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THE APPLICATION OF TIME-FLOW CURVES IN HYDROPOWER CALCULATIONS

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ABSTRACT

Curves developed by hydrologists are used to assess energy resources of rivers, and determine installation parameters of hydroelectric plants. They facilitate the determination of the flows' value, as well their long-term, annual and seasonal volatility. The installation flow rates of small-scale lowland hydroelectric plants are determined on the basis of the energy resources of watercourses, the value of net head streams and the criteria of economic feasibility of the investment. The article presents the method of applying time-flow curves in order to determine the installation flow rate of small-scale lowland hydropower plants. The analysis was carried out for the projected flows, and for the flows assumed in the development of water energy cadastre. The effective head stream was assumed as a constant unit value, presupposing the same changes in the upper and lower water level. The obtained values of annual installation flow rates were referred to the mean values of annual flow in the base years, and the mean flow in the multiyear period. The rate of growth and the amount of available energy constitute suitable criteria for the selection of installation flow rate in small-scale hydropower plants.

Keywords: water energy resources, small-scale hydropower plant, installation flow rate

INTRODUCTION

The interest in investing in small-scale hydropower facilities has been highly changeable in recent years. The construction of new facilities after 1980, and in particular the reconstruction of old hydro-power installations, resulted partly from the growing interest in alternative energy sources, from legal changes, and in particular from the Resolution 192 of the Council of Ministers of 7 September 1981 on the development of small-scale hydropower (MP 1981 No. 24 item 214). The formation of small-scale hydroelectric installations at the turn of the 20th and 21st centuries also resulted from a large number of run-down objects that could be rebuilt easily, at relatively small cost. At that time, there was also a rapid development of other renewable energy technologies (Bajkowski and Górnikowska 2013).

In the assessment of energy resources of watercourses, used in the determination of installation parameters, the same tools are used as those applied in hydrological analyses. In the gauge sections or nearby objects, we directly use historical hydrological information. This allows us to determine the flow rate, and its seasonal or multi-seasonal variability (Bajkowski and Olifirowicz 2014). We use historical information to select our base years as well as to assess the potential power resources of rivers. We assess the annual power resources of rivers for long-term flows with the duration of $Q_{95\%}$ and $Q_{50\%}$ and higher, as well as for the average annual *SQ* flow.

It is possible to diagnose the course of changes in the daily flows throughout the year using long-term hydrological observations. The curves obtained from these analyses, that is frequency curves or cumulative frequency curves, provide us with information about the

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size of the longest lasting flows, and the time of their occurrence. They also allow us to select base years for hydropower analysis, and to determine the power and energy production in individual years. For these analyses, we usually choose a medium year, a dry year, and a wet year, out of a multi-year period. According to the hydrological criterion, we assume as the average year the one in which the discharge was the closest to the mean discharge in the multi-year period. Selection of the dry year is based on the year with the lowest annual discharge, whereas the wet year is the one with the highest annual outflow in the multi-year period (Bajkowski 2009). Due to the fact that in the assessment of installation flows as well as in determining the operational characteristics of water turbines, we use flow rather than discharge, we make the selection of the base years from a multi-year period based on average annual flows.

In the hydropower analyses, we determine the flow and the net head, which are the basis for the selection of the turbine (Michałowski 1955). These parameters are called installation values, and the values guaranteed by the turbine manufacturer are referred to as nominal values, and the values achievable in the given conditions, as the installed values. We assume the efficiency of using the river's energy resources as one of the criteria for selecting the installation flow. In the presented analyses, flows were indicated, at which for the determined water impoundment conditions a high trend of the increase in the obtained energy is maintained. At the same time, periods with high flows were distinguished, in which a significant volume of incoming water cannot be used for power generation, and those in which the flows are smaller than the turbine installation outlet.

MATERIAL AND METHODS

Years selected for the analysis

Effective use of the energy generated by watercourses requires proper determination of water engine parameters (turbines). The selection of installation parameters for water turbines results from the established availability of water, that is, the value of available flows in the watercourse, and the possibility of maintaining the head stream (Karolewski and Ligocki 2004). Depending on the type of hydropower utility project being designed, we can influence (to varying extent) the values of the volume of water being worked up, as well as the ranges of the obtained head streams. The largest flow control options are achieved in hydropower reservoirs, where, with considerable capacity of the reservoir power layer at our disposal, we can collect water and then put it to work with the appropriate turbine outlet (Mosonyi 1987).

