NEW HYDROMODEL FOR MANAGING OPERATION AT THE GABČÍKOVO HYDRO PLANT

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Due to changes at the Gabčíkovo Water Structure's Provisional Rules of Operation developed in 2011 at Slovenské elektrárne Inc. – Hydro power plants Trenčín enterprise, a new hydromodel for operating the Gabčíkovo Water Structure was implemented. This hydromodel is capable of planning and exploiting the regulatory functions of the Gabčíkovo Water Structure more effectively than it was previously. The new hydromodel additionally incorporates a simulating model of flow transformation downstream of the Gabčíkovo Water Structure, which will examine the substantiality of Gabčíkovo Water Structure projected operation for compliance with nautical parameters downstream the Gabčíkovo Water Structure.

Keywords: *hydro plant, optimised operation, navigation safety, flow transformation*

1. Introduction

The fundamental goal for management of the Gabčíkovo Hydro plant ('HPGA') is optimal exploitation of the hydro-energy potential of the river Danube for covering the demands of hourly performances chart while keeping the rest the of HPGA functions working and respecting the constraints imposed by its multiple purposes and the hierarchy of individual functions as stipulated by the HPGA manipulation regulations such as safe flow of large waters, arrangements of flow into the old riverbed and international navigation, among others.

HPGA's energy regulatory functions (i.e. increasing and reducing the water plant's output as required by the demands of the energy system) are only partially utilizable, as there practically is no tail water reservoir at Nagymaros. In addition to detaining HPGA's peak run-off, the Nagymaros water structure was originally to dam the Danube water level to ensure navigability parameters downstream the Gabčíkovo stage. As a result of failing to build the Gabčíkovo – Nagymaros water structure system ('WSS G-N'), the parameters of the navigation route (particularly, the depth of the water) are directly impacted by flow manipulations at HPGA. HPGA's manipulation of flows must not reduce navigation depths below the prescribed limit values; during the Danube's low flows, HPGA must not manipulate the flows to reduce the concurrently reported navigation depths. Critical points for dangerously low water level in the navigation route are ford sections, i.e. sections with the lowest navigation depth levels. Thus, for safe navigability, it is imperative to know the impact of HPGA's regulatory operation on the flow and level regime at this particular section. To optimize HPGA's regulatory functions and in view of planned changes in HPGA's

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Provisional Manipulation Regulations, a new software hydromodel for optimal HPGA operation management was developed and implemented at the dispatch centre of Slovenské elektrárne a.s. – závod Vodné elektrárne in Trenčín in 2011 ('Hydromodel'). Unlike the one used previously, this hydromodel allows a more complex and effective planning and utilization of HPGA's regulatory functions by optimizing HPGA's operation to, among other things, ensure additional navigation route parameters of the international Danube waterway. This contribution seeks to describe the new hydromodel's functions and principles.

2. Basic functions

In terms of water management, Gabčíkovo is a hydro plant with daily regulation of flows, which is carried out by the volume of the Hrušov reservoir; it is the master hydro plant of the system of plants that includes the Čuňovo Hydro Plant, Mošon Small Hydro Plant and Small Hydro Plant Gabčíkovo S VII. Their operation is directly impacted by HPGA's operation (Fig. 1).

Hydromodel's major functions are as follows:

- Processing hydrologic inputs and modelling hydraulic states and bonds at WSGA,
- Proposing the planned outputs at HP Gabčíkovo, HP Čunovo, SHP Mošon and SHP S VII for preparing operation with respect to their regulatory reserve and/or verifying the pre-set hourly outputs including determining the eventual surpluses/shortages of the hydro-energy potential,
- Applying the new flows transformation model downstream the Gabčíkovo stage (part of the hydromodel to verify, by simulating the flow and level modes, whether the proposed WSGA operation complies with the navigation condition downstream the Gabčíkovo stage as set in the Provisional Manipulation Regulations for WSS G-N (PMR), update VIII of May 2010.

