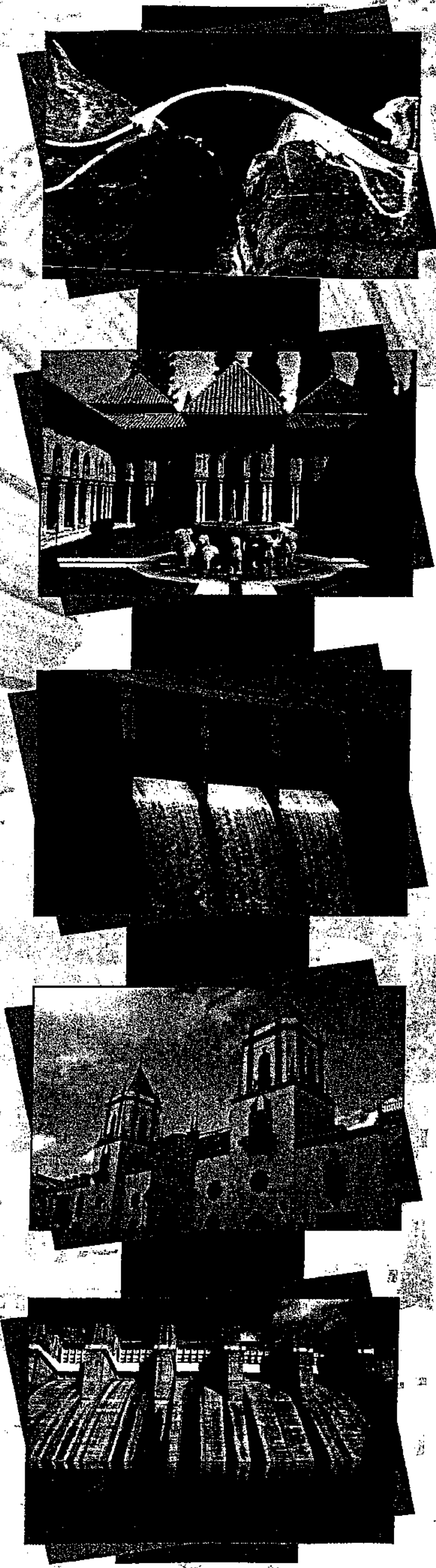

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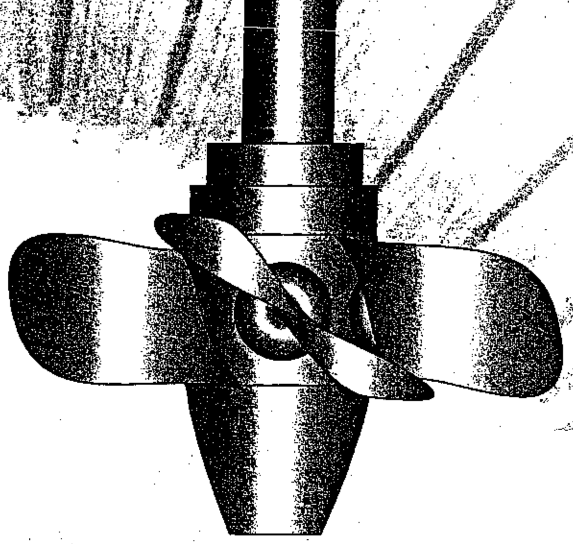

NEW APPROACHES FOR A NEW ERA

15 to 17 October 2007
Granada, Spain

Abstracts

of Conference Papers

(Full papers enclosed on CD)

HYDRO
2007

NEW APPROACHES
FOR A NEW ERA

Abstracts of HYDRO 2007 Papers

As the theme of HYDRO 2007 suggests, hydropower development worldwide has entered a new era, in which projects are planned with greater sensitivity for the environment, and with increased involvement of local stakeholders. The past year (2006-07) has seen far more major developments move ahead in Africa, Asia and Latin America, as well as in some of the original 'hydro pioneering countries' of Europe and North America. In some cases, inhospitable sites in remote areas need to be tackled, and in all cases efforts must be made to maximize investments and protect hydro assets.

The HYDRO 2007 papers represent a unique compilation of expertise from all parts of the world. The broad range of topics cover all practical aspects of hydropower development: reviewing needs and development policies; tackling challenging sites; managing large-scale projects; innovation in small-scale hydro schemes; prospects for marine energy; the role of pumped storage; refinements in machinery design; new approaches to financing; responsibility in planning; environmental protection; upgrading and refurbishment; system management, and contractual issues.

More than 300 papers were submitted this year, and the Organizers together with the Steering Committee have selected 170 for presentation at the Conference. Full papers, including some accepted for publication only, are available on the accompanying CD. This volume of Abstracts provides an overview of the contributions to HYDRO 2007.

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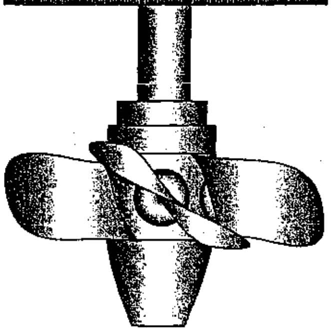

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ABSTRACTS

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18.06

The Serbian-Romanian hydropower system 'Djerdap': Mathematical model

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Abstract

A mathematical model for hydropower estimation and operational management of the Djerdap (Iron Gate) 1 HPP and Djerdap 2 HPP was developed during the 2004-2006 period at the Jaroslav Černi Institute, in collaboration with the Centre for Information Technology, the University of Kragujevac/Faculty of Mechanical Engineering. It was commissioned by PD Djerdap, a company which operates within the scope of the Electric Power Industry of Serbia. The objective of the mathematical model is to ensure efficient utilization of the Danube's hydropower potential, to address the demand of Serbian and Romanian electrical power systems which differs in terms of power and time, and to comply with a number of constraints at various control profiles of the Danube, which are defined in bilateral agreements.