In run-of-river power facilities, which include the majority of lowland small-scale hydropower plants, the determination of installation flows is based on the analysis of the energy resources of the watercourse. The regime of operation of the turbine set of such power plants depends on the current inflow, and the volumes of the channel reservoir, which are typically small. The intensity of disposable flows has the greatest impact on the value of the installation outlet of small-scale flow turbines on lowland rivers. The head stream (turbine head) of such objects results from design parameters, and it is shaped by the local topographical, natural and social conditions.

The analyses presented in the article use historical hydrological data in the Wólka Mlądzka cross-section on the Świder River. The analysis period covers 15 calendar years from 1966 to 1980. For the analysed period, annual average flows *SQ* and *SSQ* average flow in the multi-year period have been determined. Using the method of determining the base years proposed by Bajkowski (2009), the following years were selected for detailed analyses (see: Fig. 1):

- 1966 as a dry year, characterized by the smallest volume of water in the multi-year period,
- 1971 as a medium year, characterized by a water volume similar to the annual average volume over the multi-year period,
- 1974 as a wet year, characterized by the largest volume of water over the multi-year period,
- An average year, characterized by a curve of flows determined from the multi-year period average values of flows of a given duration.

Base flows

In river hydropower analyses, historical hydrological information is used, including water levels and daily flows. Difficulties arise when a hydropower investment project concerns small, uncontrolled rivers (Ciepielowski and Dąbkowski 2006). These flows are transformed using the methods applied in hydrology, from gauge crossings to the location of hydropower invest-

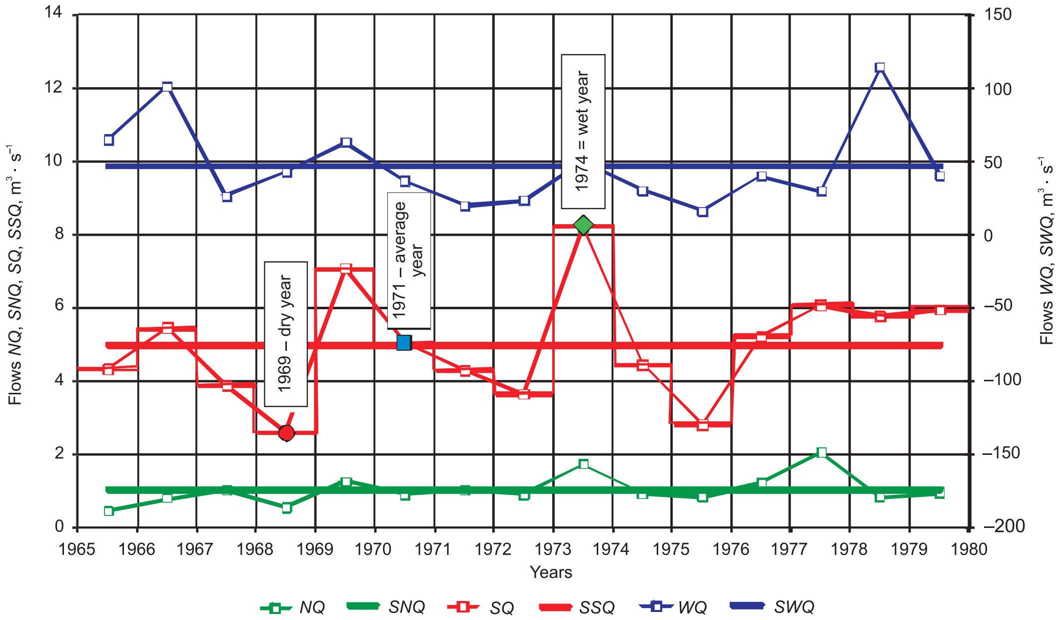

Fig. 1. Characteristic flows

ment projects. Under these conditions, the flow used to dimension the turbine is determined as a multiple of the *SQ* flow. The value of medium flow is determined using the methods proposed for non-controlled rivers (Banasik and Hejduk 2013, Bajkowski 2014, Więzik 1993). In the year selection procedure, and in the calculation of energy resources aimed at determining the installation flow, the following flows have been used:

