Negative Impact of Backwater Levels of Danube River and its Tributaries to the Groundwater Regime in Meliorated Riverside Areas

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NEGATIVE IMPACT OF BACKWATER LEVELS OF DANUBE RIVER AND ITS TRIBUTARIES TO THE GROUNDWATER REGIME IN MELIORATED RIVERSIDE AREAS

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Abstract: This paper describes updated calculation methodology of Danube backwater impact, occurred as a consequence of "Đerdap I" hydropower plant operation, onto the meliorated riverside areas. This methodology is based on hydrodynamic analysis of groundwater regime (size, duration, level and inflow changes) and quantification of melioration areas impairment which is caused by "Đerdap I" hydropower plant operation. By comparing the groundwater regime elements, obtained by variant hydrodynamic calculation in mathematical models for natural – not backed up and actual – backed up water level regime, and also designed backwater regime, the first step was to define boundary, size and duration of Danube backwater impact within this boundary, i.e. impact onto the piesometric levels within the analyzed meliorated areas. Then, additional inflow (size and duration) coming from water flows into previously defined impact zone was quantified and energy consumption necessary for operation and pumping of additional water quantities was determined. In the end, participation (in percentage) of hydropower plant in costs related to establishing and operation of the existing and designed area protection systems. This paper presents the calculation results for three distinctive meliorated areas affected by the Danube backwater (the Nera river-DTD channel, Ivanovo-Pančevo and Elemir-Aradac). The presented methodology, besides defining and quantifying the impact of "Đerdap I" hydropower plant, may be applied for system selection and optimization of riverside melioration area protection, and for presentation of adequate response to a very sensitive issue concerning objective share estimation of relevant participants in protection cost of all melioration areas under the influence of the hydropower plant backwater.

Keywords: HPP "Djerdap 1"; backwater influence; groundwater regime; hydrodynamic analysis; melioration area; drainage system; additional energy engagement

INTRODUCTION

After construction and commissioning of the "Đerdap I" hydropower plant in 1972, water level of Danube river and its tributaries (the Sava and the Tisa rivers) backed up, which caused increase of groundwater level and additional (extended) impairment of melioration areas in riverside areas of these rivers (Figure 1).

When considering operation of „Đerdap I" hydropower plant, since commissioning until present, three operating regimes, i.e. exploitation regimes may be selected: regime "68/63" (1972-1977), regime "69.5/63" (1977-1985), regime "69.5 and higher", i.e. "up to level 70.30 mnm" (1985 – until present). For lower backwater levels, in the period until 1985, negative impact of Danube backwater level propagated exclusively in the riverside area, downstream from Belgrade. When „Đerdap I" hydropower plant operation transferred to the higher backwater levels, since 1985, this negative impact included the significant part of Danube riverside, with propagation upstream to Novi Sad, and significant part of coastal area of its largest and most important tributaries – the Sava and Tisa rivers (Fig 1). Presently, the actual backwater regime is "69.5 and higher" regime, i.e. "up to level 70.30 mnm" and melioration areas in the Danube riverside are under the negative impact of „Đerdap I" hydropower plant – from the hydropower plant (km 943+000) to Novi Sad (km1255+100), then melioration