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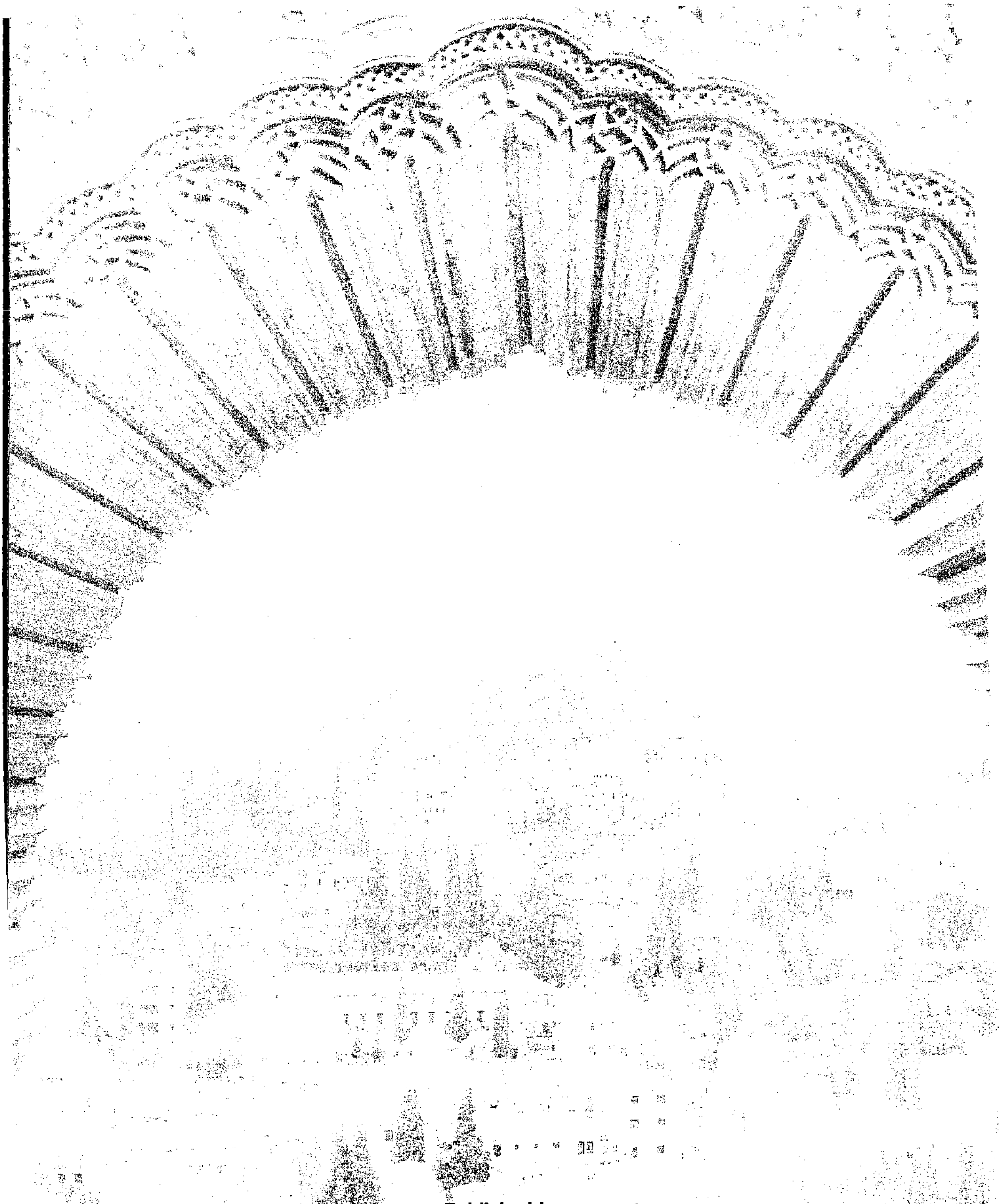

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The Serbian-Romanian hydropower system 'Djerdap': Mathematical model

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1. Introduction

A mathematical model for hydropower estimation and operational management of the Djerdap (Iron Gate) 1 HPP and Djerdap 2 HPP was developed during the 2004-2006 period at the Jaroslav Černi Institute, in collaboration with the Centre for Information Technology, the University of Kragujevac/Faculty of Mechanical Engineering. It was commissioned by PD Djerdap, a company which operates within the scope of the Electric Power Industry of Serbia. The objective of the mathematical model is to ensure efficient utilization of the Danube's hydropower potential, to address the demand of Serbian and Romanian electrical power systems which differs in terms of power and time, and to comply with a number of constraints at various control profiles of the Danube, which are defined in bilateral agreements.

