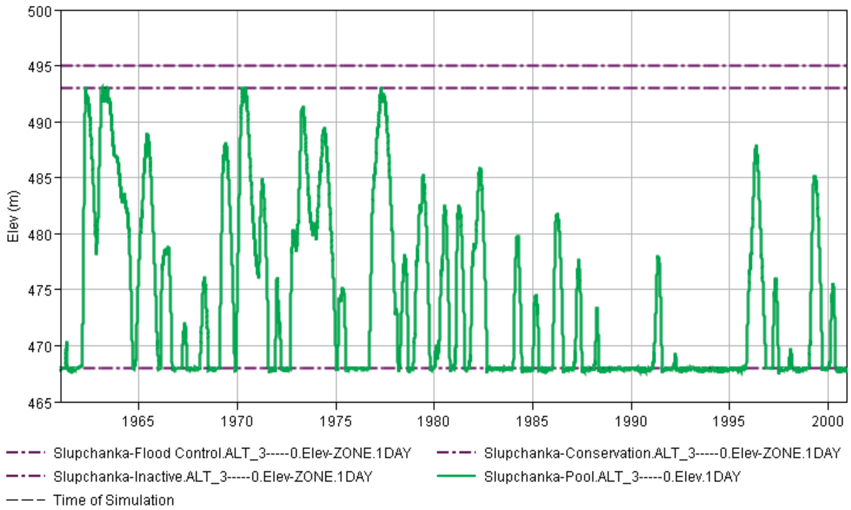

Figure 15. Water level fluctuations in 'Slupchanka' reservoir during the analyses period, for alternative 2

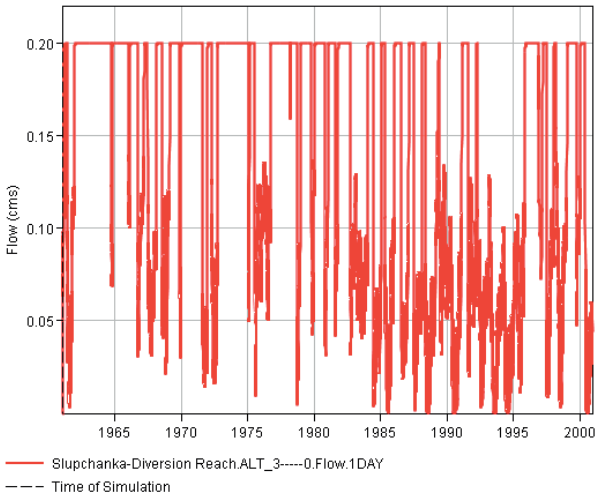

Figure 16. Intake flow through the water conveyor from 'Slupchanka' to 'Lipkovo' reservoir

By analysing the output results for alternative 2 in case of Lipkovo reservoir, there is similar oscilation of the water level (Fig. 17) as in alternative 1, with increased spillway flow. There is also variation of the input flow and output flow from the Lipkovo reservoir (Fig. 18), acording to overall reservoir capcacity. The average controlled release from Lipkovo reservoir is 1,09 m^3/s – much of which is due to spillway overflow.

On Fig. 18 are displayed output values from reservoir 'Lipkovo' for water supply, irrigation and environmental discharge, as well and spillway overflow. The environmental flow in the operation scenario is set as priority and it is matched during the full analysis period.

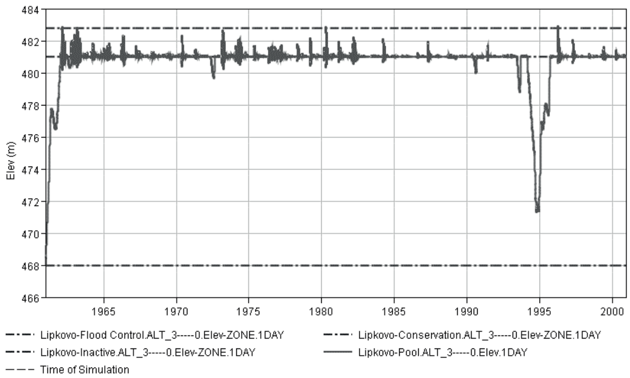

Figure 17. Water level fluctuations in 'Lipkovo' reservoir during the analyses period, for alternative 2