> Characteristic and periodic:

- *WQ* – the highest flow in the year, taken to determine the largest energy resources in the watercourse; due to the possibility of a deficiency of fall during its passage, it is not directly used for energy production in hydropower plants,
- *SSQ* – the average flow over the multi-year period, adopted for the purpose of defining the dry, medium and wet year,
- *NQ* – the lowest flow in a year, determined with the purpose of defining the working conditions of power facilities during the periods of flow deficiency,
- *NTQ* – the longest-lasting flow in the year, indicating the period of ensuring a constant flow to the power plant.

> Cadastral:

- *SQ* – the average flow in a year, defining constant power and energy in the cross-section,
- $Q_{95\%}$ – the flow occurring (along with higher flows) throughout 95% of the annual period,
- $Q_{50\%}$ – the flow that has been both exceeded and not reached for the same number of times over the year.

The ordered flow curves make it possible to estimate the flows with a specified duration (along with higher or lower flows). In analysing the possibilities for hydropower production, we use the time curves of flows along with the higher ones (see: Fig. 2). We then receive flows with a certain guarantee of occurrence during the year (Węglarczyk 2014). In cadastral analyses, we develop an ordered curve for individual years of the multi-year period (Punys, Dumbrauskas, Kasiulis, Vyciene and Silinis 2015). The values of base flows used in the analyses are summarized in Table 1. The table also lists, for subsequent years of the multi-year period, the duration of T_{SQ} along with higher *SQ* flows, T_{SSQ} flow duration times, $SSQ = 4.98\ m^3 \cdot s^{-1}$, and T_{NTQ} incidence of the longest lasting *NTQ* flow. The analyses that we have conducted show a large variation in the duration of T_{SSQ} of the *SSQ* flows in individual years; in the dry (1966) year it is 43 days, in the medium (1971) year, it is 86 days, and in the wet (1974) year, it is 157 days. Selection of the installation flow at the *SSQ* level affects the diversified value of pow-

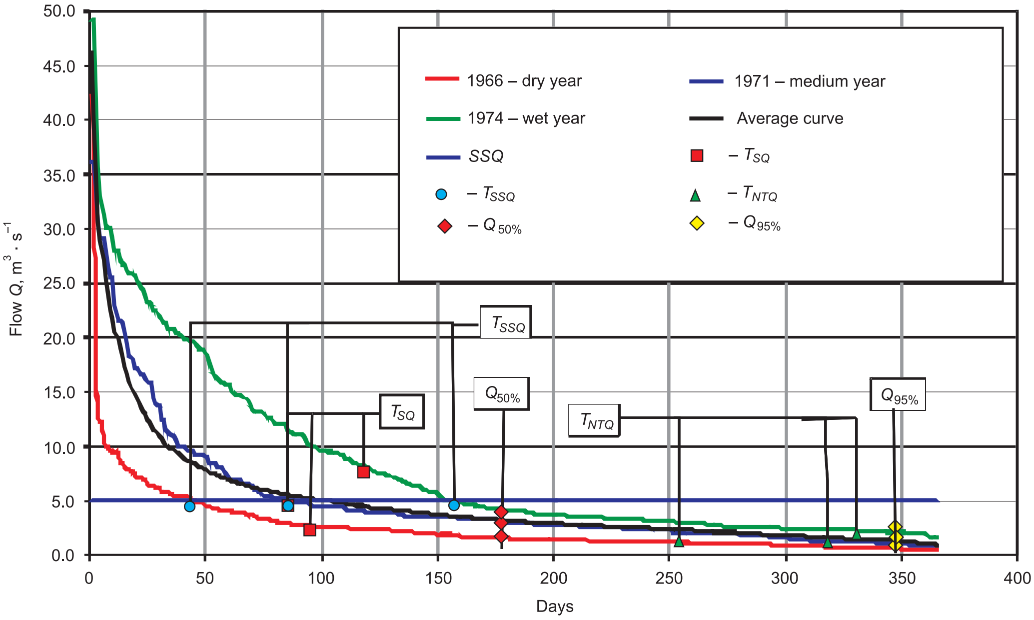

Fig. 2. Time-flow curves of the base year exceedances

er obtained with this flow in individual years. Similar variation occurs for longest-lasting *NTQ* flows. In this case, the values of flow rates and the frequency of their occurrence are changed (see: Table 1, Fig. 2)

