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State Variables Updating Algorithm for Open-Channel and Reservoir Flow Simulation Model

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Abstract

The core of the state-of-the-art decision support systems for operational planning and management of hydropower plants is a hydrodynamic simulation model that uses information about measured and forecasted values of model forcing for prediction of water levels and flows in streams and reservoirs. Having in mind the complexity of real world systems, these issues cannot be solved analytically, thus requiring application of numerical methods. This paper discusses the use of numerical procedures in solving standard full motion equations for one-dimensional unsteady flow in open channels and structures. The produced energy is estimated based on up-to-date model states. A methodology for updating of model states using measured values of physical states in order to improve operational use of the model is presented in this paper. According to presented methodology, a state updating module is designed for “Iron Gate” (“Đerdap” in Serbian; “Portile de Fier” in Romanian) hydropower plants simulation model. Regarding importance of accurate electricity generation estimates in operational use of the model, special attention is given to the design of the module and methodology in order to reduce the deviation of estimated state values from measured values. The efficiency of proposed methodology is shown on an example of operational use for several days. The example clearly shows the disadvantages of simulation model without state updating procedure applied and the benefits of using state updating module in operational management of complex hydropower plants system.

Keywords: River flow, simulation model, state updating, open channel, reservoir, state variables

1. Introduction

The analysis of recent practices in water resources management indicates certain convergence of planning methods, with the goal of reaching flexible and interactive planning under conditions of uncertainty. The application of these methods provides for a thorough analysis of water resources and the ranges of demand related to their utilization, identification of potential conflicts of interests related to utilization, development and protection of waters, defining of priorities in conflicting situations and identification of solutions that are not unambiguous and that can be adapted to the changes. At the same time there is an evident progress in the field of information-communication technologies, especially in the domain of software development, information processing and treatment of random events. That allows transformation of rigid traditional methods for planning and management of water resources to dynamic processes.

Specific features related to the nature of hydropower potential, methods of its utilization, as well as the role of hydropower subsystems in a broader electricity generation and transmission system, exert an impact on methods of planning and management of hydropower objects. The complexity and diversity of approaches to organization of electricity market make defining general rules and procedures impossible. Obtained solutions can be considered as optimal, only if specific features of each system are treated.

The objective of solving the problem of optimum hydropower plant management is to determine the system usage, as well as the engagement of each unit in the hydropower plant (whether it is in operation and in which operation regime it operates) for the given operational conditions. The optimum hydropower plant management implies as consistent as possible fulfillment of the demands of the electricity generation and transmission system, with the minimum water consumption per unit of electricity generated and full adherence to the limitations imposed by the characteristics of the plant itself, as well as to limitations related to exploitation. This type of planning of hydropower plant operation is the short-term or operational planning, i.e. short-term hydropower system management.

The complexity of hydropower plant operation is of such nature that so far there are no unique principles of its operational planning that would be applicable in all situations. One of the reasons is the fact that the inflow to hydropower plant depends on several parameters difficult to forecast; hence, they have to quickly adapt to the current situation. All the time it is neccessary to keep in mind that water is the resource which is usually not used only for electricity generation. In addition, hydropower plant operation is coupled with many other limitations, such as the protection of the environment, important objects in the vicinity of storages and watercourses, and similar.

Complex problems of the optimum management of hydropower plants and associated storages are in practice mostly reduced to defining of a certain number of procedures and guidelines, on which basis the operational plans and their execution are defined. These procedures and guidelines are relatively easy to use and they produce plans that are not always the optimum ones, but have a necessary level of safety regarding to possible violation of the predefined limitations. The main problem in application of these procedures and guidelines is related to the fact that they were defined with numerous simplifications, they do not cover all phenomena involved in the process of exploitation of hydropower potential, they are difficult to modify and are often based on knowledge of the state of the system at the beginning of its exploitation. Their modification in order to optimize operation is a complex process that consists of several phases, such as preparation, measurement, data processing, assumptions, definition of the solutions and, finally, its implementation in everyday operation. This is the reason why the implementation of flexible systems for support to the operational planning and management of hydropower plants that provide efficient decision-making related to management and are based on hydraulic and hydropower calculations, is objective here. Such systems require the existence of the corresponding simulation models, complex information-communication infrastructure and mechanisms for data collection and processing, as well as the sophisticated optimization modules that have multiple purposes in such system.

The core of modern systems for support to operational planning and management of hydropower plants is hydro-dynamic simulation model, which uses information about realized and forecasted values of model input variables, in order to forecast water levels and discharges in the river system (Divac et al. 2009). Due to the complexity of the real systems, certain numerical methods have to be applied instead, what often requires space and time discretization of the system. Since most of the developed models are related to the natural networks of open channels, the simulation of hydropower systems requires defining additional algorithms for solving complex problems with hydropower plant objects, which are treated as internal boundary conditions. Problem complexity comes from the fact that a hydropower plant is managed according to the demand related to electricity generation that depends upon the gross head (that is a consequence of the water level in the vicinity of the dam), as well as the discharge. Since all calculation variables are coupled and are obtained as the solution to the system of nonlinear equations, this system needs to be solved by an iterative procedure.

All hydropower calculations are performed using the computational states obtained by the software used for the solution of standard, full equations of one-dimensional unsteady flow in open channels and through the control structures. The accuracy of determination of discharge and gross head is of crucial importance for determination of electricity generated by each unit and, consequently, it is a key factor in the process of optimization of electricity generation. In process of model formation and defining methodology of its operative application, special attention is paid to minimization of the difference between the calculated values of system variables and the values measured in real-time. Some of the most important reasons for difference between calculated and measured values are lack of reliability of input data and deviation of initial values from the real system state (discharges and water levels at the points in the system at the initial time of simulation). In order to make the simulation results as close as possible to the values measured in the real system, it is necessary to neutralize the mentioned causes of deviation. Since in the operational application of the model numerous simulations are to be expected, including hydraulic and hydropower calculations, it is necessary to provide model state that corresponds to the state of the real system at the initial time of simulation. Because of that the method for updating of the system state, based on the measured data, must be applied, in order to minimize simulation errors and, thus, make the model use more efficient.

The application of general state updating methods on the specific problems requires certain modifications. This is required due to the fact that the configurations of various systems may differ significantly that totally different types of input data may be used that system dynamics may differ and, finally that the models may be used for completely different purposes. Therefore, method application must be analyzed in terms of model purpose, physical system under consideration and available measurements.

An overview of the most often used state updating methods and their modifications in order to answer the specific requirements of the hydropower system “Iron Gate” are given below. It should be emphasized that the developed methodology is applicable to other hydropower systems similar to this system in terms of configuration, flow dynamics and other parameters.

