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Macedonian Committee on Large Dams

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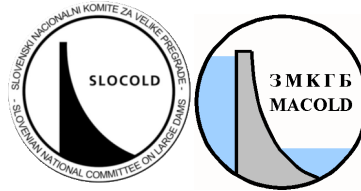
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OVERVIEW OF APPLIED METHODS FOR SUSTAINABLE HYDROPOWER DEVELOPMENT AT RIVER SCALE EXTENT

Frosina Panovska¹, Ljupcho Petkovski², Stevcho Mitovski³

Summary

Considering latest rising temperatures of the atmosphere and increasing effect of burning fossil fuels for energy, climate has shifted and we have all witnessed unusual weather conditions. Since awareness has been raised on producing electricity with burning the fossils, water is seen on as a very reliable resource for renewable hydropower generation. It can cover peak hours electricity demands, but it can also cover base energy demands – unlike sun or wind energy which are highly unpredictable renewables in space and time. Human activities have polluted available fresh water, and rising population needs more and more by the day to survive. Agriculture is thriving and needs more water than ever to feed the growing population. However, as much as we need it, we also need to protect our homes from flash flood events occurring more and more often. This and more presents a picture of a very complex water resources systems planning and management problem. Every system needs to be planned with taking under consideration all related stakeholders.

Key words: hydropower, sustainable development, water resources

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1. INTRODUCTION

Water resources systems are all natural water systems and all artificial structures on them and their surroundings, built to use water for all human activities, river bed regulations and protection of the devastating power of water, as well as protection of water itself [1]. These systems use the water as a resource – generally rainfall or snowmelt transformed in stream flow. Artificial structures in WRS are dams, reservoirs, spillway, bottom outlet, hydropower plant, irrigation canals, water supply network, river bed regulation, flood protection levees etc.

Based on the number of stakeholders using the water resource, there are three types of WRS:

- (1) Single purpose WRS, where the final consumer is solely one. An example of such system would be a dam with reservoir where the water from the reservoir is only used for water supply or only for irrigation. This WRS is relatively easy to operate with since there is only one end – user;
- (2) Multipurpose WRS, where multiple stakeholders are included in the use of water. Such example would be a dam with reservoir where the water is used for irrigation of land, water supply of a smaller village and hydropower generation. In this case, operating with the reservoir is more complex since different stakeholders have different water needs and the operator with the system needs to meet all of them. Often, these need intersect and the management with the water resource is complicated. For instance, irrigation needs the reservoir to be full at months where vegetation is thriving in the fields and uses large amounts of water. On the other hand, hydropower – working only in peak hours in the day, at all times prefers high level of the reservoir – in order to produce more electricity with less water flow. Water supply however, needs clean and cooled water whole year around. This means that all these water users have water demands that differ at quantity and quality, both in space and time.
- (3) Integral WRS management (IWRM), defined by the Global Water Partnership as ‘a process which promoted the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’. This concept aims to promote changes in practices which are considered fundamental to improved water resources management. In the current definition, IWRM rests upon three principles that together act as the overall framework (the Dublin principles): (1) social equity, (2) economic efficiency and (3) ecological sustainability [2].

Considering latest rising temperatures of the atmosphere and increasing effect of burning fossil fuels for energy, climate has shifted and we have all witnessed unusual weather conditions. Since awareness has been raised on producing electricity with burning the fossils, water is seen on as a very reliable resource for renewable hydropower generation. It can cover peak hours electricity demands, but it can also cover base energy demands – unlike sun or wind energy which are highly unpredictable renewables in space and time. Human activities have polluted available fresh water, and rising population needs more and more by the day to survive. Agriculture is thriving and needs more water than ever to feed the growing population. However, as much as we need it, we also need to protect our homes from flash flood events occurring more and more often. This and more presents a picture of a very complex water resources systems planning and management problem. Every system needs to be planned with taking under consideration all related stakeholders.