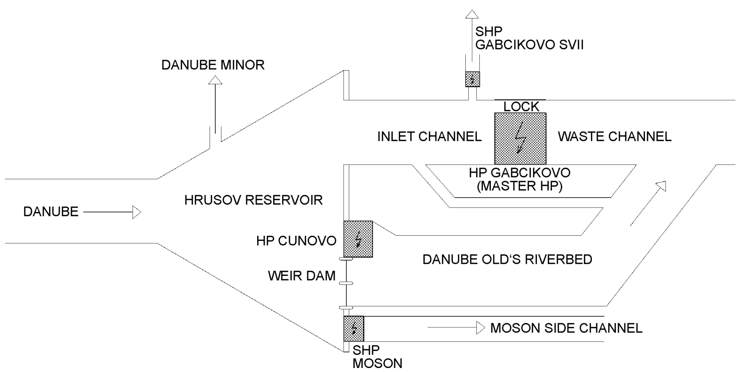

Fig.1: Scheme of the Gabčíkovo Water Structure (WSGA)

3. Computational scheme

The hydromodel's computational scheme is shown at Fig. 2.

The model's major inputs are:

- Hydro-forecast at the Devín profile,
- Required values of appreciation of generated electricity at each hour of the business diagram and/or values of required (base) outputs on hourly basis,

– Required values of ancillary services (AS),
– WSGA's construction parameters and limits,
– Required manipulation at WSGA (consumptions, levels),
– Shutdowns and technological constraints of individual hydro-plants,
– Optimization criterion – optimal redistribution of HPGA's outputs based on the required business diagram at each hour while keeping all marginal conditions of water management and energy.

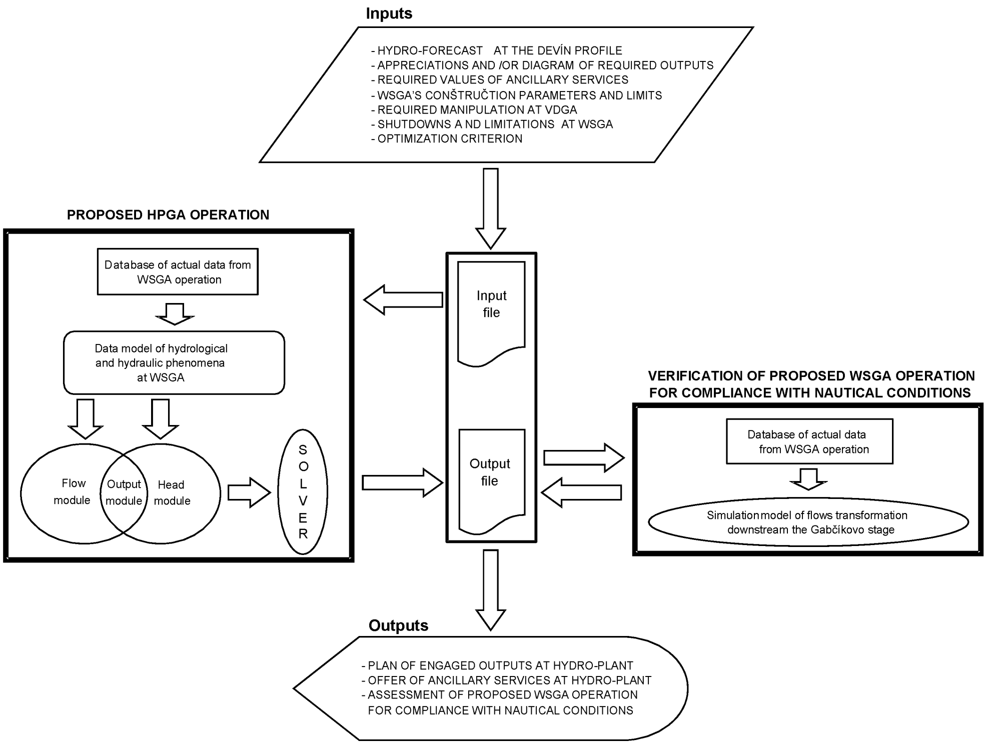

Fig.2: The hydromodel's computational scheme

The major outputs of the hydromodel are:
– The hydromodel's output is:
For optimization mode – proposed flows for WSGA's hydro plants followed by a power output plan at each hydro plant accounting for their regulatory reserves in a 1-hour time raster designed to meet the requested optimization criterion.
For simulation mode – values of flow balances through WSGA's hydro plants and the level mode of the Hrušov reservoir and HPGA's channels meeting the fixed values of required (base) outputs and the values of required ancillary services in a 1-hour time raster. The simulation model does not carry out any optimization while computing. Its outcome may eventually include 'intolerable' manipulation (such as emptying out the reservoir, which is inacceptable in practice, however). Obviously, such outcome would render the requested change in daily operation unfeasible.
– Alerting the user if the proposed WSGA operation may cause reduction of navigation depths below the prescribed statutory limits.

