Wrocław University of Technology

WROCŁAW UNIWERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

MODELLING THE FLOW CONDITIONS OVER A SIDE CHANNEL SPILLWAY OF THE PILCHOWICE STORAGE RESERVOIR ON THE BOBR RIVER

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PROBLEM STATEMENT

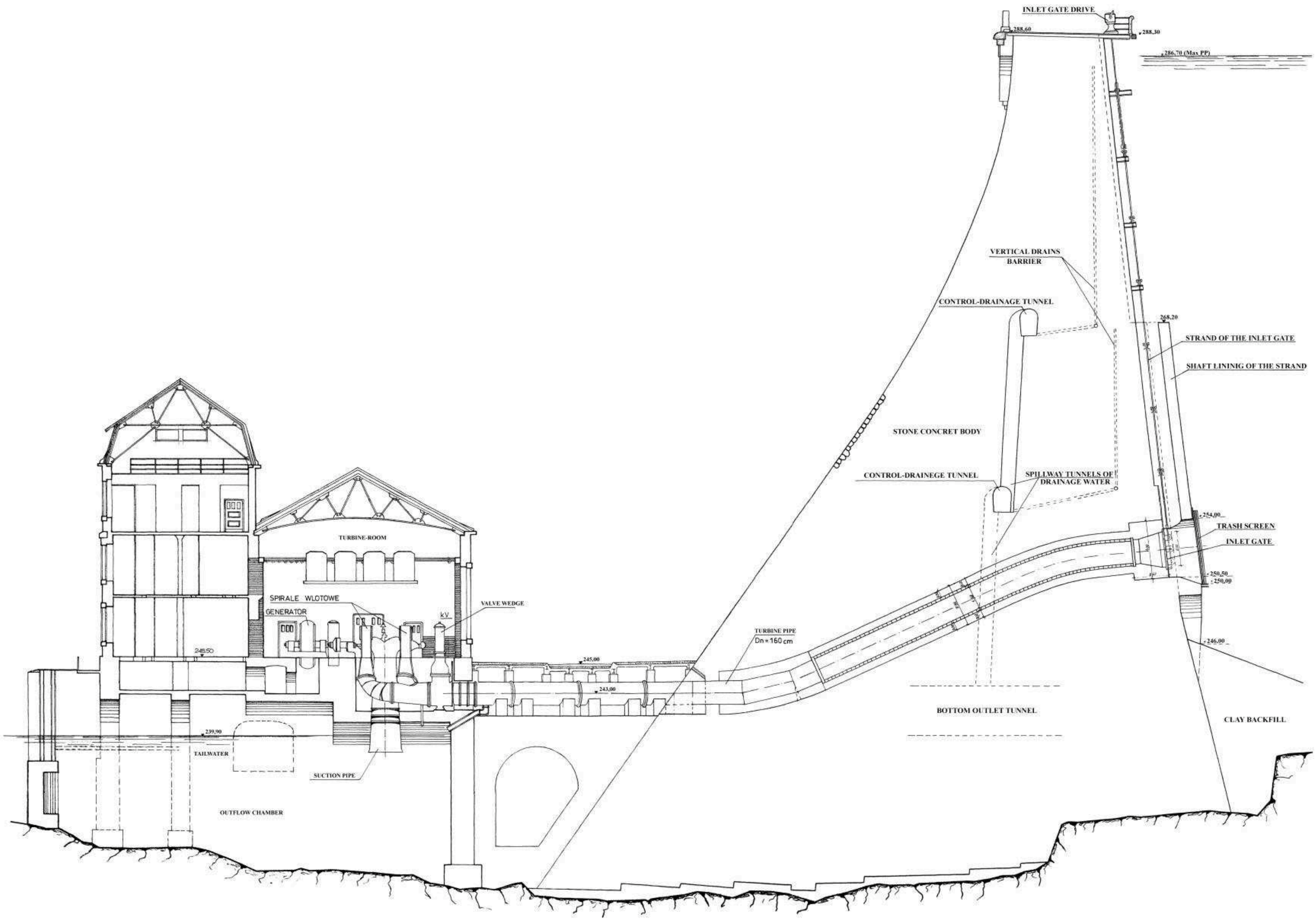
- Regulations of Minister of Environment from 1997 in matter of technical conditions for hydro-engineering structures and their location
- Pilchowice dam's technical class of importance has changed from II to I
- New computational discharges – design and so called controlled for I class
- Question has arose – if new discharges will safely pass through reservoir and dam's outlet installations ?
- Authors tried to verify and to solve this problem

OBJECT CHARACTERISTICS

- Pilchowice dam – hydro-engineering structure of I class of importance

  (according to Polish regulations)
- location: km 196+700 of the Bóbr river course
- dam: arch body made of broken stones in concrete
- maximum height – 69 m
- capacity V_{zb} = 55,12 mln m^3.
- multitasks storage reservoir
- basic tasks: flood protection and energetic purposes
- year of built 1904 – 1912

