DESIGN AND OPTIMIZATION OF SMALL HYDROPOWER TYPE SERIES FOR SURFACE WATERCOURSE

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Abstract: The optimal head and flow rate for hydropower, are determined based on axiomatic and analytical considerations by Pelz in 2011. Due to ecologic and economic reasons it is necessary to optimize the relation of the gained energy to the edificial effort and impact on nature. Therefore machines have to be designed for optimal operating conditions consistent with the constitutional boundary conditions. Considering all this, the present paper gives a method for the design of type series for small hydropower, based on the axiomatic considerations of Pelz.

1 Introduction

In the established design methods for hydropower turbines, only the turbine for given operation point of operation i.e. head H_T and the flow rate Q [2] are considered as not interdependent parameters. In these methods the head depends only on the topology of the terrain. While damming the watercourse at a certain water level height, there will be flooding of adjacent terrain. The flow rate is determined by the hydrologic conditions of the water course, as well as by legal standards, such as mandatory minimum flow in the tailwater of the hydropower plant. In current hydropower plants turbine design aims to harvest the entire head. The question behind this traditional approach is:

> *Which amount of energy can be gained by a hydropower plant within the legal framework, exploiting the topologic conditions of the terrain?*

This view results in concentration on the hydraulic efficiency only. But this quantity is only of minor importance [1]! The gained power should be considered in the first place, especially for small hydropower. With this approach the operation point is not fixed. Pelz [1] in 2011 derived the optimal head und flow rate for hydropower on basis of the axiomatic considerations, asking the question:

> *What is the maximum hydraulic power that can be transformed*
> *into mechanical energy by any possible machine in an open channel?*

It has been shown, that for optimal operating of hydropower there is a functional correlation between flow rate and head. The new results [1] are valid for all of hydropower systems regardless of the available head and flow rate.

The present paper applies the results of Pelz for the optimal operation point on open watercourse hydropower such as river runoff stations. In contrast to hydropower in mountainous terrain, for river runoff stations the possibility to store water is poor. Hence the possibility to adjust the volume flow rate passing the turbines also is within narrow bounds. The available head created by damming the water is poor, due to settlement at the riverside and shipping. This leads to the conclusion that runoff stations have to be designed to work at high coefficient of performance in the first place and high hydraulic efficiency only in the second place. Therefore the question answered by the present paper is:

> *How can a machine be designed to work at the optimal operation point [1], for naturally determined volume flow rate of an open watercourse?*

2 Optimal Operating Conditions for Hydropower

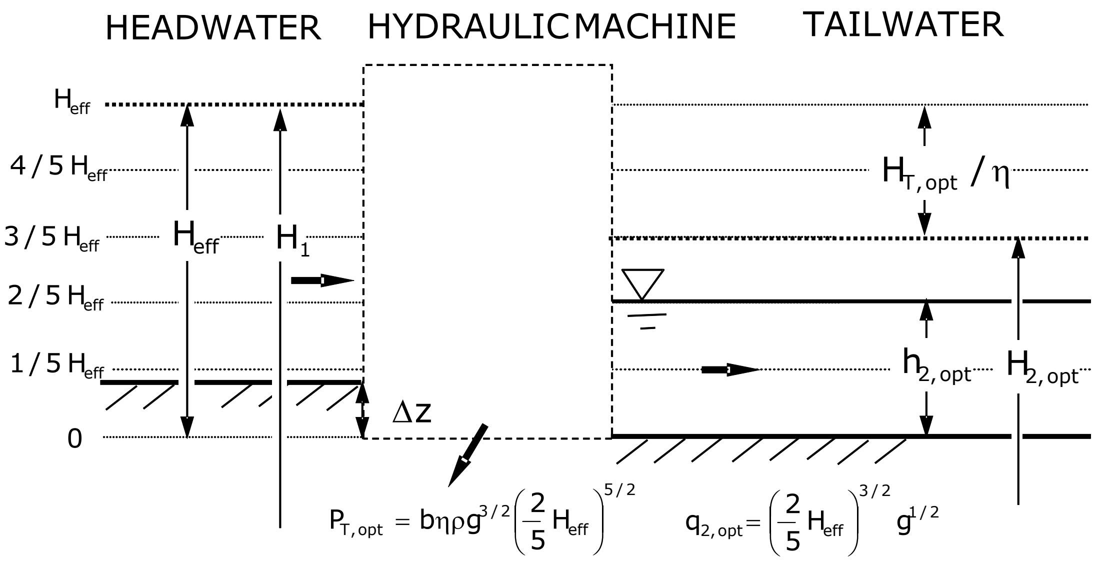

Fig. 1: Optimal operating point for hydropower [1].