2. Theoretical background of determination of the up-to-date state of the mathematical model

Since the determination of the up-to-date state of the mathematical model includes the determination of the computational state which is closest to state of the real physical system, it is necessary to take into account the complete probability distribution of all states, measurements and inputs. This provides free interpretation of the notion of "the best" estimation (for example, it can mean the minimum variance) of past, current and future states. One of the earliest methods of estimation is the implementation of the Kalman filter (Gelb, 1974). On the other hand, one can use the approach that is primarily focused on the analysis of input data quality and the possibility of their correction for the purpose of reaching as correct computational state as possible. That approach is called data assimilation. Data assimilation is achieved by application of certain mathematical models providing usage of measured data and difference between calculated and measured values in estimation of the up-to-date model and forecast of the future states of physical system. The early examples of its application can mostly be found in fields of oceanography, geophysics and meteorology (Bennett 1992).

Data assimilation procedures, depending on the variables modified in the adaptation process, may be divided into: procedures based on the correction of input values (external action on the model), procedures with updating of model states, procedures with the calibration of model parameters, and updating of output values (WMO, 1992). Updating of output values, also known as error correction, is the most used procedure in operational hydrologic forecasts (WMO, 1992; Refsgaard, 1997). The forecast model with error correction is formed upon the basis of observed model errors, which are then superimposed on the simulation model. Error correction procedures, as a part of the system for hydraulic computations, are used for updating of water level and discharge on individual locations. Generally speaking, error correction techniques do not require a significant use of computer resources; hence, they are efficient in data adaptation in the forecast systems.

2.1. Procedure for updating by filtration algorithm

Procedure of updating the state using filtration algorithm includes the period before the start of the simulation in which a number of measurements are known. Based on the existing measurements and simulation results for the given period, interpolation is used for updating the state of the whole system. The obtained improved estimation of the system state is then used as the initial condition for the real simulation (forecast) that does not include model correction.

The foundation of the filtration algorithm is the presentation of the numerical modeling system in the state space:

$$x_k = \Phi\left(x_{k-1}, u_k\right) \tag{1}$$

where Φ is the model operator that represents the numeric scheme of the modeled system, x_k is the state vector that represents the state of the modeled system in time k and u_k is the external influence on the system which includes boundary conditions. It is assumed that the measurements are available on one or more locations in the modeled system.

This can be presented by the measurement equation:

$$z_k = C_k x_k \tag{2}$$

where z_k is the measurement vector and C_k is the matrix that describes the link between the measurements and the state variables. This matrix actually maps the system state space into the measured data space.

The process of estimation of system state is performed in two steps. First, the model is used for forecast and, then, the measured data are compared to the forecasted data, in order to provide up-to-date state. The updated state variables, obtained from difference between forecasted and measured values, may be calculated as a linear combination of data and model:

$$x_k^a = x_k^f + G_k\left(z_k - C_k x_k^f\right) \tag{3}$$

where x_k^f is the forecasted state vector obtained from the equation (1), x_k^a is the updated state vector and G_k is the matrix of weighting coefficients. The vector $\left(z_k - C_k x_k^f\right)$, also called the innovation vector, is the difference between the measured and the related forecasted values. If the measurements are independent, than the sequential updating procedure can be used, which processes the measurements one by one (Chui and Chen, 1991):

$$\begin{aligned} x_k^a(j) &= x_k^a(j-1) + g_{k,j}\left(z_{k,j} - x_{k,j}^a(j-1)\right), \\ x_k^a(j) &= x_k^f, \quad j = 1,2,\ldots,p \end{aligned} \tag{4}$$

where p is the number of measurements, $z_{k,j}$ is the value of j^{th} measurement, $\left(z_{k,j} - x_{k,j}^a(j-1)\right)$ is the change in j^{th} measurement after the processing of $j-1$ observations and $g_{k,j}$ is the vector of weighting coefficients that corresponds to jt^h measurement and describes how the change $\left(z_{k,j} - x_{k,j}^a(j-1)\right)$ is distributed over the state vector. The form of the weighting coefficient vector represents the correlation between the measurements and the nearby points with accounting of unreliability of the measurements and the model. If the weighting coefficient in the measurement point equals 1, the measurements are assumed to be perfect. Smaller value of the weighting coefficient means that the assumed uncertainty of the measurement is larger than model uncertainty.

Determination of the weighting coefficient vector in the Equation (4) is the most important part of the filtration scheme and various schemes differ mainly by the method of calculation of weighting coefficients. The most comprehensive linear filtration scheme is the KF scheme (KF stands for Kalman filter), where the weighting coefficient is determined by minimization of the expected error of the updated state vector as a function of model data and dynamics (Madsen and Skotner, 2005; Drecourt, 2003; Kim et al. 2004).

The presented filtration procedure can be applied to updating of the system state until the start of the simulation, i.e. while there are available historical measurements. This state can be further used as the initial state for simulation. The increase in time difference relative to the start of the simulation weakens the effect of initial conditions and, consequently, filtration effects are weaker. This is why the application of this method is limited to the problems of shorter forecasted periods.

2.2. Correction of output values by auto-regression method

The correction of model output values is an error correction method without an analysis of its source. However, the correction of output values can be very efficient in reduction of forecast errors. The errors in output values of future simulations are often dependent on the errors already identified in the comparison of simulation results with past measured data. These systematic errors can be easily eliminated by the simple auto-regression method applied to model output values. This method is particularly useful during the first hours of forecast because it can provide establishment of the link between the measured and forecasted states.

A very often used method for correction of output values is the auto-regression (AR) method. The expected simulation error, according to this method, is dependent on the last measured error and the class of relevant state variables.

The form of AR model in the current time step t is as follows:

$$\varepsilon(t) = \varepsilon(t_0) R_t \tag{5}$$

where $\varepsilon(t)$ is the estimation of the expected error, $\varepsilon(t_0)$ is the simulation error at time t_0 and R is the regression coefficient.

In case of updating of output values of the unsteady flow model R is dependent on the flow regime. There is a stronger auto-correlation of error with low and medium discharges than in the case of high flows. The calculation of the regression coefficient is usually performed for each class of flow separately. Discharges are divided into several classes based on the statistic data from the measurement stations. The calibration of the AR model usually results in coefficient values ranging from 1, for low waters, to 0.9, for high-water periods, and the value of the regression coefficient decreases linearly with an increase in flow. If no observations are available, the value of coefficient R is assumed to be 0. i.e. the correction of the output is actually not calculated.