3.1. WSGA's draft operation

In the process of drafting WSGA operation, the hydromodel's computational parameters are obtained through computations in the individual modules. The outcomes of those in-modules computations are a combination of the outcomes of data models obtained from databases of real WSGA operation and the computations made with the help of mathematical relationships describing both hydrological and hydraulic phenomena at WSGA. The flow module provides data on flows though the system's constitutive elements. Its task (output) is to provide actual data on available water flows for WSGA hydro plants. The head module provides data on heads for WSGA's hydro plants. The output module uses the outcomes of these former modules (the flow module and the head module) to transform flows and heads to electrical power. The solver has the job of applying the computed parameters to propose HPGA's planned output. The major optimization criterion for proposing the output and/or generation is the requirement to run as close as possible to meet the required shape of the business diagram based on the pre-determined appreciation, i.e. the weight criterion. For an arbitrary length of the planning period and assuming a one-hour-step solution the optimization's goal can be noted by the following objective function:

$$F = \sum_{i=1}^{T} c_i \, ST_i \, P_i = \sum_{i=1}^{T} c_i \, (ST_i \, 9.81 \, Q_i \, H_i \, \eta_i \, 10^{-3}) \rightarrow \max \, , \tag{1}$$

where: T – number of time intervals (planning period), i – index of the solution's time intervals (hour), $i = 1, 2, \ldots, T$, c_i – weight factor (appreciation) at i-hour describing the required shape of the business diagram, ST_i – bivalent variable describing HPGA's state of operation at i-hour (1 – plant in operation, 0 – plant out of operation) (variable sought), P_i – HPGA's engaged output at i-hour [MW] (dependent variable), Q_i – discharge through HPGA at i-hour [$\mathrm{m^3s^{-1}}$] (variable sought), H_i – HPGA's average head at i-hour [m]; $H_{k,i} = f(Q_i, V_{\mathrm{in}})$, where V_{in} – initial volume of water in the Hrušov reservoir [$\mathrm{m^3}$], η_i – efficiency of energy conversion at HPGA at i-hour [–]; $\eta_i = f(Q_i, H_i)$.

Solution of the optimization issue described by function (1) is represented by the solution vector $\mathbf{s}$ that can be noted as follows:

$$\mathbf{s} = [Q_1 \; Q_1 \; \ldots \; Q_T \mid ST_1 \; ST_2 \; \ldots \; ST_T] \, .$$

The sought values of the elements of vector $\mathbf{s}$ (i.e. HPGA's operation plan) then result from maximizing the target function (1), which must be extended to include the limiting conditions (2)–(5) as based on constraints of WSGA's manipulation regulations and/or the underlying constraints of construction and operation of the water structure.

$$ST_i \, (P_{\mathrm{min}} + {}^{\mathrm{RSV-}}P_i) \leq P_i \leq ST_i \, (P_{\mathrm{max}} - {}^{\mathrm{RSV+}}P_i) \, , \tag{2}$$

$$ST_i \, (Q_{\mathrm{min}} + {}^{\mathrm{RSV-}}Q_i) \leq Q_i \leq ST_i \, (Q_{\mathrm{max}} - {}^{\mathrm{RSV+}}Q_i) \, , \tag{3}$$

$$V_{\mathrm{min}} \leq V_i \leq V_{\mathrm{max}} \, , \tag{4}$$

$$V_0 = V_{\mathrm{in}} \quad \text{and} \quad V_T = V_{\mathrm{fin}} \, , \tag{5}$$

where: P_{min} – HPGA's minimum output [MW], P_{max} – HPGA's maximum output [MW], ${}^{\mathrm{RSV+}}P_i$ – HPGA's positive regulatory reserve at i-hour [MW], ${}^{\mathrm{RSV-}}P_i$ – HPGA's negative regulatory reserve at i-hour [MW], Q_{min} – minimum discharge through HPGA [$\mathrm{m^3s^{-1}}$],

