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RULES FOR APPROPRIATE USE OF THE "ARDA" CASCADE HYDROPOWER COMPLEX

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Summary: The role of hydroelectric power plants (HPP) below large dams is to operate in independent from the inflow mode and supply power and energy during the hours of peak demand to the National Power System. "Arda" cascade with the dams "Kirdjali", "Studen Kladenetz" and "Ivailovgrad" with the HPPs to them with total power of 273,9 MW and total operating volume of 737 m^3 is one of the most significant hydropower complexes of the country. It is built to sustainably provide the national energy grid with power during the hours of highest demands of the day. However the analysis of the way the reservoirs are used over the period 2007-2022, as well as of the operating modes of their hydropower plants, shows that they do not work in autonomous, peak mode, but in accordance with the current inflow, similarly to run-of-river HPPs. In reality, dump energy is produced without making use of the inflow regulation capacities of the reservoirs. The data from their monthly balance show how the release for the HPP follows the high inflow, while in the summer months it is negligible. The ratio between the size of the annual inflow and the volumes of the reservoirs shows that the HPPs of the "Kirdjali" and "Studen Kladenetz" dams should work in autonomous mode, while for the "Ivailovgrad" HPP it is expedient to utilize the current inflow and the reservoir to provide with high reliability the water for irrigation agreed upon with Greece. An assessment of the possibilities of using the dams under these regimes was carried out and rules were formulated for appropriate management of their waters. They were carried out by the methods and software from the "Methodology for allocation of the reservoir waters and use of their water resources" developed by NIMH for the Ministry of Environment and Waters, 2022.

Keywords: hydropower, peak energy, reservoirs management, water balance assessments, inflow regulation.

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1. INTRODUCTION

Hydroelectric power plants (HPP) under large dams have many important advantages over other types of power producers. They do not pollute the environment, use renewable energy source and can be quickly switched on and off from the power system when needed. The presence of large volumes to regulate the unevenness of the inflow according to the needs of energy production, makes them independent generators of electricity in the hours of peak, time-varying power demands.

"Arda" cascade is one of the most significant hydropower complexes in the country and with the largest inflow. The average annual inflow (in million cubic meters) from 1961 to 1998 through the three HPPs of the cascade was 658.8 at "Kirdjali," 1372 at "Studen Kladenetz," and 1937 at "Ivailovgrad," according to assessments in "General schemes for the use of the water in the Regions with River Basin Management" (MoEW, 2000; Santurjian, 2003). The current size of their reservoirs volume is 498.10^6 m^3, 388.10^6 m^3 and 157.10^6 m^3, respectively. The average annual production of electricity was 443.10^6 kWh. The total power of the plants of the cascade is 273,9 MW.

The cascade was built in the 1950s with the main purpose of electricity generation as a result of the large inflow volume and the significant total maximum head of 211 m of the three HPPs. A very important advantage of this energy, which increases its value at least threefold, is the possibility to produce the majority of it during peak consumption hours. This is achieved by storing surplus inflow and releasing it when needed, effectively adjusting the timing of water availability through the considerable storage capacities of the "Kirdjali" and "Studen Kladenetz" dams.

The first step, the dam with the "Kirdjali" HPP, is significant in every respect. Its operational volume of 391.10^6 m^3, referred to the average annual inflow, classifies it as a seasonal equalizer. The next dam "Studen Kladenetz" with an operational volume of 298.10^6 m^3 is also a seasonal equalizer. The "Ivailovgrad" dam has a relatively small volume, low inflow regulating capabilities and mainly has to process the current inflow.

According to the theory of using energy from reservoir-regulated waters, the design of the "Kirdjali" and "Studen Kladenetz" HPPs assumes the following operational mode: they should systematically process a planned monthly water volume, a fraction of their average inflow, to supply peak energy to the country's power system. In this way, the dams will be discharged within their operational volume, i.e. between the lowest and highest operational water level (LOWL and HOWL). When the dam nears the HOWL, or during overflow reaching the highest water level (HWL), the hydropower plants must operate continuously with maximum power *Qmax*, to fully utilize the inflow and produce base energy. The "Ivailovgrad" HPP operates similarly, but due to its small operational volume, it follows the inflow and produces base energy. It was not designed to preserve retention volumes (RV) for flood high waves (HW) aiming at limiting the amount of overflowing of the "Ivailovgrad" dam.