2.3. Updating of system state by correction of input data

Good forecast system requires initial calculation system state at time t_0 (time of forecast start) that differs from the real system state as little as possible. It is of crucial importance for a forecast system to recalculate state in recent past, using some of the methods for updating of the system state. The correction of input values is the primary objective in improvement of the system state, what should lead to a better agreement between the calculated and the measured values.

The main goal of updating is the reduction of the difference between the simulated and the measured values in recent past. This is the reason why correction factors are applied at the points of input inflows, providing change in value of that input parameter. The correction factor may vary from one point to another and each system input has its own correction factor.

The key factor that affects optimization result is the objective function. Due to the fact that the simulated values must be simultaneously harmonized with the related measured values in several places, the objective function should account for all these deviations. The deviations of simulated values from the measured ones must be minimized. Bearing in mind the different intensities of the variables in the system, as well as the fact that the same objective function minimizes deviations of different values, the values of the variables within the objective function must be standardized (Kahl and Nachtnebel, 2008). The result of standardization is that all measurement points and all measured variables have the same weight in the objective function.

The most general objective function may be written in the following form:

$$f_i = \sum_{j=1,N} \left[k_{R_i} \left(\frac{\varepsilon_{i,j}^{R}}{R_i} \right)^2 \right] \tag{6}$$

where N is the number of steps, $\varepsilon_{i,j}^{R}$ is difference between the simulated and the measured value at i^{th} observation point in j^{th} step, R_i is the average value at i^{th} observation point in the longer time interval and k_{R_i} is the coefficient of the influence of the deviation on the objective function at i^{th} observation point.

3. Suggested methodology for determination of the up-to-date state in models of open-channel flow

A reliable system of operational hydropower calculations requires the up-to-date system state at time t_0 that represents the start of the simulation with forecasted and planned input series. This is the reason why it is crucial for the system to perform a recalculation by one of the methods for state updating at the time immediately before the forecast start. The presented methods for state updating may be in general case applied to the majority of mathematical models and, thus, to the models of the open-channel flow. However, their application to specific problems or to a class of similar problems requires an appropriate selection of the method and the associated optimization algorithms. In selection of the adequate methods for state updating in models of open-channel flow, one should bear in mind numerous criteria. Above all, one should bear in mind the characteristics of the mathematical model and the final purpose of the model so that the selection of the method would be such that it could fit to the specific features of the given model (the level of non-linearity, the degree of discretization, the required accuracy etc.). Furthermore, it is necessary to systemize and determine all variables that appear as inputs, as well as those computational values that can be compared to the measurements, and their role in the decision-making process based on simulation results. This data should also be systemized according to their reliability, because this can indicate which input values should be corrected, i.e. which weighting coefficients should be assigned to these variables in the objective function.

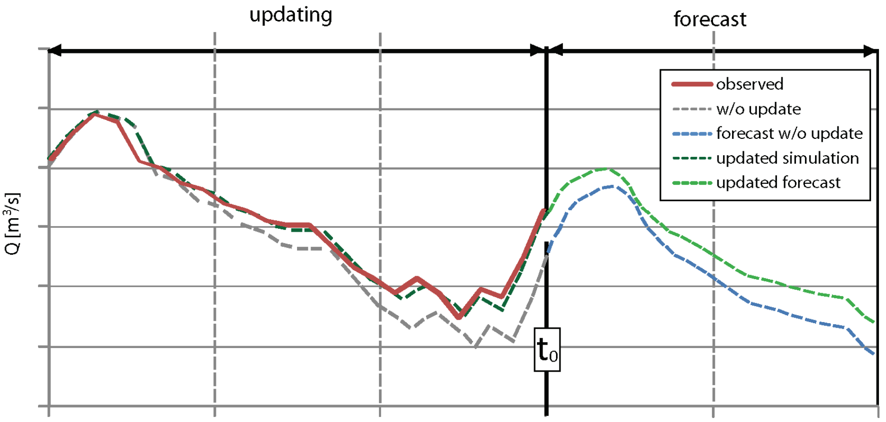

Fig. 1. Updating period and period of forecasted values

Large hydropower systems often have a cascaded structure. Therefore, large oscillations of levels in the storages are not allowed, what requires a very precise coordination of discharges on the power plants. In order to provide sufficiently precise planning of system management for the subject following period, up-to-date system state values at the start of the simulation are needed. For that purpose, it is necessary to develop methods for determination of the up-to-date system state that reflects as close as possible the state of the system determined by measurements.

Since one-dimensional model of the flow in open-channels and storages (with associated power plants) which relies on the numeric integration scheme (finite differences) is considered, it is necessary to select a robust method for determination of the up-to-date model state. This is particularly important because in each iteration of the numeric algorithm, due to the presence of active hydropower objects (dams with a power plant and a spillway), which operation depends on the current values of headwater and tailwater water levels, the correction of the outflow through these objects is performed. Using these corrected values, entire procedure of solving of the system of equations is repeated until the convergence criterion is satisfied. In addition to the convergence criterion, in the process of solving system of non-linear equations it is also necessary to fulfill the demand related to electricity generation. This formulation of the numeric algorithm requires the application of method that is as general as possible and which to the lowest possible extent depends on integration technique.

The flow in open channels and storages located in large scale river systems is predominantly dependent on the discharge in the associated rivers. In the historic period in which model is updated (i.e. few last days), availability of the recorded inflows into the system that can be used without any serious analysis and processing, can be expected. Hence, they can contain certain deviation from the real inflows. It is considered that the most accurate measurements in the hydropower systems are measurements related to electricity generation, as well as other values that can be directly related to electricity generation. Accordingly, the discharges through the units can be considered sufficiently reliable in terms of their use in hydraulic calculations. However, certain discharges that occur periodically, such as spilling, are not measured directly, but they are determined approximately on the basis of other values or the water balance in the system (the discharges determined in this manner may often significantly differ from the discharges that occur during actual system exploitation). Therefore, for the purpose of comparison of the mathematical model with the observed physical system, water levels that can be very accurately measured in many points in the flow and in the storage are used.

From the considerations mentioned above it can be concluded that for the analyzed class of models in open channel and storage flows it is most suitable to apply the procedure of updating of the system state by correction of input data. The main goal of application of this procedure is the reduction of the difference between the simulated and the measured water levels and discharges during the period immediately before the simulation period. This is the reason why correction factors are applied in the points where discharge is assigned (input inflows, spilling and similar), what leads to the change in value of that input parameter.