Hydropower is a mature and reliable generating technology with a low carbon footprint. It is extremely competitive energy source since its efficiency rate is very right among all electricity generating technologies – between 85% and 95% for conventional hydropower and between 70% and 85% for pumped – storage hydropower. In R N Macedonia, only 30% of all available hydropower potential has been used, so it is very likely that hydropower will keep playing an

important role in the energy system. So far, all hydropower built in the country is conventional, with several planned pumped – storage hydropower that are waiting for realization. Along with associated water management services like flood and drought control, hydropower can play a key role in climate change adaptation efforts.

The major impacts of using hydropower stations on river basins are: (1) shift of river biosphere life conditions with erecting dams and impounding rivers, (2) altered flow conditions of rivers, (3) change in sediment transport dynamics, and (4) changes in nutrient levels in water. In the past decades, engineering techniques have been developed to mitigate some of the above – mentioned impacts of hydropower, such as: (1) implementation of fish passes, (2) setting environmental flow as an all – time must release from the reservoir, and others. Environmental sustainability of hydropower can further improve in: (1) protection of biodiversity, (2) availability and quality of water, (3) sediment management, and (4) decommissioning of existing hydropower infrastructure [3]. Alongside direct effects of hydropower stations on river basins, effects on the surrounding environment is also inevitable. Large area of woods is often cut down to prepare the reservoir space, and many animal species leave their habitat because of reservoir impounding. In R N Macedonia, we have faced complete hydropower project shut down due to bad – mouth lobbying of environmental NGOs. Namely, large hydropower projects in the Shar Mountain – Lukovo Pole and Boshkov Most – were stopped, after ecologists lobbied in the EU that these systems affect life cycle of mountain cats in Shar Mountains. Aside environmental impacts, social issues have often led to problems in the past and therefore should be integrated in the process of planning and operation with hydropower systems.

WRS are no longer planned as single purpose systems. Planners are facing major challenges in all phases of the WRS life cycle – from planning, to realization and operation. When planning such a system, the basic input of the system – rainfall or stream flow – is a stochastic parameter to begin with. Statistical methods are used today to improve the understanding and use of input hydrologic data. Optimization mathematical methods are used to optimize and adopt physical parameters of the system, such as reservoir volume, dam crest level, spillway capacity, dam size, turbine capacity, etc. Simulation mathematical models are used to combine input hydrologic data and adopted physical parameters to take an insight in the yield of the system, i.e. the response of the system under certain hydrologic input and operation policy. A simulation model of a water resource system is a mathematical technique where the real system is expressed by arithmetical and logical procedures the dynamic behaviour of the water resource systems in discrete time steps [1]. Simulation models give the planner a chance to try-out different system configurations under different operational policies and take an insight at output results.

Often, simulation models are not only used in the planning phase of the system, but also in operational phase, when different operational scenarios can be tested on the mathematical model before applying them to the real system.

Operators of complex WRS are facing every day challenges in terms of satisfying all stakeholders' needs, at the same time releasing just enough environmental flow and keeping the reservoir at safe level. They operate systems under data obtained from local stream gauge stations and small meteorological stations that give details on atmosphere temperatures, humidity and precipitation. According to this data as well as data on water demands, operators make decisions on water release at every time step of the decision making process. The main goal of this prospective PhD research would be to define an algorithm, by applying neural networks that will generate connection between the input – hydrologic data, and output – release from WRS.

The use of artificial neural networks (ANN) modelling for prediction and forecasting variables in water resources engineering are increasing rapidly. ANN is a vigorous technique to develop immense relationship between the input and output variables, and able to extract complex

behaviour between the water resources variables such as hydropower generation and discharge. It can produce robust prediction results for many of the water resources engineering problems by appropriate learning from a set of examples. It is important to have a good understanding of the input and output variables from a statistical analysis of the data before network modelling, which can facilitate to design an efficient network. An appropriate training based ANN model is able to adopt the physical understanding between the variables and may generate more effective results than conventional prediction techniques.

