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EFFECT OF RESERVOIR ON FLOODWAVE TRANSFORMATION

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Abstract: Reservoir effects on floodwave transformation were calculated based on the concrete research. The procedure was based on the definitions of the distribution of inflow and outflow hydrograph time bases. The inflow-outflow hydrograph was divided into time intervals. The volume of inflow water in the reservoir was calculated for each interval, as well as the volume of water released from the reservoir. Lag time was calculated as the time between peak inflow to the reservoir and peak outflow from it at the spillway. The study analysis can be used as a guideline for the calculation of correct dimensions and the protection of earthfill dams from overtopping. In this way, especially in earthfill dams, a significant saving of material incorporated in the spillway parts is achieved, and general stability of earthfill dams is ensured. Based on the conducted research, it can be concluded that there is a transformation of the inflow floodwave through the reservoir. In the case when the reservoir is full, i.e. the elevation of water level in the reservoir at the moment of floodwave arrival is at the elevation of the spillway crest, the reduction rate of the outflow hydrograph is 25, 73%. Calculation is possible only based on the volume method or reservoir filling within a given time period. The increase in the water level at the spillway is in the function of inflow-outflow volume of water and the surface of water table in the reservoir.

Key words: floodwave transformation, hydrograph parameters, floodwave volume, time intervals.

1. INTRODUCTION

The construction of earthfill dams in hilly and mountainous areas creates the conditions for multipurpose use of stored water. The prerequisite of safe reservoir operation is the safe evacuation of surplus (overflow) water from the reservoir. This can be achieved by spillways - emergency, shaft, frontal, etc. (Figs 1, 2, 3). Spillway dimensions are of high significance. A spillway should ensure the safe use of dam and reservoir, as well as more cost-effective prices compared to the cost of the dam with other installations and equipment. In this aim, spillway dimensions should ensure the safe dam and reservoir utilisation, and prevent the overtopping of flood water over the dam crest.

Within the scope of integral catchment management, micro-reservoirs are some of the most significant elements of water management, (Teodor & Matreata, 2011).

Reservoirs are indispensable factors in the mitigation of drought consequences and flood and erosion impacts in the drainage basins and river channels (Letić, Gajić & Đeković, 2008). As during peak floodwaves about 90% of catchment water runs off, it is only the reservoirs that are capable of retaining the floodawave and turning the harmful flood water (in the initial phase) into valuable reserves of water for various demands. As a rule, small dams and reservoirs should be constructed in small watercourses, and large dams and reservoirs on large rivers (Mihajlović, 1985).

The time required by the inflow wave to pass from the reservoir inflow profile to the spillway crest is denoted as the lag time. As the reservoirs are most often built for multiple purposes, one of the objectives is flood protection in the downstream reach (Đeković, 1997).

Active protection depends on the spillway type and the reservoir dispatcher plan. Reservoirs with uncontrolled spillway are not always suitable for the outflow wave transformation. The maximal ordinate of the outflow hydrograph (outflow wave) is critical for the design of spillway parts. This is especially relevant in small reservoirs and micro-retentions made of incoherent materials (earthfill dams).

Figure 1. Emergency spillway; earthfill dam in the Barajevska Reka drainage basin (Photo: Đeković, 2011)

Figure 2. Shaft spillway on the dam Prvonek (Photo: Anđelković, 2010).

The dam and reservoir construction creates the conditions for floodwave retention in the reservoir and its retardation on the water table surface, i.e. reservoir impoundment (Prokić, 2002).

In earthfill dams, water spilling over the dam crest should be prevented because of the risk of dam erosion and dam failure with unforeseen consequences for the downstream section of the drainage basin (Berga, 2000).

For this reason, in practice, most often the spillway organs are designed for the discharge of design flood water, without taking into account the reservoir effect on floodwave transformation. In such conditions, very often, spillway parts are multiply oversized and consequently the construction price of such spillways exceeds many times the overall construction price of the dam and reservoir. To address this problem adequately, the complete physical process of water movement through the reservoir should be taken into account including the effect of spillway on the degree of the wave retardation, (Kolaković, 1994).

The theoretical estimation of the reservoir effect on the inflow flood retardation is important in high barrages (dams), because of the significance of the water table area at the spillway crest level. If spillways are supplied with segment gates (Fig. 3), the reservoir volume can be multiply increased at the time of peak inflow and almost entire floodwave can be retained without water overtopping, (Prokić, 2003).