The paper „*Upper Limit for Hydropower in an Open-Channel Flow*“ by the second author [1], deals with hydropower as an optimization problem. Based on strictly axiomatic derivation, the optimal flow rate and optimal head are determined, using the energy balance. Fig.1 shows the result of [1], i.e. the optimal operating point. The optimal head is $2\eta/5$ (being η the hydraulic efficiency) of the effective head $H_{\text{eff}}:=\Delta z+E_1$ for given upstream energy height $E_1:=h_{10}+u_{10}^2/2g$. The coefficient of performance is defined as usual [1]

$$C_p:=\frac{\eta P_T}{P_{\text{avail}}}\,. \tag{1}$$

P_T is the hydraulic power gained by the turbine

$$P_T = \eta \, Q \, \rho g H_T. \tag{2}$$

$q_2 = Q/b$ is the flow rate per depth unit for the tailwater width b of an open channel.

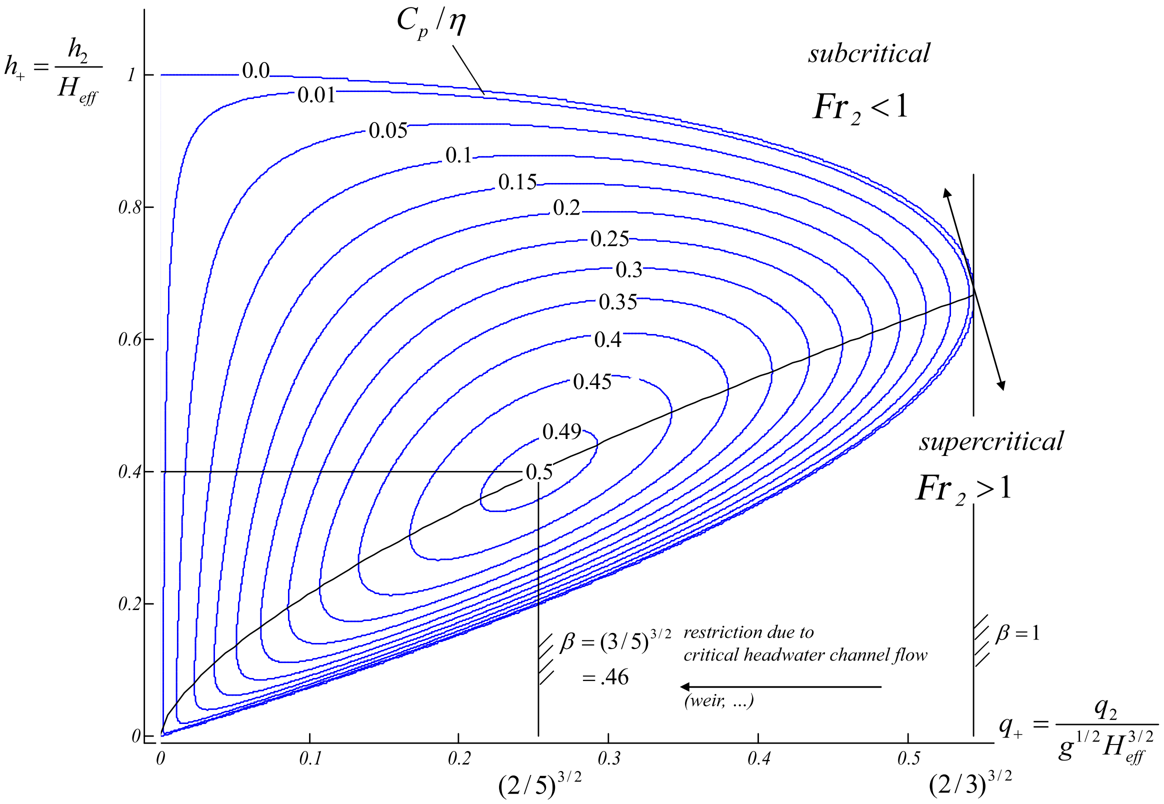

Fig. 2: Coefficient of performance as a function of dimensionless volume flow rate and head [1].