DAM
CROSS - SECTION



OBJECT CHARACTERISTICS

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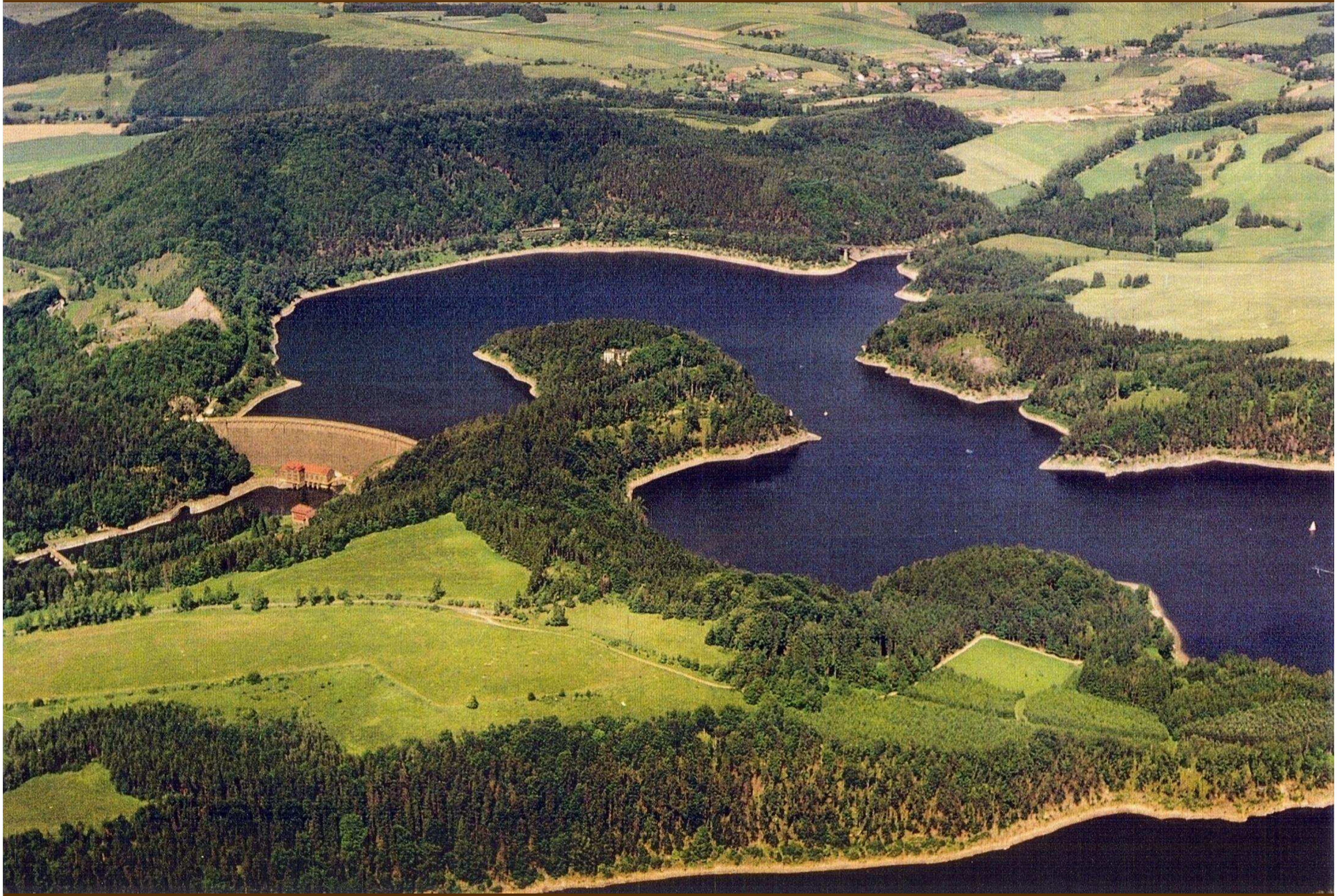
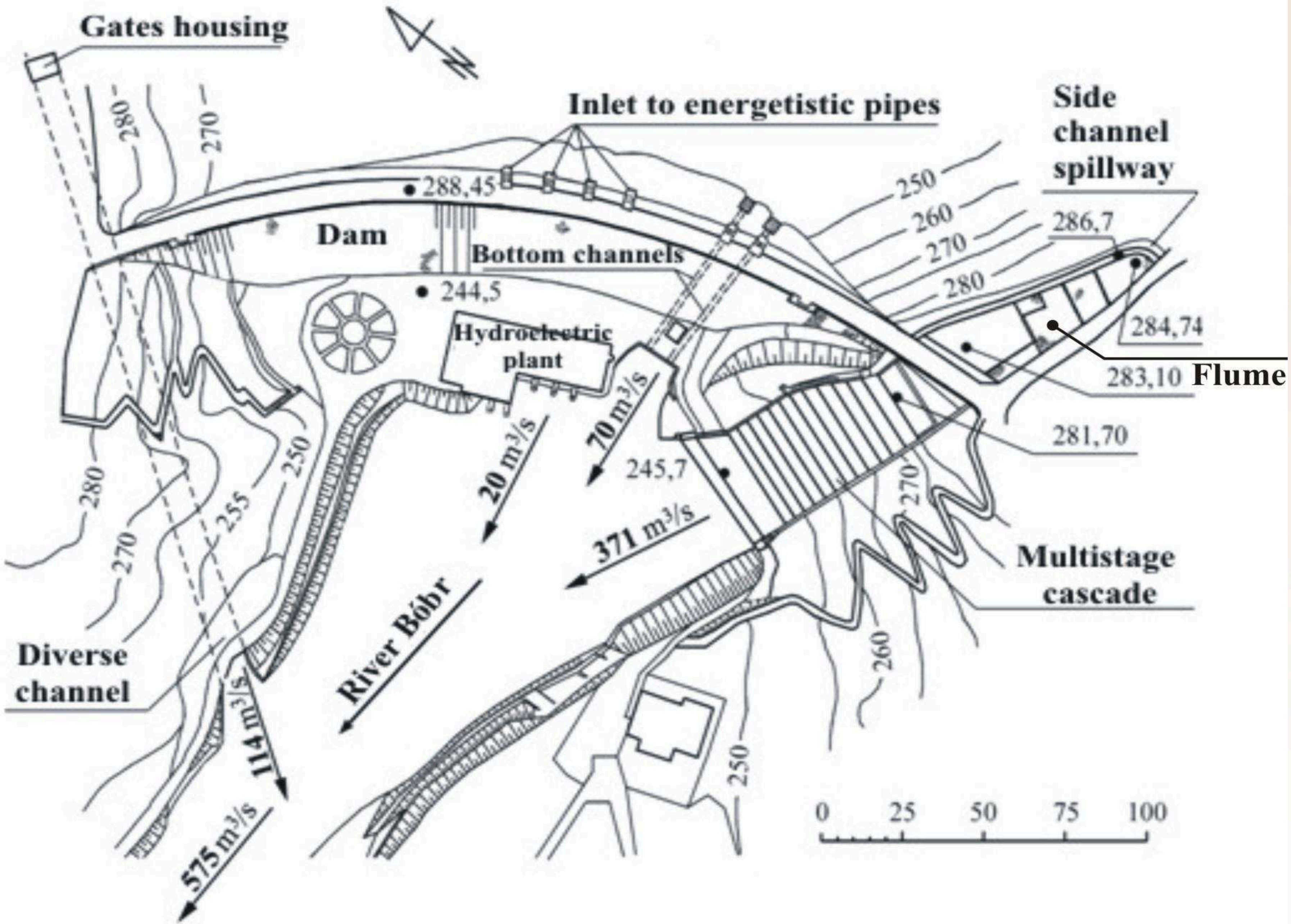


FUNCTIONAL PLAN OF PILCHOWICE DAM



OUTLET INSTALLATIONS

- side channel spillway
- multistage cascade
- diverse channel
- bottom outlets

OUTLET INSTALLATIONS
MULTISTAGE CASCADE

OUTLET INSTALLATIONS
DIVERSE CHANNEL

OUTLET INSTALLATIONS

Side channel spillway:

- 84,0 m length

Multistage cascade:

- done in the rock massif

Diverse channel:

- three conduits with diameter of 1500 mm each

Bottom outlets:

- two conduits with diameter of 1500 mm each

Electric power station:

- four conduits with diameter of 1600 mm each, one with diameter of 2000 mm
- installed total electric power output 9,20 MW, capacity 37,20 $m^3 \cdot s^{-1}$

OUTLET INSTALLATIONS

Capacity ability for water level dammed up to dam crest of 288,60 m a.s.l.

- **side channel spillway – estimated about 346 $m^3 \cdot s^{-1}$,**
- **bottom outlets – determined on the basis of field measurements:**

  right conduit – 33,30 $m^3\ s^{-1}$, left conduit – 36,0 $m^3\ s^{-1}$,
- **diverse channel – total for three conduits – 114,0 $m^3\ s^{-1}$.**

ANALYTICAL CALCULATIONS

Spillway discharge was determined assuming that it works in the whole range of expected discharges as not submerged.