2. MATERIALS AND METHODS

The dam and reservoir research was performed in the drainage basin of the river Krčevica, at the dam "Nenadovac" using the physical model method and the theory of the design floodwave movement through a full reservoir. In such conditions, the reservoir was filled and the floodwave was retarded. The lag time also depended on the water table area at the elevation of the spillway crest.

The following methods were applied:

- method of modelling the physical process of water movement through the reservoir (using analytical and graphical methods of modelling);
- methods of experimental investigation;
- comparison methods.

This study was based on the hydrological analyses of the Krčevica drainage basin in the Barajevska Reka drainage basin, the river Kolubara drainage basin in the vicinity of Belgrade, and also on the analysis of the topographic situation in the drainage basin before the dam profile "Nenadovac" (Đeković, 2006).

3. RESULTS AND DISCUSSION

The analysis was based on the division of the time base inflow hydrograph into time intervals (Δt) and the calculation of total volume of inflow water (Wsr.ul) (Table 1). The analysis of floodwave transformation requires also some additional data, such as morphology of the reservoir basin, length of water table from the spillway to inflow profile of the main stream, and the Diagram of the reservoir area (Fig. 4). The lag time of flood water in the spillway is defined (Table 1) based on the known inflow hydrographs and the volume of inflow water (Fig. 6). The design of spillway, collection drain, channel and stilling pool is based on the maximal ordinate of the outflow hydrograph (Fig. 6). The initial material for this study was the hydrological analysis database on the drainage basin of the river Krčevica at the profile "Nenadovac", which were used for the design of the micro-reservoir of the same name, as well as the morphological analyses of the reservoir basin and the adopted type of "emergency" spillway (Fig. 1) (Đeković, 2006).

The study includes the analysis of the conditions of reservoir filling after dam erection and formation of emergency spillway (Fig. 1), without the possibility of establishing active gate control. The main conditions for the design of such reservoirs are good inflow hydrological and morphological data. This paper focuses on spillway dimension issues, and on the effect of reservoir on floodwave retardation (Đeković, 1997).

Figure 3. Segment gates in the spillway; Potpeć dam (Photo: Đeković, 2011)

In the case when at the moment of floodwave arrival, water level in the reservoir is at the elevation of the spillway crest (full reservoir), water depth in the spillway is calculated based on the volume method and the water retardation velocity (Table 1). Lag time is defined as the time lapse between peak inflow to the reservoir and peak outflow from it at the spillway. The depth of water above the dam spillway is calculated by the formula:

$$Hp = \frac{\Sigma Wsr.ul - \Sigma Wsr.iz}{A}, \qquad (1)$$ where:

Hp - maximal water depth in the reservoir above the elevation of spillway crest;

$\sum Wsr.ul$ – total quantity of water entering the reservoir till that time;

$\sum Wsr.iz$ - quantity of water evacuated over the spillway crest;

A - water table surface area at the elevation of water level in the reservoir (Fig. 4).

In the reservoirs which are not supplied with the spillway gates, i.e. in the uncontrolled spillways, (Figs. 1 and 2), floodwave retardation is not appropriate, (Kolaković & Hajdin, 1997).

The retention of the maximum floodwave volume (Fig. 5) requires a good cooperation of the reservoir dispatcher and the synoptic service (rainfall forecast). In the event of storm precipitation forecast, it is possible to lower the reservoir water level. Before the storm beginning, a space should be left in the reservoir to accept the peak inflow (Fig. 7). Good inflow data must be provided to ensure a correct calculation, e.g.:

Figure 4. Spillway in the dam Kokin Brod; water level at the elevation of spillway crest (Photo: Đeković, 2010)

- precise geodetic data (river valley upstream of the dam profile), with the terrain elevations;
- water level in the reservoir at the moment of peak inflow;
- water level in spillway crest (Fig. 5) and the reservoir surface area at the elevation of spillway crest;
- maximal backwater elevation in the reservoir;
- curve of the reservoir basin area, calculated by planimetry of isohypses to the dam crest elevation (Fig. 4);
- inflow floodwave hydrograph, based on hydrometric measurement at the hydrological station or by parameter hydrology methods (Fig. 6);
- time base hydrograph (Fig. 6);
- spillway characteristics of the dam
- (spillway dimensions), width and maximal water depth in spillway.

As the method is based on the discharge of the total floodwave volume through the reservoir, water level in the reservoir is horizontal, and water velocities through the reservoir are decreased and ranging in the zone of a steady regime. It is concluded that the reduced rate of water movement through the reservoir lead to the changes in the outflow hydrograph time base. The problem should be solved tabularly, by dividing the inflow and outflow hydrograph time bases into time intervals *Δt* (Table 1). In this way, if at the moment of peak inflow the reservoir water level is at the elevation of spillway crest, the discharge of maximal water in the outflow hydrograph is reduced compared to the inflow hydrograph. As the entire water volume which entered the reservoir through the spillway has to be released, much lower spillway sizes are necessary, which justifies the analysis of floodwave transformation through the reservoir (Telford, 1996).