$Q_{\max}$ – maximum discharge through HPGA [m^3s^{-1}], ${}^{RSV+}Q_i$ – discharge equivalent of HPGA's positive regulatory reserve at i-hour [m^3s^{-1}], ${}^{RSV-}Q_i$ – discharge equivalent of HPGA's negative regulatory reserve at i-hour [m^3s^{-1}], $V_{\min}$ – minimum supply volume of the Hrušov reservoir [m^3], $V_{\max}$ – maximum supply volume of the Hrušov reservoir [m^3].

Values of the initial supply volume of the Hrušov reservoir V_{in} and the required final supply volume of the Hrušov reservoir V_{fin} are already known in the preparatory process of operation. The reservoir's supply volume at the end of i-hour V_i [m^3] is given by the balance equation:

$$V_i = V_{i-1} - 3600\,Q_i + I_i \ , \tag{6}$$

where I_i is the volume of water inflow into the reservoir at i-hour including natural inflow, losses due to leakage and evaporation and consumptions.

Additionally, all of the above constraints must be met on activation of positive or negative elements of regulatory reserves when providing ancillary services. In the hydromodel, the target function (1) is solved by using the Branch-and-Bound method (which is suitable for solving mixed non-linear integer optimization problems).

The realness of proposed WSGA operation (i.e. the **s** vector) is then checked for ensuring navigation conditions downstream the Gabčíkovo stage by using the flows transformation simulation model ('Model'), integrated directly in the hydromodel's environment.

3.2. Verification of proposed WSGA operation for compliance with nautical conditions downstream the Gabčíkovo stage

At the time of writing this, the conditions of HPGA's regulatory operation were defined in PMR for WSS G-N, update VIII of May 2010. To avoid the risk of undermining safe navigation, no flow change through HPGA (caused by regulating the hydro plant's output) can be made under PMR that could reduce the depth of water at the limiting ford within the regulated section to cause a vessel to hit the bottom (i.e. reducing the minimum navigation depth of 25 dm). Under PMR, the limiting ford at the Gabčíkovo hydro plant – Komárno is the ford at rkm 1796 where the minimum navigation depth of 25 dm is arranged at the discharge of 1260 m^3s^{-1}.

Fig. 4 shows an example of temporal development of the total of discharge through the HPGA profile and the Danube's old riverbed and the temporal development of discharges at the limiting ford. As shown, the reduction of discharge (HPGA + old riverbed) down