Calculations were carried out using formula for free spillway, with its crest as semicircle:

$$Q = \varepsilon \, 2/3 \, \mu \, B \sqrt{2g} \, H_o^{3/2}$$

where:

ε – coefficient of side contraction weir, ε = 1,0

μ – discharge coefficient, μ = 0,654

B – spillway crest length, B = 84,0 m

H_o – energy height calculated with relation to spillway crest

ANALYTICAL CALCULATIONS

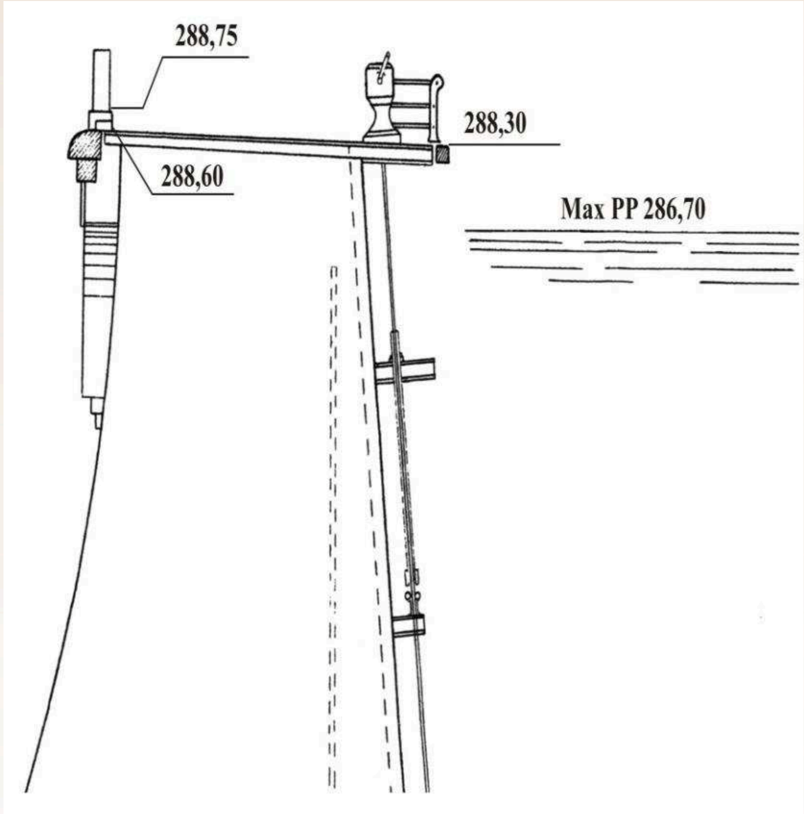
They result from water level with regard to weir crest (286,70 m a.s.l.) and dam crest, determining water layer thickness and the resultant energy of stream.

The calculation results are as follow:

288,75 – 286,70 = 2,05 m →
Q = 476,15 m^3 s^{-1}

288,60 – 286,70 = 1,90 m →
Q = 424,86 m^3 s^{-1}

288,30 – 286,70 = 1,60 m →
Q = 328,32 m^3 s^{-1}



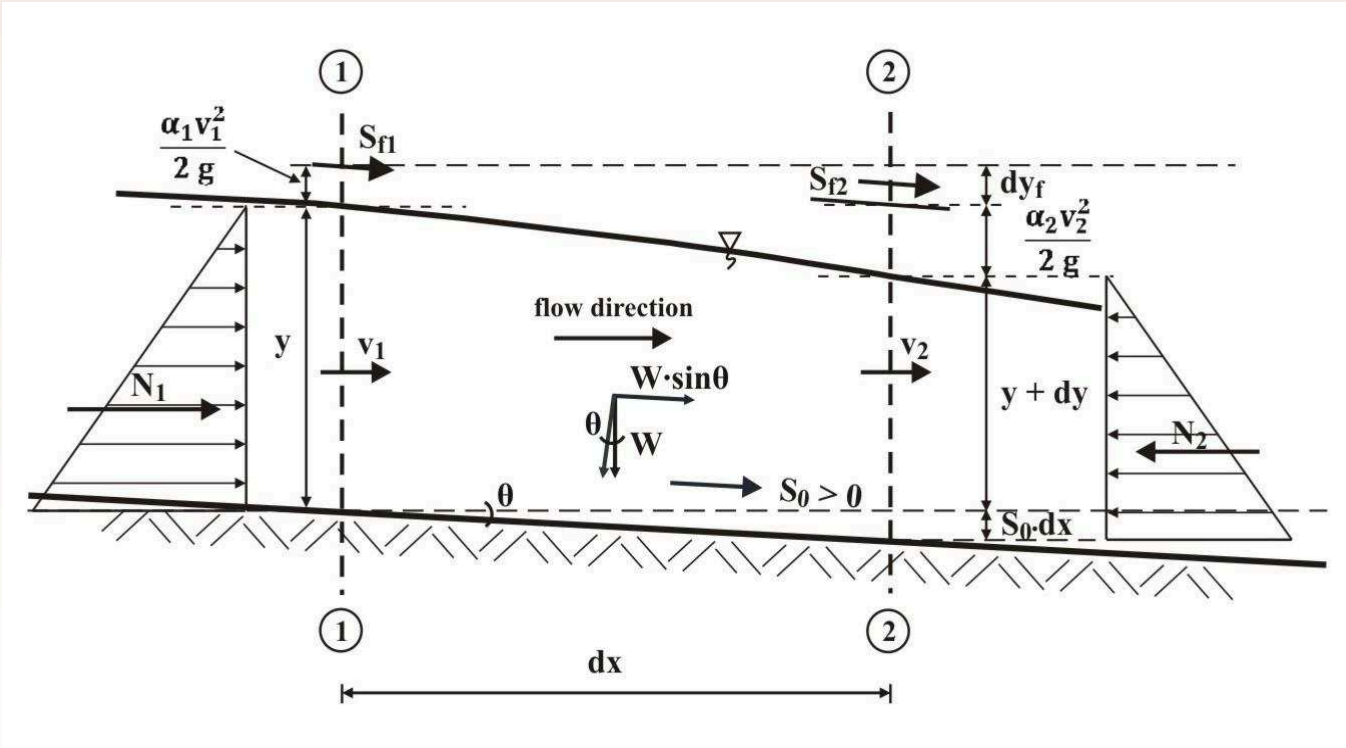
In a further analysis for flume parameters determinations, the discharge equal to 424,86 m^3 s^{-1} was assumed.

ANALYTICAL CALCULATIONS

ANALYTICAL CALCULATIONS

In professional literature, according to classification of water motion in open channels, water motion in the side channel spillway's flume is defined as spatially variable steady flow.

Hence, in the calculations for determination of the flume parameters, an impact of external forces, in compliance with Newton's second dynamic principle, should be considered in two cross-sections, 1-1 and 2-2, at distance *dx*, including gravity force, material roughness of the flume cross-section and resultant force of hydrostatic pressures.