2. Description of the Djerdap 1 and Djerdap 2 HPP system

The Djerdap 1 system was built on a stretch of the Danube (rkm 943+000) which is shared by Serbia and Romania. The main structure (dam) is 1280 m long and is symmetrically divided into its Serbian and Romanian portions, each of which is comprised of: a navigation lock; non-overflow earth dam, a hydro power plant (HPP) with 6 power units, and the respective portion of a gravity concrete dam with 14 spillways (25 m clearance). The major characteristics of the dam are: net head 15.4 - 31 m, total installed discharge 9,800 m^3/s, and total installed power 2,165 MW. The Djerdap 1 Reservoir was formed in a complex river system comprised of the Danube and its tributaries: the Tisa, Sava, Velika Morava, Tamiš, Nera, Mlava, Pek and Porečrivers. An important characteristic of the Djerdap 1 Reservoir is its variable length, extent of backwater and volume, as a function of the flow rate and HPP operating modes. The volume of the reservoir under average hydrologic conditions is 3,500 million m^3.

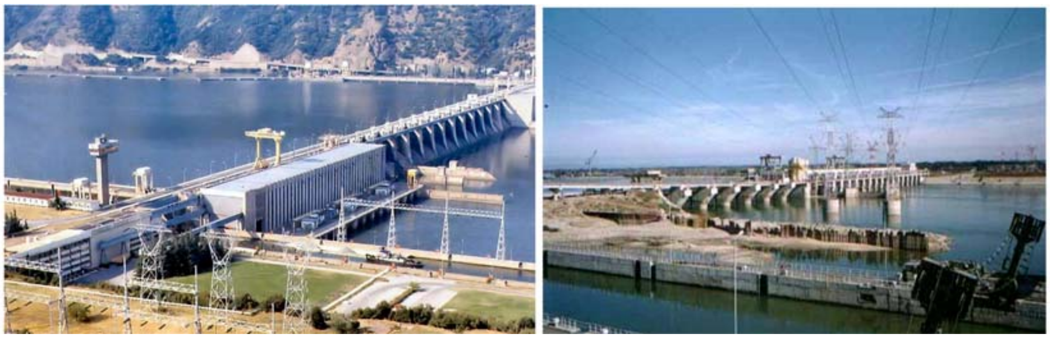


Fig. 1 *Djerdap 1 and Djerdap 2 dams.*

The Djerdap 2 system is the downstream part of a cascade and its operation is coupled with that of the Djerdap 1 system. Two HPPs, with 8 power generating units each, are located on the dam at rkm 862+800 of the Danube's main stream, along its left bank. At mid-section, there is an overflow dam with 7 spillway fields, and closer to the right bank there is a Serbian navigation lock and an additional HPP with two power generating units. The Romanian navigation lock is located in a channel running through the Island of Mare. The dam on the Gogoš Arm of the Danube (rkm 875) has a spillway at mid-section with 7 spillway fields, and an additional Romanian HPP with 2 power generating units, adjacent to the right bank of the river arm. The HPPs are equipped with horizontal encapsulated power generating units whose installed power is 27 MW each, making up a total of 540 MW. The total installed discharge is 8,500 m^3/s. Gross head varies from 2.5 m to 12.75 m, depending on the flow of the Danube. The Djerdap 2 Reservoir is an 80 km long stretch of the Danube's channel. At maximum water levels, the volume of the reservoir is 820 million m^3. No significant tributaries empty into this reservoir.

3. Model scope and objectives: Optimum management of the system of HPPs

The mathematical model can simulate and optimize the operation of the complex Djerdap 1 and Djerdap 2 hydropower system based on pre-defined individual facility performance levels, Serbian and Romanian electrical power demand, water level and discharge constraints at control profiles, and initial and boundary conditions, whereby it can address various scenarios of initial data and required outputs. This allows for efficient daily management decision-making with regard to appropriate operating modes.

Namely, water is evacuated by both Romanian and Serbian facilities (each drawing on its portion of the potential), via respective power units and dam spillway fields. The system is managed in such a way as to ensure optimum utilization of the Danube's hydropower potential, provide for unhindered navigation, and ensure that riparian lands are not threatened [1], [2]. It is especially noteworthy that the upstream portion of the Djerdap 1 Reservoir stretches over lowland and that the riparian lands of the Djerdap 2 Reservoir also lie relatively low. As a result, bilateral agreements impose water level restrictions at characteristic flow profiles, implicitly determining HPP operating modes.

In compliance with Djerdap 1 and Djerdap 2 Operation Regulations [18], daily production plans for the current day and following days are generated and synchronized by the Romanian and Serbian parties. The daily plan defines: daily average water levels, daily average discharges, water evacuation modes for the dams, amounts of water to be evacuated, total available energy, maximum/minimum HPP power, and overflow magnitude expressed by means of overflow energy. The daily plan is adjusted if daily plan reviews, previous day analyses, and updated forecasts of the Danube's flow rate indicate that water levels will exceed set constraints, which cannot be tolerated.

Therefore, the basic task of the mathematical model is to determine the sequence and dynamics of power unit engagement (and of spillways, as needed), relative to predicted inflow rates and pre-defined hourly output plans, or pre-defined hourly production priorities for each Serbian and Romanian HPP, while complying with pre-defined constraints and striving to minimize any departure from plan and minimize water consumption (i.e. maximize hydropotential utilization).