Proposed case study of this research is the basin of Crna Reka. Crna Reka has only one large water resources system in operation – Tikvesh dam with hydropower plant, dating back from 1968. Two other major reservoirs are planned upstream from Tikvesh, in a cascade, for maximal use of hydropower of this river's potential. The idea with this method is to assess new cascade layout in light of new criteria in addition to the classical energy, power, LCOE, such as hydropeaking, sediment management, CO₂ emissions from river systems and reservoirs and fish mitigation. In order to do that, optimization models should be generated to define optimized parameters of systems that are planned but not built yet, followed by run of simulation models with optimized physical parameters and optimized operational policy in order to generate input and output data. This data will be 'fed' to a neural network to train and create an algorithm. The algorithm will be tested for its accuracy with different data, than the input and output data, and conclusions will be made on its further implementation.

2. A BRIEF OVERVIEW OF PREVIOUS RESEARCH

In the past half century or so, water resources professionals have been engaged to preparing integrated, multipurpose master development plans for many of the world's river basins. These plans normally consist of several parts – appendices, such as hydrology, pedology, hydro power, multipurpose water resources systems etc. These appendices are completed with recommendations, numerical analyses on water use with structural and non-structural management options. This master planning exercise is dominating the water management sector, however, using this approach there is usually little if any active participation by interested stakeholders. The approach assumes that one or more institutions have the ability and authority to develop and implement the plan, in other words, they will oversee and manage the development of the basins' activities [3]. In today's environment where publics are calling for less governmental oversight, regulation and control, an increasing participation in planning and management activities, top-down approaches are becoming less desirable.

One such example of a master development plan is the one prepared in 1973 for water management of the basins in R Macedonia, as constituent republic within Yugoslavia. This master plan consists of several parts: (1) Natural factors, (2) Social and industry conditions, (3) Single purpose water resources plans, (4) Urban waters, (5) Complex water resources plans. In the third part – Single purpose water resource plans, an appendix on hydropower utilization of water resources is elaborated. In this appendix, it is explained in details on location, type, installed capacity and expected electricity input from each and one hydropower plant. However, in the past decade many hydropower plants have been built that are out of the Master plan, and several major hydropower candidates are being discussed on with altered characteristics in dam size, reservoir size, type of HPP (conventional, reversible), installed capacity, etc.

Planning, designing and managing water resource systems today inevitably involve impact prediction. Impact prediction can be aided by the use of mathematical models. As models can be useful and give us plenty of information, we have to acknowledge the limitation of models as representation of any real systems. Model structure, input data, objectives and other assumptions related to how the real system functions or will behave under alternative design and management, may be uncertain. Modelling provides a way to predict the behaviour or

performance of proposed systems. The past 50 something years have witnessed major advances in our abilities to model the engineering, economic, ecologic, hydrologic aspects of complex multipurpose water resource systems. These models have improved our understanding of such systems and hence have often contributes to improved system design, management and operation. Computer based modelling is used to produce these mathematical models. Mathematical simulation and optimization models packaged within an interactive program provide a common way for us planners and managers to make decisions for a certain system. Mathematical models used in water resources systems planning can be: (1) optimization models, (2) simulation models, and (3) combined models [1].

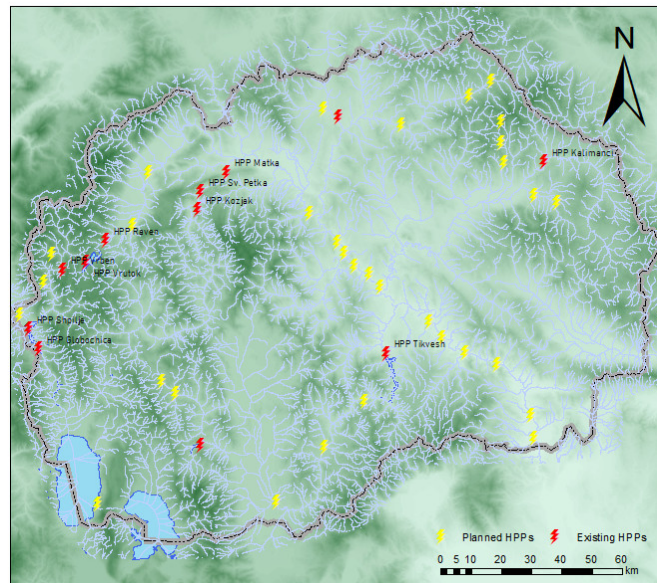


Figure 1 An overview of existing major hydropower plants and major planned hydropower plants in R Macedonia, according to the 1973 Master Plan.

