Data assimilation for operational reservoir management on the Danube river

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***Abstract*— In this paper, a novel data assimilation method for improved management of open channel hydraulic system is presented. As opposed to standard data assimilation methods, which either require linearization of the used numeric simulation model or time-consuming data analyzing steps, the proposed method involves the use of "full" free surface flow equations and simple data correction step based on the proportional-integral-derivative (PID controller) theory. The novel method is verified in the case of river Danube and reservoir management of the Iron Gate I and Iron Gate II power plants. As described in this paper, the presented data assimilation methodology is particularly suitable in the operational management of systems with high inertia, such as reservoirs on the Danube River.**

I. INTRODUCTION

Water resource management requires accurate and timely knowledge of the states of available water resources. In operational management, for given forecast of input variables (inflows and meteo data), complex nonlinear 1D simulation model of river flow and power plant operation is used to optimize the energy production while satisfying the given constraints (water levels and needs of other water users). The imperative is to use the up-to-date simulation model hence it has to be constantly updated with current river states (levels) and known flows (in power plants).

Data assimilation is the technique to keep the simulation model up-to-date. It is the process where, for each time step, the "most probable" state of the system is computed based on real-time measured variables (with their intrinsic uncertainty assessed by data quality control), and results of simulation model (assimilated to the previous time stamp). During assimilation, only system state variables are updated while calibrated model parameters are kept constant.

Some well-known data assimilation methods are Kalman Filter, particle tracking and data-variation [1]. To apply the most used Kalman filter, the river flow equations requires linearization [2] which opens the new problems and uncertainties. Kalman Filter can be used also with nonlinear models (known as Extended Kalman Filter) but in each time step the time consuming calculation of uncertainty is needed (mostly done using Monte-Carlo method) which prevents the usage of this method in every-day operational usage. In some papers [3] the Extended Kalman Filter is compared with particle tracking method, with conclusions that both methods are applicable for nonlinear river models, but since both use Monte-Carlo method in each time step, they are too slow for regular hourly assimilation purposes.

We present in this paper the feasible data assimilation technique for real-time update of model's hydraulic states based on PID (Proportional-integral-derivative) controller theory. At every computational step, the controller with proportional and integral terms (PI controller) updates the water levels by tuning water discharge along the river. Such kind of assimilation is possible since total upstream volume of Danube section upstream of HPP Iron Gate 1 is large and will filter out the PI controller's incompetency to adopt to nonlinearity of system.

Two case studies shown that the model is applicable on long and large rivers with high inertia, such is the Danube River's reach from Novi Sad to downstream the Iron Gate II. The proposed method is fast enough to be used on regular daily basis, improving the optimization of hydropower production on the Danube river.

II. METHODS

The 1D model of the Danube river, between Novi Sad and Iron Gates 1 and 2 HPP, is formulated in the FEQ (*Full EQuation Model*) solver [4] and calibrated based on historical hydrologic data series. The level and flow rate at Iron Gate 1, as downstream condition are considered as quantities with least uncertainty, while input flowrates are assumed to be with high margin of error. Data assimilation is applied on several characteristic sections along the river, where water levels are measured at hydrologic stations. Using PI controller's simulation in FEQ model, the measured water levels are applied to correct the model's state (water level). Applied methodology assumes that simulation model in FEQ is well calibrated so induced state changes by assimilations are small.

In proposed method, dummy tributaries are added at locations where measurements of water levels take place. At every computational time step, discharge through additional (dummy) river reach is corrected. This correction is actualy sum of proportional and integral terms of PI controller. Both terms are calculated using differences between measured (accurate) values of the water level and the values calculated using the hydraulic model. To calculate an increment (correction) of discharge through the dummy reach, the following formula is used:

$$\Delta Q\,(t) = k_p \cdot e(t) + k_i \int_0^t e(t')dt' \qquad (1)$$

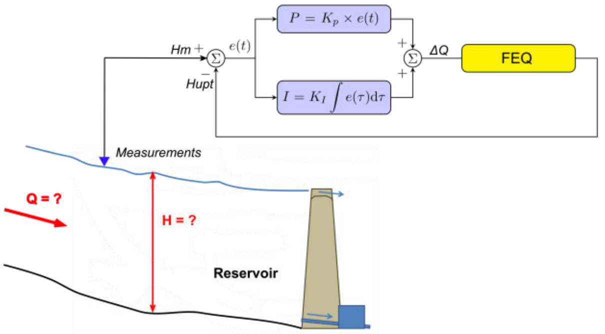

Figure 1. A block diagram of PI controller applied to correct system's state in FEQ model. *Hm* is measured water level ("set point"), and *Hupt* is water level calculated (updated) using FEQ model.

where $e(t)$ is error in water levels (difference between measured and predicted levels), k_p is coefficient for proportional term and k_i is coefficient for integral term. The procedure of correction is depicted in Fig. 1.