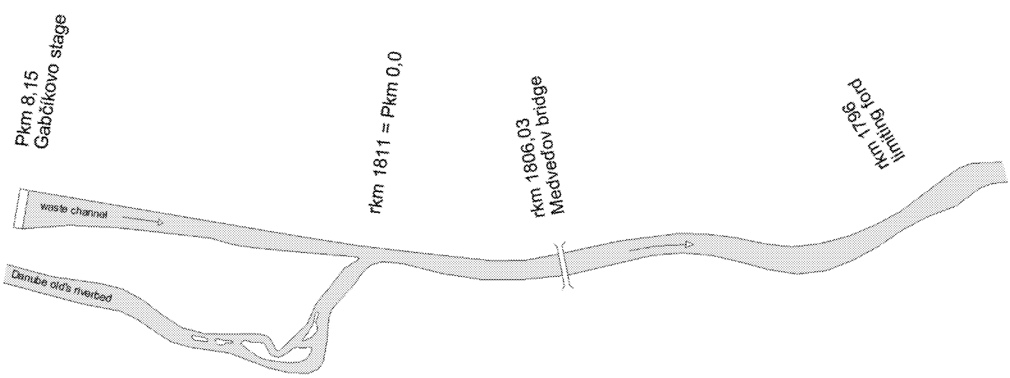

Fig.3: Gabčíkovo Water Structure – the section downstream the Gabčíkovo stage

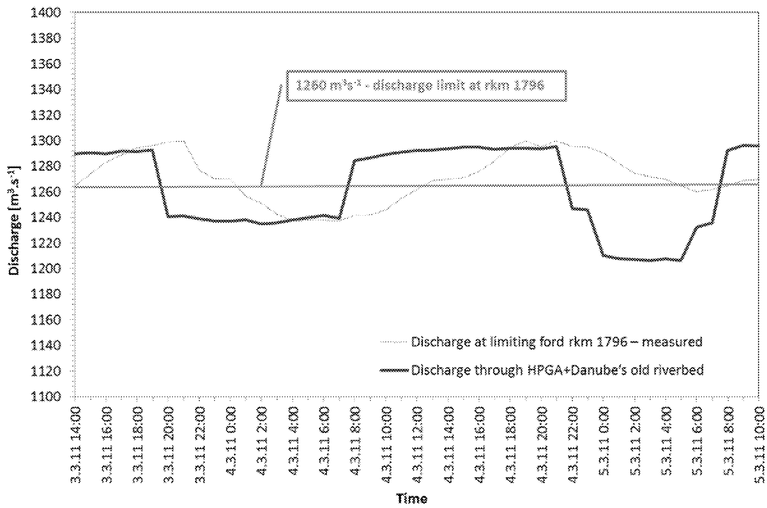

Fig.4: Temporal development of flows through HPGA + the old riverbed at the limiting ford rkm 1796

to approx. 1240 m^3s^{-1} from 3 March 2011 20:00 until 4 March 2011 17:00 caused reduced discharge at the limiting ford below the flow limit. On the other hand, the aggregated discharge reduction down to 1200 m^3s^{-1} from 5 March 2011 0:00 until 5 March 2011 15:00 did not cause any below-the-limit discharge at the limiting ford. Clearly, the constant discharge at the Danube section downstream the hydro plan makes it impossible to set a definite minimum discharge limit through HPGA + old riverbed (i.e. makes it impossible to set a definite discharge through HPGA + old riverbed that would cause the navigation depth at the limiting ford to be below the minimum).

No minimum discharge through HPGA + old riverbed is set under the current PMR either. Conditions of regulatory operation are defined in Attachment 3 in the form of tables with granted durations of negative manipulation for particular values of flow reductions through HPGA and flow at the Medveďov bridge profile. According to [2], the regulatory conditions were determined on the assumption that any negative manipulation of flows at HPGA is preceded by a well-established constant flow at the Medveďov bridge profile; however, this condition is virtually unattainable in actual operation. Thus, HPGA operation planning based on PMR's tables poses considerable demands on the operator's experience and ability to make the right estimate. The uncertainties grow with errors of flow forecasts at key water-level metres. Often, this results in conditions of operation that are less than optimal for utilizing the HPGA effects. Ultimately, such management mode can threaten safe navigation downstream HPGA.

As seen above, the process of planning HPGA's regulatory operation makes it indispensable to have an instrument that is capable of continued assessment and a reasonably accurate forecasting of navigation conditions at the limiting ford (i.e. an instrument for simulating the flow transformation at the HPGA – limiting ford section).

In 2011, with respect to the new conditions of HPGA's regulatory operation under the updated PMR, the existing hydromodel (as used by the Dispatch centre in Trenčín) was extended to include the hydrological transformation model of flows downstream the Gabčíkovo stage. The model was designed using the Muskingum method, one of the most widely used methods in hydrological flow transformation modelling due to its simplicity and universal applicability. The Muskingum method was applied at the Danube's river section beginning at HPGA on through the limiting ford at rkm 1796. Available were the measured values of average quarter-hourly discharges through the HPGA profile (hydro plant+lock), quarter-hourly values at the water-level metre of the transportable limnigraph at the limiting ford (see Note), average quarter-hourly values of discharges at the Medveďov bridge profile and quarter-hourly values of water levels recorded by the water-level metre at the 5143 Gabčíkovo – Danube profile for the period 04 November 2010 – 31 January 2011.