Optimization mathematical models are used to maximize or minimize certain parameter (diameter of inlet pipe, width of spillway, height of dam etc.) under a defined function. Simulation models are used to simulate real behaviour of a system based on known input data, physical parameters of the system and defined operational policies.

Methods used for optimization models, are: (1) linear programming, (2) non-linear programming and (3) dynamic programming. Linear programming is the simplest of all optimization methods. With this method, each and one optimization task solves one out of two problems – either maximize or minimize a parameter to achieve certain function with given resources, or achieve certain functions with minimum or maximum resources. All limitations and functions are linear. Non – linear programming is an optimization method where at least one of the functions in the mathematical model is a nonlinear function. Dynamic programming, developed by Richard Bellman in 1957 is still in use today and can solve nonlinear and stochastic tasks – just like tasks related to water resources systems planning and management.

Simulation models are often made with the aid of a computer software. In the past, simulation models were single – purpose mathematical models, only applicable to a one certain system. Such models had been created in USA in the late 1950s with the help of FORTRAN, PL/I, COBOL programming languages. First simulation models of complex water resources systems are noted in USA when in 1953 USACE were in the making of a study on management with six reservoirs in the Missouri basin [4]. Ever since, different single – purpose simulation models have been created such as SSARR, SUPER, BRASS, HYSSR, HLDPA and others. Today, software applicable to any simulation run are available and all kinds of basins can be modelled

with their help. Some of them are: RIBASIM, WEAP, HEC-ResSim. All of the numbered have been extensively used in the past decade in planning of water resources systems and have proved to be efficient and helpful in the decision making process.

Artificial neural networks (ANN), along with fuzzy logic, genetic algorithms and fuzzy – neural networks represent examples of a modern interdisciplinary area, especially when it comes to solving specific types of engineering problems that could not be solved with the use of traditional modelling methods and statistical methods [4]. ANN neural networks functioning is analogue to the way human neuron networks function. The neuron in the human body is consisted of axon, soma and dendrite. The soma is the body, dendrites are connections to other neurons and axon transfer electric signals among cells. ANN is also consisted of neurons, and they practically imitate biological processes that normally happen in the neuron network of a living organism. The mathematical model of artificial neural networks is basically a network comprised of a large amount of neurons interconnected with connection links of specifically defined weight coefficients. ANN consists of: (1) input data layer, (2) weight coefficients, (3) hidden layer/s and (4) output data layer [5]. Weight coefficients are key elements in neural networks. Their value represents the relative importance of each neural input and they define the ability of input activation of neurons. Neural networks have the ability of ‘training/learning’. This process occurs as a result of adjustments in the value of weight coefficients, based on the array of input and output data. Activation function defines the output of a neuron given an input or set of inputs. Linear or non – linear functions serve as activation functions, however, one of the most commonly used one is sigmoid function (Figure 2):

$$Y_t = \frac{a}{1 + e^{-y}}$$

According to the type of relationship between the nodes, neural networks can be: ANN in layers (Figure 3), closed – loop neural networks (Hopfield neural network) (Figure 4) and cellular neural networks (Figure 5) [4].