III. Results & Discussion

The capability of proposed method was tested on two case study [5]. An application of the assimilation method for 1D model for river Danube between Iron Gate 1 hydropower plant and Iron Gate 2 hydropower plant during nonstationary flow in turbines at both river reach ends was analyzed in first case study. The correction of model states during flood waves propagation on a portion of Danube river between Novi Sad and Iron Gate 1 were analysed in second case study.

In each case study, three simulations were done. The first simulation was run to generate model states that were considered as accurate ("true") states (levels and discharges). Random errors in input flowrates were added to the second simulation data. White noises were introduced to simulate "false" flowrates prediction at hydro power plants and hydrological stations. Using the same (false) input data, the assimilation technique were tested running third simulation to conclude weather the proposed method is capable to correct false states obtained from the second simulation.

The tuning of discharges, based on PI controller theory, were applied at every computational time step of hydraulic model in both case studies (Δt = 15 min). Both coefficients of equation xx, the proportional and the integral gain, were held constant during assimilation process. The proportional gain (k_p) was set to 1000 m^2/s and the integral gain (k_p) was set to 1 m^2/s^2.

Satellite image of river reach under consideration in the first case study are shown in Fig. 2. There are two downstream ends, first one at location of Iron Gate 2 hydropower plant, and second one at location of hydropower plant Gogos. The upstream end of the reach corresponds to the location of Iron Gate 1 power plant. It is assumed that "accurate" levels measurements are available near the town of Kladovo. At same location, dummy reach was added to the 1D model as tributary of the Danube in order to apply proposed method.

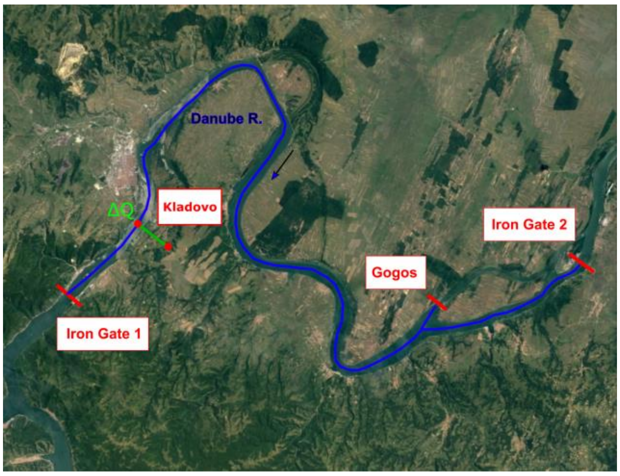

Figure 2. Portion of the Danube river between Iron Gate 1 and Iron Gate 2 hydropower plants. Green line represents the dummy reach added to correct discharges and water levels.

At locations of both Iron Gate 1 HP and Iron Gate 2 HP, same real hydrographs were used as boundary conditions (Fig. 3). These hydrographs represent predicted discharges through turbines of hydropower plants. Zero discharge was used as boundary condition at location of Gogos hydropower plant.

The method was assesed through the comparison of the computed water levels during the three simulations at location where water levels are assumed to be measured, Fig. 4. By visual evaluation of the results, it can be concluded that proposed method is capable to correct water levels in conditons of highly variable flow rates induced by hydropower plants operation.