4. Spatial decomposition of the system, theoretical background and general logic of the mathematical model

The model addresses water flow and power generation in the entire Djerdap 1 and Djerdap 2 system. The entry of water into the system is represented by the flow rates at river system profiles upstream from the reservoir (the main stream of the Danube and all of its tributaries). On the other hand, it has to cope with user demand (Serbian and Romanian electrical power demand as a function of time) and prescribed constraints. As a result, the model includes all relevant types of linear flow: morphology-based flow in natural watercourses and flow through facilities (HPPs, dam spillways, dam outlets, navigation locks, and the like). Additionally and very importantly, modeling includes the variation in flow conditions as a function of time, due to management decisions. The model has been developed for an hourly time-step environment.

In view of the spatial and functional complexity of the system, the modeled area has been broken down into various elements which can be used to simulate different types of water flow, both natural and artificial (Fig. 3) [3].

The basic element of the river network is a river reach which is used to model a portion of open flow between the junction, bifurcation and man-made hydropower assets. The model which describes the complex river system is obtained by joining river reaches which define open flow, introduce tributaries, create river islands, locate hydropower assets, and hydraulically link such assets within an integrated model [4], [16], [17]. The complexity of the system, from both the modeling and numerical solving perspective, results from a large number of bifurcations, of which the most important is the Gogos-Djerdap 2 loop. In this portion of the system there are two HPP dams in two parallel branches, so that internal conditions dictated by hydropower system management have to be met, in addition to the necessary compliance with constraints at the initial bifurcation and the point where the river arm ultimately re-joins and the main stream.

The dam structure (which includes both the HPP and spillway fields) has been modeled using internal boundary conditions. The flow through the HPPs and over the spillways is a function of the headwater and tailwater, as well as other parameters which define the operating modes of these facilities. Headwear and tailwater levels are recorded at each time step, as are other parameters which affect the operation of an HPP or spillway. The discharge is determined based on the obtained values and functions which describe the operation of an HPP or spillway. This discharge is set at one or both boundary nodes of the dam structure. Such an approach to HPP and spillway modeling allows for the definition of non-analytical forms, such as a number of decision-making methods and the inclusion of various parameters which might affect HPP or spillway operation [10].

In the above context, it should be noted that an HPP asset constitutes a set of individual power generating units which are engaged in accordance with the criterion which requires minimization of the total flow through the HPP. The transformation of gross head and discharge into energy, or the definition of the required discharge for a certain level of power relative to the current net head, is performed at every step, for each power unit based on its characteristics, or turbine hill charts (power – net head – discharge), taking into account losses in the inlet-outlet tract (whereby losses are time-dependent parameters) [5]. Consequently, the number of engaged power units is defined for each time step of the simulation, based on the minimum water consumption criterion and with the aim of achieving the required electrical power output. The spillway facility constitutes a set of individual spillway fields with their respective characteristics (overflow curves: water level – clearance – discharge), which are engaged if water evacuation through the HPPs cannot respond to all the prescribed constrains.

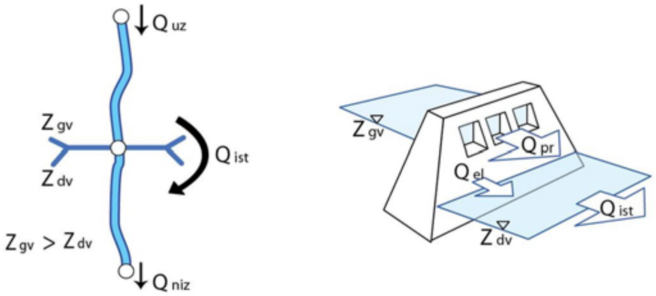


Fig. 2. *Representation of the dam, including HPPs and spillway, as an internal boundary condition.*

In general, flow simulation is based on a one-dimensional model of unsteady flow which is used to solve basic equations of mass conservation and momentum conservation laws [6], [7]. Approximate numerical integration of 1D unsteady-unconfined flow equations was performed by implementing the „four point“ method. Four points in the *x-t* plane are used to define the area in which these equations are (approximately) integrated, in order to obtain a system of algebraic equations for the reach. The weighted trapezoidal rule [8] was applied in the model.

The defined equations describe the laws of discharge and water level variation within an open flow network. Once the system of equations is formed, all equations must be solved simultaneously. Unknown variables of the system include discharges and water levels for a given simulation time step. Upon completion of calculations for a time step, computed values become initial values for the next time step. Once the characteristics of the entire model for a given time step have been determined, the system of non-linear equations is solved iteratively, applying the Newtonian method. Since there are active hydropower facilities (dam with HPP and spillway), whose functioning depends on current headwater and tailwater levels, it is also necessary to adjust discharges through the given facilities. Using such adjusted values, the entire equation solving procedure is repeated until the convergence criterion has been achieved.

5. Optimization within the mathematical model

A very important aspect of the mathematical model developed for the Djerdap 1 and Djerdap 2 HPP system is the solving of operation optimization problems, whereby different objectives may be encountered in practice. For example, the objective may be to achieve maximum utilization of the hydropotential based on pre-defined hourly production priorities. The objective may also be minimal variation from the pre-defined production plan. In both cases, the number of engaged power generating units is also optimized based on the minimal water consumption criterion. All of these optimizations have to adhere to prescribed constrains (generally water level restrictions at characteristic flow profiles).