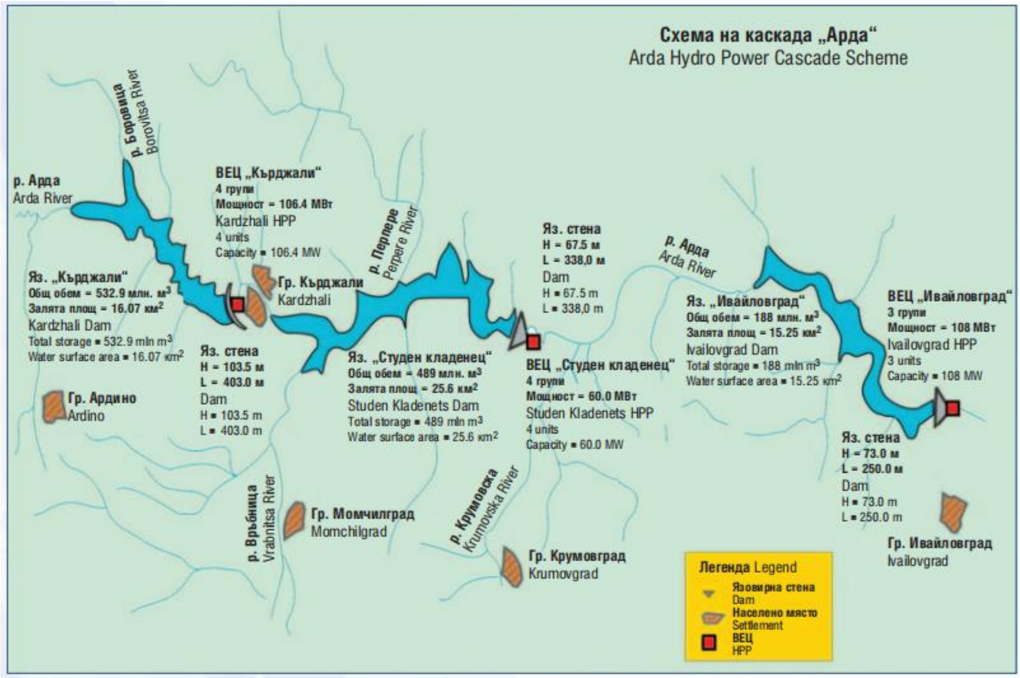


Fig. 1. Scheme of "Arda" cascade power complex

Subsequently, the good neighborly relations with Greece and Turkey imposed limitation on the magnitude of overflowing the "Ivailovgrad" dam by keeping RVs up to 20% of all reservoirs volume, without this being in any way assessed as necessary and sufficient. Thus, in fact, now the filling of the reservoirs "Kirdjali", "Studen Kladenetz" and "Ivailovgrad" is respectively reduced to 398.10^6 m^3 (RV=100.10^6 m^3), 310.10^6 m^3 (RV=$77,8.10^6$ m^3) and 125.10^6 m^3 (RV=$31,7.10^6$ m^3).

2. ANALYSIS OF THE EXPLOITATION OF THE "ARDA" CASCADE RESERVOIRS DURING THE PERIOD 2007-2022

The analysis of the operation of the hydropower plants was made on the basis of the data from the monthly balance of the dams prepared by the operator. Graphs of end-of-month inflow, release and reservoir filling values over the period 2007-2022 are plotted and illustrated for each dam on the figures below.

Dam and HPP "Kirdjali" - the graphs (Figure 2) show a lack of any visible system in the operation of HPP "Kirdjali" during the entire period, suggesting the presence of a peak mode of its performance. The release is irregular, within large intervals. Usually, but with a few exceptions, large monthly releases occur after a significant inflow. However, during the summer periods in many months the HPP consumption is mostly negligible, i.e. it is hardly used. Such a way of operation of a HPP does not correspond to that of a peak mode. This analysis leads to the conclusion that the "Kirdjali" HPP actually produces forced, random base energy.

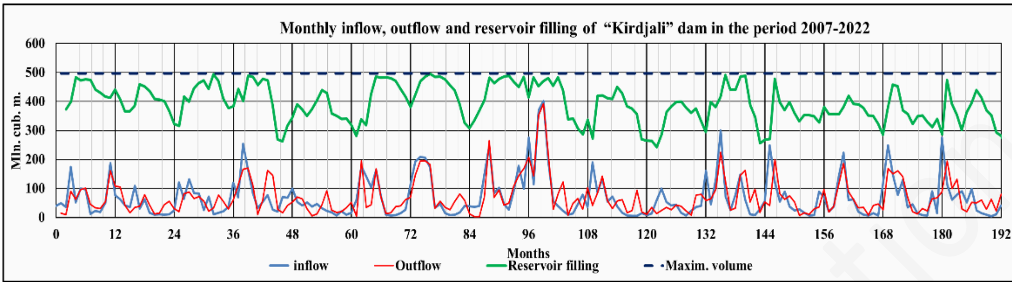


Fig. 2. Graphs of "Kirdjali" reservoir monthly filling, inflow and outflow in the period 2007-2022

Dam and HPP "Studen Kladenetz" - similar, but even more pronounced, conclusions can be maid for the "Studen Kladenetz" reservoir (Figure 3). During months with low inflow, the consumption is negligible, far below the level needed for the hydropower plant to produce guaranteed peak energy despite the reservoir having an average monthly inflow of 120.10^6 m^3. During several high inflow months, consumption exceeded the HPP's capacity of 300.106 m^3 per month. This resulted in overflows or discharges through the main outlet, leading to unused inflow. Many of these overflows could have been avoided if the dam had been less full, allowing for more efficient use of the inflow for regular HPP operations. In general, the HPP does not operate independently like a peak power plant. As a result, the dam's regulating capacity is not effectively utilized, leaving it nearly full most of the time. This forces the HPP to process inflows in a rushed manner during high-water months, often causing the dam to overflow. Overall, the analysis indicates that neither the hydroelectric plant nor the dam is being used effectively.

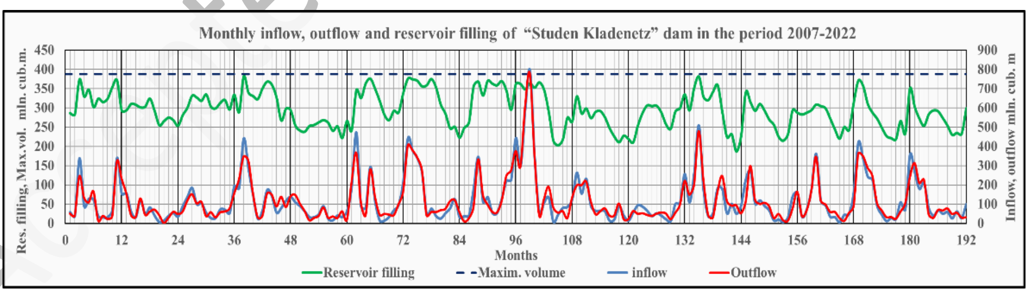


Fig. 3. Graphs of "Studen Kladenetz" reservoir monthly filling, inflow and outflow in the period 2007-2022

Dam and HPP "Ivailovgrad" - due to its insignificant operational volume, compared to the average inflow (96/1780= 5,4%), the dam can hardly have a consistent role as a seasonal equalizer of the inflow. Its main task is to create head and to regulate the inflow within short time intervals - up to several months. The graphs show an almost complete alignment between the monthly inflow and outflow from the dam. Only in March 2015, the outflow of 942.10^6 m^3 exceeded the capacity of the "Ivailovgrad" HPP to fully process it through its turbines. In prevailing part of the time, the filling of the dam is high (perhaps to maintain a high head for the HPP), so it overflows relatively frequently and not all of the inflow is processed by the HPP, despite the large Q_{max}. With a more expedient use of the dam volume, this wouldn't be the case.