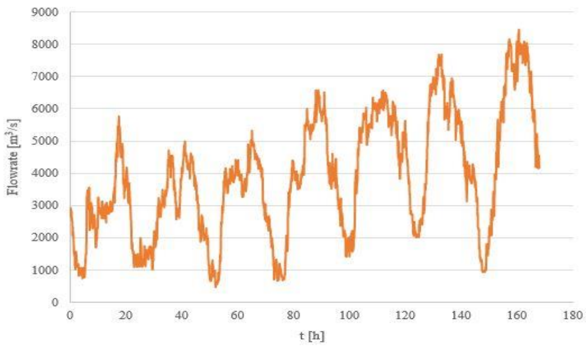

Figure 3. The discharges through hydropower plants

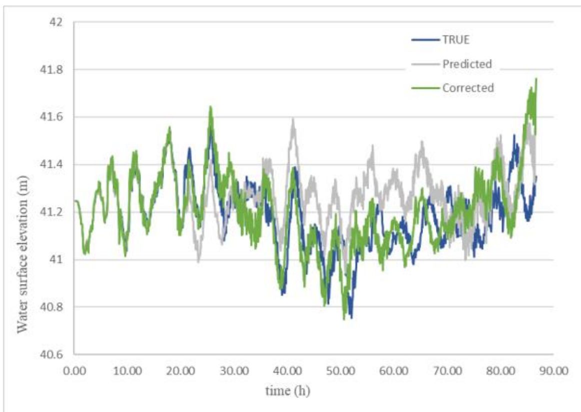

Figure 4. Water levels calculated at location near the town of Kladovo

In the second case study, application of two dummy reach at same time was tested. Satellite image of computational domain in the second case study are shown in Fig. 5. In contrast to first case study, there are two upstream ends and one downstrem end at the location of Iron Gate 1. The upstream ends correspond to locations of hydrological stations, Novi Sad (the station on the Danube river) and Sremska Mitrovica (the station on the Sava river). Flow rates are predicting with high margin of error at both hydrological stations. Two dummy reaches were added at locations of hydrological stations that are used for water levels measurements (water levels are measured with low margin of error). The first one dischargingig into the Danube at the location of hydrological station Zemun and the second one flows into the Danube at the location of hydrological station Pančevo. Therefore, two dummy reaches had been simultaneously used for the tuning of discharges.

In order to run three types of simulations performed in the first case study, two groups of inflow hydrographs were used as upstream boundary conditions, Figs. 6 and 7. The first one is considered as accurate and was used to generate "true" model state (the first simulation). The second one was created by introducing errors in inflows and was used during the second simulation. It was assumed that flow rates are underpredicted in the first part of simulated time period and overpredicted in the second part. The same hydrograph shown in Fig. 3 was used as downstream boundary condition.

Figs. 8, 9 and 10 present comparison of water levels obtained during the three simulations at locations where dummy reach was added and one location downstream from the dummy reaches (near town of Smederevo), while the comparison of calculated flow rates at same location downstream from dummy reaches are presented in Fig. 11 All figures prove that model states are well corrected using disharge correction method proposed in this paper. Additionally, it can be concluded that dummy reaches are not mutually interfering. This can be explained by system high inertia.

Figure 5. Portion of the Danube river between Novi Sad and Iron Gate 1 hydropower plant. Green lines represent dummy reaches added to correct discharges and water levels.

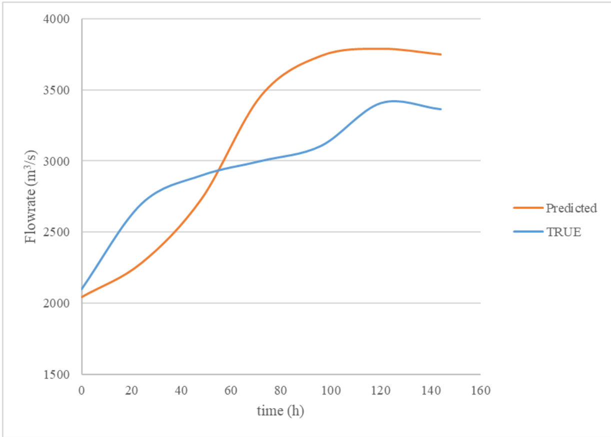

Figure 6. Hydrographs used as boundary conditions at location of Novi Sad hydrological station.

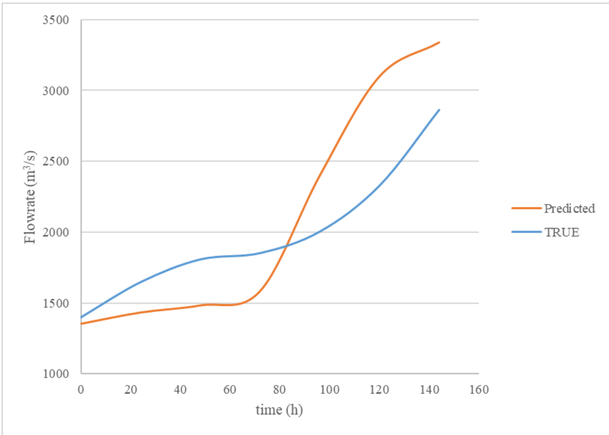

Figure 7. Hydrographs used as boundary conditions at location of Sremska Mitrovica hydrological station.