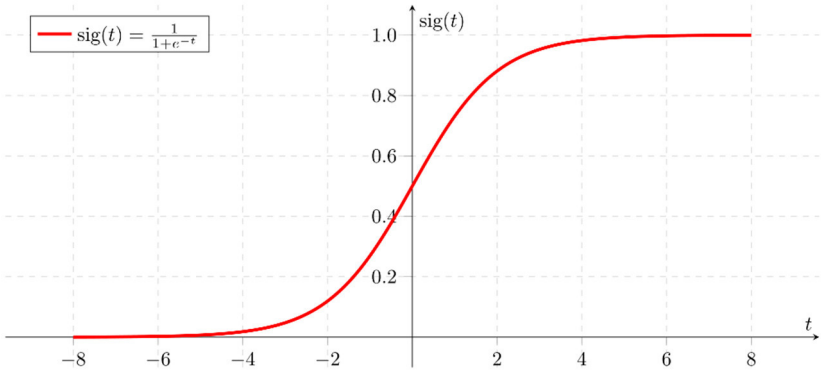


Figure 2. Sigmoid function diagram.

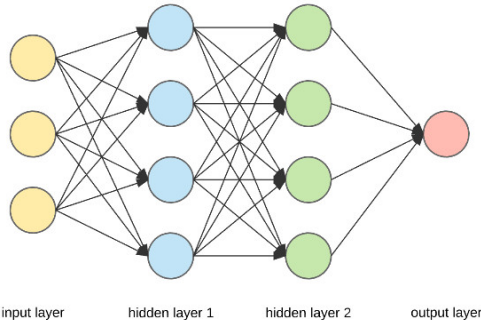


Figure 3. Schematic of neural network in layers (Courtesy of www.towardsdatascience.com).

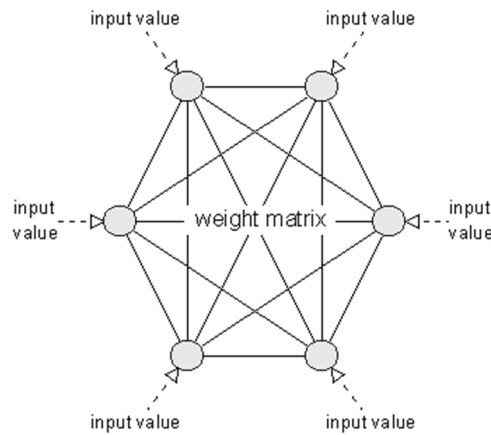


Figure 4. Schematic of Hopfield closed - loop neural network (Courtesy of www.nnwj.de).

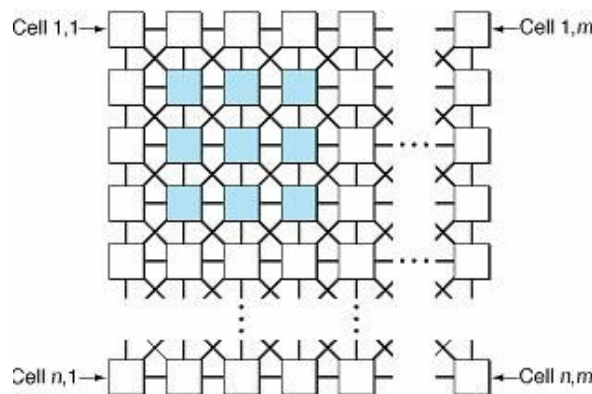


Figure 5. Schematic of cellular neural network (Courtesy of www.techbriefs.com).

According to the number of layers in the neural network, it can be: one layer ANN or multi-layer ANN [6].

According to the type of training implemented with ANN, they can be: (1) ANN with supervised training and (2) ANN with unsupervised training. Neural networks with supervised training use known input and output data to create relationship between the input and output data, with adjustments between the weight coefficients. Unsupervised training uses only known input data and tries to create mutual relationship among input data. Data used in the training process can be: (1) data used for training, and (2) data used for testing the results.

3. SCOPE OF THE RESEARCH

The main scope of this model would be assessment of new cascade layout for a multi - purpose, multi - reservoir cascade reservoir system, with creation of a mathematical models for operation of the system with consideration of environmental and social effects of hydropower. As a result, a mathematical model will be created that would be used by operators in real time operation with the complex system. This mathematical model would be based on neural networks, comprised of data obtained by simulation and operation models made for the specific case studies.

Basins of Crna Reka is chosen as case studie since its basin in R N Macedonia has great hydropower potential, that is yet to be exploited.