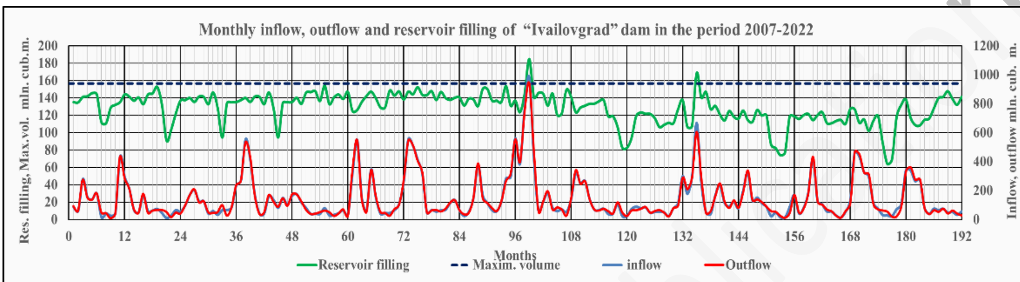


Fig. 4. Graphs of "Ivailovgrad" reservoir monthly filling, inflow and outflow in the period 2007-2022

The graphs in the figures above show increasing synchrony of inflow and outflow down the cascade over the entire 16-year period. The equalization of the outflow with the inflow, especially expressed at the "Ivailovgrad" dam, clearly testifies that the HPPs of the cascade actually work in a dependant from the inflow mode, and not with regulated waters.

2. REGIMES AND CORRESPONDING MANAGEMENT RULES FOR APPROPRIATE USE OF THE INFLOW IN THE CASCADE DAMS

HPPs of the cascade now operate without a monthly scheduled power generation concept. They process the inflow, aiming at its thorough utilization, producing forced base power and avoiding overflow. Such a way of using the cascade is too inexpedient and needs no management rules, as it is done according to the circumstances.

Hydroelectric plants below large reservoirs must operate according to the peak power requirements of the National Power System. As such, they must process as much of the average annual inflow as possible relatively evenly throughout the year. When the operational volume of the reservoirs is not filled, the hydroelectric power stations must work with a stable schedule - HPP "Kirdjali" and "Studen Kladenetz" supply energy according to the needs in the peak part of the energy demand, and HPP "Ivailovgrad" processes the dam current inflow.

The present study aims to estimate the peak energy (its corresponding water volume) that the HPPs can provide daily with an acceptable reliability. Water release from the dams should follow rules that enforce an efficient mode of operation. These rules should take into account the dam's current water level and aim to maximize energy production from the total inflow.

In order to achieve these goals, the operational volume of the reservoir must be divided into at least two zones - a zone of stable independent peak mode for hydropower and a higher zone for operation under flood inflow conditions. When the filling is in the lower zone the water will be released for peak power, but when entering the upper zone the hydroelectric plant will run continuously with full capacity until it gets empty, producing base power. This zone also acts as a flood waves retention space as it will be filled when a large inflow occurs. When conducting water balance assessments to determine the size of the zones and establish management rules, a portion of the average annual inflow is considered. This portion represents the water volume that the HPP should use to meet a planned part of the demand during specific times of the day. In the water balance assessment, the monthly distribution of this volume is accepted as uniform. This is only approximation of the reality, but it is sufficiently credible to support the reliability of the assumption, as well as the determination of the reservoir's zone sizes and management rules. The evaluation methods and computation tools used in this analysis are based on the "Methodology for Allocation of the Waters of the Reservoirs and Use of Their Water Resources," prepared in 2023 by the NIMH for the Ministry of Environment and Waters. In the following text, it will be referred to as the "Methodology...".

The water balance assessments for the three dams were conducted using monthly inflow data similar to that from the 16-year period of 2007-2022, assumed to be the most representative for the next 16 years, based on the available data. For the "Studen Kladenetz" and "Ivailovgrad" dams, the inflow in the assessments was calculated as the sum of their own inflow and the monthly outflow from the upper dam, according to the accepted operational scenario of its hydropower plant.

3. ANALISIS OF THE INFLOW OF THE “ARDA” CASCADE RESERVOIRS

3.1. Quantitative assessment of the monthly inflow

As pointed out above the monthly inflow in the "Arda" cascade used for its reservoirs balance calculations was assumed similar to the one during the period 2007-2022. On this basis, the expediency of the regarded different modes of operation of the HPPs was assessed. For the "Studen Kladenetz" and "Ivailovgrad" dams, the own inflow was calculated, as the difference between the one actually made out from the dams monthly balances and 90% of the outflow of the upper dam.

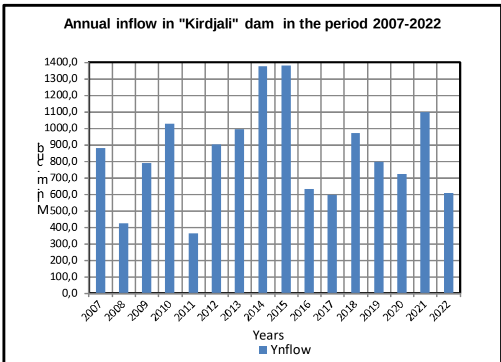
The catchment areas of the "Kirdjali", "Studen Kladenetz" and "Ivailovgrad" dams are 1882 km^2, 1925 km^2 and 1421 km^2, respectively. The tables 1, 2 and 3 contain the statistical characteristics of the 16-year monthly inflow series of the three reservoirs in the 2007-2022 period. The graphs below show the annual inflow over the period and the empirical and approximating exponential curves of their exceedance probability by years.

The representativeness of these hydrology series with respect to the reservoirs water balance assessments is judged by the size of the standard deviation of their average value $\bar{x}$, which is assumed to be below 10% of $\bar{x}$. For all three dams it is close to 10%.

