APPLICATION OF SIMULATION MODEL IN CASE OF MULTI-RESERVOIR SYSTEM PLANNING

FROSINA PANOVSKA[1], STEVCHO MITOVSKI[2], LJUPCHO PETKOVSKI[3]

[1] *Ss. Cyril and Methodius University, Civil Engineering Faculty, Republic of North Macedonia, frosinapanovska@yahoo.com*

[2] *Ss. Cyril and Methodius University, Civil Engineering Faculty, Republic of North Macedonia,*

smitovski@gf.ukim.edu.mk

[3] *Ss. Cyril and Methodius University, Civil Engineering Faculty, Republic of North Macedonia,*

petkovski@gf.ukim.edu.mk

1. Abstract

In this paper an analysis of the future hydropower utilization of Crna Reka is conducted with application of simulation models for different configuration alternatives and reservoir operation policies.

Crna Reka is one of the largest tributary of river Vardar, with average annual flow of $Q_{aver}=30\ m^3/s$ before entering Tikvesh lake, and a 5890 km^2 river basin in the south-west of North Macedonia. Back in 1968 the first hydropower plant on river Crna Reka was built – Tikvesh, with an overall installed capacity of $Q_{ins}=4x36\ m^3/s$ and $P_{ins}=113$ MW. The alternatives of potential water utilization of Crna Reka, analysed with the simulation models, are defined based on existing technical documentation, design plans and development analyses made for river Crna Reka.

The modelling of the complex multi-reservoir cascade system was done by application of HEC ResSim software. Within the paper are analysed Alternative 0, as existing state, composed of dam and reservoir Tikvesh with hydropower plant, incorporating both hydropower and irrigation water use, with hydropower as priority user and Alternative 1, where beside Tikvesh hydro-system, Chebren and Galishte dams with reservoirs and hydropower plants are included in model, with conventional hydropower units.

Hydropower production in both alternatives is analysed for three different operation policies: (1) Low non-linear policy, where power capacity of the plant is high for low reservoir levels, (2) Linear policy, where power capacity is in linear correlation with reservoir level, and (3) High non-linear policy, where power capacity of the plant is high for higher reservoir levels.

The upgrade of the existing state of utilization of water at Crna Reka watershed is estimated upon the annual hydropower production within period of 60 years.

Keywords: water resources systems, simulation models, hydropower generation, multi-reservoir systems, HEC ResSim.

2. Introduction

In an era where electricity power is constantly on high demand and environmental issues arise from using conventional power resources such as fossil fuels, more and more pressure is put on hydropower as one of the cleanest, high efficacy sources of energy (Jermar, 1987). In Republic of North Macedonia alone, over 1/3 of all annual production of electricity comes from hydropower (AD ELEM, 2016). However, not even half of the potential of electricity production of hydropower is utilized in the Republic, so there is still a lot to be done in this sector.

In North Macedonia, only a few rivers' hydropower potential is completely utilized – the one on Crn Drim river and Treska river. Vardar is our largest river and no hydropower plant has been built on this mighty stream. The case is similar with Crna Reka, where only one hydropower plant is in operation since 1969 – Tikvesh HPP. Many other smaller streams are waiting on investments in hydropower use, some being built at the moment.

Possibilities of implementation of hydropower are open to incorporating power plants to existing water resources systems where hydropower lacks, such as single purpose reservoirs with dams (irrigation, water supply, flood control water systems).

In both cases – building completely new hydropower systems from scratch, or incorporating hydropower to existing ones – an extensive analyses on electricity production should be done. The analyses should answer the question on the plant's capacity for power production for a certain time series of registered/generated inflows on the stream.

Such analyses are done with simulation models – mathematical models that reproduce the potential real behaviour of the plant under certain input (inflows) and physical parameters of the system (Votruba, 1988). Simulation models have been developed since mid 90's and are improved by the day – alongside technology development. Many software are available for the purpose of water resources simulation and analysis, such as MITSIM, WEAP, HEC ResSim, RIBASIM.

In this paper, simulation model on hydropower potential is conducted on Crna Reka as a case study, by implementation of HEC ResSim software. In the model, input parameters such as observed water inflows registered at three gauging stations are used, physical parameters of the systems as planned or built, and operation policies for hydropower production. Crna Reka is one of the largest tributary of river Vardar, with average annual flow of $Q_{aver}=30\ m^3/s$ before entering Tikvesh lake, and a 5890 km^2 river basin in the south-west of North Macedonia. Back in 1968 the first hydropower plant on river Crna Reka was built – Tikvesh, with an overall installed capacity of $Q_{ins}=4x36\ m^3/s$ and $P_{ins}=113$ MW. The concept of utilization of the waters in Crna Reka exists since the middle of 20th century, when very first conceptual solution has been made on multipurpose and multi reservoir use of the river. This solution consisted of building three cascade dams with hydropower plants on Crna Reka – Chebren, Galishte and Tikvesh Lake and HPPs (ХЕП Скопје, 1961). Later on, this concept somewhat changed and different concepts were made, dividing the capacity of the river in more, smaller reservoirs with dams and hydropower plants. However, not to this day any of these concepts lived the light of the day except Tikvesh dam and hydropower plant, which was built as first of the three cascade dams.