In most cases, this type of problem is solved by evolutionary algorithms [11], [12], dynamic programming [13] and the augmented Lagrange multiplier method [14]. In the present model, satisfying imposed constrains is a complex problem since there can be a time lag between the cause and the actual violation of a constraint. The time interval between the occurrence of the cause and its effect has not been uniquely defined, since it depends on a large number of other system parameters and on the flow of the simulation itself. In a view of the complexity of this problem, the model employs a genetic algorithm mechanism which will be described using an example involving a problem related to the optimum operating regime of all facilities of the system, based on pre-defined hourly production priorities.

The priority plan is given for two complete systems (Serbian and Romanian), in tabular form and such that preference is defined by priority level instead of the weight coefficient for every hour. The priority structure is entered into target programming and the assumption is made that constraints are primary criteria which have to be met and they are, therefore, given the highest priority. The task is addressed by the weight coefficient method, which is the most frequently applied method in multicriteria optimization. This method introduces weight coefficients w_i for all criteria functions f_i^*, $i=1,...,n$, and the vectorial optimization problem is reduced to scalar optimization $\max\sum w_i P_i \Delta t$, $i=1,...,24$, where $P_i \Delta t$ is the generated energy E during time interval Δt.

The target function for production optimization in terms of pre-defined hourly priorities has the form of $\max\{\sum\sum w_{i,j} P_{i,j}\}$, $i=1,...,n$, $j=1,...,m$, where $w_{i,j}$ are priority levels for the j^{th} HPP facility in the i^{th} step, and $P_{i,j}$ is the power achieved by the j^{th} facility in the i^{th} step.