Bearing in mind that the assigned discharges (inflows, spilling and similar) are known for a certain number of discrete time steps during the updating period and that the number of steps can be rather large (depending on period length and the time step size) it is clear that it is not realistic to look for the optimum discharge correction in each time step t (see Equation(6)). This is the reason why coefficients ${}^{t}k_{i}$ are varied in a limited number of moments in time

$\left({}^{t_1}k_i, {}^{t_2}k_i, ..., {}^{t_M}k_i\right)$, and for other moments in time their values are determined by linear interpolation, as shown in Figure 2.

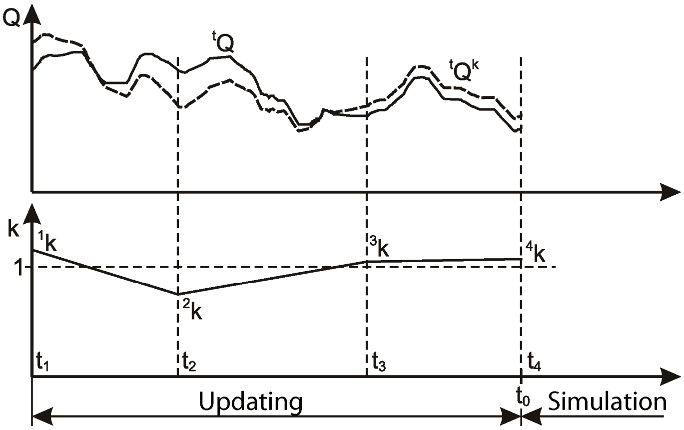

Fig. 2. Interpolation of correction factors

In this manner the set of input parameters to be corrected is reduced to $N \times M$ discharges ${}^{j}Q_i \equiv {}^{t_j}Q_i$, $(i = 1..N,\ j = 1..M)$, i.e., to $N \times M$ correction factors ${}^{j}k_i \equiv {}^{t_j}k_i$. Optimization algorithms are used for determination of the coefficient set that provides model state closest to the real system.

In general case the input discharges, measured in time t may be denoted with ${}^{t}Q_i$, $(i = 1..N)$, where N represents the number of system inputs. Bearing in mind that the difference between the input inflows in different rivers and the discharges over the spillways may amount to several orders of magnitude, it is clear that the discharge correction $\Delta {}^{t}Q_i$ must be proportional to the real discharge ${}^{t}Q_i$. To preserve the proportionality of the real and corrected discharges, an increase, i.e. decrease, of observed discharges k_i in percents was selected as the parameter of correction by optimization algorithm; hence, the corrected discharge is as follows:

$$ {}^{t}Q_i^{k} = {}^{t}k_i \, {}^{t}Q_i \tag{7} $$

where ${}^{t}k_i$ may have values between $k_i^{\min}$ and $k_i^{\max}$.

In order to make the use of these algorithms possible it is necessary to mathematically define the relation between the real system and the mathematical model. In case of the recommend methodology, the measure of compliance is the time-weighted mean absolute error or water level on several typical profiles, where the measured values of water level are known for the entire updating period. The mean error of the absolute water level on L profiles at the time t may be written in the form:

$$ {}^{t}E = \sum_{l=1}^{L} {}^{t}e_l \tag{8} $$

where ${}^{t}e_{l}$ is the absolute value of deviation of the calculated from the measured water level. As acceptable solution cannot be accepted the solution that provides minimum error only at the end of the updating period, but it is necessary to look for a solution that provides for the minimum deviation during the entire period. On the other hand, bearing in mind that the goal of updating is the correct initial system state to be used in future simulation, the errors must be weighted, so that the ones at the start of simulation have the lowest and the ones at its end the biggest influence on the value of the objective function.

This is the reason why the solution of the optimization problem with the following form is proposed:

$$\min \sum_{t} p(t)\, {}^{t}E \tag{9}$$

where $p(t) = t / T$ has been selected as the weighting function, where T is the total updating period. This is the way to perform a linear increase in impact of certain deviations on the objective function from the start to the end of this period.

Finally, one can say that the proposed methodology of determination of the up-to-date state in the models of flow in open channels consists of solving of the problem of determination of the optimum set of discharge correction factors (inflow and spilling), i.e. the maximization of the objective function. The corrected discharges represent input series that at the end of the updating period result in the computational state of the mathematical model that is close to real system state. Depending on the complexity of the optimization problem (the number of factors, non-linearity of the model, the length of the updating period and similar), it is necessary to select the corresponding optimization algorithms that would be efficient in the operational application of the systems developed upon the proposed methodology.

4. Applied optimization algorithms

Genetic algorithms have been proposed for solving the problem of determination of the up-to-date state in the models of open-channel flow. Genetic algorithms are heuristic methods of optimization that imitates the natural evolution process. The analogy of evolution, as a natural process, and genetic algorithm, as an optimization method, is reflected in the selection process and genetic operators. The selection mechanism applied to some species of living creatures in the evolution process is comprised of the environment and the natural conditions. In genetic algorithms the key to the selection is the objective function that appropriately represents the problem to be solved. Namely, the rule of the nature is that the individual that is best adapted to the environment and conditions of living has the greatest probability of surviving and breeding, and thus of transferring of its genetic materials to the offspring. For the genetic algorithm one solution is one individual. The selection is used to choose good species and the combination of their genetic material creates a new generation of species. Such a cycle of selection, reproduction and manipulation of genetic material of the species is repeated until the condition of termination of the evolution process is achieved. Figure 3 shows the scheme of genetic algorithm functioning.

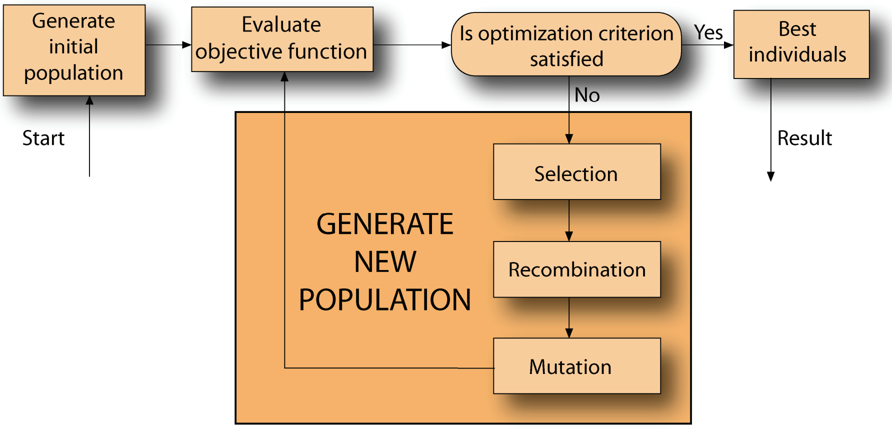

Fig. 3. The structure of the evolution algorithm with one population (Milivojević, 2008).