The purpose of this paper is to emphasize the importance of building these capacities in numbers of produced electrical energy annually.

3. Methods

Simulation mathematical model is used to perform the analyses. Simulation model is a mathematical replica of the original system, describing the system with logical relations and mathematical equations (Votruba, 1988). Often, the simulation model is a simplified version of the original system. 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 (Votruba, 1988).

HEC ResSim software for simulation of complex water resources systems operation is applied. The software consists of three basic modules: (1) Watershed setup, (2) Reservoir network, and (3) Simulation module. 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.

Two different models are elaborated. For the purpose of comparing results, the first model – Alternative 0, represents the current situation – Tikvesh dam, reservoir and hydropower plant in operation. The second model – Alternative 1 is an upgrade to the first one, where alongside Tikvesh, both Chebren and Galishte dams, reservoirs and hydropower plants are included and in power (Panovska, 2019).

In both alternatives, three sub alternatives are made in relation to three different operating rules for the hydropower plants. Basically, in order to explore the optimal operating rules for the hydropower plants, we created three operating curves: (1) Low non-linear, (2) Linear, and (3) High non-linear curves. All curves represent a relationship between water level in the reservoir (Power Storage) and engaged power capacity in the power plant (Plant Factor).

Low non-linear operating curve defines an operation rule for the plant where it will work with high capacity when low water levels in the reservoir (Figure 1).

Linear operating curve defines an operation rule for the plant where the relationship between water level in the reservoir and engaged power capacity is linear (Figure 2).

High non-linear operating curve defines an operation rule for the plant where it will work with high capacity for high water levels in the reservoir only (Figure 3).

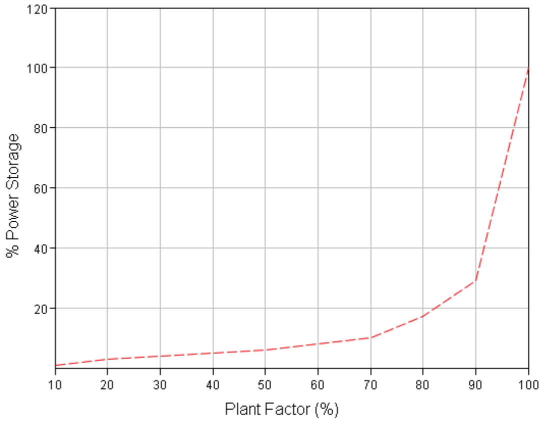

Figure 1. Operating rule 'Low non-linear'.

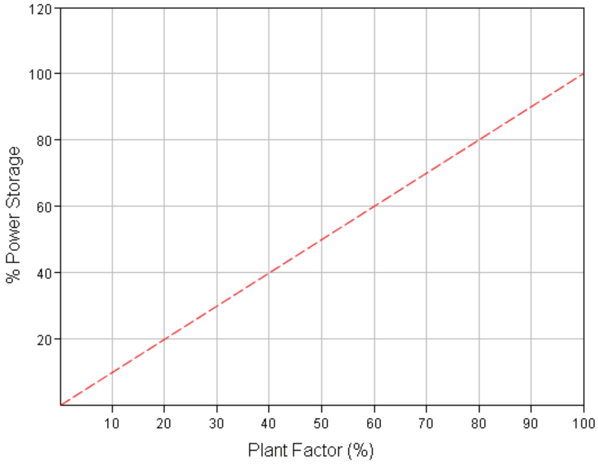

Figure 2. Operating rule 'Linear'.

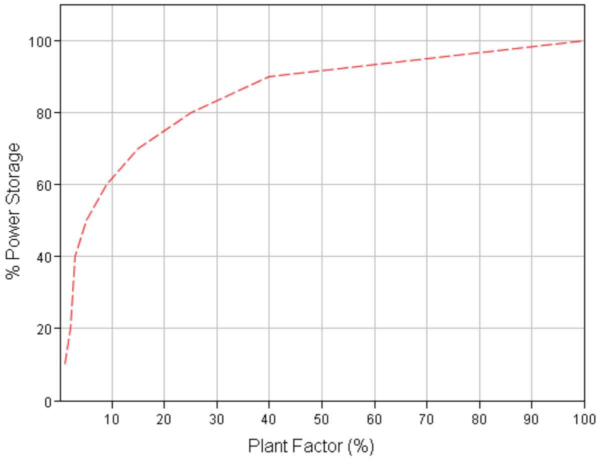

Figure 3. Operating rule 'High non-linear'.

3.1 Alternative 0

Alternative 0 consists of Tikvesh reservoir, dam and hydropower plant. This system serves two major consumers: irrigation of Tikveshko Pole, and production of electricity. Physical elements that are modelled in the simulation run, are: (1) reservoir Tikvesh, (2) hydropower plant Tikvesh with penstock characteristics, (3) uncontrolled spillway, (4) irrigation channel, and (5) bottom outlet.