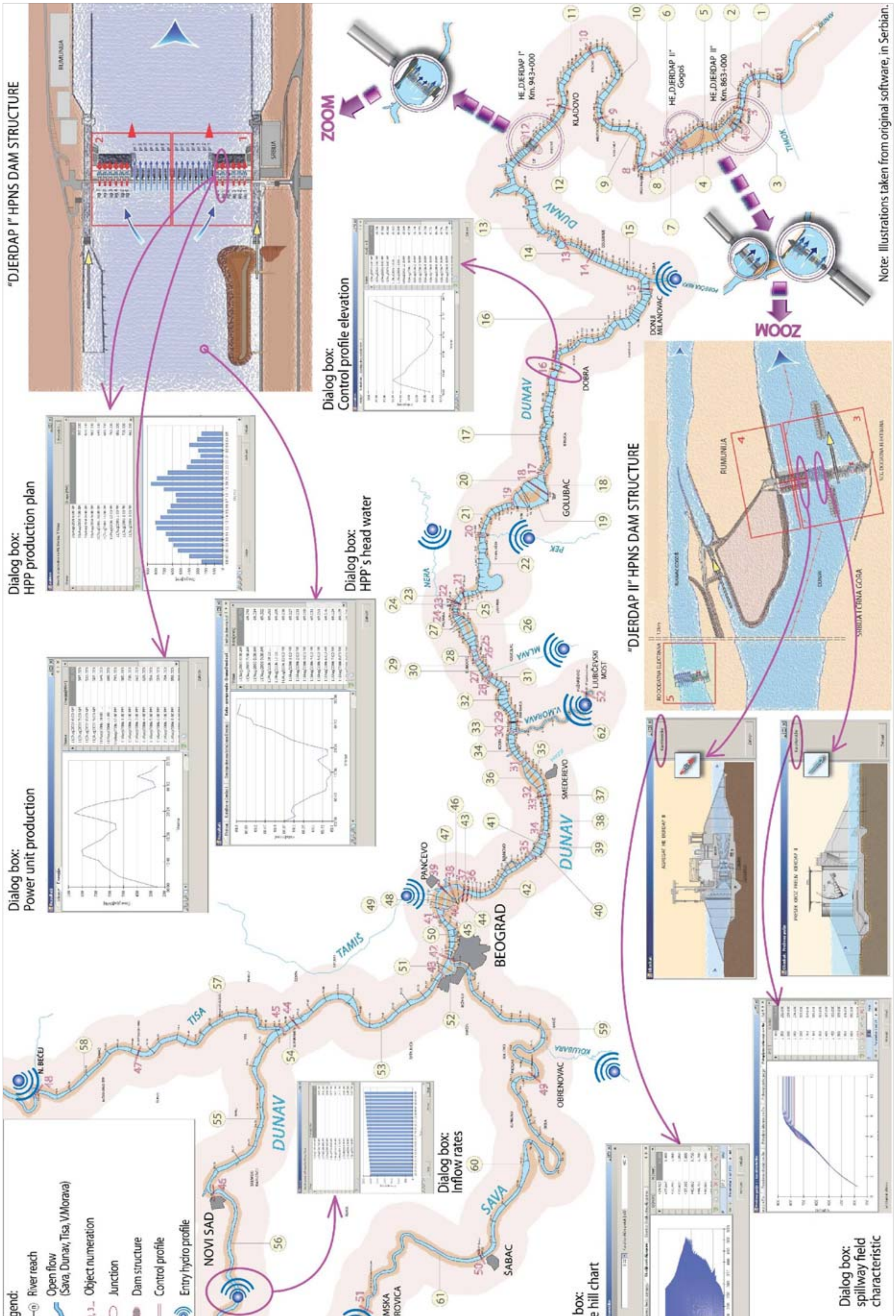


Fig. 3 *Schematic representation of the model.*

In order to improve algorithm efficiency, solutions which violate constraints, or lie outside of the feasible space, are also addressed and the proposed plan assessed with regard to the intensity of the potential constraint violation. This is achieved by an internal addition of a penalty term to the target function $\sum\alpha_k\sum|g_l(z_k)|$, $k=1,...,q$, $l=1,...,r$. Functions $g_l(z_k)$ represent a numerical value which describes the number and intensity of violations of the l^{th} constraint at the k^{th} flow profile. To achieve better convergence of the algorithm, a separate weight coefficient is added to each constraint. It should be noted that a solution is acceptable if, and only if, the sum $\sum\alpha_k\sum|g_l(z_k)|=0$, since in that case there is no violation of any system constraint. However, even though the basic objective is to comply with all constraints, the introduction of this factor allows for the evaluation of solutions which violate any of the constraints, but in such a way that the next step favors the proposed adjustment which was closest to satisfying the imposed system constraints. Weight coefficients α_i allow for preference to be given to particular internal terms of the fitness function.

Unit commitment is implemented on an hourly basis, during which time a particular HPP facility is engaged based on the proposed HPP output and the power generating units are engaged based on minimum consumption. The solution, in the form of hourly production plans for individual power generating units, is coded into the binary gene. The process results in one or more genes which, in effect, represent the optimum hourly plan for a particular power generating unit and the extent of any achieved optional overflow. Genetic algorithm performance improvements, in terms of maintaining a favorable exploration/exporation ratio during the entire optimization process, were achieved by introducing fuzzy logic controllers which were used to adapt genetic algorithm parameters [15]. The adaptive genetic algorithm approach is such that at every *n* generations, applying the proposed fuzzy rules, the mutation probability (p_m) is determined on the basis of its value in the previous generations and the achieved best individual fitness (f_n) improvement.

6. Software structure

Major software modules are: a user interface, a module which simulates unsteady flow in the open-flow network and optimizes operation of hydropower facilities, and a database [21].

User interface. A user-friendly, modern, graphically oriented interface has been developed, which interactively guides the user through all simulation model application stages: database search, handling of input data and model object parameters, initiation of the simulation/optimization process, handling of output data, and creation of reports.

Simulation/optimization module. This module activates implemented numerical analysis methods and optimization algorithms which were described earlier in the text. The module provides two-way communication with the user interface (problem definition and output review/analysis).

Database. The database integrates required data with an appropriate record structure, and is based on existing hardware platforms and types of databases used within the system. The database contains diverse data: comprehensive system configuration information (e.g., hydrographic network, facilities, monitoring sites, and riverbed morphology), comprehensive facility performance data (e.g., turbine hill charts, spillway-field discharge characteristics, etc.), constraints, history of measured reservoir water levels, history of measured HPP electrical and non-electrical parameters (e.g., power, discharge, net and gross head, power output, spillway field discharge), and the like.

The software has been designed for a Windows platform and developed using a three-layer model, which makes a clear distinction between functional units: a presentation layer, a business logic layer, and a data layer. The portion of the application which interacts with the user is referred to as the presentation layer; it is implemented via Windows forms. The business logic layer has been implemented as a code within the forms. The data layer represents any database which is supported by the .NET environment (in this case the Microsoft SQL Server), and communicates with the business logiccentral layer via ADO.NET objects [4].

7. Parameter estimation and accuracy verification

In addition to experimental data relating to the performance of all system components (e.g., overflow curves or turbine hill charts) or riverbed morphology, the database includes „model parameters“ which cannot be determined by observation or direct measurement of flow characteristics [20]. These include Manning coefficients of roughness, which vary as a function of the physical position along the flow and the flow rate. Model parameters have been estimated through optimization, with the goal of achieving the best possible match between computed and measured water levels at control profiles. Based on known inflow and outflow data, the computed value is obtained through an iterative process (simulation, assessment, comparison, correction, and repeated simulation). The previously-described evolutionary algorithms are also included in the estimation procedure. The target function of the evolutionary algorithms is minimum deviation of computed water levels from corresponding measured water levels.

The roughness coefficient estimation process encompasses a wide range of total flow rates to the reservoir, from 2500 to 10000 m^3/s, including both quasi-steady flow periods and periods of sudden flow rate variation. Figure 4 is a graphical representation of a comparison between measured and simulated values for the dam and the most important control profile, reflecting an arbitrary historic period of 7 days.