ANALYTICAL CALCULATIONS

- gravity force is represented by horizontal component of water weight *W* between two cross-sections, 1-1 and 2-2, as

$$W \sin\theta = \gamma\, S_o\, A\, dx$$

- force resulting from an impact of roughness of the flume material can be expressed as

$$F_s = \gamma\, A\, S_f\, dx$$

- force resulting from differences of hydrostatic pressures in cross-sections 1-1 and 2-2 can be written as

$$N_1 - N_2 = -\gamma\, A\, dy$$

- resultant change of momentum in time unit between cross-sections 1-1 and 2-2 is equal to the sum of external forces

$$\frac{dM}{dt} = N_1 - N_2 + W \sin\theta - F_s$$

ANALYTICAL CALCULATIONS

After substitution of $A = Q/v$ and $q = dQ/dx$ and transformations, the following equation is derived

$$\frac{dy}{dx} = \frac{S_o - S_f - 2\,\alpha\, Q\, q / g\, A^2}{1 - \alpha\, Q^2 / g\, A^2\, D}$$

where:

- α is the kinetic energy correction coefficient (Saint Venant), $\alpha = 1{,}10$;

- q is the rise of flow per length of flume dQ/dx;

- D is the hydraulic depth, $D = A/B$ and,

- B is the width of flume.

ANALYTICAL CALCULATIONS

The differential equation can be solved in two ways: either by applying numerical methods available for equations of this type or by applying simplified methods, which in general consist in introduction of finite differences in place of differentials.

$$\Delta y = -\frac{\alpha\, Q_1\,(v_1 + v_2)}{g\,(Q_1 + Q_2)}\left[(v_2 - v_1) + \frac{v_2\,(Q_2 - Q_1)}{Q_1}\right] + S_o \Delta x - S_f\, \Delta x$$

Applying the above formula, the flume parameters were determined to ensure a possibility of whole discharge passage in amount of 424,86 m^3 s^{-1} with simultaneous guarantee that spillway works as not-submerged.

ANALYTICAL CALCULATIONS

From analytical calculations reveal that a free flow of computational discharge through the existing side channel spillway is not possible due to too shallow and too narrow flume in its upper part. Therefore, the operating conditions of the spillway are changing quickly into conditions of submerged weir. For that reason the flume should be deepened with simultaneous set of its width at 22,50 m. Only under such conditions the assumed discharge of spillway can be obtained for reservoir water level elevation equal to 288,60 m a.s.l.

Applying the above formula, the flume parameters were determined to ensure a possibility of whole discharge passage in amount of 424,86 $m^3 s^{-1}$ with simultaneous guarantee that spillway works as not-submerged.

ANALYTICAL CALCULATIONS

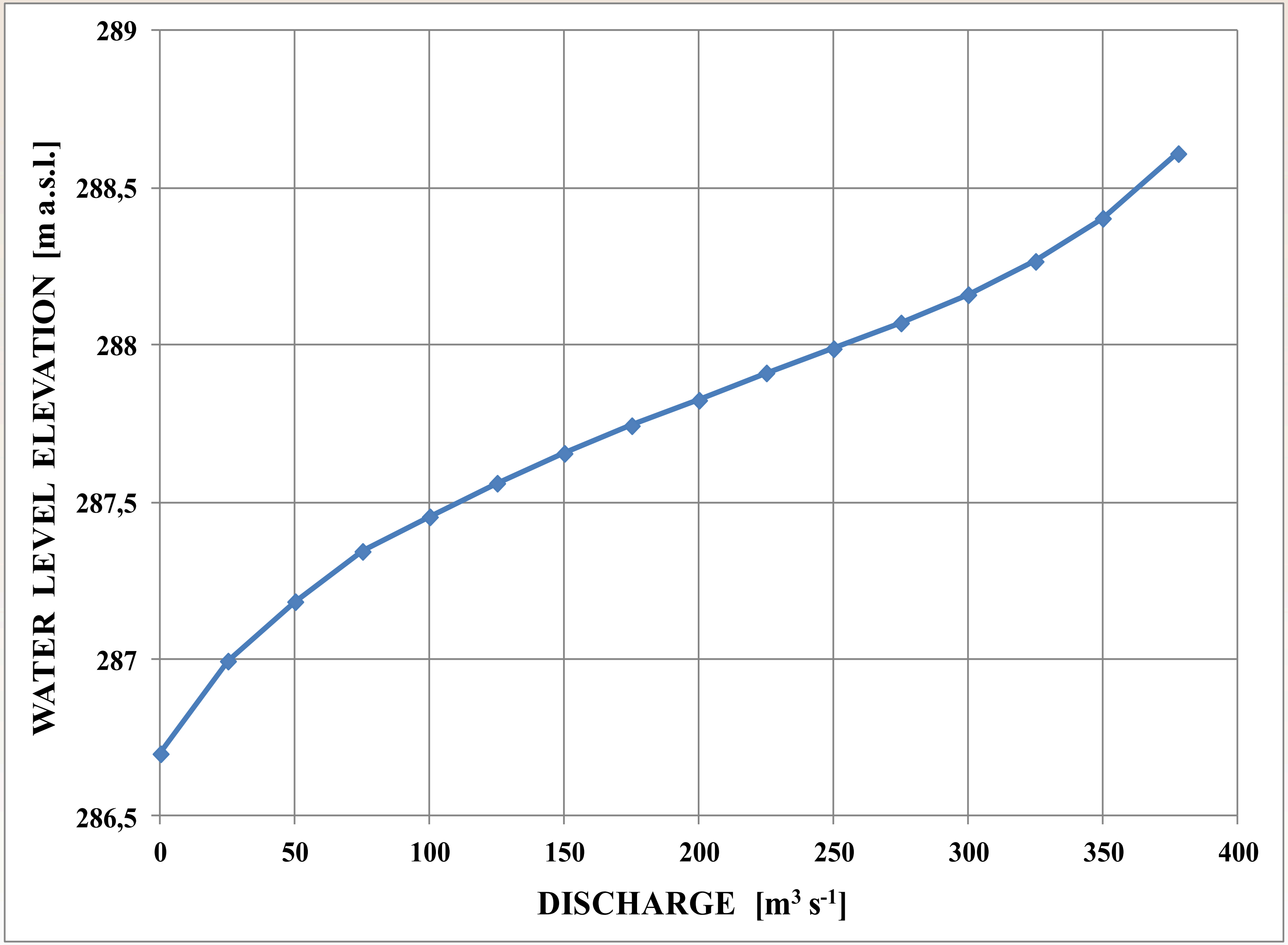
- ✓ **These requirements put under a big question the possibility of the flume rebuilding, mainly in terms of economic calculations.**

- ✓ **The reconstruction would forced the necessity of constructional changes of a weir – new static conditions of its work and also a necessity of constructional changes of outer wall on the opposite side.**