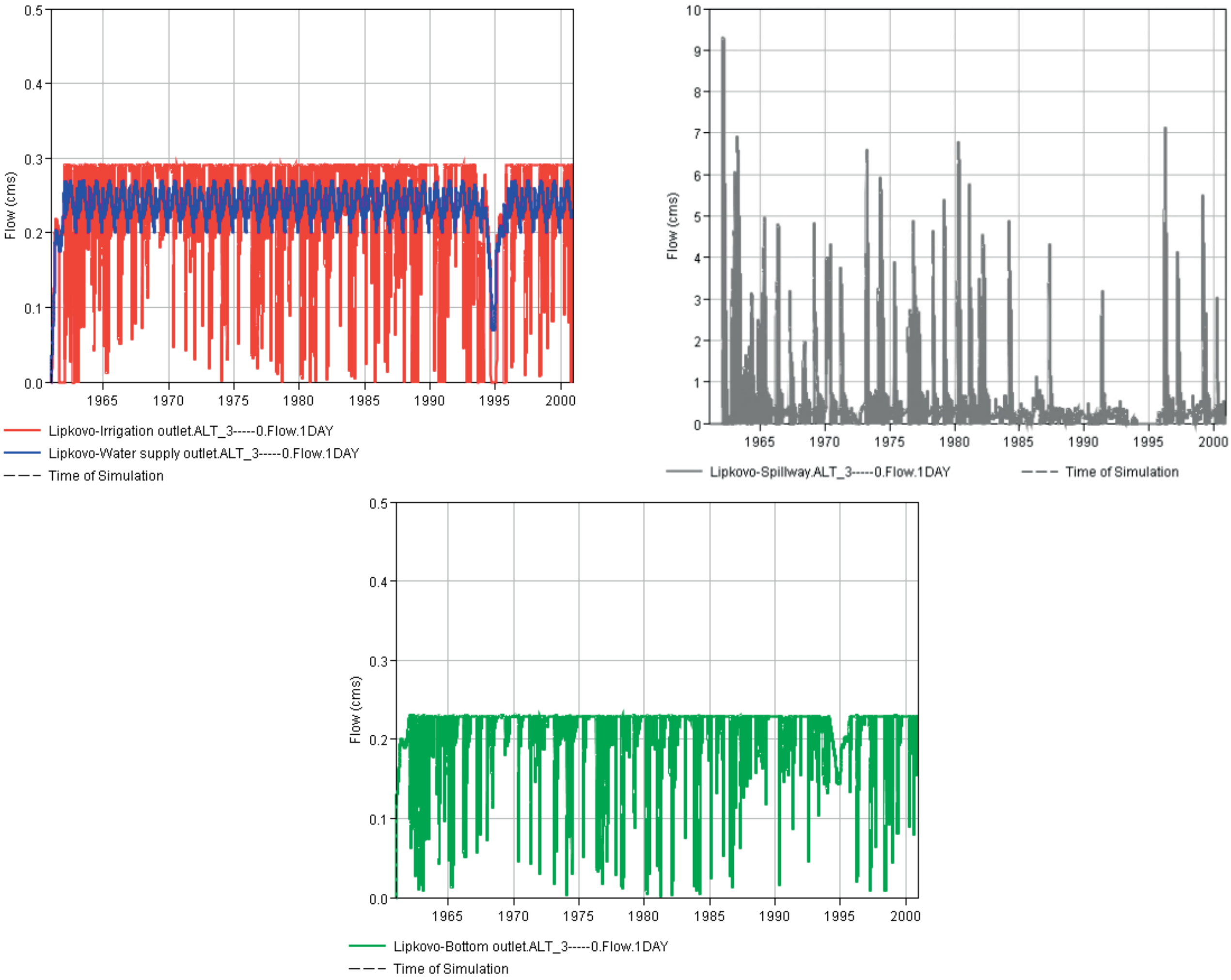

Figure 18. Releases from 'Lipkovo' reservoir for water supply, irrigation, (upper left), spillway release (upper right) and environmental flow (bottom) during the whole simulation period for alternative 2

According to the results, with average release of 1,1 m^3/s from 'Glaznja' reservoir and 0,17 m^3/s from 'Slupchanka' including a tandem operation with 'Lipkovo', almost every month during the analyzed period covering the target water needs in range between 68% (January) to 100% for most of the other period during the year (Figure 19, left), whereas 85% to 89% of the irrigation needs are covered during the vegetation period with this operation policy (Figure 19, right). Both water supply as primary, and irrigation as secondary water purposes are meeting the specified water demands according to the output results from alternative 2. From Figure 18 (right) it can be noted that there is increase in spillway release from 'Lipkovo' reservoir which is due to the incresed inflow from 'Slupchanka' – approximately

0,500 m^3/s. These quantities of water can be counted on for future planning of expansion of the water supply and the irrigation system.