"Kirdjali" reservoir inflow

Table 1. Hydrological parameters of the "Kirdjali" reservoir inflow

Waverage	102.8	117.2	146.5	112.1	59.9	57.8	35.3	16.7	16.7	37.7	47.9	96.0	847
st.dev.	79.3	96.0	98.0	63.7	35.0	24.2	37.0	14.3	21.2	46.6	30.9	85.0	295
Cv	0.77	0.82	0.67	0.57	0.58	0.42	1.05	0.86	1.27	1.23	0.65	0.89	0.35
Cs	0.78	1.42	1.54	0.92	2.26	0.74	2.31	2.60	3.51	2.37	0.89	1.25	0.30
MAX	249.2	369.6	402.3	246.0	164.3	102.9	148.4	61.7	90.9	179.0	188.2	275.6	1380
MIN	14.0	37.5	36.1	37.1	25.8	24.6	10.2	6.6	6.1	5.0	6.6	8.2	360



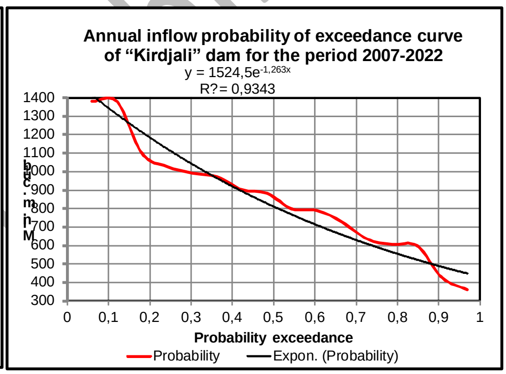


Fig. 5. Graphs of the dam annual inflow **Fig. 6.** Annual inflow exceedance probability

"Studen kladenetz" reservoir inflow from the own catchment

Table 2. Hydrological parameters of the "Studen Kladenetz" reservoir own inflow

Waverage	121.8	132.2	122.3	76.3	33.6	23.8	11.7	4.0	4.9	25.4	39.0	99.0	695
st.dev.	95.0	99.1	112.5	47.4	31.8	14.0	13.6	8.5	10.7	26.3	32.8	91.7	293
Cv	0.78	0.75	0.92	0.62	0.95	0.59	1.16	2.14	2.17	1.04	0.84	0.93	0.422
Cs	0.75	0.64	2.06	1.30	3.12	0.88	2.24	2.57	2.25	1.51	0.70	0.82	0.065
MAX	311.2	295.3	441.5	193.4	141.5	51.2	52.5	31.0	31.1	92.8	195.7	278.2	1241
MIN	17.0	23.7	17.3	27.2	13.2	5.3	0.7	0.0	0.0	0.3	3.2	4.8	221

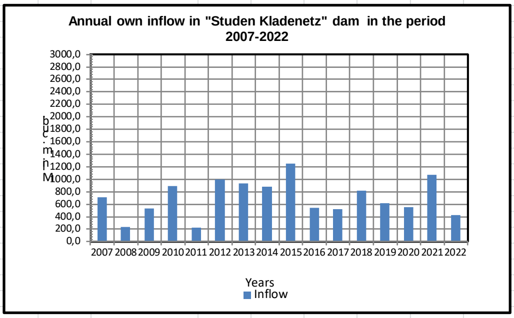


Fig. 7. Graphs of the dam annual inflow

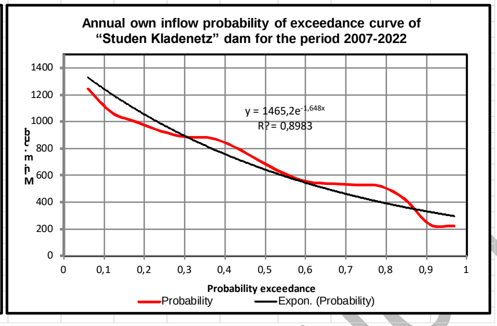


Fig. 8. Annual inflow exceedance probability

"Ivailovgrad" reservoir inflow from the own catchment

Table 3. Hydrological parameters of the "Ivailovgrad" reservoir own inflow

Waverage	**76.7**	**94.9**	**82.8**	**54.1**	**24.0**	**13.0**	**6.0**	**4.2**	**5.0**	**15.2**	**26.9**	**60.8**	**464**
st.dev.	**56.2**	**79.5**	**77.5**	**29.1**	**21.2**	**8.4**	**6.3**	**4.4**	**5.4**	**15.2**	**34.6**	**60.8**	**190**
Cv	**0.73**	**0.84**	**0.94**	**0.54**	**0.88**	**0.65**	**1.07**	**1.06**	**1.07**	**1.00**	**1.29**	**1.00**	**0.41**
Cs	**0.56**	**0.84**	**1.80**	**0.78**	**2.88**	**1.16**	**1.26**	**1.90**	**1.25**	**2.07**	**3.10**	**1.38**	**0.18**
MAX	**190.2**	**242.0**	**280.5**	**114.2**	**94.6**	**29.9**	**21.2**	**17.1**	**17.9**	**61.8**	**145.3**	**222.8**	**840**
MIN	**8.9**	**19.6**	**18.8**	**20.0**	**9.0**	**3.9**	**0.0**	**0.0**	**0.0**	**1.5**	**4.2**	**4.0**	**180**