In order to implement genetic algorithms within a certain problem it is necessary to define several standard steps: the method of coding/decoding, the fitness function and the algorithm termination criteria. Each of these steps will be discussed below.

4.1. Coding method

The process of translation of the real solution to the problem into the coded form is one of the most important procedures in the implementation of genetic algorithms, because the efficiency of the algorithm depends to a great extent on the appropriate selection of coding. In present paper the procedure of binary coding of the solution was used, which is probably the simplest one in terms of implementation. The elementary approach to such a solution to the problem consists in writing of the real number x in the form of series of bits that form one chromosome, i.e. in binary coding. The real number x is in this manner represented with the accuracy that depends on the number of used bits n. Decoding, or translation of the binary coding into a real number is performed according to the simple formula:

$$x = a + \frac{\sum_{i=0}^{n-1} c_i 2^i}{2^n - 1}(b-a) \tag{10}$$

where a and b are the boundaries of the search area and c_i represents the bit with the weights of 2^i (Milivojević, 2008).

Binary coding of normalized correction factors ${}^j r_i = R\left({}^j k_i, k_i^{\min}, k_i^{\max}\right)$ is performed by translating of the value of each coefficient ${}^j r_i$ into the binary coding with a certain number of bits, called the *gene*. It is worth mentioning that the number of bits defines the accuracy of the conversion into the binary form. The complete genetic code of one solution, the *chromosome*, results from the joining of the binary coding of the coefficients ${}^j r_i$, as shown in Figure 4.

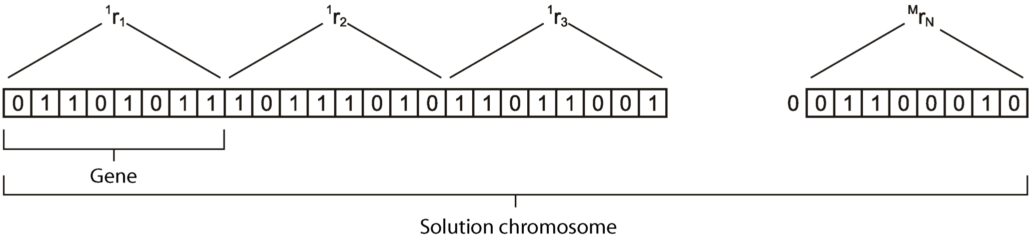

Fig. 4. Binary coding of the solution

As already mentioned, in case of correction of input variables in open-channel flows, the coefficients ^tk_i are varied in a limited number of moments in time ($^{t_1}k_i, {}^{t_2}k_i, ..., {}^{t_M}k_i$), and then, the coefficient values for the other moments in time are obtained by linear interpolation, as shown in Figure 2.

In order to avoid solution search outside the range defined by the condition $k_i^{\min} \le {}^jk_i \le k_i^{\max}$ it is necessary to define the function $R\left(k, k^{\min}, k^{\max}\right)$ that unambiguously maps the set of values of the coefficient k into the set of the normalized coefficients *r*, so that the condition $0 \le r \le 1$ holds true. Function R must be of such nature that there exists its inverse function $R^{-1}\left(r\right)$ that maps the normalized values of the correction factors into the set of their real values.

4.2. Fitness function

In order to perform the selection of species, it is necessary to determine the fitness of each corresponding solution. Therefore, it is necessary to define mathematically the notion of the congruence between the actual system and the mathematical model, because the model with a better congruence is of better quality, i.e. it has better fitness. In case of the proposed methodology, as the measure of congruence is used the reciprocal time-weighted mean absolute error of the water level on several typical profiles presented by the expression (8), the proposed fitness function will have the form as follows:

$$F = \frac{1}{\sum_t p\left(t\right) {}^tE} \tag{11}$$

where the selected weighting function is $p\left(t\right) = t / T$, and *T* is total updating period.

4.3. Description of the procedure

The initial state during updating is the system state obtained by the previous calculation based on historic data at the initial time of updating. Initial population will consist of several sets of randomly selected correction factors ^jk_i within the predefined limitations, based on which the corrected system inflows $^jQ_i^k$ are to be calculated. The application of these inflows provides unsteady calculation for the predefined updating period. After the calculation, the deviations of water levels on control profiles from the measured data are calculated and based on that, the values of the objective function *F* are also calculated. If the optimization criterion is achieved, the obtained solution is declared to be the optimum one, what terminates the optimization procedure.

However, if the optimization criterion is not achieved, the selection among the obtained solutions is performed according to one of the methods described in (Milivojević, 2008). All selection methods require previous quality estimation of all solutions based on the value of objective function. Based on that, only those solutions whose quality meets the predefined rule are selected as the parents of the new population.

After the end of the selection process, the generation of the new population is performed by combining the genetic codes of the solutions which passed the selection procedure. In case of the present model, the obtained correction factors are normalized by the function *R,* then translated by binary coding into the genes and, finally, into solution chromosomes. New species that make the new population, are created by the crossover of high-quality solution chromosomes. In order to avoid the identification of local maxima of the objective function, the mutation of the resulting genetic codes is introduced into the process of creation of a new population. This provides for scattering of a certain number of solutions beyond the local maxima that the majority of populations gravitate to.

After the new populations have been created, the entire procedure is repeated iteratively until a satisfactory solution is achieved, or until a certain number of iterations have been performed. After that, the solution can be declared acceptable due to the lack of solutions with the required accuracy.

5. Application of the methodology for determination of the up-to-date state of the “Iron Gate” system

5.1. Description of the system and the model of the “Iron Gate” system

The “Iron Gate” system is the hydropower and navigation system that consists of the two hydropower plants (“Iron Gate 1” and “Iron Gate 2") with hydro-technical structures, associated storages and riparian areas (Figure 5). The “Iron Gate” system exerts a large influence on the level of Danube River along the course of more than 300 km. The available hydropower potential is divided into parts that belong to the Serbian and Romanian sides, according to the mutually approved procedures. In Serbia a simulation model for hydropower calculations and management of the exploitation of the of hydropower plants “Iron Gate” was developed for the purpose of the efficient use of the Danube River hydropower potential and meeting the demands of Serbian and Romanian electricity generation and transmission systems with observance of the series of limitations on the control profiles on Danube River, defined in the state-level documents. The detailed description of the “Iron Gate” system and simulation model is given in paper (Divac et al. 2009). The setup of the model of the “Iron Gate” system includes, among the others, the division of the river course into the sub-courses along which the flow process has been described by a hydraulic model which is based on Saint-Venant equations. Within the standard hydraulic module, the advanced calculation formulations provide for the simulation of the flow through various objects (internal boundary conditions), such as power plants, spillways, gates and similar. For the solution of the problem of the unsteady flow in open channels, the present equations were used to define the matrix forms of the problem. Solving of these forms is based on the application of the finite differences method (Grujović et al. 2009).