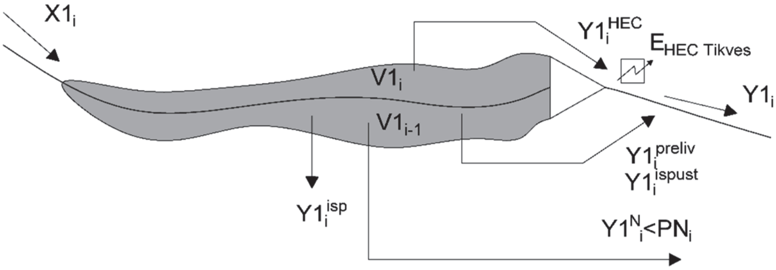

Figure 4. Schematic of simulation model Alternative 0.

Mass balance equation for the system is:

$$V1_i = V1_{i-1} + X1_i - [Y1_i + Y1_i^N + Y1_i^{isp}] \ldots \qquad (1)$$

Outflows of the reservoir are defined as:

$$Y1_I = Y1_i^{preliv} + Y1_i^{ispust} + Y1_i^{HEC} \ldots \qquad (2)$$

$$Y1_i^N \leq PN_i \ldots \qquad (3)$$

$$Y1_i^{isp} = f(Z_{akum}, T) \ldots \qquad (4)$$

Abbreviations in the equations (1) and (2) have the following meaning:

$X1_i$	- inflow in the reservoir at i-moment,
$Y1^{isp}_i$	- water loss due to evaporation at i-moment,
$Y1^{HEC}_i$	- water flow through penstock, at i-moment,
$Y1^{preliv}_i$	- spillway flow at i-moment,
$Y1^{ispust}_i$	- bottom outlet flow at i-moment,
$Y1^N_i$	- delivered water quantities for irrigation purposes, at i-moment,
PN_i	- water needs for irrigation at i-moment,
$Y2_i$	- total outflows from reservoir Tikvesh, at i-moment,
$V1_i$	- volume of water at the reservoir at i-moment.

Inflow hydrograph is gauged hydrograph for the period of 1946 – 2005 (60 years in total)

(Figure 54), at gauging station Tikvesh. Since the hydrograph is of measured values, the model itself is deterministic. The time step of simulation run is 1 Day, common for analyses of this type.

Irrigation needs are implemented as average monthly values, obtained by gauged values from delivered water quantities for the period of 2005 – 2012. Basically, irrigation only occurs in vegetation period – starting from march until the end of september. Average irrigation needs vary from 2 – 8 m^3/s of water per day.

3.2 Physical characteristics of the model

Physical characteristics of the model are implemeted for the following elements: (1) reservoir Tikvesh, (2) hydropower plant Tikvesh with penstock characteristics, (3) uncontrolled spillway, (4) irrigation channel, and (5) bottom outlet.

The reservoir's physical capacity is defined through surface and volume curves.

The hydropower plant is defined through several characteristics:

1. Penstock capacity,
2. Installed capacity of the agregates,
3. Energy loss through the penstock,
4. Relation between coefficient of efficiency and flow,
5. Flow curve for downstream riverbed.

All these parameters are neccessary in the model for it to calculate produced energy at every time step, using the equation:

$$E = \frac{\rho\ g\ Q\ H\ t}{\eta} = \cdots [W]\ldots \qquad (5)$$

,where:

E - produced energy in Watts,

Q - turbine flow in m^3/s,

H - water head minus loss, in m,

t - time frame, in hrs,

η - coefficient of efficiency.

Overall installed capacity of the modelled power plant is 4 turbines with installed capacity of 28.83 MW – the same as in Tikvesh hydropower plant.

The spillway is defined through a flow curve, with maximum capacity of $Q_{10\,000}$= 2150 m^3/s and H_p= 3.5m. Spillway elevation is H_{spill}= 265 m.a.s.l. Maximum elevation at the reservoir is H_{max}= 268.5 m.a.s.l. and crest elevation is H_{crest}= 270 m.a.s.l.

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) Dead zone. Flood control zone is normally the zone above H_{spill}, when the elevation in the reservoir rises above the normal level and spills out. Conservation zone is the zone where all normal functioning rules are applied, such as rules for hydropower generation, irrigation, water supply or whatever the purpose of the reservoir is. Basically, the volume of water in the conservation zone is the water that we want to operate with. Conservation zone is located between H_{min} and H_{spill}. Below H_{min} its the dead zone, where no rules can be applied since this water levels are considered to be below the physical capacities of the outflow structures.