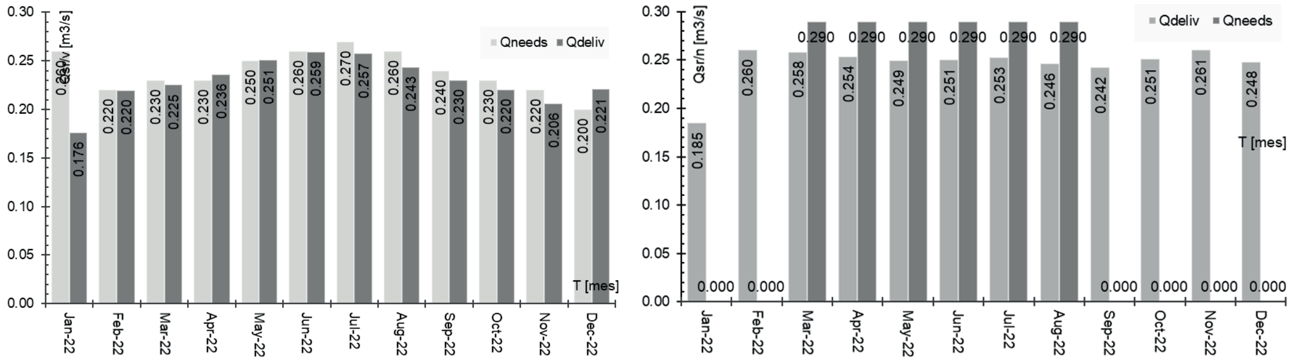

Figure 19. Water demands and delivered m^3/s for water supply (left) and irrigation (right) for alternative 2

5. Conclusion

With application of simulation models, two alternatives are analysed for 'Lipkovo' hydro system – alternative 1 (existing state with Glaznja and Lipkovo reservoirs) and alternative 2 – hydro system Lipkovo' upgraded with 'Slupchanka' hydro system. The main purpose of the analyses is to assess the reservoirs capacity and matching of the water demands for water supply of Kumanovo city and irrigation of the Kumanovo region, for input flow hydrographs for period of 40 years of measured data.

According to the output results from the analyses, the following conclusions can be derived:

1. The current state of the operation of hydro system 'Lipkovo' (reservoirs 'Glaznja' and 'Lipkovo'), modelled as alternative 1 in HEC ResSim, can suffice at great scale both water supply and irrigation needs in the Kumanovo region, covering the target water needs in range between 69% (January) to 100% for most of the other period during the year, whereas 88% to 95% of the irrigation needs are covered during the vegetation period with the adopted operation policy.
2. For both alternatives, irrigation needs are derived from a longer period of recorded delivered water quantities to Kumanovo from 'Lipkovo' hydro system, differencing every month – as expected, higher during the summer period, and lower during the winter period. These quantities account for 1300 ha of land – approximately 50% of the planned agricultural land to be irrigated with this hydro system. This means that in future, shall agricultural land increase, water needs will also increase compared to the current available data for this water user. On the other hand, water supply needs for Kumanovo region are approximately 0,2 m^3/s.
3. All reservoirs are modelled using the 'tandem operation' rule which forces upstream reservoirs to provide sufficient water quantity for the downstream reservoirs' accommodation of needs. This is a real representative of the current state of operation with the system, where water releases from 'Lipkovo' reservoir is much regulated through the 10-times-larger 'Glaznja' reservoir. Such operation rule, set in HEC ResSim applies for cascade reservoirs' management.
4. Since 'Lipkovo' is a much smaller reservoir compared to 'Glaznja', there is quite some water flow overflowing the spillway. On average, for alternative 1 this quantities are 0,38 m^3/s and 0,50 m^3/s for alternative 2. These quantities of water can be accounted for future planning of development of the hydro systems – whether for increasing water supply, irrigation of agricultural fields, or adding a hydro power plant to harvest the potential energy of water.
5. According to the results, with average release of 1,1 m^3/s from 'Glaznja' reservoir and 0,17 m^3/s from 'Slupchanka' including a tandem operation with 'Lipkovo', almost every month during the analyzed period covering the target water suplpy needs is in range between 68% (January) to 100% for most of the other period during the year, whereas 85% to 89% of the irrigation needs are covered during the vegetation period with the adopted operation policy in alter. 2.
6. By inclusion of the hydro system 'Slupchanka' in the existing hydro system 'Lipkovo', an improved management is achieved. Namely, there is possibility for more flexible management of the hydro system 'Lipkovo', especially in critical periods of low water such as the period from 1998–1996 in the analysed timeline.

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