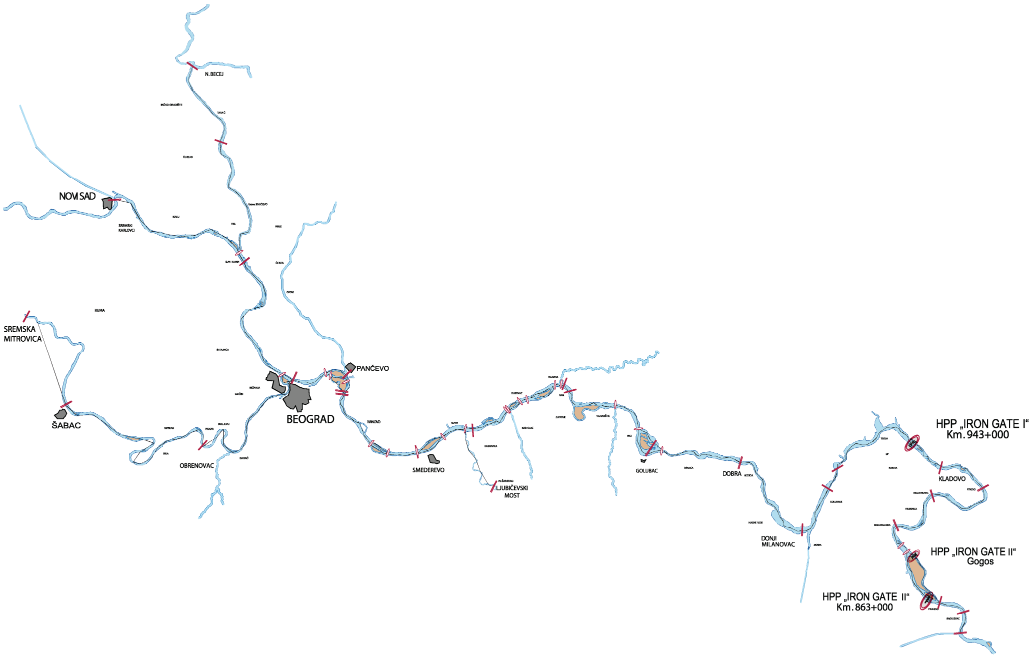

Fig. 5. Hydrographic network with the objects of the “Iron Gate” system

5.2. Role of the up-to-date state of the “Iron Gate” system and its influence on operational management

According to the Rule Book of organization and operation of Joint Energy Dispatching Service, the exploitation of the “Iron Gate” system requires the preparation of the daily plan of exploitation for the current and the following days. The daily plan of exploitation is then harmonized by the Romanian and Serbian sides and afterwards applied. System utilization is performed according to the corrected and harmonized daily plan of operation for the given day. The corrected and harmonized daily plan of operation determines the method of exploitation of the system during the current day. The current day is the period between 6 AM of the calendar day and 6 AM of the next calendar day CET.

The preparation of the daily plan of exploitation under all conditions (when, according to the forecast, the inflows are expected that can be released through the hydropower units and under the conditions when the forecasted inflows exceed the capacity of units) is performed according to several indicators. Some of the main indicators are the water level in the storage at 6 AM on the current calendar day, forecasted mean daily inflow into the storage of the “Iron Gate 1” system for the current and next 4-6 days, global daily priorities defined both for Romanian and Serbian sides, observance of all limitations on all control profiles foreseen by the Rule Book and similar.

The daily plan harmonizes (between the system users both on Serbian and Romanian sides) the elements such as the mean daily level of Danube River at the Nera River confluence, mean daily outflow from the “Iron Gate 1” and “Iron Gate 2” systems, volume of spilled water expressed in the form of equivalent energy and similar.

"Iron Gate” simulation model is very useful tool to the dispatchers. It can be used in design, testing and correction of the daily plans of electricity generation. For the simulation model to give useable results, it is also very important to have good-quality input data and to have up-to-date state at the start of each day. Up-to-date system state means that initial conditions of the simulation model are harmonized with the latest available data measured in the system (real-time data). The everyday use of the “Iron Gate” simulation model includes the two following steps:

- Adjusting the simulation model to the current up-to-date computational state using the new updating tools and the existing previous computational state (i.e., 3 days old state) and
- Performing the simulation.

Determination of the current up-to-date computational state within the simulation model is performed according to the same method, regardless of the simulation regime, i.e. of the purpose of application of the simulation model. This step is a necessary precondition for the application of the simulation model in terms of plan testing, accuracy of event reconstruction and similar.

5.3. Analysis of available data

In the course of verification of the mathematical model the data on values that change in time (time series), obtained upon measurements performed by the Investor or Republic Hydrometeorology Service of Serbia (RHMS), is used. It is necessary to collect data in different time discretizations, i.e. in five-minute, fifteen-minute, hourly and daily discretizations. Further, an overview of the time series classified according to the value being measured and the location where this value is measured is presented below.

5.3.1. Inflows into system

Mean daily discharges are issued by RHMS on the following profiles and they also represent the inflows into the storage “Iron Gate 1”: Bogojevo (River Danube), Senta (River Tisa), Sremska Mitrovica (River Sava), Beli Brod (River Kolubara), Jaša Tomić (River Tamiš), Ljubičevski bridge (River Velika Morava), Veliko Selo (River Mlava), Kusić (River Nera) and Kusiće (River Pek).

These discharges are determined according to the measured values of level and discharge curves. For the discharge values to be acceptable, it is necessary to regularly update the discharge curves, because the riverbed flow capacity changes in time due to sediment deposits or erosion.

Another problem is caused by the intermittent interruptions in measurement of water levels of small rivers: Kolubara, Tamiš, Velika Morava, Nera, Mlava, Pek and Porečka. For the needs of the “Iron Gate” model the missing data was filled in; however, regardless of the correctness of the method for filling-in of data, the errors in input inflows are inevitable due to the lack of original data.