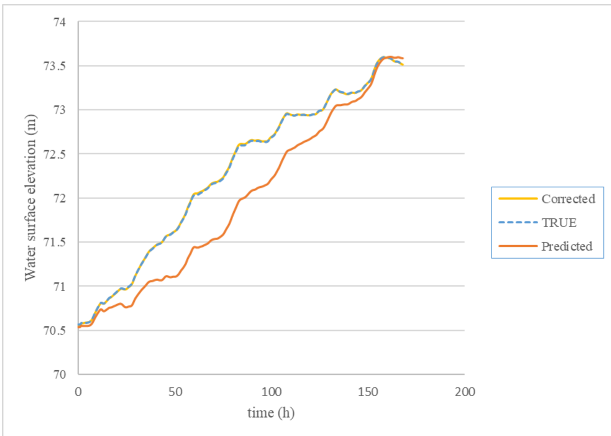

Figure 8. The Comparison between "Corrected" (yellow line), "True" (dashed line) and "Predicted" (red line) water levels at location of Zemun hydrological station.

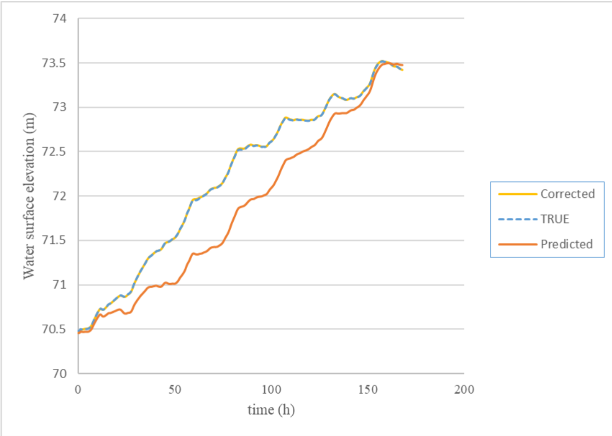

Figure 9. The Comparison between “Corrected” (yellow line), “True” (dashed line) and “Predicted” (red line) water levels at location of Pančevo hydrological station.

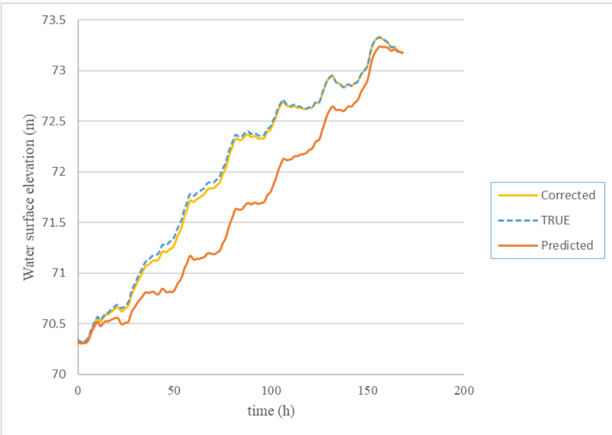

Figure 10. The Comparison between “Corrected” (yellow line), “True” (dashed line) and “Predicted” (red line) water levels at location near the town of Smederevo.

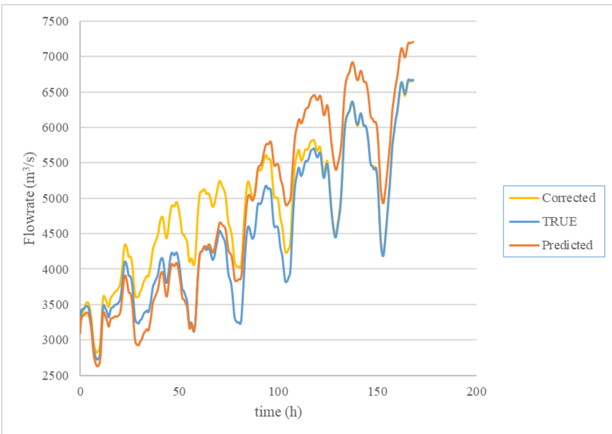

Figure 11. The Comparison between “Corrected” (yellow line), “True” (dashed line) and “Predicted” (red line) water disharges at location near the town of Smederevo.

IV. CONCLUSION

The main goal of the presented study was to present novel assimilation method for river flow, non-linear simulation models. We demonstrate that PID controller theory can be applied as robust computational technique to keep simulation model up-to-date. The proposed method requires 1D river flow model to be extended by adding additional- dummy river reaches. The proportional and integral gains of PID controller were used to control discharges through dummy reaches and consequently through the whole computational domain. The method is verified in two case studies that deals with different river’s flow scenarios for the river Danube reach between Novi Sad and Iron Gate 2. It was shown that more than one dummy reaches can be used without affecting each other.

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