Installation flow

The energy criterion for selecting the installation flow of hydropower plants is determined by the degree of increase in the value of obtained energy, and effective power determined for the specified base flows over the multi-year period. Calculations were made for flows specified for particular years (SQ, NTQ, $Q_{50\%}$, $Q_{95\%}$) as well as multi-year SSQ flow, which reflect the varied hydrological conditions of the watercourse. It is also possible to select the installation flow from a larger range of flows, therefore the calculations have been extended to include specified flows between 1.5 SQ and 3.0 SQ (see: Table 2, column 3).

The energy calculations for the specified flows were made at a unitary head stream of $H = 1.0$ m. At this stage of the analysis, the adoption of a fixed unit head stream was considered justified, due to the interpretation of the head stream for run-of-river power plants (Juniewicz and Szling 1964). The assumption made of constant head stream with the specified base flows does not reflect the actual operational situation of all types of hydropower plants. The level of water impoundment in the upper station of the hydroelectric power plant depends on the concept of hydro-technical development of the river, as well as being dependent – to a large extent – on the concepts and design parameters of the development. With the use of periodical storage of water at the retention volumes of the watercourse or upper reservoir, the values of head streams are subject to fluctuations, and are shaped by the output of the flow devices and the capacity of the lower station.

The daily effective power of the watercourse at the specified flows was calculated from the following formula:

$$E_d = \eta_e \cdot g \cdot Q_o \cdot H_o \cdot T_o, \text{ kWh} \tag{1}$$

where:

$\eta_e \cdot g = 7.0 \text{ m} \cdot \text{s}^{-2}$ – ratio of power plant installation efficiency and force of gravity,

Q_o – base flow [$\text{m}^3 \cdot \text{s}^{-1}$] assumed to be equal to:

$$Q_o = Q_z \quad \text{when} \quad Q_z \leq Q_d$$

$$Q_o = Q_d \quad \text{when} \quad Q_z > Q_d$$

Q_d – actual observed flow [$\text{m}^3 \cdot \text{s}^{-1}$],

Q_z – specified flow [$\text{m}^3 \cdot \text{s}^{-1}$],

H_o – base head stream for the observed flow ($H_o = 1.0$ m),

Table 1. Base flows and their duration (along with higher flows)

No.	Year	SQ [$m^3 \cdot s^{-1}$]	T_{SQ} [day]	T_{SSQ} [day]	$Q_{95\%}$ [$m^3 \cdot s^{-1}$]	$Q_{50\%}$ [$m^3 \cdot s^{-1}$]	NTQ interval	NTQ [$m^3 \cdot s^{-1}$]	Frequency of T_{NTQ} [day]
1	2	3	4	5	6	7			
1	1966	4.31	94	75	0,.2	2.69	2.20 ÷ 2.10	2.10	44
2	1967	5.45	91	102	1.23	2.92	1.60 ÷ 1.40	1.50	33
3	1968	3.88	141	66	1.23	2.97	1.60 ÷ 1.40	1.50	35
4	1969	2.61	96	43	0.70	1.70	1.40 ÷ 1.20	1.30	43
5	1970	7.07	109	147	1.56	3.50	2.80 ÷ 2.60	2.70	45
6	1971	5.02	86	86	1.16	3.10	1.40 ÷ 1.20	1.30	36
7	1972	4.29	135	93	1.50	3.60	1.80 ÷ 1.60	1.70	25
8	1973	3.64	113	61	1.05	2.80	1.20 ÷ 1.00	1.10	34
9	1974	8.23	118	157	2.18	4.14	2.40 ÷ 2.20	2.30	29
10	1975	4.45	120	86	1.82	2.90	2.60 ÷ 2.40	2.50	62
11	1976	2.80	132	31	1.08	2.32	2.40 ÷ 2.20	2.30	36
12	1977	5.19	80	96	1.78	3.75	2.00 ÷ 1.80	1.90	25
13	1978	6.07	112	163	2.62	4.76	3.20 ÷ 3.00	3.10	29
14	1979	5.76	52	74	1.02	2.76	2.00 ÷ 1.90	1.90	41
15	1980	5.94	107	136	1.45	4.00	4.20 ÷ 4.00	4.10	25