The available power P_{avail} represents the power that can be gained by the hypothetical ideal machine at its best operation point. It is defined as [1]

$$P_{avail} \coloneqq 2\rho b \left(\frac{2}{5} H_{\text{eff}}\right)^{5/2} g^{3/2}. \tag{3}$$

With (1), (2) and (3) the coefficient of performance C_p can be written as a function of the operating point, with a maximum of $C_{p,max} = \eta/2$. I.e. even for a hydraulic efficiency of 100%, max. 50% of the available hydropower can be transformed into mechanical power in the best operation point sketched in Fig. 2.

Fig. 2 shows the coefficient of performance as function of the dimensionless water depth of the tailwater $h_+ \coloneqq h_2/H_{\text{eff}}$ and the dimensionless specific volume flow rate $q_+ \coloneqq Q/(bg^{1/2}H_{eff}^{3/2})$. The maximum of C_p/η determines the optimal operating point, with the optimal head [1]

$$H_{T,opt} = \frac{2}{5}\eta H_{\text{eff}} \ , \tag{4}$$

the optimal volume flow rate [1]

$$Q_{opt} = b\left(\frac{2}{5}\right)^{3/2} g^{1/2} H_{eff}^{3/2} \quad , \tag{5}$$

and the optimal water depth level in the tailwater

$$h_{2,opt} = \frac{2}{5} H_{eff} \ . \tag{6}$$

Thus the optimal turbine power is

$$P_{T,opt} = \rho g H_{T,opt} Q_{opt} = \eta b \rho g^{3/2} \left(\frac{2}{5} H_{\mathrm{eff}}\right)^{5/2} . \tag{7}$$

3 Dimensioning of Dam for Optimal Operation

Goy [1] concludes that for economic profitable hydropower in open watercourse the design flow rate Q_{design} (Fig. 3), should be the volume flow rate that is exceeded for minimum 100 days a year. To gain information about flow rates, runoff data for rivers, often is usually available in hydrologic departments of the local government, or can be measured.

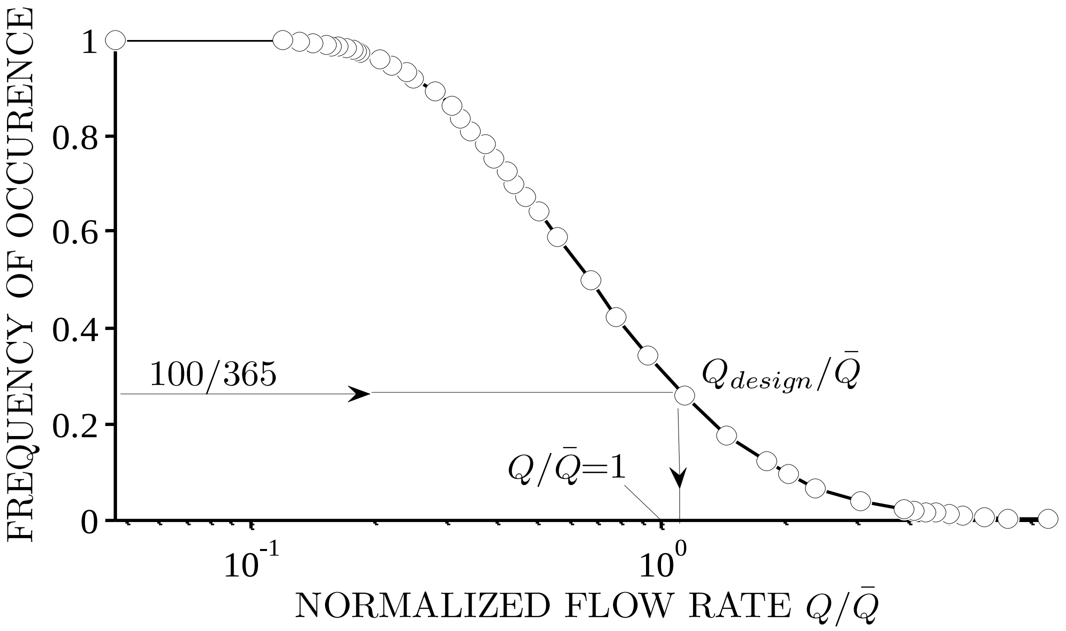

Fig. 3: Cumulative histogram of runoff for Weschnitz, Baden Württemberg, Germany, Average over the years 1962-2009, $\bar{Q} = 0.643\, m^3/s$ [5].