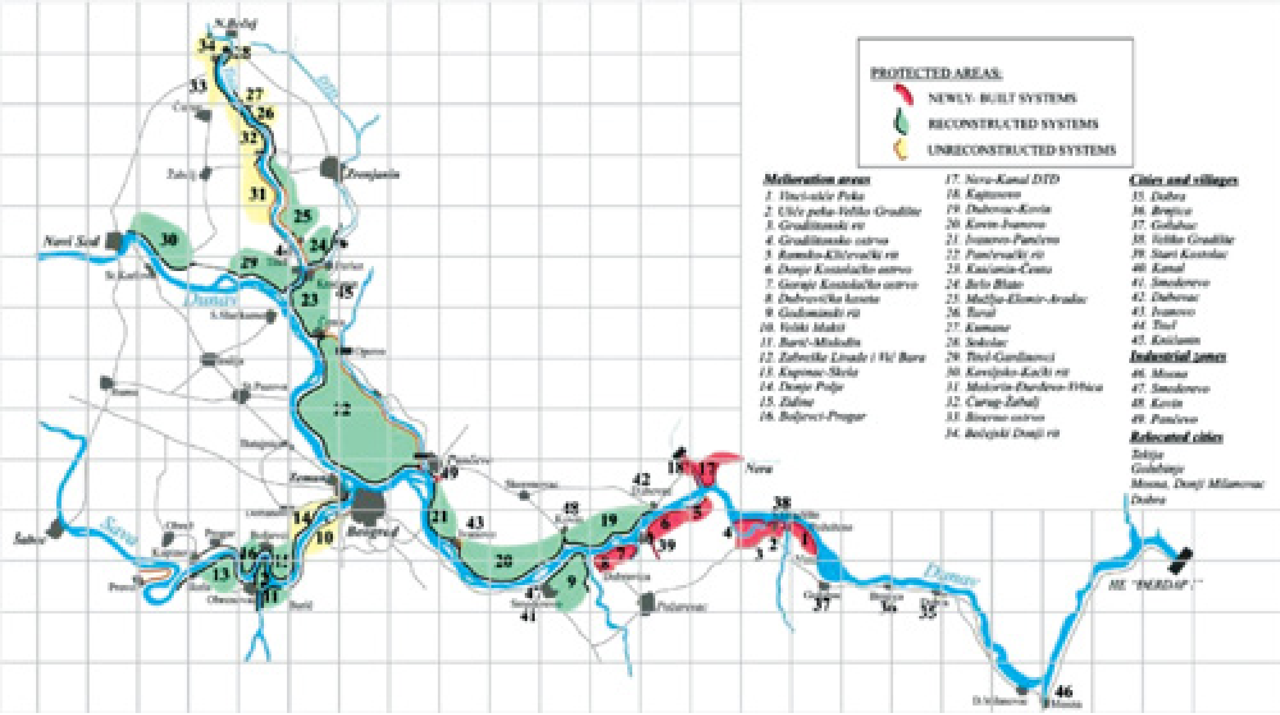

Figure 1: Melioration areas under the Danube backwater negative impact for the present operating regime of the HPP “Đerdap I” (”69.6 and higher, up to the 70.30 masl”)

areas in the Sava riverside – from the confluence into the Danube to Šabac (km 105+100), and also melioration areas in the Tisa riverside – from the confluence into Danube to Novi Bečej (km 60+850).

Prior to construction of hydropower plant and backwater formation (1972), melioration areas in riverside areas of the Danube and its tributaries were mostly impaired by high groundwater levels only under extremely unfavorable hydrological conditions – long-term high water levels. In the beginning, these melioration areas were mostly protected only by dewatering system for agricultural areas, and later by established protection system for external and internal waters (protective embankments along the water flows, open, shallow channel network inside the territory with pumping stations, and other). By transferring to the higher Danube backwater regimes, the existing system mostly proved as insufficient, i.e. inefficient system. The new systems were established and the old ones were subsequently refurbished and upgraded to fulfill the newly set and more strict criteria for protection of these melioration areas.

APPLIED METHODOLOGY

The presented calculation methodology for Danube backwater impact is based on hydrodynamic analysis of groundwater regime and quantification of area impairment caused by Đerdap I hydro power plant operation. Hydrodynamic analysis included preparation of mathematical models of groundwater flows (plane and cross-section) in unsteady filtration conditions, for the period from 1985 until 2011, for natural – not backed up and observed – backed up, and also designed – Danube backwater levels. The applied methodology is based on numerical – engineering solution for partial differential equation system which define flow in two-layer porous media. The engineering solution of unsteady flow differential equations consists of approximation of unsteady state of the flow process with a series of steady motions with finite time interval Δt. Theoretical bases are well known to the engineering public and thus here shall not be presented in detail.

Input data for conducting mathematical modeling are: monitored water levels of Danube and its tributaries, simulated in conditions prior to hydropower plant construction and commissioning, and calculated designed water levels of Danube and its tributaries; water levels (monitored and designed) in pumping stations of drainage system, monitored groundwater levels in the existing piesometric network at the observed area; elements of vertical balance (effective infiltration and evapo-transpiration) etc., and other results of previous and newly purpose made investigations. Spreading and discretization of mathematical models are defined based on natural and adopted hydrodynamic boundaries of mathematical models. Data on spreading and hydrogeological properties of basic and surface low-permeable layer are obtained by data interpretation gained from structural and piesometric boreholes and wells and from results of other purpose-designed investigations (aquifer geometry (terrain level, layer boundaries and thickness, etc.), hydraulic conductivity, porosity, specific yield, etc.). Depending on available data for certain area, time discretization (calculation step) accounts for 7 days or 30 days for the period from 1985 to 2011.