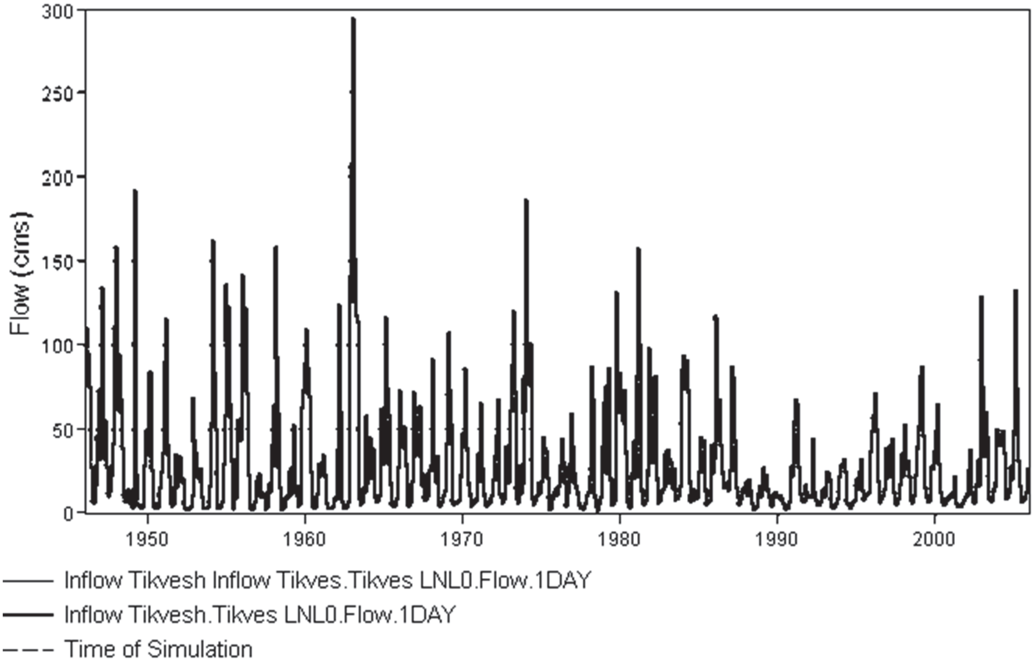

Figure 5. Hydropraph of gauged flows for station Tikvesh, 1946 – 2005.

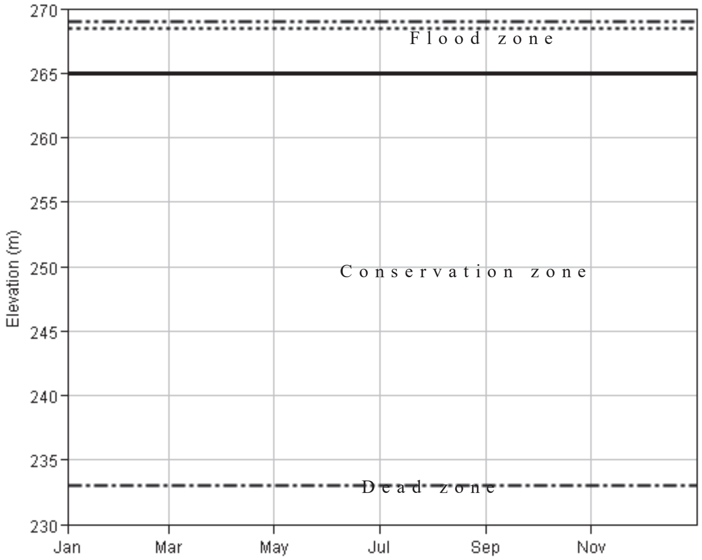

Figure 613. Definition of zones in the reservoir Tikvesh for the purpose of simulation model in HEC ResSim.

In the case of Tikvesh reservoir, Flood control zone is between elevation 265 m.a.s.l. and 270 m.a.s.l., where rules for including the spillway and bottom outlet for quick reservoir draining are defined. Conservation zone is between elevation 265 m.a.s.l. and 233 m.a.s.l. where operating rules for the power plant are defined and rules for irrigation purposes as well. Dead zone is under 233 m.a.s.l (Figure 6).

3.3 Alternative 1

This alternative is an upgraded alternative 0, with two more added systems: Chebren and Galishte. The configuration model can be seen in Figure 7. Chebren is the first and largest reservoir and dam in the cascade, with capacity of 555 10^6 m^3. Galishte is the second in line, similar in capacity of reservoir as Tikvesh, with volume of 256 10^6 m^3. The furthest in line is the existant Tikvesh reservoir.

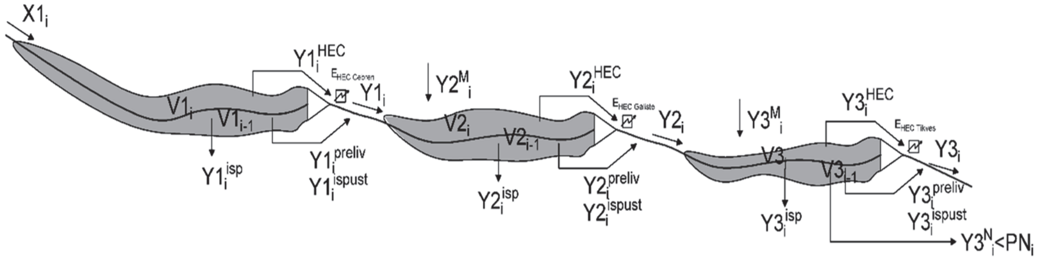

Figure 714. Schematic of Alternative 1.

In order to connect the reservoir's operating rules and make them 'work for one another', there is a Tandem Operatin Rule definition in HEC ResSim. What this rule does, is basically make the upper reservoir work for the lower reservoir in order for it to achive mass balance (HEC Ressim 3.1, User's Manual, 2013).