5.3.2. Powers and discharges through the HPP units

The realized powers are recorded for all units both on the Serbian and Romanian sides of the “Iron Gate 1” HPP (6+6 units) and the “Iron Gate 2” HPP (10+10 units). Data is recorded in ten-second, five-minute and hourly discretization. The realized powers in the system “Iron Gate” are the variables that are measured with the greatest accuracy and that can be considered the most reliable. The direct measurement of the discharge through the turbines in the five-minute discretization exists only on the “Iron Gate 1” HPP units, both on Serbian and Romanian sides, while the discharge through the “Iron Gate 2” HPP units is calculated by the means of the value of specific consumption, the electricity generation during the current hour and mean gross head during the current hour, what results in certain inaccuracy (because the inside-hour HPP operational regime is not accounted for, i.e. the unit efficiency, as well as the degree of obstruction of trash racks on water intakes for the units). These hourly values of discharge as derived values (i.e. the values that were not directly measured) exist for all units in the "Iron Gate 1" HPP and the "Iron Gate 2" HPP.

5.3.3. Degree of opening of spillway gates

Spilling over the dams is not an everyday event. Spilling over the "Iron Gate 1" HPP and "Iron Gate 2" HPP dams takes place mainly during the spring season. The degree of opening of the gates on each spillway field is recorded with a variable time step. The measurements are not performed automatically, but the data is recorded manually (the start and the end of the spilling and the degree of the gate opening are recorded). Illogical values, i.e. accidental errors occur in data due to the factor of human error and the lack of control. The balancing analyses have indicated that there is an extreme lack of accordance between the volume of water that flows into the "Iron Gate 2" HPP lake and the volumes of water that flow out of it, particularly during the spilling periods; hence, one can say that there are serious indications that the existing spilling curves are not adequate.

5.3.4. Water levels on automatic water level recorder stations

The data related to the current water levels is measured on the automatic water level recorder stations in storages, on dam profiles and before and after units. Automatic water level recorder stations are located in: Pančevo, Ram, Bazjaš, Golubac, Dobra, Donji Milanovac, on "Iron Gate 1" dam, in Kladovo, Brza Palanka, on "Gogoš" dam, on "Iron Gate 2" dam, on Timok confluence, in Turn Severin (Dubova) and Pristol. The measured values are archived in ten-second, five-minute and the hourly discretization. The control of the measured values can be performed at the locations with multiple measurement sources (for example, in Ram, i.e., on the River Nera confluence, the measurements are comparable with RHMS hydrological station Banatska Palanka). Accidental errors on measurement stations are easily eliminated, while systematic errors are difficult to identify. In addition to mentioned errors, the interruptions in the operation of measurement stations occur.

Headwater levels of the "Iron Gate 1" HPP are measured before the water intake for each unit and in another the upstream points, what results in 14 measurement stations in total. The tailwater levels are measured in the niches of all draft-tube gates and in two more points along the flow, which also results in 14 measurement stations in total. There are occasionally major differences between the individual measurements (the difference can amount even up to several tens of cm), which is the consequence of either accidental or systemic errors of the level gauges. The "Iron Gate 2" HPP headwater and tailwater levels are separately measured both on the Serbian and Romanian sides. In addition to these levels, the "Gogoš" HPP headwater and tailwater levels are also measured. As on the other automatic water level recorder stations the measured values are archived in the ten-second, five-minute and hourly discretization.

6. Example of the application of the proposed methodology

The proposed methodology was used for the check of the daily plans for the period from June 25th, 2006 till June 28th, 2006.

At the start of the given period, i.e. on June 25th, an up-to-date state of the model is available, as well as current daily production plan and inflow forecasts. By inputting daily production plan and inflow forecasts into the model, the dispatcher is provided with predicted model states for the current day (shown in Figure 6 as blue line). This way the dispatcher is able to review daily production plan, i.e. to check results against constraints and whether the plan is achievable. Upon reviewing the daily production plan, the dispatcher can begin with its realization following the guidelines for optimal unit commitment provided by the simulation model.

Since the daily plan cannot account for the variability of the demand in the distribution network, and due to the lack of the knowledge regarding the exact inflow into the storage, the realized water level in the storage at the end of the work day will not be equal to the expected one (the actual values of water levels are shown in Figure 6 as red line). The difference in predicted and realized water levels at the end of current day is obvious, and this difference is emphasized on Figure 6. Should next daily plan check nave been performed with current computational state, the model would continue to increase the attained difference and provide false energy production predictions.

The state updating module performs state update of simulation model using measured values for June 25th and realized production plan for same day. The module is based on optimization algorithm which at the beginning of next production day performs inflow correction using realized production values and brings model to up-to-date state. The result of this process is new up-to-date state of the model at the beginning of production day June 26th, and previous reconstructed states are shown in Figure 6 as green dashed line.

This procedure is performed daily and it represents the foundation of the operative application of the simulation model. The procedure of model state updating is shown in Figure 6.

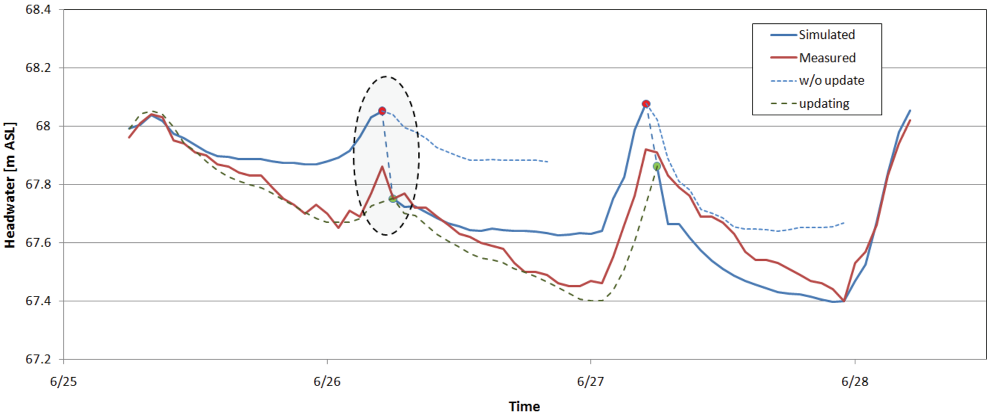

Fig. 6. Procedure for updating of model state illustrated by the example of the "Iron Gate 1" HPP headwater water level

For the updating time on June 26th, 2006 at 6 AM (as marked in Figure 6), the Figures 7, 8, 9, and 10 show the comparison between the measured and the simulated values of longitudinal level slope and water levels on the control profiles, with and without updating.