Figure 5. Frontal sinusoidal spillway, Dam Kokin Brod (Photo: Đeković, 2008)

Time base of the floodwave inflow hydrograph in this study was divided into time intervals of 10 minutes each, and water discharge was read from the hydrograph ordinate. In the subsequent procedure, inflow water quantity was calculated for the design time interval and also lag time till the period of floodwave outflow at the spillway. Based on tabular analysis, peak flow lag time at the spillway was 50 min. water discharged over the spillway was calculated by the overtopping equation:

$$Q\max = m \cdot b \cdot \sqrt{2 \cdot g} \cdot Hp^{\frac{2}{3}}, \quad (2)$$

where:

Q_{max} – maximal ordinate of outflow hydrograph ($m \cdot s^{-1}$);

m – overtopping coefficient;

b – width of spillway edge (m^{-1});

$\sqrt{2 \cdot g}$ – acceleration of gravity ($m \cdot s^{-1}$);

H_P – water depth in spillway (m^{-1}).

The volume of outflow water from the reservoir was determined and outflow hydrograph was developed based on the defined water depth in the spillway (Chauhan & Bowles 2003).

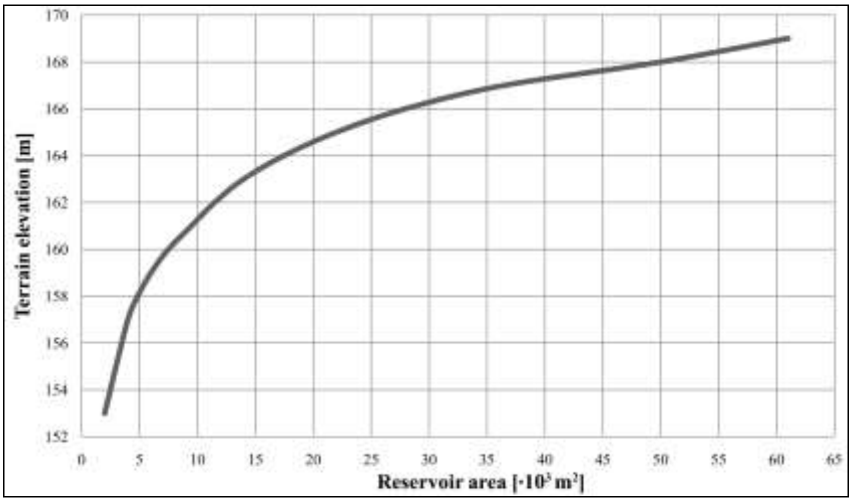

Figure 6. Curve of the reservoir area ”Nenadovac”. (Source: original)

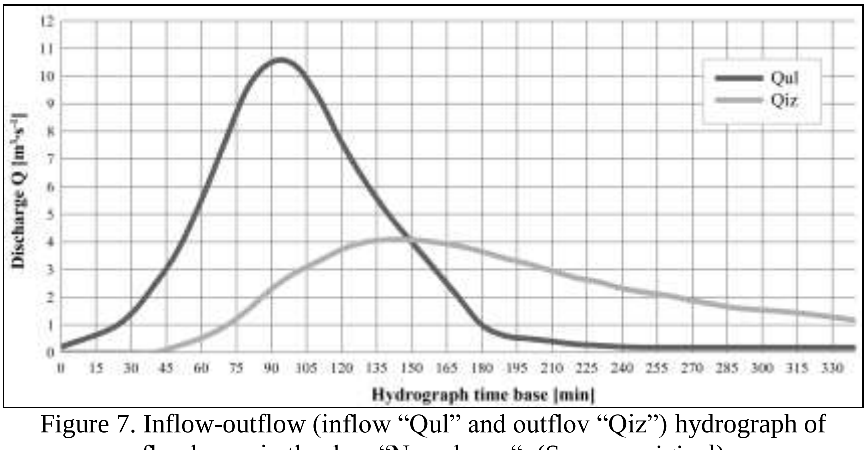

Figure 7. Inflow-outflow (inflow “Qul” and outflov “Qiz”) hydrograph of floodwave in the dam “Nenadovac“. (Source: original)

The quantity of water which outflows from the reservoir must be equal to the volume of water reaching the reservoir, under the condition that water level at the moment of floodwave arrival was at the elevation of the spillway crest. The time base of the outflow hydrograph was much longer than the time base of the inflow hydrograph (Fig. 2). This is understandable, because it is the case of slow movement of water through the reservoir and the floodwave retardation over the entire water area.