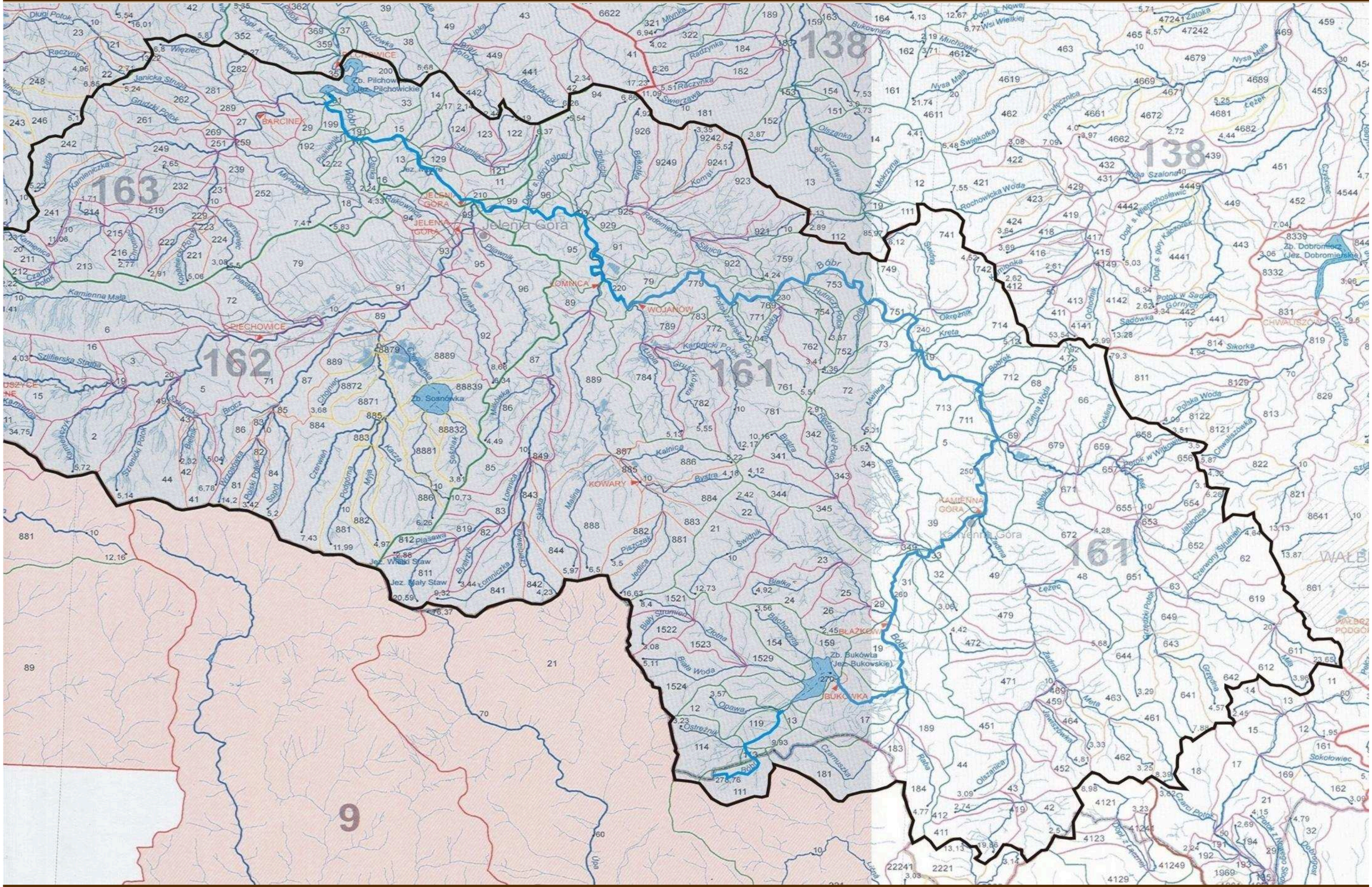
- ✓ **In that situation it is assumed that by numerical analysis a minimum of works, necessary to improve spillway functioning, i.e. increasing its capacity ability, will be determined.**

- ✓ **Verified by numerical analysis side channel spillway characteristic for its existing state is shown below.**

ANALYTICAL CALCULATIONS



THE UPPER BÓBR RIVER BASIN



HYDROLOGICAL CHARACTERISTICS OF THE BÓBR RIVER TO THE DAM CROSS - SECTION

Catchment area – 1209,0 km²

River length to the dam cross-section – 79,7 km

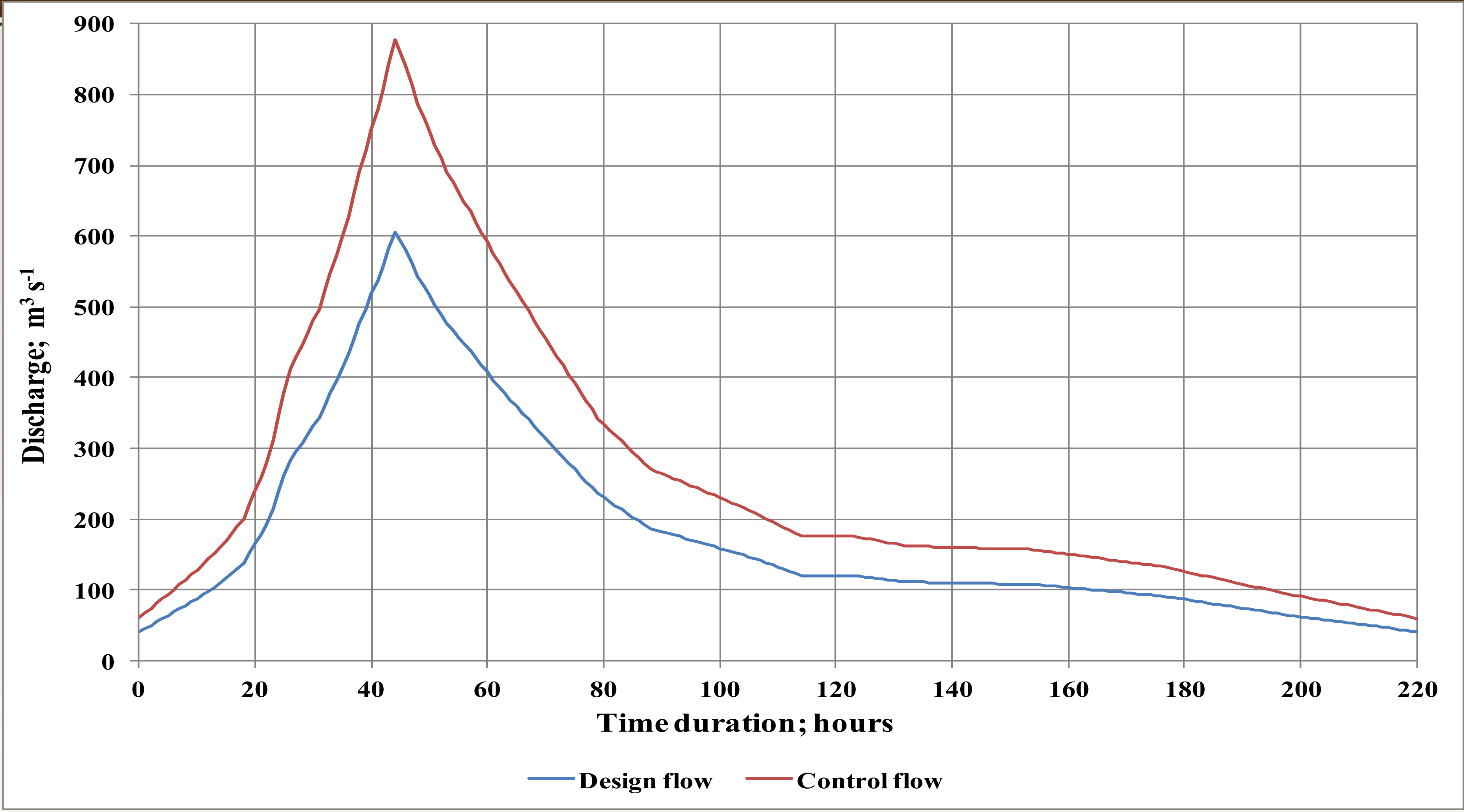
Longitudinal slope of the river to the Pilchowice dam – 11,94 ‰