Crna Reka's basin is situated in the south – west of the country, taking an area of 5 800 squared kilometers (Figure 6). With an average annual flow of 24 cubic meters at its confluence point,

today only one out of the three planned hydropower plants is operating on this river – Tikvesh HPP, with four Francis turbines with installed capacity of 24 cubic meters per second, with average annual production of 155 GWh. Tikvesh WRS consists of a dam with reservoir, catchment for irrigation of agricultural land in Tikvesh valley, morning glory spillway, and hydropower plant. Primary user of the water in Tikvesh WRS is Tikvesh valley and irrigation, second is use for environmental flow and third is hydropower production.

Two more hydropower plants with dams and reservoirs are planned upstream of Tikvesh WRS – Galishte WRS and Chebren WRS (Figure 7). Galishte is planned as an embankment dam with reservoir the size of $256 \times 10^6 \text{ m}^3$. The hydropower plant should be equipped with three Francis turbines with installed capacity of $60 \text{ m}^3/\text{s}$, per turbine, or in total – $180 \text{ m}^3/\text{s}$ installed. Chebren is planned as the first in the cascade and with largest reservoir, with pump – storage hydropower plant. The size of the reservoir should be approximately 555×10^6 cubic meters, with hydropower plant with installed capacity in turbine regime of $333 \text{ m}^3/\text{s}$ in total, and in pump regime $150 \text{ m}^3/\text{s}$ in total. For regular work of the pumps, just downstream of Chebren dam, another small reservoir with dam Orlov Kamen is planned as a lower reservoir (Figure 8). These two WRSs are planned solely for electricity production.

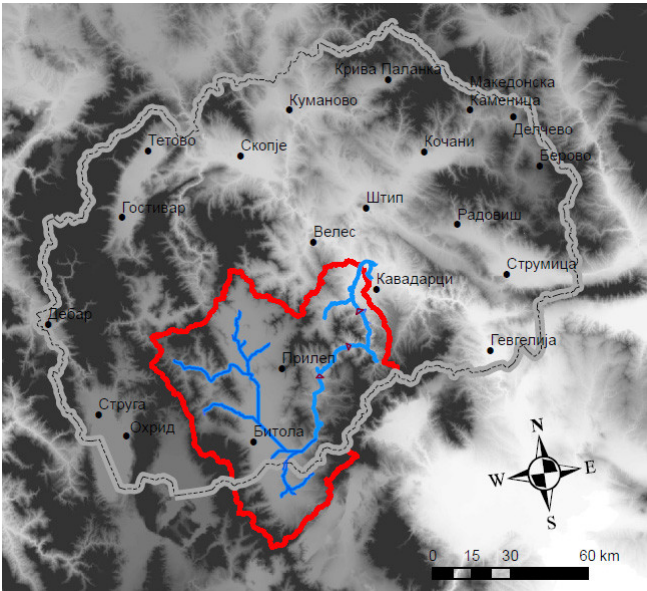


Figure 6. Basin of Crna Reka (red polygon).

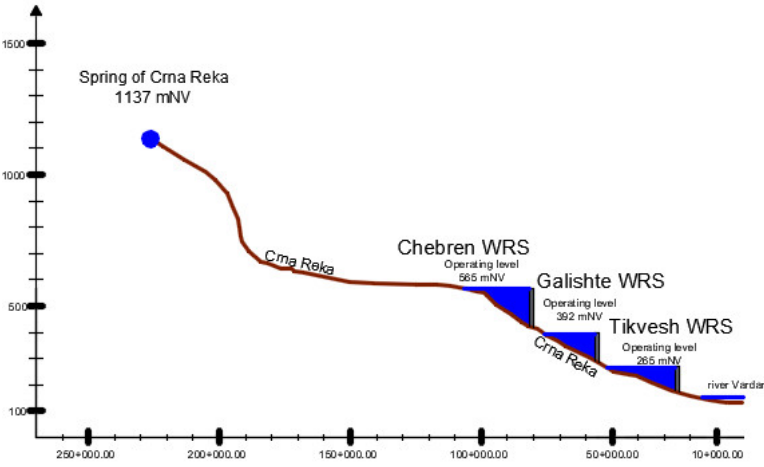


Figure 7. Longitudinal section of Crna Reka from its spring to the confluence with river Vardar, with Chebren and Galishte as planned WRS and Tikvesh WRS as existing system.