Calculations were conducted on formed mathematic 2D and 3D models for the following boundary conditions:

- For natural Danube water levels, for conditions that would have been created if there had not been "Đerdap I hydropower plant backwater and formation of protective system;
- For natural Danube water levels, for conditions that would have been created if there had not been "Đerdap I" hydropower plant backwater with drainage system operation simulation in designed and monitored regime,
- For monitored Danube water levels and water levels designed for backwater regime "up to level 70.30 mnm at the Nera river confluence", without drainage system operation,
- For designed Danube water levels in backwater regime "up to level 70.30 mnm at the Nera river confluence" and drainage system operation as per design,
- For monitored Danube water levels in backwater regime "up to level 70.30 at the Nera confluence" and monitored operation of drainage system.

According to performed hydrodynamic calculations, calibration and verification of mathematical models, valid results are obtained in the form of groundwater level fluctuation and duration, groundwater flow fluctuation and duration through water-bearing layer by sections of calculation profiles, for the named conditions, and in the form of groundwater inflow into drainage channels and pumping stations.

By comparing obtained results (fluctuation and duration of level and flow) of groundwater regime for named boundary conditions (natural and monitored Danube levels), an impact boundary of "Đerdap I" hydropower plant onto analyzed meliorated areas was set within such defined boundary. This boundary of "Đerdap I" hydropower plant backwater impact was defined as part of the area where achieved and natural groundwater levels (and flows) equalize, in the named Danube water level conditions and for the same (identical) conditions of area regulation (with or without protection system). Further, a zone is analyzed within melioration areas where groundwater level are observed to be higher than designed, in order to define the efficiency of the existing drainage systems for different durations (10% and 50% duration).

Also, the amount (percentage) of impact was determined for "Đerdap I" hydropower plant backwater onto the analyzed meliorated areas. "Đerdap I" hydropower plant operation and backwater formation caused increase of groundwater inflow into the observed meliorated areas. This inflow increase, within the previously defined backwater impact zone boundary, expressed in percentage in relation to the natural status, is also defined by calculations in mathematical model, for the characteristic levels of area regulation and different boundary conditions of Danube and Tisa river water level. Share coefficient of increased inflow (for monitored and designed conditions in reservoir) is equal to:

$$K_Q^{monitored} = \frac{Q_{monitored\_river} - Q_{natural\_river}^{monitored\_system\_operation}}{Q_{observedriver}} \tag{1}$$

$$K_Q^{designed} = \frac{Q_{designed\_river} - Q_{natural\_river}^{designed\_system\_operation}}{Q_{natural\quad river}} \tag{2}$$

In the presence of "Đerdap I" hydropower plant backwater, due to increase water inflow from the river into the water-bearing medium and increased suction lift during pumping, in relation to natural regime, pumping stations operate more intensively at the observed meliorattion areas. The calculation results of groundwater inflow in the named conditions were firstly used for power calculation, and then energy necessary for water evacuation from the area during different river water level regimes and operation of the existing systems. Simplified equation (Vuković and Soro) for power necessary for pumping of waters inflowing to the pumping stations:

$$E = 15\ x\ Q\ x\ (\Delta H + \xi)\ x\ t \tag{3}$$

where is: Q - flow or quantity of pumped water (m^3/s), ΔH - difference between water level in Danube and water level in channel in pumping station (m), ξ - hydraulic loss, t - time (s)

Energy is calculated as a product of calculated necessary power and total number of hours in calculation interval. In the end, participation (in percentage) of "Đerdap I" hydropower plant in total used energy for water evacuation from the area during different river water level regimes and operation of existing systems was defined. Share coefficient of increased energy consumption (for monitored and designed conditions in reservoir) is equal to:

$$K_E^{observed} = \frac{E_{monitored\_river} - E_{natural\_river}^{monitored\_system\_operation}}{E_{omonitored \quad river}} \tag{4}$$

$$K_E^{designed} = \frac{E_{designed\_river} - E_{natural\_river}^{designed\_system\_operation}}{E_{designed\_river}} \tag{5}$$

RESULTS AND DISCUSSION

Restricted by the paper itself, the following areas have been selected as representative examples for considering the presented upgraded calculation methodology for Danube backwater impact onto the riverside meliorated areas from the stated aspects: Nera river – DTD channel, on Danube river (No. 19, Fig. 1), as area closest to the Đerdap I hydropower plant; Ivanovo – Pančevo, on Danube river (No. 21, Fig. 1), as area in the middle of Đerdap I hydropower plant backwater impact; Elemir –Aradac, on Tisa river (No. 25, Fig. 1), as area at the longest distance from "Đerdap I" hydropower plant.