Fig. 3 serves to choose the design volume flow $Q_{design.}$. It is read as the following: 100/365 = 27% of volume flow is smaller than the design volume flow Q_{design}. In case of river runoff stations for the calculation of the effective head $H_{eff} := \Delta z + h_1 + u_1^2/2g$ the drop in the ground level Δz can be neglected, as well as the head of the kinetic energy $u_1^2/2g$ for small square of Froude number $Fr_1^2 = u_1^2/gh_1$. So the effective head [1] is approximated by the water level height in the head water h_1. To keep the damming water level constant, while operating optimal, we demand the entering volume flow to be equal to the optimal volume flow in the tailwater

$$q_{design} \overset{!}{=} q_{2,opt} = \left(\frac{2}{5}h_1\right)^{3/2} g^{1/2} \ . \qquad (8)$$

Solved for h_1 this leads to the damming height for optimal operating

$$H_{eff,opt} \approx h_{1,opt} = \frac{5}{2} q_{design}^{2/3} \, g^{-1/3} . \qquad (9)$$

Preliminary for an optimal operating of hydropower for runoff stations is the following: The stowage height at optimal operating is in a range that is reasonable with regard to impact on nature and civilization. Fig. 4 shows the optimal stowage height as function of the volume flow rate per depth unit q_{design}. Two examples of open water courses are added. For creek Weschnitz (Baden Württemberg, Germany) the optimal stowage height is $h_1 \approx 0.5\,m$, for river Nahe (Rheinland-Pfalz, Germany) it is $h_1 \approx 1.4\,m$. For both cases it can be savely assumed, that damming the water to optimal height would not lead to flooding of adjacent terrain.

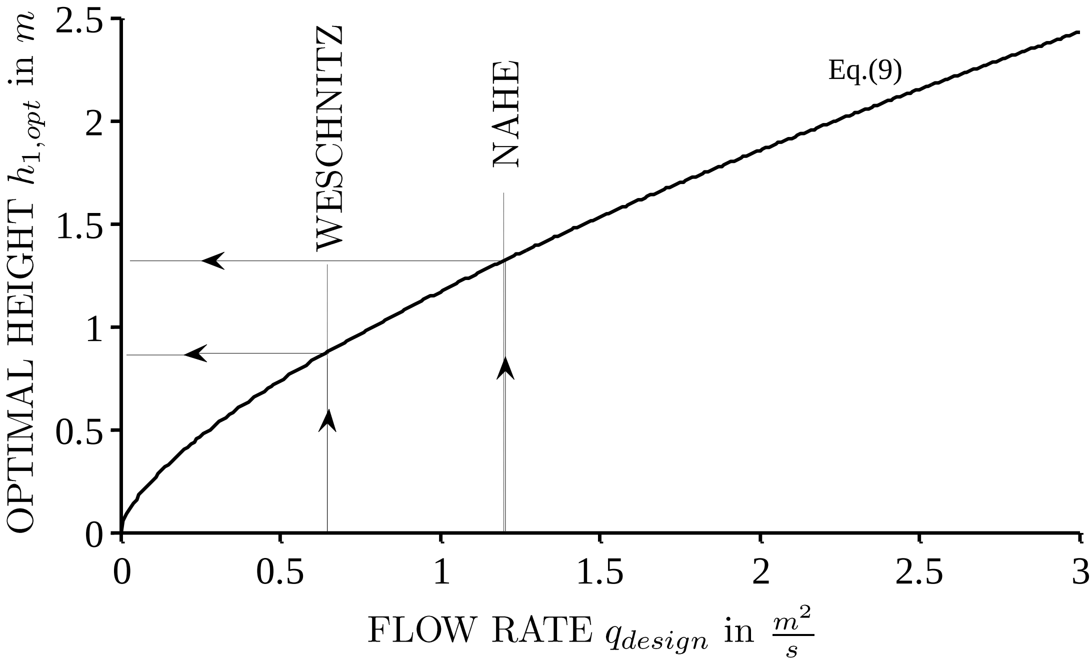

Fig. 4: Stowage height for optimal operation of hydropower.

Hence it can be concluded that optimal operation for hydropower requires only minor damming of open watercourses.

4 Dimensioning of Turbines for Optimal Operation

Pelz & Metzler [4] determined axial turbines, like Kaplan or bulb turbines, to be the most appropriate for small hydropower in terms of investment costs for river runoff stations. Fig. 5 shows the geometric model for turbine dimensioning.