The most frequent occurence of flood waves period: July – October

Characteristic discharges (Polish abbreviations) and maximum discharges with a given probability of exceedance – transferred from Jelenia Góra gauging station:

- **NNQ = 0,500 $m^3\ s^{-1}$ – minimum**
- **SNQ = 2,320 $m^3\ s^{-1}$ – average low flow**
- **SSQ = 14,80 $m^3\ s^{-1}$ – mean**
- **SWQ = 109 $m^3\ s^{-1}$ – average maximum flow**
- **WWQ = 494 $m^3\ s^{-1}$ – maximum (1997)**
- **$Q_{50\%}$ = 145 $m^3\ s^{-1}$**
- **$Q_{1\%}$ = 538 $m^3\ s^{-1}$**
- **$Q_{0,5\%}$ = 605 $m^3\ s^{-1}$ (design discharge)**
- **$Q_{0,1\%}^{\alpha}$ = 877 $m^3\ s^{-1}$ (controlled discharge)**

HYPOTHETICAL WAVES



Probability of computational discharges for hydro-engineering structure of the I class of importance, not subjected to destruction due to their overflow (Regulations ME, 2007):

$p_{des.}$ = 0,5 %, $p_{contr.}$ = 0,1 % with the upper extension,

Computational discharges: $Q_{des.} = 605\ m^3\ s^{-1}$, $Q_{contr.}^{\alpha} = 877\ m^3\ s^{-1}$.

FLOOD WAVE TRANSFORMATION

In the concept of reconstruction the Pilchowice reservoir's outlet devices, the reservoir safety was taken into account due to computational discharges and capacity ability of existing (corrected) outlet devices. First, conditions of computational discharges passage through the reservoir were determined, analyzing possibilities of their reduction to safe discharges both for downstream area and for reservoir.

Analysis of reservoir flood routing was carried out using Puls method, often called inlet-storage-outlet method. In that method a flood wave transformation through a reservoir is described by continuity equation written in differential form:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

where Q is discharge; $m^3\ s^{-1}$, x is co-ordinate consistent with flow direction; m, A is flow cross-section area; m^2, t is time; s.

FLOOD WAVE TRANSFORMATION

After integration from x_1 to x_2 and modification takes the form in which an integral means a water capacity stored in reservoir or flowed out from reservoir:

$$Q(x_1) - Q(x_2) + \frac{d}{dt}\int_{x_1}^{x_2} A\,dx = 0$$

and further:

$$Q(x_1) = Q(x_2) + \frac{\Delta V}{\Delta t}$$

where x_1 is co-ordinate at inflow cross-section, x_2– is co-ordinate at dam cross-section, $Q(x_1)$ is reservoir inflow; $m^3\,s^{-1}$, $Q(x_2)$ is reservoir outflow; $m^3 s^{-1}$, $\Delta V/\Delta t$ means changes of reservoir capacity in time.

FLOOD WAVE TRANSFORMATION

Knowing a flood wave hydrograph, reservoir storage curve and characteristics of outlet devices, calculations of flood wave transformation through the reservoir, using above written equation, were carried out for general assumptions:

- ✓ **safe height differences between dam crest and water level elevations: 1,0 m and 0,10 m respectively for design and control discharges,**
- ✓ **during control flood wave passage through the reservoir all outlet devices are opened except water power station turbine No V of 9,62 m^3s^{-1},**
- ✓ **during design flood wave routing, two bottom outlets of diameter 1500 mm and water power station turbine No V of 9,62 m^3s^{-1}, are excluded from exploitation,**
- ✓ **verified characteristic of side channel spillway elaborated on the basis of own analytical calculations was applied,**
- ✓ **maximum permitted water level elevation in the reservoir referring to the dam crest equal to 288,75 m a.s.l.,**
- ✓ **calculations were carried out for initial water level in the reservoir equal to 272,40 m a.s.l. which corresponds to normal water level elevation NPP.**

ANALYTICAL CALCULATIONS

Calculations of flood waves transformation showed that for existing outlet installations there is no possibility to preserve a safe dam crest height above the maximum water level in reservoir equal to 1,0 m .

For flood wave $Q_{0,5\%}$ passage:

- **initial state of water level 272,40 m a.s.l. – water level in the reservoir reaches 288,29 m a.s.l. – 0,08 m above the dam crest**

For flood wave $Q^{\alpha}_{0,1\%}$ passage:

- **initial state of water level 272,40 m a.s.l. – water level in the reservoir will exceed 0,97 m dam crest**

CONCEPTION OF OUTLET INSTALLATION RECONSTRUCTION

Free flow of computational discharge through existing spillway is not possible:

because flume in its upper part is too shallow and too narrow

Solutions:

- **the flume should be deepened to about 3,0 m with simultaneous set of its width at 22,50 m (under such conditions the assumed discharge of spillway can be obtained for damming water level in reservoir for 288,60 m a.s.l.)**

Drawbacks and advantages:

- **the reconstruction would force a necessity of constructional changes of weir – new static conditions of its work and a necessity of constructional changes of wall on the opposite side,**
- **spillway can be reconstructed without a necessity of reservoir emptying,**
- **its safety is ensured because flood waves can pass through spillway without any negative consequences,**
- **lack of possibility of improving the operating conditions of freshet wave routing. At present the operation of outlet installation is carried out until a damming level in reservoir will reach spillway crest, i.e. an outflow will be somewhat over 200 $m^3 s^{-1}$.**