Results of the conducted groundwater flow mathematical modeling are presented in Table 1 for piesometric levels of characteristic duration of 10% and 50% along the calculation profiles for the period from 1985 until 2011.

River regime			Melioration area		
			Nera – Kanal DTD	Ivanovo – Pancevo	Elemir – Aradac
Reservoir backwater	Backwater regime	Water level duration	Elevation (mnm)	Elevation (mnm)	Elevation (mnm)
Non-retarded	Natural	10%	68.2 -68.5	70.0 -70.4	73.2 -74.0
		50%	66.8 -68.0	68.8 -69.0	72.2
Retarded	Monitored	10%	68.5 -70.0	68.8 -70.2	73.4 -74.2
		50%	68.0 -69.8	68.2 -69.5	72.4 -72.7
	Designed	10%	66.5 -70.0	68.8 -70.2	73.4 -74.2
		50%	66.5 -69.8	68.2 -69.5	72.4 -72.7

Table 1. Piesometric level values in riparian parts of chosen melioration areas (between river dikes and the first drainage line), for different regimes of the Danube and its tributaries, for calculation period 1985-2011.

By analyzing the monitored and calculated groundwater regime with Danube water level changes within the investigated melioration areas, the areas with characteristic conditions for groundwater regime formation may be observed: riverside area, internal (protected) part of the areas and area along the hinterland. In riverside parts of melioration areas, surface water level changes have dominant impact onto the groundwater level change, and then effects of the area protection drainage system operation. In the internal (protected) are of melioration area, the most significant impact on groundwater levels have effects of drainage system operation and vertical balance parameters. The operation of drainage system within Danube backwater level conditions not only eliminates harmful effect of backwater, but provides favorable groundwater regime in the most part of the area and decreases their impairment, which further reflects on damage decrease and provision of better conditions for agricultural production (Pajić and Urošević, 2012). In part of melioration areas along the hinterland, dominant impact is taken over by groundwater inflow from the direction of hypsometrical higher terrains.

According to the calculation result analysis of groundwater regime (groundwater level fluctuation and their flow through water-bearing layer), position of backwater impact boundary was defined for different conditions in Đerdap reservoir. Backwater impact boundary can be defined for not backed and backed water regime in the river and for the same conditions of area protection. Figure 2 presents an example of defining backwater impact boundary in the area profile Nera river – DTD channel.

In melioration area Nera river – DTD channel, backwater impact boundary spreads in parallel to DTD channel, at the distance of 0.8 to 1.5 km and in parallel to Danube river, at distance of 1.5 to 1.8 km to Nera river, at melioration area Ivanovo – Pančevo spreads in parallel to the Danube river, at distance of 3.0 to 4.0 km from the river, and in melioration area Elemir – Aradac, it is parallel to Tisa river, at distance of 1.5 to 2.5 km from the river.