Table 2. Specified flows and calculated power

No.	Flow description	Discharge [$m^3 \cdot s^{-1}$]	1969		1971		1974	
			$Q_{95\%}$ [$m^3 \cdot s^{-1}$]	Power [kWh]	Q [$m^3 \cdot s^{-1}$]	Power [kWh]	Q [$m^3 \cdot s^{-1}$]	Power [kWh]
1	2	3	4	5	6	7	8	9
1	$Q1$	$3.0 \cdot SQ$	12.94	9255	15.05	11365	24.70	20062
2	$Q2$	$2.5 \cdot SQ$	10.78	8981	12.54	10859	20.59	19237
3	$Q3$	$2.0 \cdot SQ$	8.62	8660	10.03	10261	16.47	17836
4	$Q4$	$1.5 \cdot SQ$	6.47	8160	7.53	9372	12.35	15910
5	$Q5$	SSQ	4.98	7561	4.98	8129	4.98	9953
6	$Q6$	SQ	4.31	7171	5.02	8151	8.23	13099
7	$Q7$	$Q_{50\%}$	2.69	5693	3.10	6473	4.14	8962
8	$Q8$	NTQ	2.10	4827	1.30	3272	2.30	5833
9	$Q9$	$Q_{95\%}$	0.82	2071	1.16	2932	2.18	5549

T_o – daily power maintenance time [h] (T_o = 24 h for the observed flow occurring 24 hours a day). In run-of-the-river power plants, when the daily flow is smaller than the installation flow, the power plant can still operate according to less favourable operating characteristics, or it is possible to plan to switch it off periodically. The time of maintaining the installation capacity in power plants equipped with an upper reservoir depends on the current inflow and the volume of the energy layer of the reservoir.

Figure 3 shows the curves of raw power, effective power, and specified flows for selected years: 3a – dry year, 3b – medium year and 3c – wet year, whereas table 2 summarizes the results of the effective energy calculation of the watercourse at specified flows, for selected characteristic years.