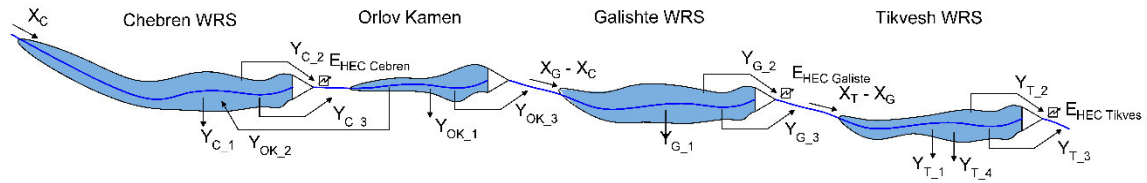


Figure 8. Schematic configuration with all input and output flows from the systems of the planned WRSs Chebren and Galishte, and Tikvesh WRS, on Crna Reka, (C) stands for Chebren, (OK) for Orlov Kamen, (G) for Galishte, (T) for Tikvesh, indexes have the following meaning (1) evaporation water loss, (2) water demands for the hydropower plant, (3) spillway flow, (4) demands for irrigation.

The mathematical model with neural networks would consist of all water resources systems in the valley of Crna Reka – Chebren, Galishte and Tikvesh, with their adopted physical characteristics and operational policies. For Galishte and Chebren, some additional optimization models should be done to confirm the proper choosing of installed capacities for turbines and pumps. After arranging all data on physical parameters, an operational policy for all reservoir will be defined. An example of adopted operational policy is shown in Figure 9.

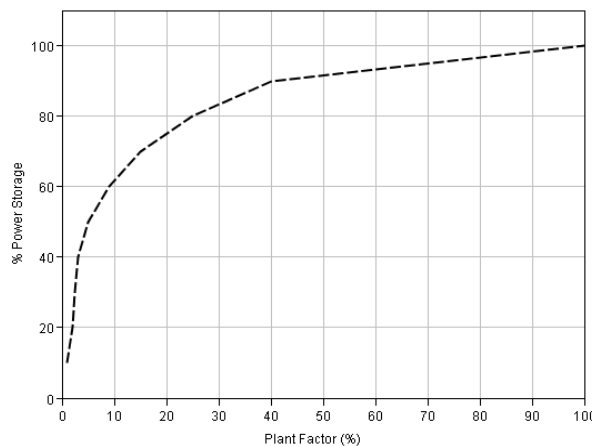


Figure 9. Operational policy for the work of the hydropower plant. With this operational policy, the hydropower plant will work with high capacity only when the level of the reservoir is at high level [7].

4. CONCLUDING REMARKS

Having flexible mathematical models that we can test different operational policies on, is of great significance for operators with hydropower schemes. With the implementation of optimization and simulation models, we will create enough input and output data to generate a neural network model that will be usable in real – time operation with the system.

A simulation run can be done for the whole model and output of the model can be observed (outflows from each system). This information can serve as output data for a neural network mathematical model. Basically, the neural network will be “fed” with input data – physical parameters of the system and hydrological input, and output data – outflows from the system observed with the simulation models. The artificial neural network will then start the process of ‘training’ and will try to create relationship between input and output data, with adjustments of the weight coefficients. After million iterations per se, the neural network will have ‘obtained knowledge’ on the data and will be able to give output results based on some random input that we enter. Lastly, we would create a model that could tell us at any given time, what will the

output of the water resources system be, under certain input information, and the scale of their environmental and social impact.

This kind of model will give us the most sustainable hydropower scheme for the elaborated case study in sense of hydropower production, environmental and social impacts. The implemented method could be used further with implementation in other case studies, to estimate their sustainable hydropower development considering all effects of building a hydropower scheme.

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