ANALYTICAL CALCULATIONS

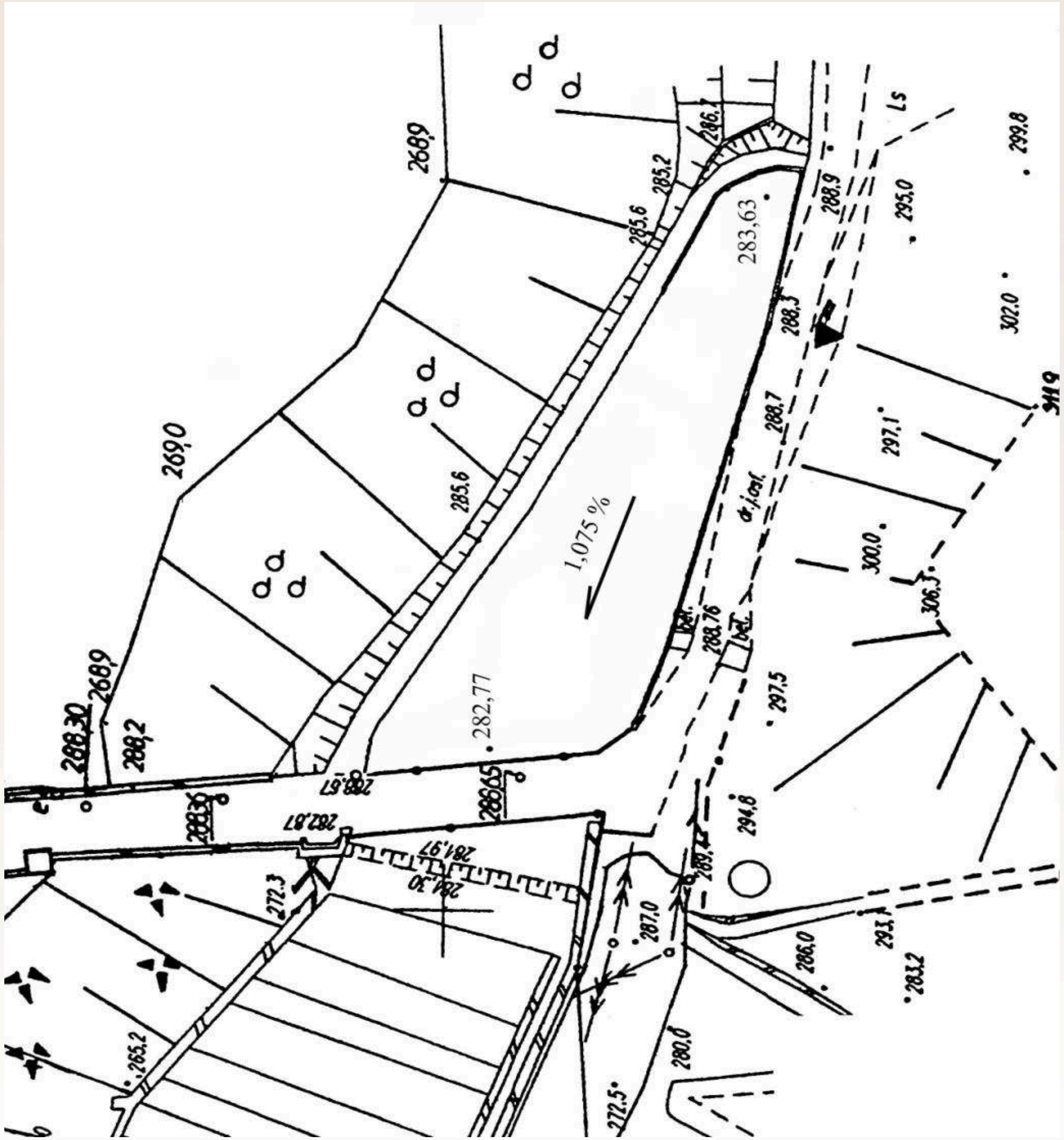
On the basis of numerical calculations, consist in changing a depth and width of flume and in determining a free water level along flume length, a required range of works for spillway's flume rebuilding were determined.

It is necessary to deepen a flume with simultaneous adjustment its bottom longitudinal slope with small widening its upper part.

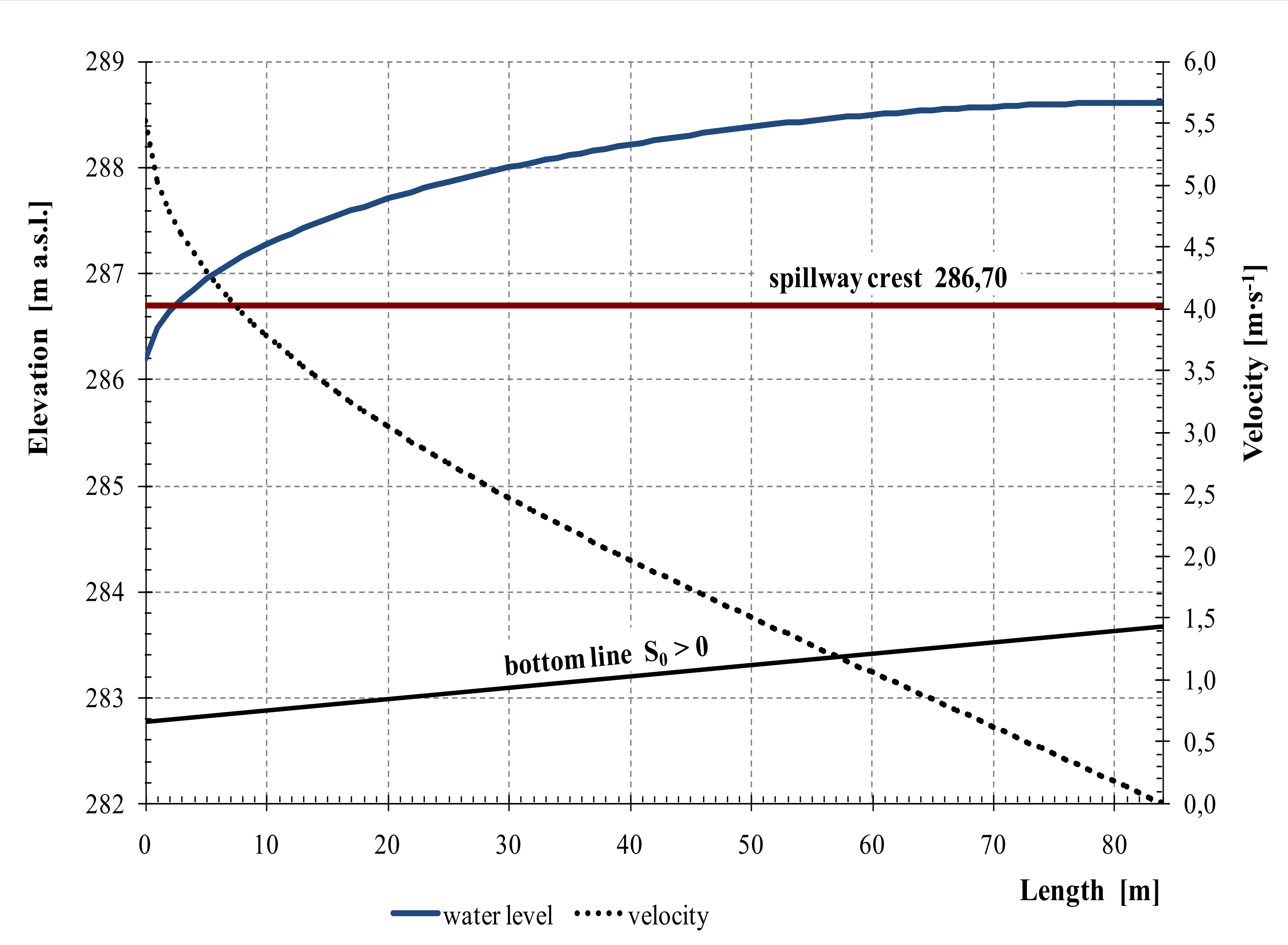
These requirements can be realized without significant interference in construction of the whole object, therefore they can be accepted in economic respect.