Note: *On the strength of a great deal of simulated HPGA flow manipulations made on the hydrodynamic model of the Danube's HPGA – Komárno section, we can say that, with normal flow manipulations at HPGA, the water level at limiting ford shows a clear dependency on flow. With HPGA's regulation of flow, the 'undulating' impact on water level at limiting ford vanishes. According to [2], the steepness of flow reduction through HPGA has no dramatic impact on the extreme of the decreased water level at rkm 1796. Beside the sufficient distance of the limiting ford (approx. 23 km) from the origin of 'wavelike movement', the absorption is further propelled by the interaction between the flow in the particular section and the flow in the Danube's old riverbed. Once flow through HPGA is reduced, water from the old riverbed is effectively 'sucked in' and the flow downstream the confluence point is subsidized. Increasing, in turn, the flow through HPGA has the opposite effect, steering the waste channel water into the Danube's old riverbed.*

Given the complex hydraulic flow mode in the Danube's old riverbed, there is no official measurement curve set for profile 5143. For the sake of parameterizing the flows transformation model at the particular section, a measurement curve has been computed for the section's sufficiently long-established flow conditions, by making a balance of observed flows through HPGA and the Medveďov bridge profile. Discharge values in the Danube's old riverbed in the period from 04 November 2010 until 31 January 2011 were fluctuating between 340 and 1900 m^3s^{-1}.

Based on recommendations [1], the modelled Danube section was divided into two submodels (see Fig. 5). The model's parameterization (i.e. finding the optimal relationship between the travel times and flows Q_1^{in} and Q_2^{in}) was made by using a genetic algorithm directly integrated into the model of the particular section.