Mass balance equation for the system Alternative 1 is shown as follows:

$$V1_i = V1_{i-1} + X1_i - [Y1_i + Y1_i^{isp}] \ldots \tag{6}$$

$$V2_i = V2_{i-1} + X2_i^M - [Y2_i + Y2_i^{isp}] \ldots \tag{7}$$

$$V3_i = V3_{i-1} + X3_i^M - [Y3_i + Y3_i^N + Y3_i^{isp}] \ldots \tag{8}$$

Outflow from the reservoirs is shown as follows:

$$Y1_i = Y1_i^{preliv} + Y1_i^{ispust} + Y1_i^{HEC} \ldots \tag{9}$$

$$Y2_i = Y2_i^{preliv} + Y2_i^{ispust} + Y1_i^{HEC} \ldots \tag{10}$$

$$Y3_i = Y3_i^{preliv} + Y3_i^{ispust} + Y3_i^{HEC} \ldots \tag{11}$$

$$Y3_i^N \leq PN_i \ldots \tag{12}$$

$$Y1{,}2{,}3_i^{isp} = f(Z_{akum}, T) \ldots \tag{13}$$

$$\mathrm{Q}_{TIKVES}^{BASIN} = Q_{TIKVES}^{GAUGED\ FLOW} - Q_{GALISTE}^{GAUGED\ FLOW} \ \ldots \tag{23}$$

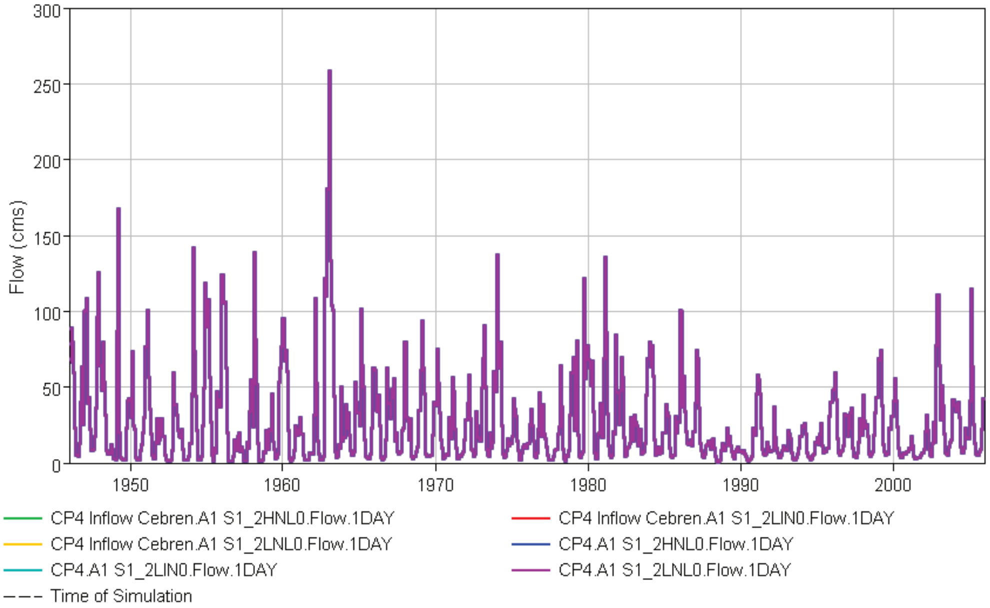

Figure 8. Hydrograph of gauged flows for Chebren reservoir (1946 - 2005).

Mass curve for Chebren is an observed hydrograph in the period from 1946 – 2005 (60 years) at gauging station Rasimbegov most on Crna Reka (Figure8). There are gauged flows for Galishte and Tikvesh, however, those cannot be used in the model since they have been once included in the measured flow in Chebren (Figure 9159). In order to extract the mass curve entering the reservoirs of Galishte and Tikvesh, measured values had to be extracted:

$$Q_{GALISTE}^{BASIN} = Q_{GALISTE}^{GAUGED\ FLOW} - Q_{CEBREN}^{GAUGED\ FLOW} \quad \dots \qquad (14)$$

$$Q_{TIKVES}^{BASIN} = Q_{TIKVES}^{GAUGED\ FLOW} - Q_{GALISTE}^{GAUGED\ FLOW} \quad \dots \qquad (23)$$

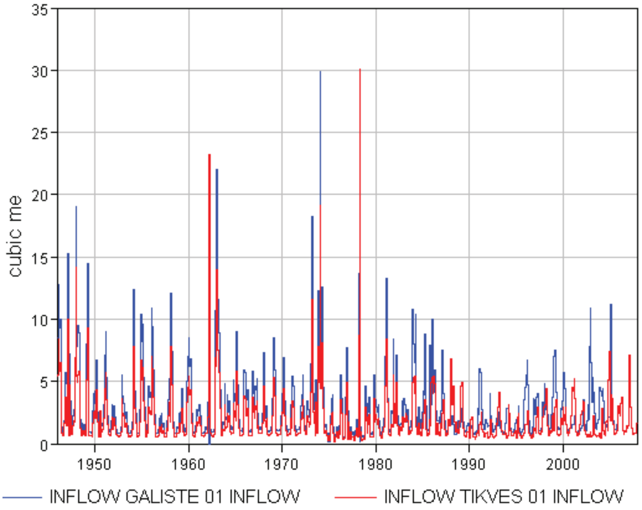

Figure 915. Hydrograph of extracted flows for Galishte and Tikvesh reservoir (1946 - 2005).