Proposed solutions of spillway rebuilding are shown below, whereas in next figure a free water surface and velocity along the flume is presented.

ANALYTICAL CALCULATIONS



ANALYTICAL CALCULATIONS

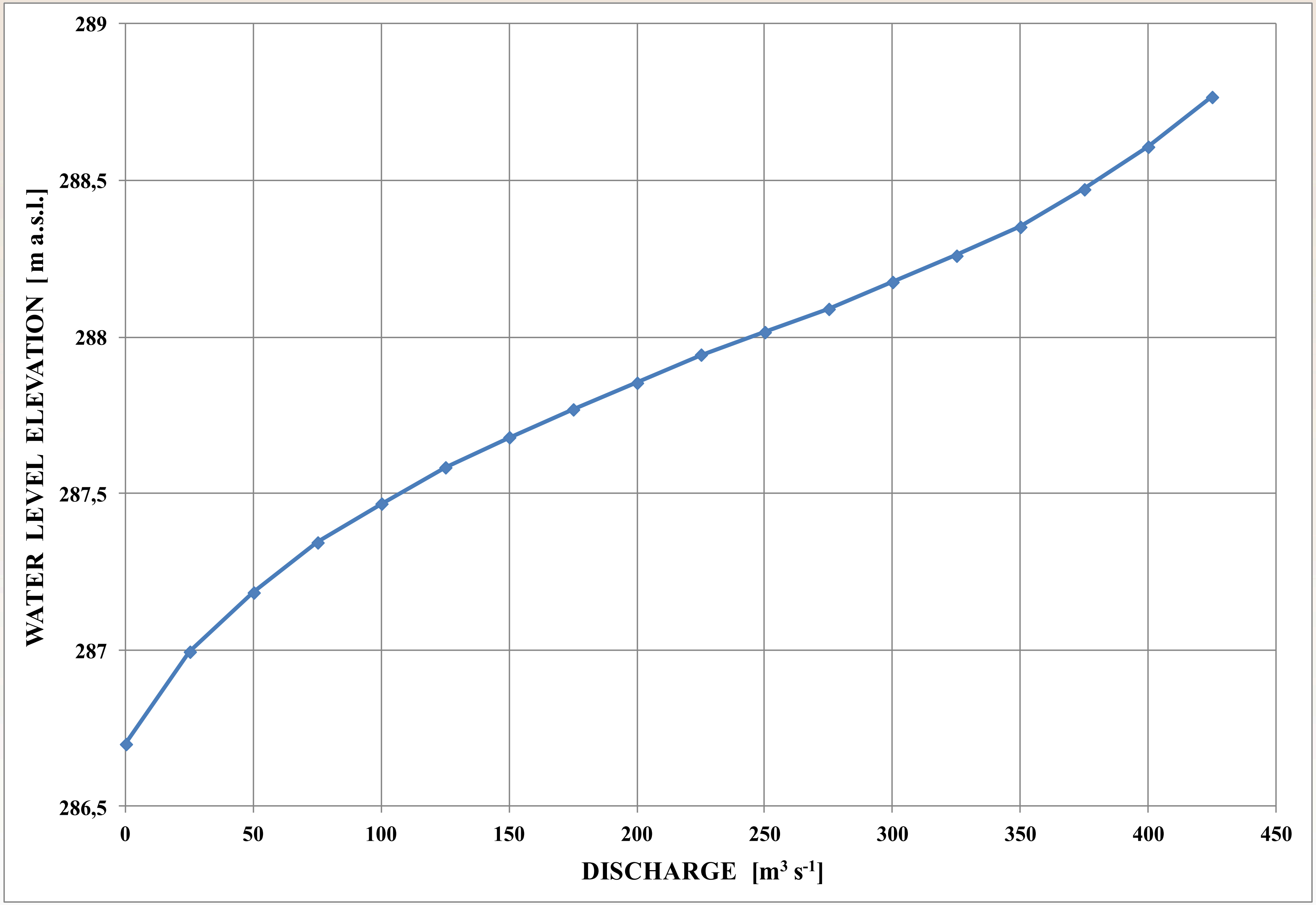


ANALYTICAL CALCULATIONS

- **Because investigations concerned an existing object, it was important to determine the conditions for the changes in character of the weir work and expected capacity ability. The spillway capacity ability, obtained on the basis of numerical analysis, is close to the required. This corresponds to discharge of about 425 $m^3 s^{-1}$, which could be obtained for corrected spillway layout in plan and flume parameters.**

- **Hydraulic characteristics of side channel spillway, corrected by analytical calculations, is determined for discharges in range from 0,0 to 425 $m^3 s^{-1}$ and in the range of water level elevations in reservoir from 286,70 m a.s.l. (spillway crest) to 288,75 m a.s.l. (dam crest from downstream).**

HYDRAULIC CHARACTERISTIC OF SIDE CHANNEL SPILLWAY FOR PROPOSED SOLUTIONS



RECAPITULATION

Recapitulating the numerical analysis of side channel spillway of Pilchowice reservoir connected mainly with hydraulic characteristics of its basic elements, weir and flume, there is a possibility of improving the capacity ability of this device.

Proposed solution that correct the configuration of the flume and its width in the upper part are verified by numerical analysis.

This confirmed a necessity of flume rebuilding, guarantying exploitation safety of reservoir mainly because of computational discharges, significantly exceeding the capacity ability of outlet devices in the existing state.

In numerical analysis an attention was paid to possibility and outright the necessity of drawing the flume with constant longitudinal slope bigger than zero.

CONCLUSIONS

This allow to draw the following conclusions:

- In order to improve the exploitation safety of the Pilchowice reservoir, it is necessary to introduce the proposed changes in existing state of a flume of the side channel spillway.
- A change in side channel spillway solutions consists in the deepening of flume bottom with the maintenance its longitudinal slope bigger than zero and the widening in its upper part.
- Introduced in minimal range the proposed changes of side channel spillway layout in plan, its capacity ability increase about 75 $m^3 s^{-1}$.

THANK YOU FOR YOUR ATTENTION