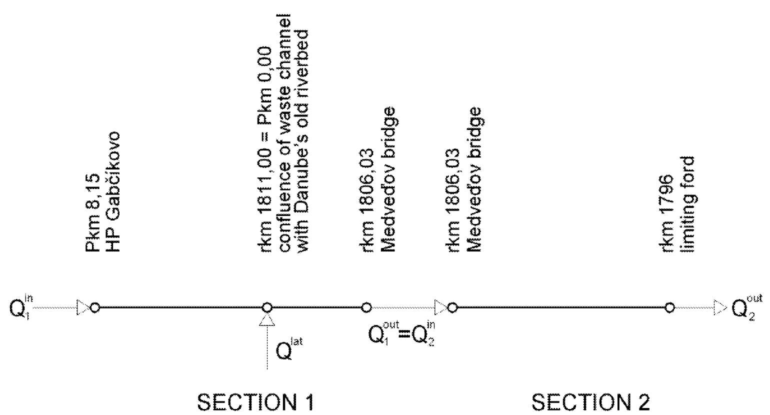

Fig.5: The model's computational scheme

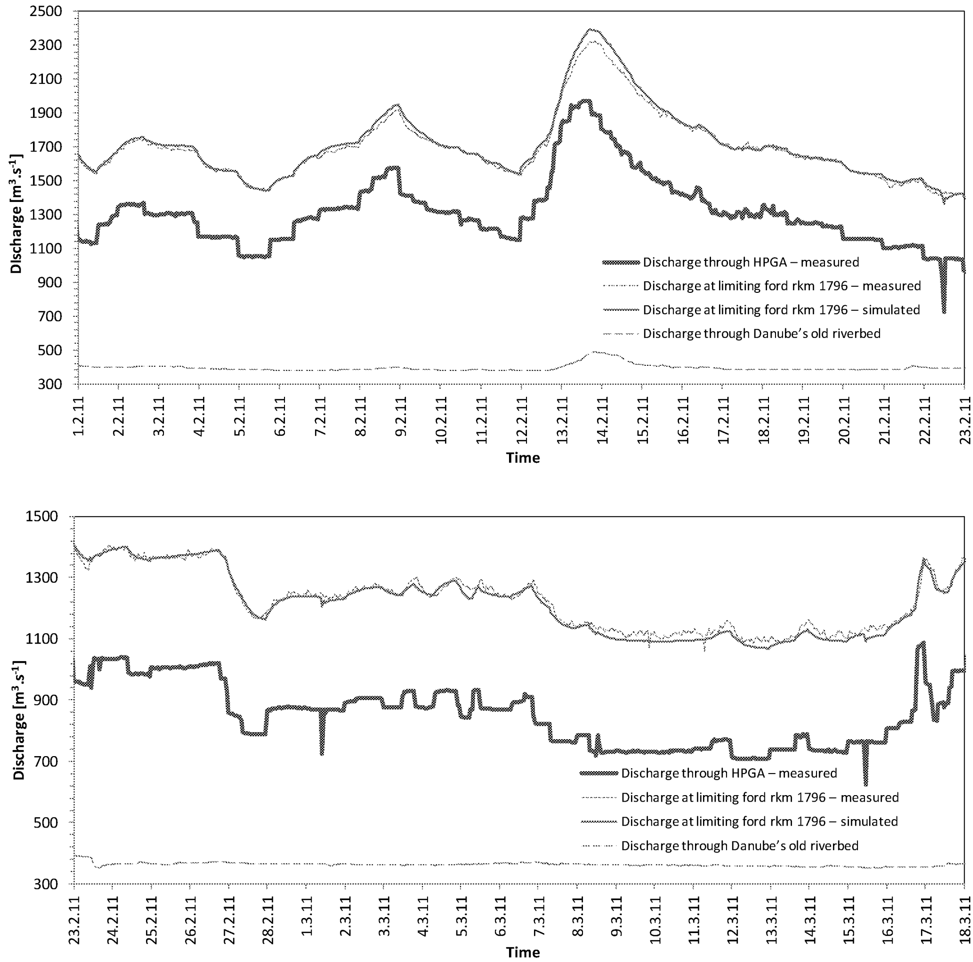

Fig.6: Example of the transformation model's verification

The model was verified on the flows in the period from 01 February 2011 until 16 May 2011. Verification of the transformation model is exemplified at Fig. 6. A visual check confirms that the transformation model does justice to reduced discharges at limiting ford caused by HPGA's negative manipulation, particularly in the discharge range of $1500\,m^3s^{-1}$ and below.

4. Conclusion

2007 saw the commissioning of the hydromodel for preparing operation and operative management of WSGA as part of the 'Complex information system of preparing operation of energy sources of ENEL SE, a.s.'. Its main job was to design HPGA's operation to meet the requirements of the energy system while ensuring and respecting all marginal conditions of water management and energy. With respect to the new conditions of HPGA's regulatory operation under the updated PMR, a new hydromodel was designed and commissioned in 2011, which included the transformation model of flows downstream the Gabčíkovo stage. This flows transformation model features a user alert in case that the proposed WSGA operation may cause reduction of navigation depths below the prescribed statutory limits.

Based on the outcome of simulations of artificial flow waves in the Danube section running downstream the Gabčíkovo stage up to the limiting ford rkm 1796 using the Muskingum method and on comparison of these simulations with actual measurements at this section, the following conclusions can be made:

1. Despite some recommendations that the Muskingum method is suitable for watercourses with continuous flow variations and without a considerable tributary flow, the results obtained show that this method is usable in the process of modelling transformation of artificial flow waves generated by a hydro plant's flow manipulation.
2. Clearly, the Muskingum method has some limitations, particularly with simulating a hydro plant's extreme shutdowns and/or start-ups such as in emergency states. Nevertheless, the experience of actual water structure operation with gradual flow variations attests that, for regular manipulations, the used model provides sufficiently accurate results.
3. The conditions of regulatory operation in the new hydromodel are dictated by PMR, Update VIII of May 2010. These were determined on the basis of simulated water level and flow regimes on the 2008 riverbed morphology and older (measurements of riverbed sections at different times) and the consumption curve in Medveďov in 2007. Downstream of Sap, the Danube undergoes intense morphological variations, as documented by regular measurements of the riverbed shape and reassessments of consumption curves at the water level recording station in Medveďov. These morphological variations alter the flow-level position-navigation depths relationship and necessitate:
   – calibration and verification of a simulated model of flows transformation downstream the Gabčíkovo stage relative to current Danube riverbed conditions, and
   – revision of the conditions of HPGA's regulatory operation.

   With constant morphological changes of the Danube riverbed, some of the 'de iure' conditions of regulatory operation under PMR are no longer applicable 'de facto'.
4. The necessity of altering the limits of regulatory operation due to morphological variations of the Danube riverbed downstream of must be assessed on regular and reasonably frequent basis. We recommend such assessment to be made once annually and in events that have impact on the riverbed shape (passage of high water, riverbed adjustment by the flow administrator).

   Failure to do so would run the risk that the regulatory operation on de facto inapplicable limits would case navigation accidents with direct responsibility of those who manage such operation.

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