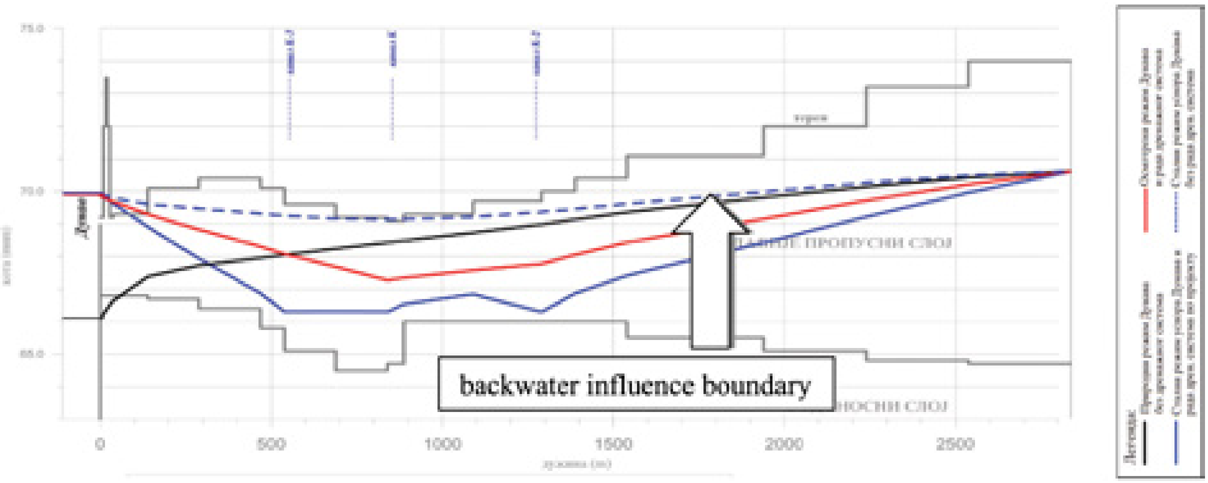

Figure 2: 50 % duration groundwater level lines, for different reservoir, area protection and backwater influence boundary conditions, calculated for the Nera-kanal DTD area profile.

Analysis of calculation results in mathematical model shows that groundwater inflow into pumping stations increases in backwaters, for monitored and designed regime, in relation to natural regime, which is a consequence of increased Danube water levels and their prolonged duration. By comparing the results of groundwater inflow for named conditions in Danube river and area protection system operation effects, values of participation of increased calculation inflows due to backwater are calculated as total inflow to pumping stations in the selected melioration areas. Table 2 shows the participation coefficient of increased calculation inflows due to backwater in total inflow into pumping stations of the selected meliorated areas (as per formulas 1 and 2), for the period from 1985 to 2011. It may be concluded that in downstream melioration areas, which are closer to "Đerdap I" hydropower plant, where river backwaters are more significant, share coefficient of increased calculated inflows due to backwater is higher within the total inflow into pumping stations; and vice versa.

According to the mathematical model results, energy necessary for groundwater evacuation from selected melioration areas is calculated, for Danube natural and backed up water levels and monitored and designed operation regime of drainage protection systems (Table 3). Calculation result analysis in mathematical model shows that in backed up conditions, for monitored and designed regime, due to increased groundwater inflow into pumping stations, in relation to natural regime, electricity consumption increases to order to pump the groundwater into the recipient. Table 3 shows participation coefficient of increased energy consumption due to backwater in total consumption for evacuation of collected groundwater in pumping stations in the meliorated areas (as per formulas 4 and 5), in calculation period from 1985 until 2011. In downstream melioration areas, due to larger Danube backing up, the share coefficient of increased calculation energy consumption in total energy consumption in pumping stations is higher, and vice versa.

Analysis of all calculation results of groundwater flow simulation at selected melioration areas in the named conditions quantifies impact of "Đerdap I" hydropower plant backwaters onto the groundwater regime formation. "Đerdap I" hydropower plant backwater impact within the defined spreading boundary is defined according to evaluation coefficient of backwater impact. The evaluation coefficient of "Đerdap I" hydropower plant backwater onto the groundwater regime formation in meliorated areas is proportional to average monthly participation (share) of energy consumption in total energy consumption for groundwater evacuation in the

Melioration area (pumping station)	River regime	Drainage system regime	Groundwater inflow (m^3/s)	Share of increased in total inflow, due to the backwater effect (-) (1)	(2)
Nera – Kanal DTD (Karaš 1)	natural	designed	0.52	0.74	0.91
		monitored	0.08		
	designed	designed	2.03		
	monitored	monitored	0.94		
Ivanovo – Pancevo (Marijino polje) (Ist drainage line /basin)	natural	designed	0.16 (0.26)	0.47 (0.22)	0.48 (0.37)
		monitored	0.12 (0.18)		
	designed	designed	0.30 (0.41)		
	monitored	monitored	0.23 (0.20)		
Elemir – Aradac (Elemir – Aradac (4-5)) (1st drainage line /basin)	natural	designed	0.11 (0.18)	0.21 (0.15)	0.19 (0.13)
		monitored	0.11 (0.17)		
	designed	designed	0.14 (0.20)		
	monitored	monitored	0.14 (0.20)		

Table 2. Average monthly groundwater inflow and the share coefficient of increased calculated inflow in total groundwater inflow for the chosen melioration area pumping stations.

monitored backwater and area protection conditions.