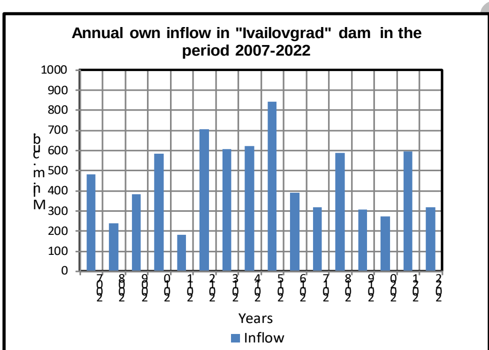


Fig. 9. Graphs of the dam annual inflow

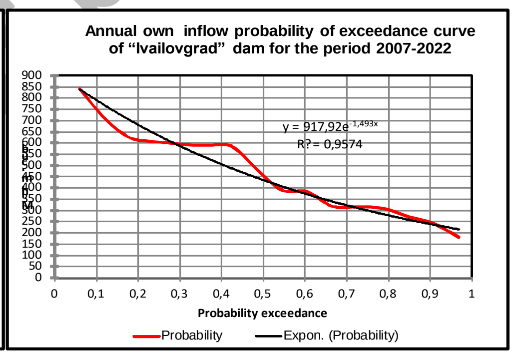


Fig. 10. Annual inflow exceedance probability

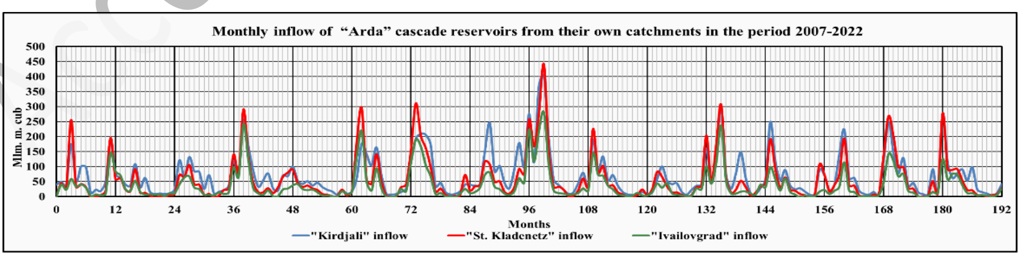


Fig. 11. Graphs of "Arda" cascade reservoirs monthly inflow from their own catchment in the period 2007-2022.

Figure 11 shows the graphs of the monthly inflow from the own catchment of the three dams. There is apparently good synchronization in time between the months with high inflow values containing the maximum annual high waves (HW) at the three dams. Therefore, if the HWs are not fully or partially retained in the reservoirs RVs, they will in many cases superimpose down the cascade.

3.2. Assessment of the retention role of the cascade at high waters. Maximum annual high wave exceedance probability curves.

One of the important functions of the cascade is the retention of the flood waters of the Arda River, distinguished by their large dimensions. By now, there are no limitations of the amount of overflowing the "Ivailovgrad" dam, which is practically not possible. If, however, agreements are made with neighboring countries on this issue, they should and can only concern the method of warning of an expected overflow. Therefore, it would be helpful to conduct a direct probabilistic estimate of the frequency of high waters (HWs) that have passed through the three dams so far. This estimate should also assess the potential for these high waters to be retained and compounded along the cascade.

The analysis of the daily inflow data of the three dams during the HW in the period 2007-2022 shows a diverse configuration of their formation in terms of the number and volume of their daily inflow values.

The data shows that the duration of flood waters ranges from 3 to 10 days. Given this, the only common parameter by which the high waters (HWs) can be ranked is their volume. Using the data from Tables 4 and 5, empirical exceedance probability curves for the maximum annual HWs of the own inflow in the three dams, as well as for the sum of their simultaneous values, were constructed and presented in Figures 12 and 13. These curves were interpolated using logarithmic functions, which can be considered as their approximate theoretical exceedance probability curves.

Estimating the probability of all three reservoirs simultaneously reaching their full capacity (RV) and encountering a high inflow wave with a specific exceedance probability, leading to a certain degree of overflow at the Ivailovgrad dam, is a very challenging task that may not be feasible to solve theoretically. A more practical and meaningful approach would be to base this assessment on historical data of actual overflow events at the Ivailovgrad dam over an extended period. Using this data, one could construct a curve showing the annual frequency of overflows of varying magnitudes, including discharges that are added to the HPP's maximum discharge capacity of Q_{max} = 279 m³/s, typically released through its turbines.

High floods are a characteristic feature of the Arda River, with volumes that can match or even exceed the capacity of the reservoirs. To manage these floods, retention volumes (RV) must be maintained. These RVs serve not only to partially accumulate and retain floodwaters but also act as buffer zones, allowing for the more effective use of surplus inflow during floods to generate base energy. These zones should be managed so that the HPP operates continuously at full capacity until the zone is emptied.

Table 4. Annual high waves maximum

Maximum annual high wave volumes in mln. cub. m.				
Years	Kirdjali	Stud. Klad.	Ivailovgrad	Joint
2007	144	216	101	462
2008	49	39	29	118
2009	46	77	37	161
2010	102	194	199	495
2011	12	11	13	36
2012	67	59	49	175
2013	73	144	101	318
2014	142	98	103	343
2015	273	321	242	836
2016	113	168	146	427
2017	95	102	19	216
2018	69	84	142	295
2019	173	104	29	305
2020	107	119	46	273
2021	147	160	107	414
2022	38	17	4	59

Table 5. Annual HWs exceedance probability

Max. annual high wave vol. exceed. probability					
	Kirdjali	St. Klad.	Ivailovgr.	Joint	Exc. prob.
1	273	321	242	836	0.061
2	173	216	199	495	0.121
3	147	194	146	462	0.182
4	144	168	142	427	0.242
5	142	160	107	376	0.303
6	113	144	103	343	0.364
7	107	119	101	318	0.424
8	102	104	101	305	0.485
9	95	102	49	295	0.545
10	73	98	46	273	0.606
11	69	84	37	216	0.667
12	67	77	29	175	0.727
13	49	59	29	161	0.788
14	46	39	19	118	0.848
15	38	17	13	59	0.909
16	12	11	4	36	0.970

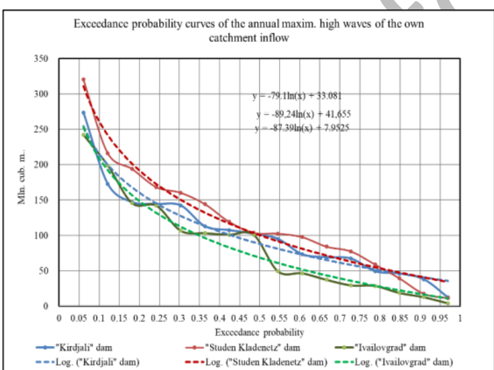


Fig. 12. Annual max. HWs exceedance probability curves.

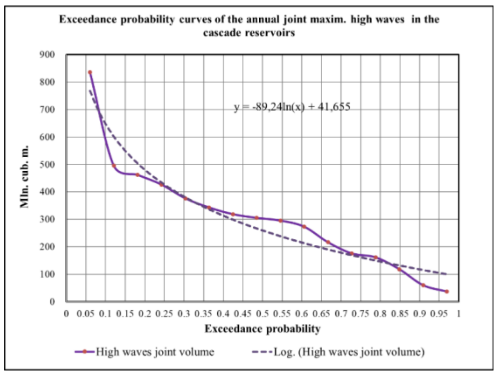


Fig. 13. Annual max. joint HWs exceedance probability curve.