Physical characteristics of the model

Physical parameters of the system are concisely shown in Table 2. The parameteres for Tikvesh reservoir, dam and power plant are as existant. Galishte and Chebren have higher installed capacities, according to the Water Master Plan of Macedonia, adopted back in 1973. The parameters, as shown, are implemented in a simulation model for hydropower generation, where hydropower is the primary user and irrigation is implemented only for Tikvesh reservoir.

Zones are also defined in order to apply rules for the reservoirs. Same operating rules for the hydropower plant apply as described in Alternative 0 – Low non linear, Linear and High non linear curves for hydropower engagement.

Table 2. Physical parameters of Alternative 1.

System	Physical parameter	Alternative 1	
Tikvesh	Normal operating level	265	[m.a.s.l.]
	Minimal elevation	233	[m.a.s.l.]
	Volume of reservoir	$310\ 10^6$	[m^3]
	Crest level	269	[m.a.s.l.]
	Capacity of power plant	115.32	[MW]
		144	[m^3/s]
Galishte	Normal operating level	392	[m.a.s.l.]
	Minimal elevation	342	[m.a.s.l.]
	Volume of reservoir	$256\ 10^6$	[m^3]
	Crest level	398	[m.a.s.l.]
	Capacity of power plant	190.83	[MW]
		180	[m^3/s]
Chebren	Normal operating level	565	[m.a.s.l.]
	Minimal elevation	515	[m.a.s.l.]
	Volume of reservoir	$555\ 10^6$	[m^3]
	Crest level	567	[m.a.s.l.]
	Capacity of power plant	324.48	[MW]
		231	[m^3/s]

4. Results

Results are discussed on: (1) electricity generation [MWh/day, MWh/year], (2) engagement of power [MW], and (3) average water levels in reservoirs [m.a.s.l.].

4.1 Alternative 0

In this alternative, a simulation run was conducted for a single reservoir with main use – production of electricity and secondary use - irrigation. As described in detail in section 0 and with implementation of three different operating rules for power plant engagement, results will be discussed for the operating rule that contributed to highest results.

When comparing water level fluctuation during the analysed period of 60 years (1946 – 2005), highest maintained water level in the reservoir is achieved with implementation of operating rule High non-linear, with average elevation in the reservoir of $H_{high}=$

259.95 m.a.s.l (Figure 1010).

It is only logical to expect that the implementation of operating rule High non-linear will give out the highest values for energy production as well. Mainly, the average power engaged on daily is P_{aver}= 18.84 MW and average production of electricity is E_{aver}=452.28 MWh/day. Annually, the production of electricity would exceed 160 GWh/year.

Implementation of operating rules Low non-linear and Linear result in annual production of electricity of E_{aver}=149.4 GWh/year and E_{aver}= 156.6 GWh/year respectively.

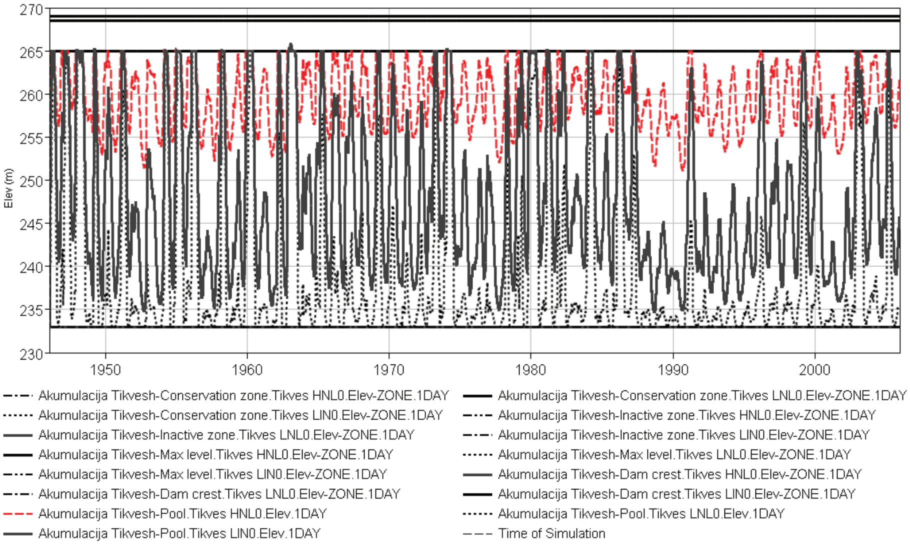

Figure 10. Water level fluctuations under operating rules and physical limitation of the Tikvesh system.