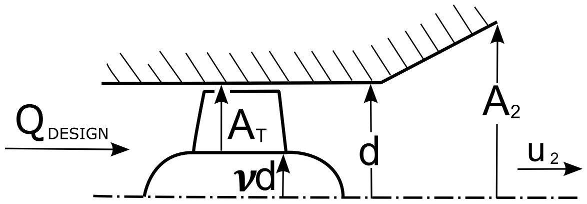

Fig. 5: Turbine geometry.

Using (4) in (9) the optimal head of the turbine as function of the flow rate per depth unit is

$$H_{T,opt} = \eta q_{design}^{2/3} g^{-1/3}. \tag{10}$$

For energetic optimal operation (Eq. (8)) we demand no bypass operation resulting in a constant stowage height. Thus the volume flow rate entering the turbine must equal the volume flow rate at the exhaust of the turbine:

$$q_{design} b = u_2 A_2 \quad . \tag{11}$$

It is assumed that the open water course can be approximately considered as a channel with rectangular cross section. For optimal operation. We demand following Pelz [1] (see Fig. 2)

$$u_{2,opt} \overset{!}{=} \sqrt{g h_2}. \tag{12}$$

Using (6) and (9) in (12) the optimal flow velocity in the tailwater, as a function of the volume flow rate per depth unit is

$$u_{2,opt} = g^{1/3} q_{design}^{1/3}. \tag{13}$$

With hub ratio ν of the turbine the cross section area ratio $\kappa = A_2/A_T$ is introduced:

$$\kappa := \frac{A_2}{d^2 \pi (1-\nu^2)/4} \quad . \tag{14}$$

Using (13) and (14) in (11) the resulting design equation reads

$$q_{design} b = g^{1/3} q_{design}^{1/3} \kappa \, d_{opt}^2 \frac{\pi}{4} (1-\nu^2) \ . \tag{15}$$

The above equation solved for the diameter leads to the energetic optimal diameter

$$d_{opt} = 2 q_{design}^{1/3} \ g^{-1/6} \sqrt{\frac{b}{\pi \kappa (1-\nu^2)}} \quad . \tag{16}$$

Using Equation (16) a turbine can be designed or selected for optimal operation of hydropower in open water courses knowing the naturally determined parameters b *and* q_{design} *of an open water course and the important design parameters* κ *and* ν *of the turbine.*

5 Type Series for Open Watercourses

Nowadays small hydropower plants are mostly designed and manufactured to specifications of one single watercourse, in which it is supposed to be applied. This causes high production costs and hence high power-specific investment costs for small hydropower. Alternatively to manufacture hydropower plants they can be designed as type series and scaled for different watercourses. One possibility to scale hydropower plants is to apply one single turbine design varying its diameter. Another possibility is to keep the diameter constant varying the number of turbines (modules), raising production quantities at the same time.

Furthermore the power weight ratio can be enhanced by varying the number of modules. The following section concerns the relation between power weight ratio and number of modules Z.

Pelz & Metzler [4] assume that the power-specific investment costs k_p, which are most important for the long term success of any power plant technology, for a first approach are proportional to the power-specific volume. Using Eqs. (16) and (7) they are defined as

$$k_p := \frac{INVESTMENT\ COSTS}{ELECTRIC\ POWER} \sim \frac{d_{opt}^3}{P_{T,opt}} = \frac{b^{1/2}}{q_{design}^{2/3}\eta g^{7/6}\rho}\frac{8}{[\kappa\pi(1-\nu^2)]^{3/2}}\ . \qquad (17)$$

Equation (17) shows, that the power-specific investment costs k_p decrease for increasing flow rate per depth unit q_{design} and increasing surface area ratio κ. For decreasing hub ratio ν, power specific investment costs decrease as well. Furthermore they are proportional to the square root of the width b of the open watercourse.