4. DETERMINATION OF RULES FOR THE MANAGEMENT OF THE "ARDA" CASCADE RESERVOIRS.

The rules of operation of the HPPs, respectively the release of the reservoirs are determined at peak mode for HPP "Kirdjali" and "Studen Kladenetz" and these of HPP "Ivailovgrad" follow the inflow. Their advisability was assessed by numerical simulation of the release of the three dams under these regimes over a 16 years long period with an inflow scenario equal to that of the period 2007-2022. This was done consecutively from the upper to the lower cascade dam.

For the first two dams, several volume options, fraction of the average annual inflow, with evenly months distribution have been evaluated. They are assumed as the guaranteed water use of the hydropower plant to cover peak energy demands of the day. The operation of "Ivailovgrad" HPP is in accordance with the need to provide the necessary water quantity for irrigation for the Republic of Greece in the period May-September. The inflow into the "Studen Kladenetz" and "Ivailovgrad" dams is calculated as the sum of the own inflow and the outflow from the upper dam, with the most appropriate water use scenario.

4.1. Assessment of the size of the guaranteed annual water volume, processed in independent mode by HPP and rules for managing the operation of the "Kirdjali" and "Studen Kladenets" dams.

The volumes of the dams but the dead one (DV) are considered as operational volumes (OV) and are equal to 390.10^6 m^3 and 296.10^6 m^3 respectively at the "Kirdjali" and "Studen Kladenetz" reservoirs. Two modes of operation of the HPPs are adopted, for which the OV is divided into two zones. When the filling is in Zone 1 (between the lowest in view of the turbines efficiency OWL and the lower limit of Zone 2), the HPP will operate in an independent, peak mode several hours a day with the required power. When the filling of the dam enters Zone 2 (between Zone 1 and HOWL), the hydropower plant operates continuously at full power until the zone is emptied. So Zone 2 serves as a RV for accommodation of a HW, as well as enables the complete use of the inflow. The energy produced in this mode of operation is considered by the simulation model as basic. Only the energy produced in Zone 1 is peak energy. However it is possible that in cases of short HWs, lasting only part of the month, the hydroelectric power plant may operate in an independent mode for the rest of the time. So the produced peak power is actually greater than that shown as a result of the calculations, because of the monthly computation interval.

When Zone 2 is full, the dam will overflow. This can occur during a prolonged period of large inflow (high wave), when the volume of incoming water exceeds the processing capacity of the HPPs. The daily processing capacities are substantial, with HPP "Kardzhali," "Studen Kladenetz," and "Ivailovgrad" handling $14{,}1 \times 10^6$ m^3, 10×10^6 m^3, and $24{,}1 \times 10^6$ m^3, respectively.

The evaluations for both dams were conducted using two different options for the zone sizes, each with three sub-options for the monthly guaranteed water volume for peak energy production. After assessing the results in terms of the HPPs' reliability in peak energy production and the dams' capabilities in retaining high waters (HWs), the following sizes for Zone 1 and Zone 2 were determined to be appropriate. They are equal respectively: for the "Kirdjhali" dam to 300.10^6 m^3 and 90.10^6 m^3 and for the "Studen Kladenetz" dam to 200.10^6 m^3 and 96.10^6 m^3. The guaranteed monthly water volume is assumed to be 60.10^6 m^3 for HPP "Kirdjali" and 110.10^6 m^3 for HPP "Studen Kladenetz". They are close to the dams average monthly inflow. With them, the "Kirdjali" HPP can operate daily at full power up to 3,5 hours, and the "Studen Kladenetz" HPP - up to 8,5 hours.

The realization of the options was tested by simulating the monthly performance of the HPPs with hydrology presented by a 16-year series of monthly inflow occurred in the period 2007-2022 and taken as representative for the cascade. For the "Kirdjali" dam, its statistics are presented on Table 1 and the annual volumes in Figure 5. For the "Studen Kladenetz" dam, the inflow was obtained by adding to its own inflow, shown on Table 2 and in Figure 7, 90% of the monthly outflow from the "Kirdjali" dam. This outflow is a result of processing 60.10^6 m^3 per month by its HPP. The simulation and reservoirs inflow-outflow balance was calculated using the specialized software RESERVOIR1 from "Methodology...". The reliability of the peak energy production is estimated in percents determined by comparing the actual water volumes used to the volumes planned for this purpose over the period. This reliability assessment is based on volume rather than years, and the threshold criteria for the HPP to adopt the peak operation regime are less strict. This is due to the absence of current regulations and the possibility of replacing HPP power in the National Energy System with other power sources in case of water shortages.

For the "Kirdjali" HPP the peak energy is guaranteed 78.5% by volume and equals 76,3.10^6 kWh/a. The total energy amounts is 109,5.10^6 kWh/a. From the graph in Figure 14, it can be seen that throughout the period there are several monthly periods of water shortage in which the hydroelectric plant operates at reduced capacity. The possibility of replacing the HPP's output within the country's closed energy network suggests that occasional depletion of the dam is not as critical. Approximate estimations indicate that for flood waves lasting 5 days, a retention volume (RV) of 90.10^6 m^3 reduces the probability of a significant overflow at the "Kardzhali" dam to less than 10-12%. This corresponds to a frequency of less than once every 8-10 years.