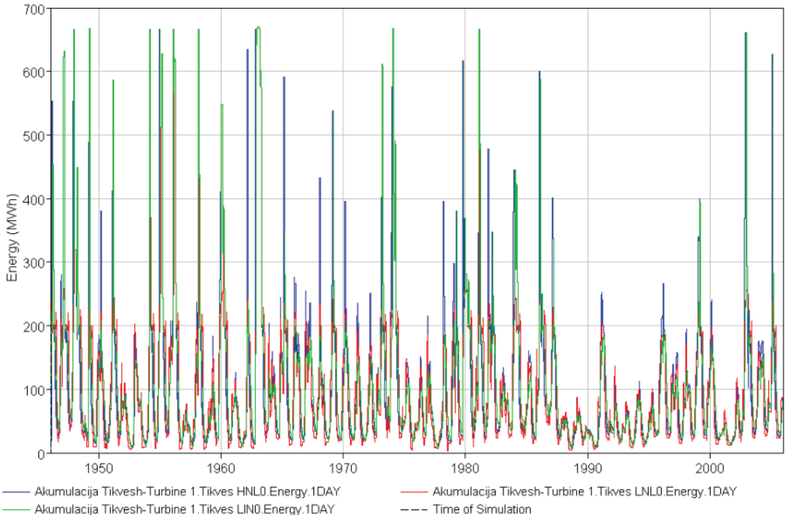

Figure 11. Energy production of each turbine in Tikvesh HPP for the 60 year simulation run.

In comparison to produced electricity from Tikvesh HPP for the period of 1994 to 2016 (Figure 121612), the results we got with the simulation model are matching to the real values. Namely, with the simulation run, we got an average production of electricity of around 160 GWh/yearly. Real delivered values show somewhat of 150 GWh in average produced electricity of Tikvesh HPP for the period of 1994 to 2016.

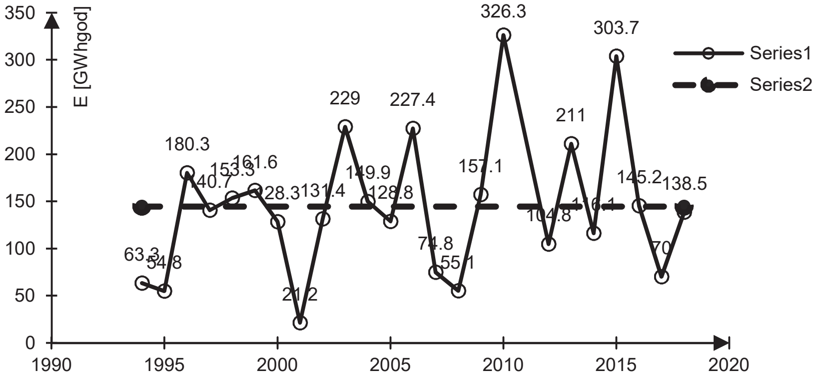

Figure 1216. Produced electricity in Tikvesh HPP in the period from 1994 – 2016 (AD ELEM, 2016).

4.2 Alternative 1

The simulation model of Alternative 1 consists of three cascade reservoirs with hydropower plants: Chebren, Galishte and Tikvesh. All plants are equipped with conventional units ant their physical characteristics are in details explained in section 0. Three operating rules for hydropower generation are applied, of which only the highest results will be discussed.

In Figure 131713 and Figure 14 water fluctuating levels are given for Galishte and Chebren reservoirs, with implementation of operating rules 1,2 and 3. Highest water levels are obtained with implementation of High non-linear operating rule for the hydropower plant, with H_{aver}= 386.31 m.a.s.l. for Galishte and H_{aver}= 558.68 m.a.s.l. for Chebren. Maximal obtained water level for Tikvesh reservoir in this configuration is H_{aver}= 260.90 m.a.s.l.

The annual production of energy per plant is highest when implementing operating rule High non linear for each and one of the power plants. The average annual production of electricity in Chebren HPP is E_{aver}=243.1 GWh/year, in Galishte HPP is E_{aver}= 196.7 GWh/year and in Tikvesh HPP is E_{aver}= 153.1 GWh/year. Adding up the numbers, when putting HPPs Chebren and Galishte in operation, our state would get over 439 GWh/year clean electricity:

$$E_{Chebren} + E_{Galishte} = 243.1 + 196.7 = 439.8\, GWh/year \ldots \qquad (16)$$

Implementation of operating rules Low non-linear and Linear results in lesser production of electricity annualy. Namely, for Chebren HPP these numbers are E_{aver}= 193.4 GWh/year for Low non-linear, and E_{aver}= 216.6 GWh/year for Linear operating rules. For Galishte HPPs, these numbers are E_{aver}= 142.9 GWh/year for Low non-linear, and E_{aver}= 167.1 GWh/year.