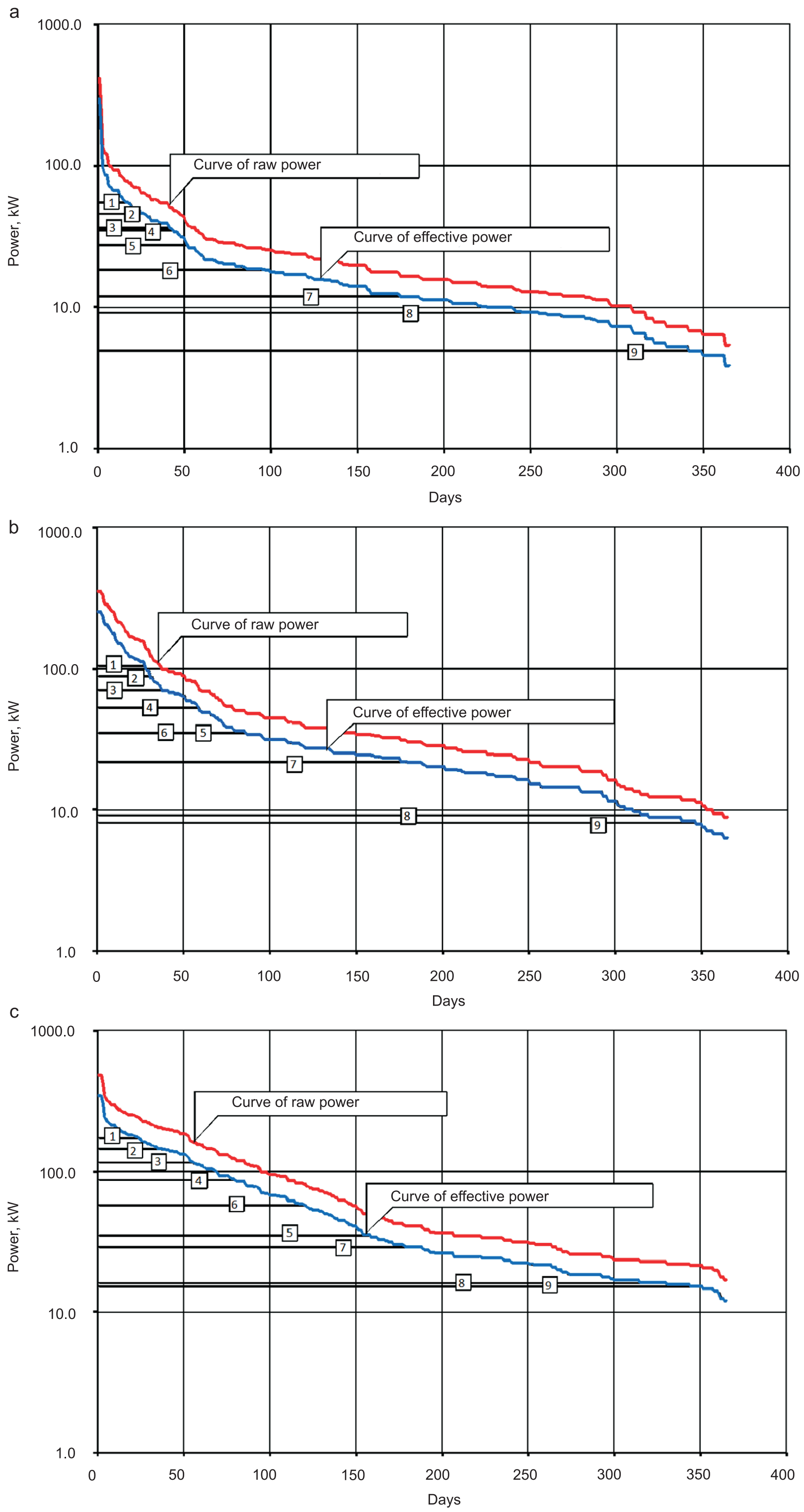

Fig. 3. Power curves: a – 1969 dry year, b – 1971 – medium year, c – 1974 – wet year, 1 – 3.0*SQ*, 2 – 2.5*SQ*, 3 – 2.0*SQ*, 4 – 1.5*SQ*, 5 – *SSQ*, 6 – *SQ*, 7 – $Q_{50\%}$, 8 – *NTQ*, 9 – $Q_{95\%}$

CONCLUSIONS

The energy criterion for the selection of the installation flow of a run-of-the-river hydro power plant assumes that optimal conditions for the selection of this particular flow occur when a high growth dynamics of the watercourse's power is maintained. From the range of specified flows, we choose a flow that still maintains has a high growth of energy. After surpassing that flow, there is still a growing trend in the energy of the watercourse, but that growing trend is decreasing considerably. With this interpretation, the installation flow is the abscissa of the centre of the curvature of the function describing the dependence of the effective power on the specified flows (see: Fig. 4). The value of the installation flow was calculated from the point of intersection of tangents to the end of the function $E_i = f(Q_i)$, determined for individual years of the multi-year period. Figure 4 shows the procedure for determining the installation flow for the three selected years. These flows are arranged in the central zone of the specified values, in which the SQ and $Q_{50\%}$ flows are also located. The values of installation flows and the power of watercourse calculated for these values, for the years of the multi-year period, have been summarized in Table 3.