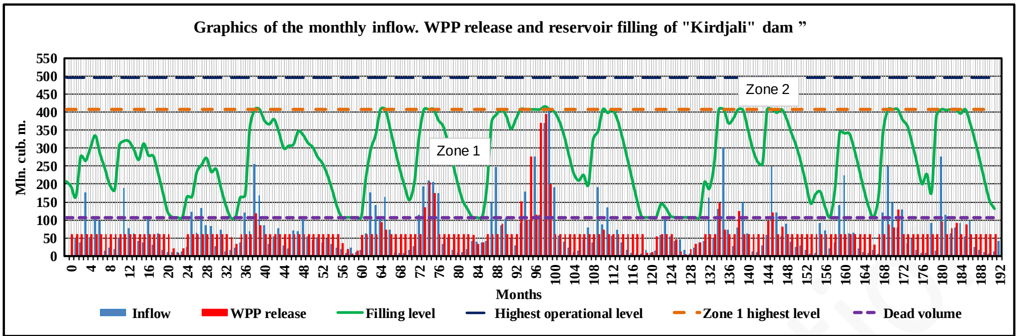


Fig. 14. Graphics of the "Kirdjali" dam performance simulation output with guaranteed monthly water use 60.10^6 m^3

The water balance evaluations and considerations about the HW retention possibilities of "Studen Kladenetz" dam lead to the assumption of the following parameters for the management of the dam - Zone 1 with a volume of 200.10^6 m^3 and Zone 2 - 96.10^6 m^3 at a monthly volume equal to 110.10^6 m^3, specified for independent (peak) mode of operation of the HPP. Despite the comparatively low provision reliability, it is assumed that the hydropower plant is appropriate to work at the top part of the demand diagram for a great part of the year (Figure 15), and according to the large inflow in the rest of the time.

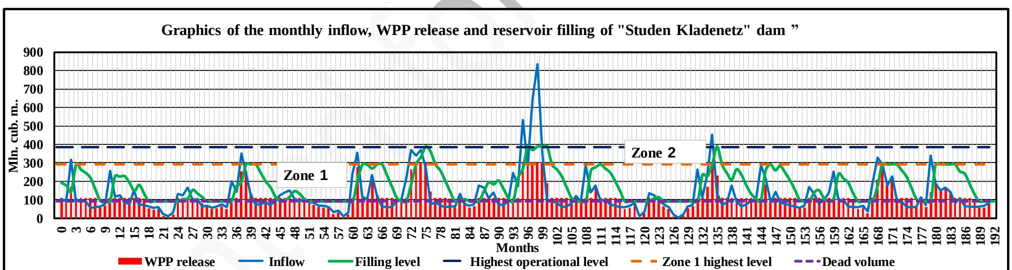


Fig. 15. Graphics of the "Studen Kladenetz" dam performance simulation output with guaranteed monthly water use 110.10^6 $m^{3.}$

The management of the "Kirdjali" dam must be carried out by observing the Rule Curves for water release shown in Figure 16. They indicate the following modes for HPP operation:

a. When filling is in Zone 1, the HPP will operate in an independent from the inflow mode according to the actual demands using water resource varying around the planned monthly release of 60.10^3 m^3 for peak energy, in the frame of the annual one of 770.10^6 m^3.

b. When Zone 1 is full the daily water release from the dam depends on the inflow forecast and the operator. At the beginning of flooding and filling of Zone 2, the HPP works with its full capacity as long as necessary to keep it empty.

c. Filling below the dashed red line means a possibility of occurrence of water shortage in the following months if the inflow is below the required monthly volume. Then the operator must reduce the release until the filling rises above the curve.

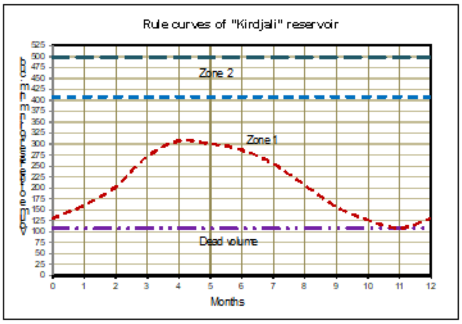


Fig. 16. Rule curves of “Kirdjali” dam

Similar are the rules for management of the "Studen Kladenetz" dam.

4.2. Reservoir release management and assessment of the frequency and size of HWs overflowing the “Ivailovgrad” dam

4.2.1 Selection of operating mode

The operational volume of 97,2.10^6 m^3 of the "Ivailovgrad" dam is too small, relative to the inflow, to effectively function as a seasonal equalizer and provide the HPP with a reliable, autonomous mode of power generation. However, the dam's capacity of *Qmax* = 279 m^3/s allows it to process the entire current inflow, including most of the high water (HW) events, without causing the dam to overflow. It is also important to consider the obligation of Bulgaria to release approximately 190.10^6 m^3 for irrigation in the Republic of Greece from May to September. In some years, the dam is emptied during the summer months. Given these circumstances, the reservoir release rules must ensure optimal use of inflow for base energy generation while also guaranteeing the required irrigation water supply from May to September, in accordance with the agreement with Greece.

In order to achieve such a management of the dam, the irrigation water supply for Greece and the power generation are regarded as two different water users with first and second priority. The OV of the dam is divided into two zones. When filling in Zone 1, water will be released only for irrigation after passing through the HHP turbines. In Zone 2, the water will be released to the both users, and the hydropower plant will operate without time and power limitations until it is emptied. The water balance calculations for this mode of use of the "Ivailovgrad" dam were carried out using the "RESERVOIR 1" software based on hydrology with an average annual inflow of 1845.10^6 m^3 (±200.10^6 m^3 standard deviation). The latter was obtained as the sum of the own inflow (Table 3 and Figure 9), similar to the one in the period 2007-2022, plus the outflow from the upper dam with HPP "Studen Kladenetz" processing a guaranteed water volume of 110.10^6 m^3 per month.

The graphs in Figure 17 show that Zone 1 remained full throughout most of the period, except in the 11th year, when due to low inflow in the summer months, the dam's water level dropped to the DV, and instead of supplying 186.10^6 m^3 for irrigation to Greece, only 166.10^6 m^3 were provided (the graphs reflect values at the end of each month). At all other times, water release for the HPP and for Greece was managed from Zone 2. The model shows the zone fills and overflows significantly only once in the 9-th year, since the inflow in February and March amounted to 1,7.10^9 m^3 in total, exceeding significantly the HPP water processing capacity. In the remaining months of the 16-year period, the latter exceeded the monthly inflow and Zone 2 remained empty at the end of the month time interval. In fact, in some years there were HWs with a daily inflow exceeding the daily HPP water processing capacity plus the space of the RV (Zone 2). Additionally, there was an overflow that the model did not account for, due to the one-month length of the computational time step.