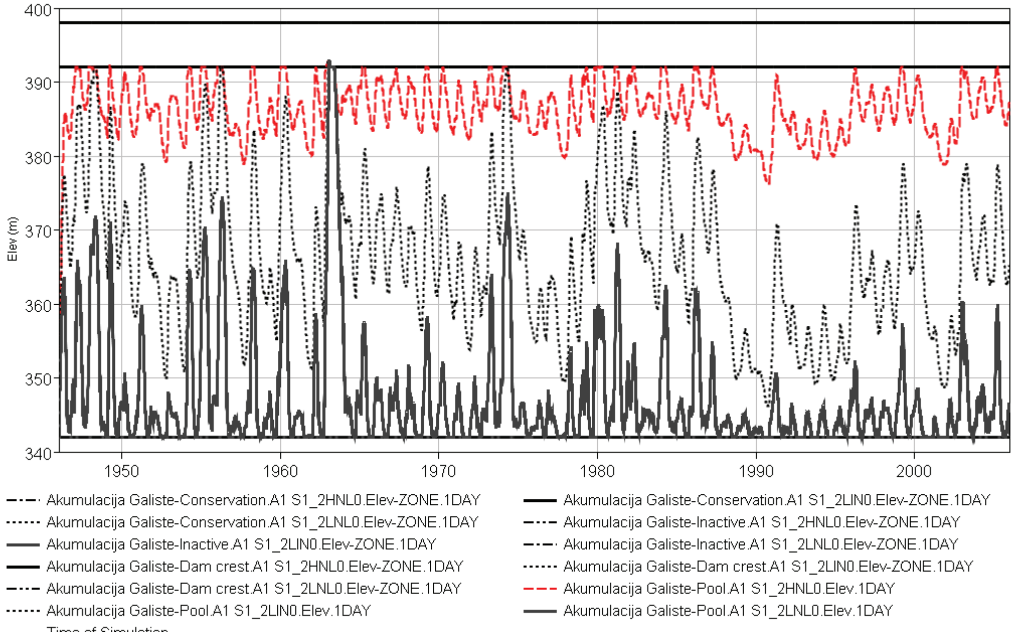

Figure 1317. Fluctuation of water level in Galishte reservoir.

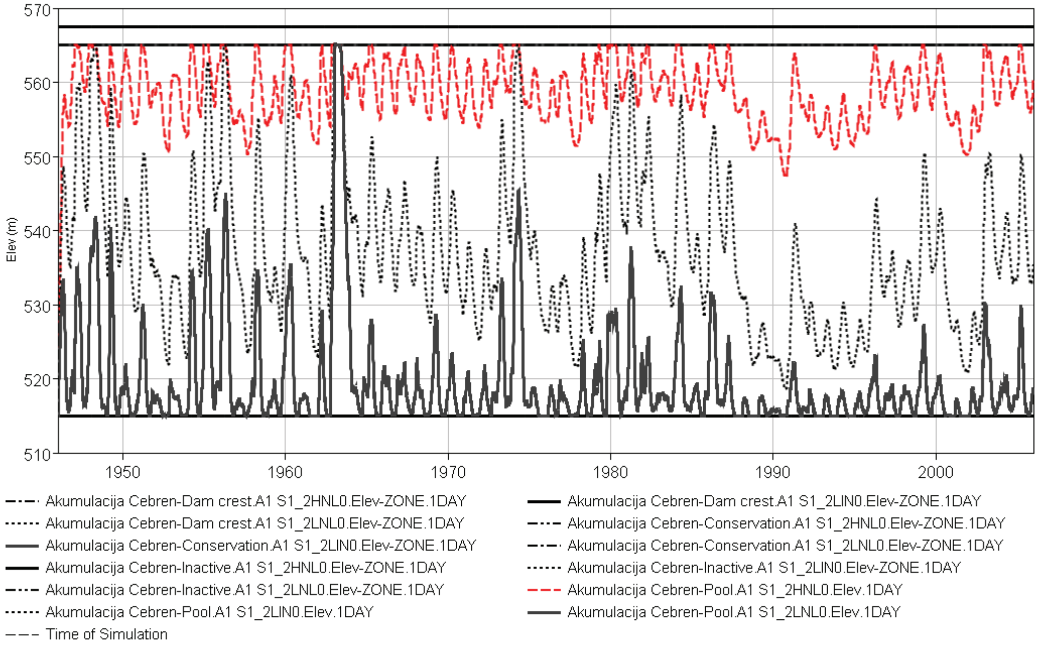

Figure 14. Fluctuation of water level in Chebren reservoir.

5. Conclusion

Simulation models for hydropower generation in complex water resources system is applied. For each simulation run, hydrological inflow, physical parameters and operation rules are defined. HEC ResSim software is used for the analyses. A 60 year time frame is analysed with gauged flows on river Crna Reka.

Alternative 0 consists only of one water resources system – Tikvesh reservoir, dam and hydropower plant. Three different operating rules are applied to investigate the optimal operating rule and maximize electricity production. Alternative 1 consists of three cascade reservoirs with dams and hydropower plants – Chebren, Galishte and Tikvesh.

Results show that implementation of operating rule High non-linear in both alternatives give the maximal values for electricity production. This operating rule runs the power plant under high capacity only when the reservoir is full.

Average annual production of electricity of Tikvesh hydropower plant alone in Alternative 0 varies from 149 GWh/year for Low non-linear, 154 GWh/year for Linear and 160 GWh/year for High nonlinear operating rule. It is interesting to notice that only by changing the operating rule, generated electricity can exceed 10 GWh/year in this configuration alone.

Average annual production of electricity of all capacities simulated in Alternative 1 varies from 456.83 GWh/year for Low non-linear, 517.33 GWh/year for Linear and 592.98 GWh/year for High non-linear operating rules. Excluding the existing plant Tikvesh, when putting Chebren hydropower plant and Galishte hydropower plant in operation, with physical parameters as implemented in the simulation run, over 350 GWh/year would be placed on the national grid as clean and renewable energy.

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