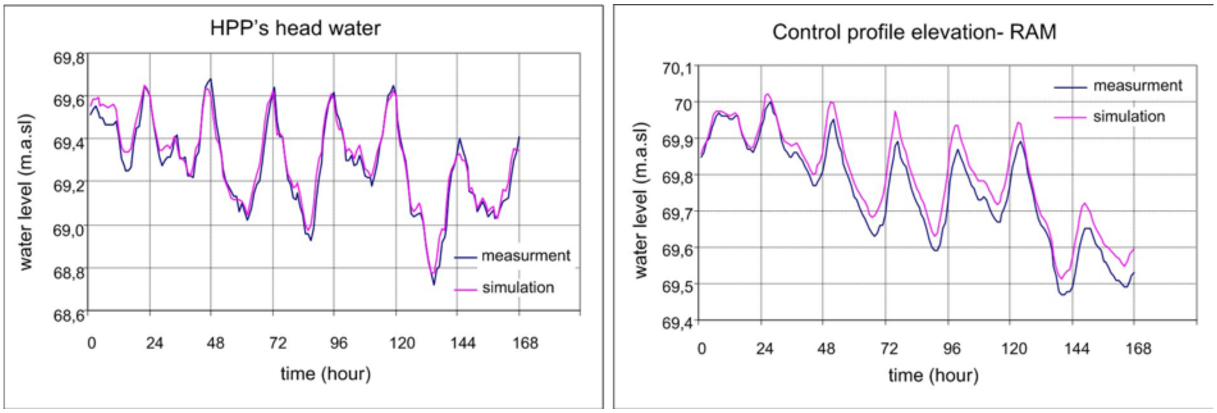


Fig. 4 *Measured vs. simulated values: Dam profile and control profile.*

Even though historic data contained a certain degree of inaccuracy (e.g., dam discharges and, particularly, estimates of natural flow to the reservoir), their careful interpretation and the application of the described parameter estimation procedure resulted in sound mathematical model calibration, and it is, therefore, possible to re-compute an episode from history to a desired level of accuracy.

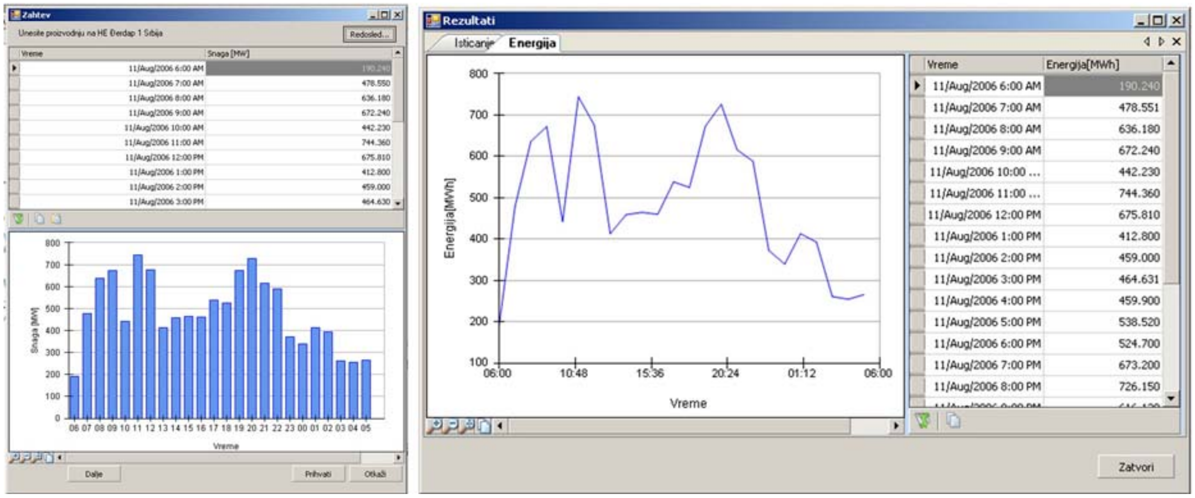
8. Application of the mathematical model

When applying the mathematical model, the first step is to define its spatial and temporal framework, model performance levels and parameters, constraints which have to be complied with, input flow time series, and the functional mode (which determines the simulation/optimization procedure for solving a specific problem), along with relevant energy requirements [19]. The next step is pre-processing, or numerical computation of the initial status of the system. Then, based on the initial status and given incoming flow rates and electrical power demand, hydraulic/hydropower simulations and system operation optimization are conducted based on pre-defined management criteria.

Management criteria are primarily defined by the model's functional mode, as well as by selection of relevant attributes depending on the type of analysis being conducted. In the widest sense, there are three mathematical model functional modes:

Mode 1: Review and adjustment of a specified production plan

This functional mode of the mathematical model is used to check and modify the existing (daily) production plan and to define the needed spillway field discharge regime (as required), with the goal of complying with constraints and minimizing any departure from the proposed plan. This, of course, implies that system inflow forecasts, initial water levels and the production plan are available.