4. CONCLUSIONS

Based on the study analysis, it can be concluded that there was a significant transformation of outflow hydrograph, i.e.:

1. Outflow hydrograph maximal ordinate decreased compared to inflow hydrograph by 58%, (maximal inflow hydrograph ordinate $Q=10.50$ ($m^3 \cdot s^{-1}$), and outflow ordinate $Q=4.08$ ($m^3 \cdot s^{-1}$));

2. Lag time in the spillway

Table 1. Calculation of outflow hydrograph retardation, results of the analysis (Source: original).

[min⁻¹]	*Qul* $[m^3 \cdot s^{-1}]$	*Qsr* $[m^3 \cdot s^{-1}]$	*Δt* $[s^{-1}]$	*Wul* $[m^3]$	*Wsrul* $[m^3]$	*ΣWsrul* $[m^3]$	*Hp* $[m^{-1}]$	*Qp* $[m^3 \cdot s^{-1}]$	*Δt* $[s^{-1}]$	*Wiz* $[m^3]$	*Wsriz* $[m^3]$	*Σwsriz* $[m^3]$
0	0.10				90	90	0.00	0.00	600	0.00		
		0.15	600	90							0.00	0.00
10	0.20				195	285	0.00	0.00	600	0.00		
		0.50	600	300							0.00	0.00
20	0.80				480	765	0.00	0.00	600	0.00		
		1.10	600	660							0.00	0.00
30	1.40				907	1675	0.00	0.00	600	0.00		
		1.925	600	1155							0.00	0.00
40	2.45				1500	3175	0.00	0.00	600	0.00		
		3.075	600	1845							70.5	70.5
50	3.70				2302	5477	0.10	0.23	600	141		
		4.60	600	2760							227	297
60	5.50				3345	8822	0.17	0.52	600	312		
		6.55	600	3930							435	732
70	7.60				4545	13367	0.25	0.93	600	558		
		8.60	600	5160							741	1473
80	9.60				5595	18962	0.35	1.54	600	924		
		10.05	600	6030							1200	2673
90	10.50				6150	25112	0.45	2.46	600	1476		
		10.45	600	6270							1599	4272
100	10.40				6083	31195	0.53	2.87	600	1722		
		9.825	600	5895							1821	6093
110	9.25				5475	36670	0.57	3.20	600	1921		
		8.425	600	5055							2077	8170
120	7.60				4597	41267	0.63	3.72	600	2232		
		6.90	600	4140							2313	10483
130	6.20				3750	45017	0.66	3.99	600	2394		
		5.60	600	3360							2421	12904
140	5.00				3030	48047	0.67	4.08	600	2448		
		4.50	600	2700							2448	15352
150	4.00				2400	50447	0.67	4.08	600	2448		
		3.50	600	2100							2421	17773
160	3.00				1867	52315	0.66	3.99	600	2393		
		2.725	600	1635							2366	20139
170	2.45				1153	53468	0.65	3.90	600	2340		
		1.12	600	672							2249	22388
180	0.90				561	54029	0.62	3.60	600	2159		
		0.75	600	450							2128	24516
190	0.60				390	54419	0.60	3.49	600	2097		
		0.55	600	330							2009	26525
200	0.50				300	54719	0.57	3.20	600	1921		
		0.45	600	270							1845	28370
210	0.40				240	54959	0.54	2.95	600	1770		
		0.35	600	210							1698	30068
220	0.30				187	55146	0.51	2.71	600	1626		
		0.275	600	165							1578	31646
230	0.25				150	55296	0.49	2.55	600	1530		
		0.225	600	135							1462	33107
240	0.20				125	55421	0.46	2.32	600	1393		
		0.19	600	114							1348	34455
250	0.18				111	55532	0.44	2.17	600	1303		
		0.18	600	108							1267	35722
260	0.18				108	55640	0.42	2.05	600	1231		
		0.18	600	108							1181	36903
270	0.18				108	55748	0.40	1.88	600	1132		
		0.18	600	108							1085	37988