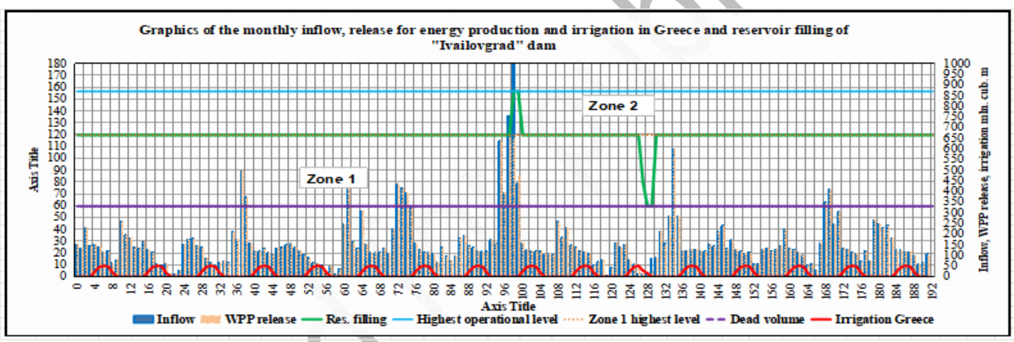


Fig. 17. Graphs of the "Ivailovgrad" dam performance simulation output under the proposed operational regime.

Despite the large annual inflow into the "Ivailovgrad" dam, amounting to 1000.10^6 m^3 with a 95% exceedance probability, significant monthly variation from May to September may cause the inflow to repeatedly fall below the required volumes for irrigation as per the agreement with Greece. Therefore, it is logical to maintain a certain volume in the dam during this period to ensure that the inflow meets the required quantity for irrigation.

4.2.2. Assessment of the frequency and size of the maximum annual HWs into "Ivailovgrad" reservoir

This issue is crucial for maintaining good relations with neighboring countries Greece and Turkey. It should be addressed with the understanding that the construction of the cascade inherently reduces the dimensions of maximum floodwaters crossing the borders of both states.

In order to further reduce the maximum overflow discharges after the "Ivailovgrad" dam, it is planned to preserve retention volumes (RV) to absorb a part of the HW. The rules for the management of the cascade dams, discussed above, provide for the preservation of RV in each of them with a total space equal to 223.10^6 m^3.

"Ivailovgrad" dam will overflow with discharges, significantly exceeding the regular one of Q_{max}=279 m^3/s from the HPP, when the three dams are full to the RV and at the same time they are filled simultaneously by large HWs from their own watersheds leading to their overflow. From Figure 10 it is seen that very often the HWs from the own watersheds coincide in time. As discussed in subsection 3.2, a practically feasible approximate approach to the problem of overflowing the “Ivailovgrad” dam, is by using the curve in Figure 13. Through it the probability of exceedance, respectively the frequencies of the annual maximums of the joint HWs with different sizes entering the cascade, were evaluated.

Thus, with the accepted total RV=223.10^6 m^3 and daily discharge capacity of "Ivailovgrad " HPP equal to 24.10^6 m^3, the dam will overflow in the case of simultaneous HWs in the reservoirs filled up to RV, with a joint volume greater than $(300\text{-}340).10^6$ m^3. From the curve in Figure 13, it is seen that such are HWs with a probability of exceedance below (35-40)%, i.e. with a frequency of less than once every 3 to 2,5 years. The maximum spillway discharge, amounting to about 2000 m^3/s and more, occurred with high waves with a volume of around 800.10^6 m^3, will have an exceedance probability less than 6% (less than once per 16 years).

These probabilities are in fact overestimated because they do not account for the fact that joint HWs with enormous volumes not always happen into a full up to RV reservoir. Therefore, a truly reliable estimate would be based on the exceedance probability curve of maximum annual discharges released downstream in the Arda River. This curve should be constructed using data from direct measurements of these events over the long period of dam operation by the operator, which we did not have access to.

5. CONCLUSIONS

A water management assessment and analysis of the modes of operation of the dams and hydropower plants of the "Arda" cascade for the period 2007-2022 was carried out. They show that the country's richest in water and energy resources hydropower complex operates without an established regime, the release follows the inflow, similarly to run-of-river hydropower plants. Base energy is produced in order to fully utilize the inflow without making use of the reservoir volumes to regulate it and generate peak energy.

Studies were carried out with water balance assessments and an independent, peak mode of operation of the HPPs "Kirdjali" and "Studen Kladenetz" was justified by drawing up rules for managing the release of reservoirs, introducing a division of the operational volume of their dams into two zones. Zone 1 regulates the seasonal variation of the inflow and provides for independent peak mode of operation of the hydroelectric power plants with acceptable reliability. Zone 2 fills at flood waters and high waves. Then the HPP operates at full capacity producing base energy. The rules are experimented by numerical simulation of the dam balance under a 16 year monthly inflow series with a hydrology pattern similar to the one in the period 2007-2022.

"Ivailovgrad" dam is also divided into 2 zones in order to provide the supply of irrigation volumes in the May-September period for the Republic of Greece with a high reliability.

Concerning the retention of HWs an approximate assessment of the sizes and the annual frequency of occurrence of the overflowing volumes and discharges downstream "Ivailovgrad" dam was made.

In order to put into effect these modes of operation of the cascade, any limitations on the minimum levels of the dams for the purpose of fish farming should be lifted.

The conducted research with its results aims at showing to the National Electricity Company the existing possibilities for the expedient use of Bulgaria's largest cascade of reservoirs with significant energy capacity.

REFERENCES

"Methodology for allocation of the waters of the reservoirs and the use of their water resources". Prepared at NIMH for the MoEW , 2023 (in Bulgarian). https://www.moew.government.bg/bg/vodi/povurhnostni-vodi/kompleksni-i-znachimi-yazoviri/

Santurjian O. "General schemes for water use in the Basin Management Regions". BAS Magazine, 2003 (in Bulgarian).