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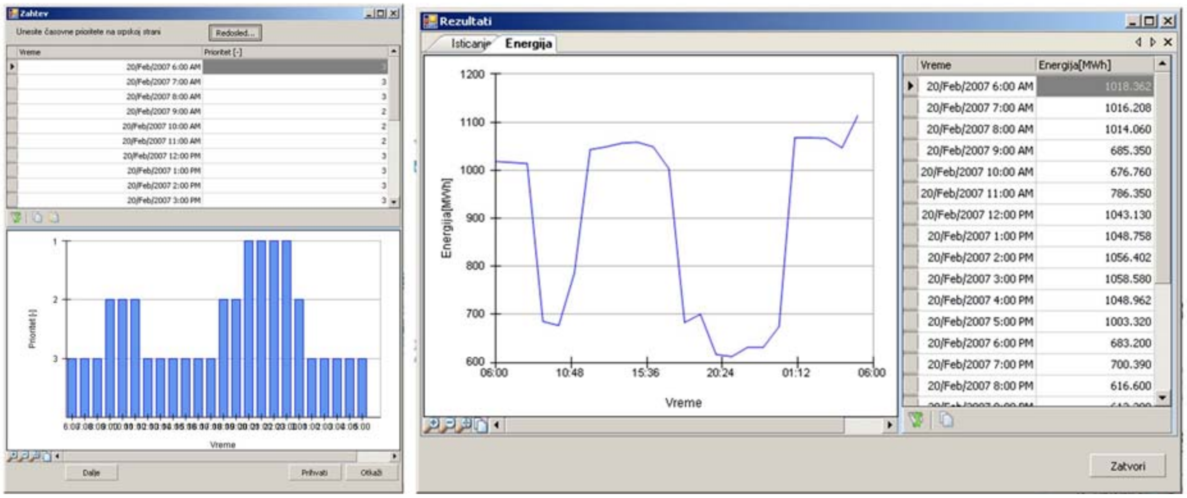
Vreme	Snaga [MW]
11/Aug/2006 6:00 AM	190.240
11/Aug/2006 7:00 AM	478.550
11/Aug/2006 8:00 AM	636.180
11/Aug/2006 9:00 AM	672.240
11/Aug/2006 10:00 AM	442.230
11/Aug/2006 11:00 AM	744.360
11/Aug/2006 12:00 PM	675.810
11/Aug/2006 1:00 PM	412.800
11/Aug/2006 2:00 PM	459.000
11/Aug/2006 3:00 PM	464.630

Vreme	Energija[MWh]
11/Aug/2006 6:00 AM	190.240
11/Aug/2006 7:00 AM	478.551
11/Aug/2006 8:00 AM	636.180
11/Aug/2006 9:00 AM	672.240
11/Aug/2006 10:00 ...	442.230
11/Aug/2006 11:00 ...	744.360
11/Aug/2006 12:00 PM	675.810
11/Aug/2006 1:00 PM	412.800
11/Aug/2006 2:00 PM	459.000
11/Aug/2006 3:00 PM	464.631
11/Aug/2006 4:00 PM	459.900
11/Aug/2006 5:00 PM	538.520
11/Aug/2006 6:00 PM	524.700
11/Aug/2006 7:00 PM	673.200
11/Aug/2006 8:00 PM	726.150

Fig. 5 *Energy at the Djerdap 1 HPP: Serbian side*
(a: Input data – given production plan; b: Simulation output, adjusted production plan).

Mode 2: Optimum operation in the absence of a specified production plan

The second mode is used to solve problems which do not include a pre-defined hourly production plan. The hourly production plan is replaced with set hourly priorities, which give preference to particular periods during the day. Priority plans are specified for all HPPs included in the configuration, in tabular form, with preference defined by the priority level for each hour. The priority level is represented by an integer which, in the general case, can be from 1 to 24 in a 24-hour time step sequence. The goal of this mode is to arrive at an hourly plan of power unit engagement (and an overflow plan, as needed), based on specified hourly priorities which do not violate constraints and maximize power output. This, of course, implies that system inflow forecasts and initial water levels are available.



Vreme	Prioritet [-]
20/Feb/2007 6:00 AM	3
20/Feb/2007 7:00 AM	3
20/Feb/2007 8:00 AM	3
20/Feb/2007 9:00 AM	2
20/Feb/2007 10:00 AM	2
20/Feb/2007 11:00 AM	2
20/Feb/2007 12:00 PM	3
20/Feb/2007 1:00 PM	3
20/Feb/2007 2:00 PM	3
20/Feb/2007 3:00 PM	3

Vreme	Energija[MWh]
20/Feb/2007 6:00 AM	1018.362
20/Feb/2007 7:00 AM	1016.208
20/Feb/2007 8:00 AM	1014.060
20/Feb/2007 9:00 AM	685.350
20/Feb/2007 10:00 AM	676.760
20/Feb/2007 11:00 AM	786.350
20/Feb/2007 12:00 PM	1043.130
20/Feb/2007 1:00 PM	1048.758
20/Feb/2007 2:00 PM	1056.402
20/Feb/2007 3:00 PM	1058.580
20/Feb/2007 4:00 PM	1048.962
20/Feb/2007 5:00 PM	1003.320
20/Feb/2007 6:00 PM	683.200
20/Feb/2007 7:00 PM	700.390
20/Feb/2007 8:00 PM	616.600

Fig. 6   *Energy at the Djerdap 1 HPP: Serbian side*
(a: Specified priority plan - input data, b: Simulation output).

Mode 3: Explicit setting of power unit/spillway field operational parameters

This mode, which explicitly specifies operational parameters for the power units and spillway fields (e.g., power unit discharge, spillway field discharge, or individual power unit output and gate clearance of individual spillway fields), is used to repeat historic periods and to check the operation of HPP and spillway facilities, as well as to perform supplemental estimations of mathematical model parameters.

9. Conclusion

The mathematical model for hydropower estimation and operational management of the Djerdap 1 and Djerdap 2 HPP system is a complex software product which has been designed to simulate and optimize operation of Djerdap 1 and Djerdap 2 HPPs, based on pre-defined facility performance levels, initial/boundary conditions, electrical power system demands, and prescribed constraints at control profiles and facilities.

This software is expected to provide daily management support and is a means by which the outcomes of operational planning within different hydrologic, economic, legal and other frameworks can be assessed. The development and application of this software is a step toward the strategic goal: the creation of conditions for optimum water resource management and the resolution of existing and potential conflicts in the region with regard to any mis-alignment of stakeholder interests.

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