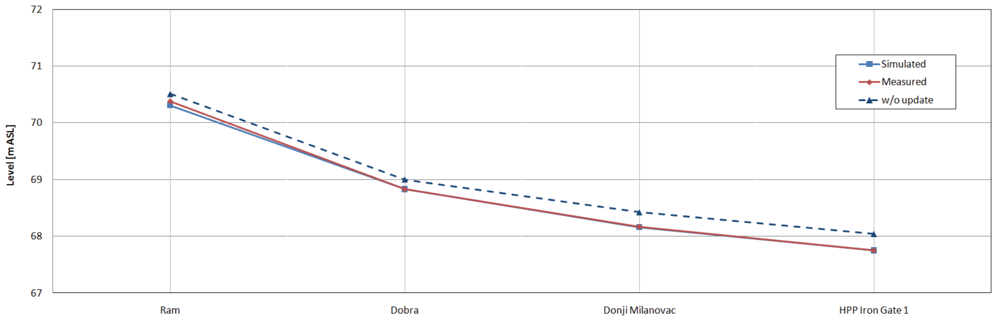

Fig. 7. Comparison between the actual and the computational water levels on the profiles with automatic level gauging

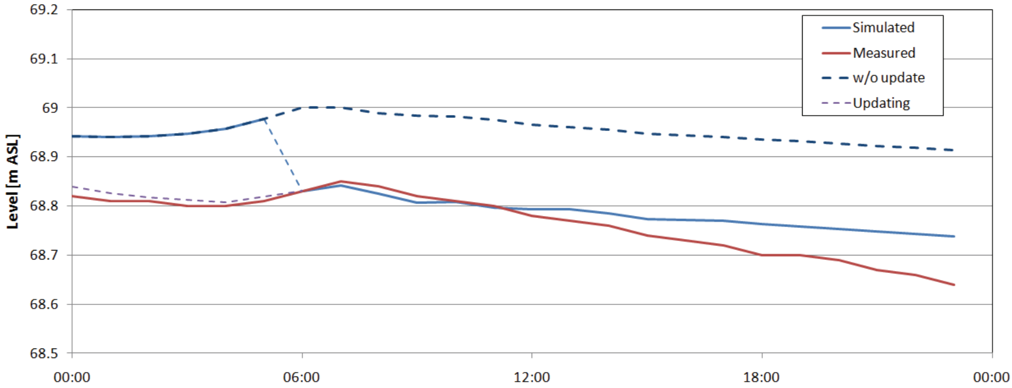

Fig. 8. State updating on "Dobra" Profile

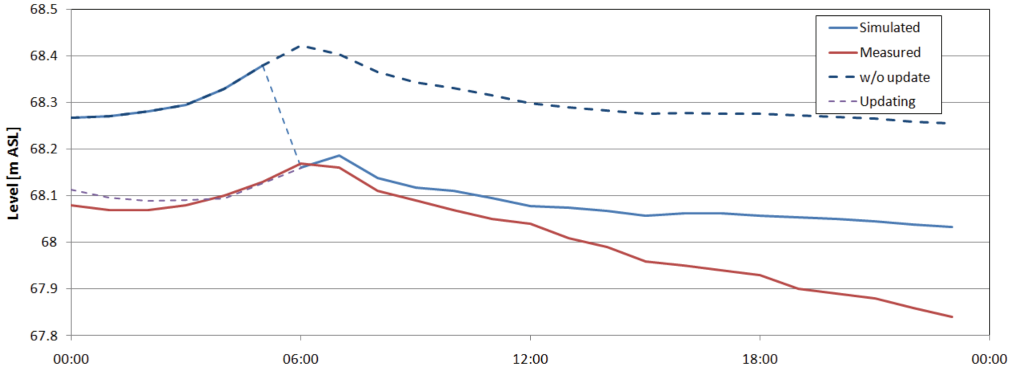

Fig. 9. State updating on "Donji Milanovac" profile

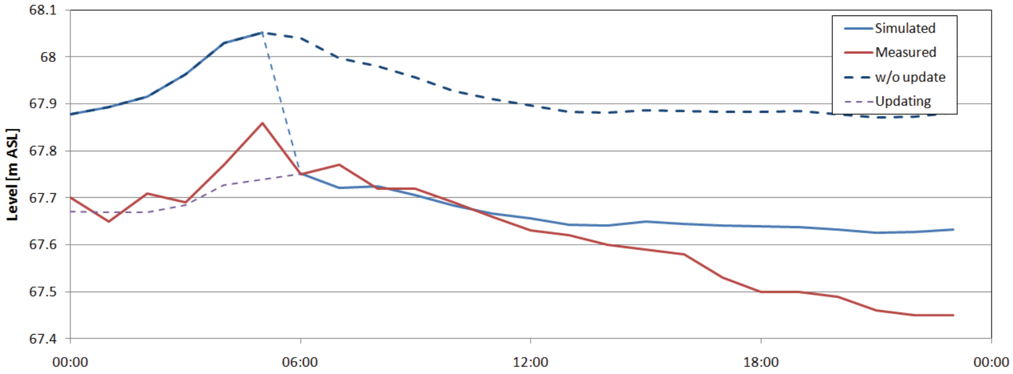

Fig. 10. State updating on "Iron Gate 1" HPP headwater profile

The diagrams above show that the application of the presented method provides for a significant reduction of the deviation of the simulated state values from the measured ones. The up-to-date system state obtained in this manner significantly reduces the error during the system forecast period. It is worth noticing that the correction of the input inflows considerably influences the water level in the "Iron Gate 1" storage. Bearing in mind the model scale, the forecasted inflows into the storage represent less reliable input data; hence, it is justified to perform their correction in order to obtain the up-to-date model state.

7. Conclusions

The module for updating of the system state by the method of input data correction represents an irreplaceable component in the systems that rely on the operational use of simulation models of unsteady open-channel flows with hydropower objects. One of the shortcomings of this method may be the problem of determination of correction factors in the case of numerous system inputs. Since, due to their complexity, these models usually cannot be described by the mathematical formulae in closed form, it is not possible to define the procedures which would directly lead to the optimum solution. In order to overcome this problem, genetic algorithms were selected for the variation of correction factors, where the optimum solution search is based on the fundamental evolution laws. By selecting a suitable objective function, coding method, selection and mutation methods, genetic algorithms can also be quite successfully applied to the problems of determination of the optimum correction factors for input values. An example of the mathematical model for the hydropower and system management of the "Iron Gate" system of hydropower plants shows that the correction of input values by genetic algorithms may result in a satisfactory convergence of the simulated values towards the real values in the model updating period. The up-to-date state at the start of simulation obtained in this manner results in a significantly better forecast of system behavior as compared to the forecasts obtained without the correction of the input values; this confirms the efficiency of the presented methodology. In times of extremely fast development of parallel and multi-core computers, it is apparent that the future application of genetic algorithms in determination of the up-to-date state of hydrologic systems will gain additional importance in simulations of flows in open channels and storages.

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