280	0.18				108	55856	0.38	1.73	600	1038		
		0.18	600	108							1000	38988
290	0.18				108	55964	0.36	1.60	600	962		
		0.18	600	108							923	39911
300	0.18				108	56072	0.34	1.47	600	885		
		0.18	600	108							856	40768
310	018				108	56180	0.32	1.38	600	828		
		0.18	600	108							800	41568
320	0.18				108	56288	0.31	1.28	600	772		
		0.18	600	108							734	42302
330	0.18				108	56396	0.29	1.16	600	697		
		0.18	600	108								

t – hydrograph time base divided into time intervals (min^{-1});
Qul – data on inflow hydrograph, for each time interval (m^{3}·s^{-1});
Qsr – mean value of inflow discharge (m^{3}·s^{-1});
Δt – time interval between hydrograph ordinates in seconds (s^{-1});
Wul – water volume which inflows within a time interval (m^{3});
Wsr.ul – mean volume (m^{3});
ΣWsr.iz – total inflow (m^{3});
Hp – water depth in the reservoir above the spillway elevation $Hp = \frac{\Sigma Wsr.ul - \Sigma Wsr.iz}{A}$ *(m^{-1});*
Qp – outflow $Qp = m \cdot b \cdot \sqrt{2 \cdot g} \cdot Hp^{\frac{2}{3}}$ *(m^{3}·s^{-1});*
A- water table surface area (m2), at the elevation of water level in the reservoir in the time interval (Δt);
Wiz – volume of discharged water (m^{3});
Wsr.iz – mean volume of discharged water (m^{3});
ΣWsr.iz – total volume of discharged water from the reservoir (m^{3}).

from the moment of water arrival to the reservoir was 50 minutes, simultaneously, the reservoir was filled with W=5477m^3, without any overtopping or outflow from the reservoir or with minimal outflow;

3. Spillway dimensions can be corrected for the discharge of peak water (*Q=4.08* (*m^3·s^{-1}*)), which reduces the price of the spillway by about 58%;

4. This analysis is fully justified when spillways with segment (active) gates are applied.

The application of such analysis is feasible and it can be a guideline for the correct design and protection of earthfill dams against water overtopping the dam body. By this method, especially in earthfill dams, a significant part of material built in spillway parts can be saved, and at the same time general stability of earthfill dams is increased.

REFERENCES

Berga, L., 2000. *Dams and floods*, Polytechnical University of Barcelona, Spain, ICOLD, 5-10.

Chauhan, S.S., & Bowles, D.S., 2003. *Dam Safety Risk Assessment with Uncertainty Analysis*, ICOLD Launceston, Tasmania Australia, 1-17.

Đeković, V., 1997. *Design in Torrent Management*, University Textbook, ISSN 86-7299-045-5, Faculty of Forestry Belgrade, 1-264.

Đeković, V. 2006. *Hydrological Study of the Reservoir Krčevica, the Barajevska Reka Drainage Basin*, Faculty of Forestry, Belgrade,1-200

Kolaković, S. & Hajdin, G., 1997. *On the Unsatisfactory State of Structures for the Release of Peak Water from the Reservoirs with Earthfill Dams*, 1st Congress of JDVB, Budva, 103-108.

Kolaković, S., 1994. *Examples of Built Evacuation Organs where Poor Conditions Prevent Access to Collection Drain*, 11th Conference of JDHI and JDH, International Conference, Belgrade, 246-252.

Letić, Lj., Gajić, G., & Đeković, V., 2008. *Suspended Sediment Yield and Transport in the Drainage Basin of the River Gvozdačka Reka on Goč*, Bulletin, Faculty of Forestry, No. 8, Banja Luka, 25-38

Mihajlović, M., 1985. *Small Hydropower Plants*, Research, Design and Construction Monograph, Hydro-Design, Belgrade, 5-328.

Telford, T., 1996. *Floods and Reservoir Safety* 3rd Edition, ISBN: 9780727725035 Thomas Telford Ltd, London UK, 13-16.

Teodor, S. & Matreata, **S.,** 2011. *A way of determining how small river basins of Somes River are susceptible to flash-floods*, Carpathian Journal of Earth and Environmental Sciences, Vol. 6, No. 1, 89 - 98.

Prokić S., 2002. *Study of Evacuation of innovated Peak Water of the Dam HE Bočac 2002*, Measurement and research activities. Institute Jaroslav Černi, Belgrade, 24-127

Prokić S., Prohaska S., Macanović J., & Milanović G., 2003. *Risks and potential damage or investment in safe evacuation of peak water in the Dam HE Bočac (Rizici i moguće štete ili ulaganje u sigurnost evakuacije velikih voda na brani HE Bočac)*, Vodoprivreda 2003. Vol. 35. No. 5-6, 341-348

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