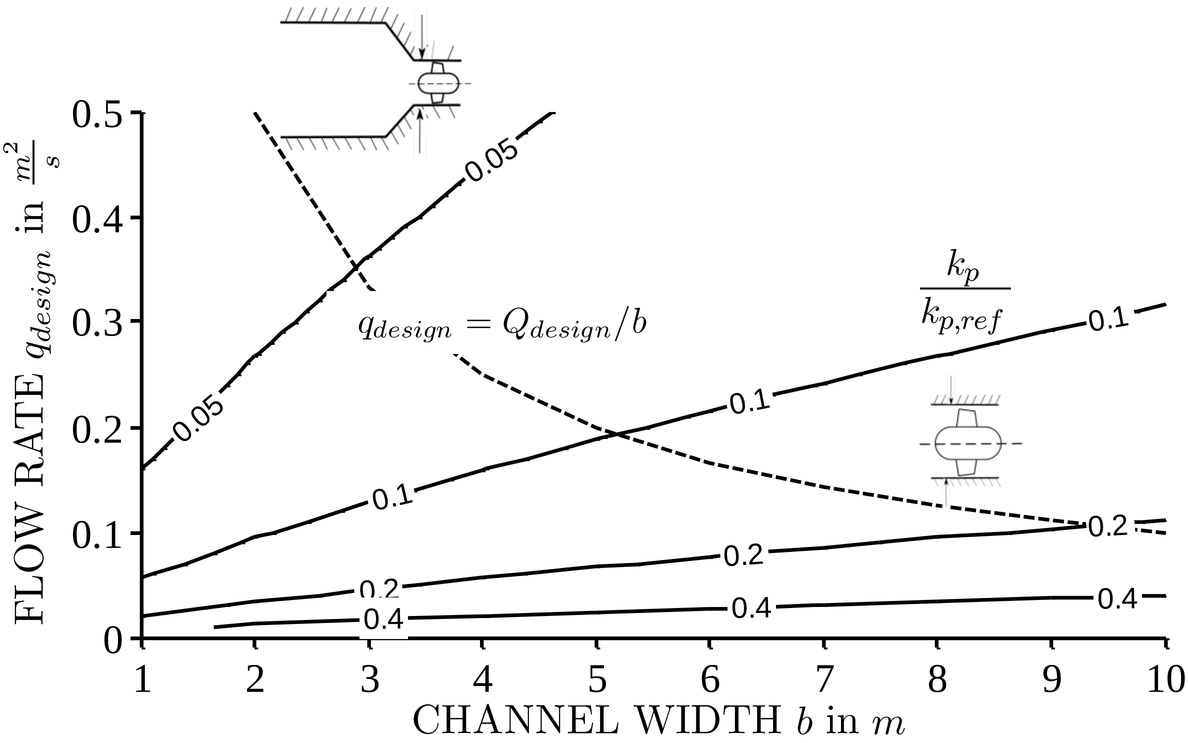

Fig. 6: Power-volume ratio as function of channel width b and flow rate q_{design}.

The only way to vary b is to narrow, or to widen the channel cross section. This causes high edificial effort and impact on nature. Fig. 6 shows the normalized power weight ratio for. The dash dotted line in Fig. 6 shows, how power volume ratio and thus power specific investment costs can be lowered along the path of the functional correlation of channel width and flow rate $q_{design} = Q_{design}/b$. Another, more feasible possibility to lower power specific investment costs is to apply more than one turbine (module) to the channel. In case of applying Z modules to the channel [4] the module width is

$$b_m = b/Z \tag{18}$$

being Z the number of modules [4]. Hence, with (17) the power-specific investment costs for each module are

$$k_p \sim \frac{b^{5/2}}{Z^{1/2} Q_{design}^{2/3} \eta g^{7/6} \rho} \frac{8}{[\kappa\pi(1-\nu^2)]^{3/2}}. \tag{19}$$

In Equation (17) the volume flow rate per depth unit q_{design} is reciprocal dependent of the channel width and proportional to the naturally determined design flow rate Q_{design}. Hence, the only way to decrease investment costs is an appropriate selection of the design parameters κ and ν. With the number of modules Z, another independent parameter is added to Equation (17), i.e. by changing the number of modules the power-specific investment costs can be lowered while keeping natural determined Q_{design} and b constant.

To judge the influence of module number Z on the power specific investment costs, the dimensionless power-specific investment costs k_p^+ are defined as

$$k_p^+ = \frac{k_p}{k_p(Z=1)} = \frac{1}{\sqrt{Z}}\,. \qquad (20)$$

As consequence of Equation (20), the power weight ratio can be halved by applying 4 instead of one module to any watercourse, for example.

With (20) it can be concluded that for any hydropower plant, the power-specific investment costs can be decreased by increasing the number of modules applied to the open water course. Thus designing small hydropower plants as type series can be an appropriate measure to lower power specific investment costs and hence make small hydropower more competitive.

6 Summary

The present paper provides new approaches for design of hydropower for energetic optimal operation. The optimal stowage height for most watercourses lies in a feasible range. It is shown that lowering hub ratio ν and increasing cross section area ratio κ are appropriate measures to decrease power specific investment costs. Also the design of hydropower plants as type series applying several modules of same dimension to a channel can lower power specific investment costs significantly.

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