Melioration area (pumping station)	River regime	Drainage system regime	Energy consumption E(MWh)	Share of increased in total energy consumption (-) (4)	Share of increased in total energy consumption (-) (5)
Nera – Kanal DTD (Karaš 1)	natural	designed	13.9	0.87	0.94
	natural	observed	3.0		
	designed	designed	105.7		
	observed	observed	48.5		
Ivanovo – Pancevo (Marijino polje) (Ist drainage line /basin)	natural	designed	7.8 (11.2)	0.49 (0.49)	0.50 (0.51)
	natural	observed	5.5 (7.6)		
	designed	designed	15.2 (21.6)		
	observed	observed	11.0 (15.6)		
Elemir – Aradac (Elemir – Aradac (4-5)) (1st drainage line /basin)	natural	designed	(2.5) 5.1	0.22 (0.19)	0.22 (0.17)
	natural	observed	(2,5) 5.1		
	designed	designed	(3.2) 6.3		
	observed	observed	(3.2) 6.3		

Table 3. Average mouthy energy consumption and the share coefficient of increased calculated inflow in total groundwater inflow for the chosen melioration area pumping stations.

CONCLUSION

This paper presents updated methodology calculation of (negative) backwater impact, on the example of three melioration areas on the Danube and the Tisa riverside, which is based on hydrodynamic analysis of groundwater regime and quantification of observed melioration areas impairment. By comparing groundwater regime, obtained by variant hydrodynamic calculations in mathematical models for natural, not backed up, and actual (monitored and designed) backwater regime, boundary and impact size are defined for Danube backwater within this boundary, introducing additional groundwater quantities and additional energy necessary for pumping additional groundwater quantities, formed as a consequence of the before mentioned backwaters.

The presented methodology, beside the fact that it defines and quantifies the “Đerdap I” hydropower plant backwater impact, may serve as valid response to very sensitive question of objective share estimation of relevant participants in cost of protection of all meliorated areas under the backwater impact of the named hydropower plant, according to the share (in percentage) defined by presented methodology of backwater impact evaluation. Apart from that, the presented methodology is practical and universal as it can be applied for all other melioration areas in the riverside of the Danube and its tributaries, and with (possible) smaller adjustments to the actual conditions, to all other examples where similar natural and/or artificial conditions are present essential for backwater formation in water flow.

REFERENCES

Alldredge, B., Moore G., 2012. : Assessment of Riparian Vegetation Sensitivity to River Hydrology Downstream of a Major Texas Dam. River Research and Applications, doi: 10.1002/rra.2625.

Anđelić L., Pajić P., Urošević U., 2012. : The Influence of the HPP „Djerdap 1“ on Vulnerability of Melioration Areas on the Left Bank of the Tisa River, Due to High Groundwater Levels, YWP, Budapest, Hungary, ISBN 978-963-87507-8-5, IWA-9802

Dimkić M., Brauch H. J., Kavanaugh M., 2008. : Groundwater Management in Large River Basins, Water Science and Technology, ISBN: 9781843391906

Institute for the Development of Water Resources “Jaroslav Černi” Belgrade, 2012. “Expert consult on the building conditions and the effects of coastal protection of HPP “Đerdap I"”; Vol. 1: Backwaters for different regimes of HPP "Djerdap I"

Institute for the Development of Water Resources “Jaroslav Černi” Belgrade, 2012. “Expert consult on the building condition and the effects of coastal protection of HPP “Đerdap I"”; Vol. 9: Protection against the impact of the HPP "Đerdap I" Backwater on the groundwater regime

Li R., Chen Q., Mynett A., Wu S., Wang H., 2009. : Modeling of the Flow Changes Due to Reservoir Operations and the Impacts on Aquatic Ecosystem Downstream, Advances in Water Resources and Hydraulic Engineering”

Pajić P., Anđelić L., Urošević U., Radovanović M., 2012. : Assessment of Vulnerability and Damage Caused to the Agricultural Production on the Area of Veliko Selo by the High Level of Groundwater on Account of the Performance of Hydroelectric Power Plant “Đerdap I”, 5th Conference on Water, Climate and Environment-BALWOIS 2012, Ohrid, Republic of Macedonia, ISBN 978-608-4510-10-9.

Pušić M., Dimkić M., 2008. : Mathematical modeling, a tool for groundwater regime management, Groundwater Management in Large River Basins, Chapter 5, pp. 457-519, IWA Publishing Alliance House, London, UK, ISBN: 1843391902.