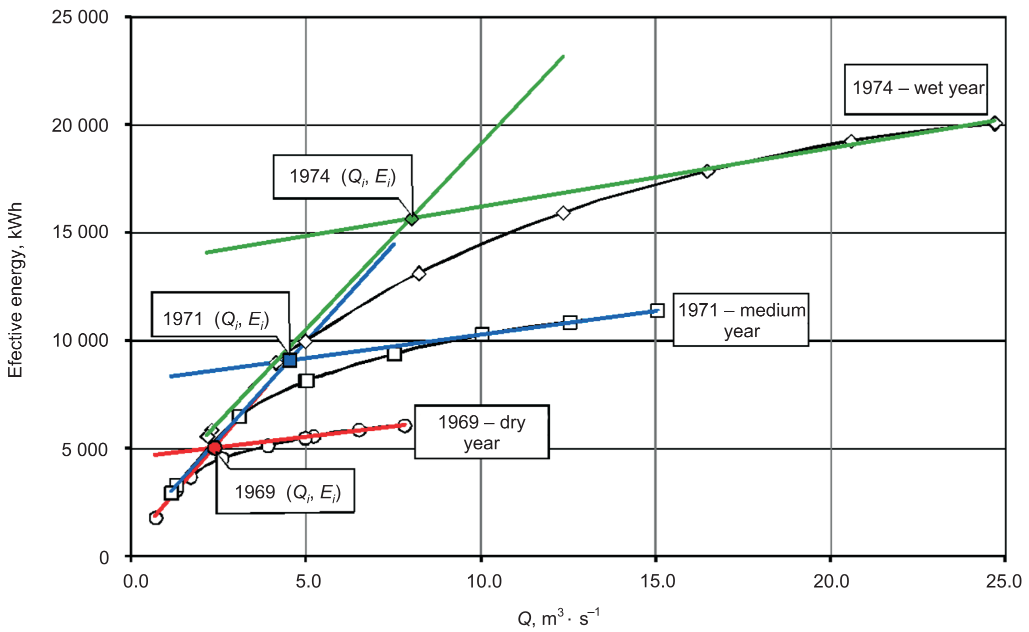

Fig. 4. Effective power as a function of the specified discharge

The established installation flows have been matched to the annual average flow rates SQ (see: column 5 of Table 3), and to the average flow in the SSQ multi-year period (see: column 6 of Table 3). The values of the ratio of installation flows to annual average flow rates SQ and the average of SSQ multi-year period are shown in Figure 5 (Q_i/SQ in point 1a, Q_i/SSQ in point 2a, respectively). According to the analyses, the installation flow in the examined multi-year period equals $Q_i = (0.961 \pm 0.116)\ SQ$ (see: row 1b, Fig. 5). The reference of the annual installation flows to the average flow from the multi-year period shows a functional dependence (see: line 2b, Fig. 5), which is described by the following function:

$$\frac{Q_i}{SSQ} = 0.0076 \cdot SQ^2 + 0.0943 \cdot SQ + 0.2772$$

$$R^2 = 0.849 \qquad (2)$$

in which: R^2 – coefficient of determination, other symbols as above.

For the Wólka Mlądzka cross-section on the Świder River, the installation flow of the run-of-river power plant according to the energy criterion is $0.48 \cdot SSQ$ for the dry year, $0.91 \cdot SSQ$ for the medium year, and $1.61 \cdot SSQ$ for the wet year.

Table 3. Installation flows

No.	Year	Q_i [$m^3 \cdot s^{-1}$]	E_i [kWh]	Q_i/SQ [$m^3 \cdot s^{-1}$]	Q_i/SSQ [$m^3 \cdot s^{-1}$]
1	2	3	4	5	6
1	1966	3.80	6 705	0.881	0.763
2	1967	4.78	7 794	0.877	0.959
3	1968	4.25	7 377	1.097	0.854
4	1969	2.39	4 316	0.916	0.479
5	1970	6.29	10 302	0.890	1.262
6	1971	4.54	7 738	0.904	0.911
7	1972	4.86	8 731	1.130	0.975
8	1973	3.83	6 803	1.054	0.770
9	1974	8.02	12 889	0.973	1.609
10	1975	4.12	7 899	0.926	0.827
11	1976	3.03	5 754	1.081	0.609
12	1977	4.98	9 394	0.959	0.999
13	1978	6.63	12 118	1.092	1.331
14	1979	3.96	6 853	0.688	0.795
15	1980	5.64	10 147	0.950	1.133
		Mean		0.961	
		Sy – Standard deviation		0.116	

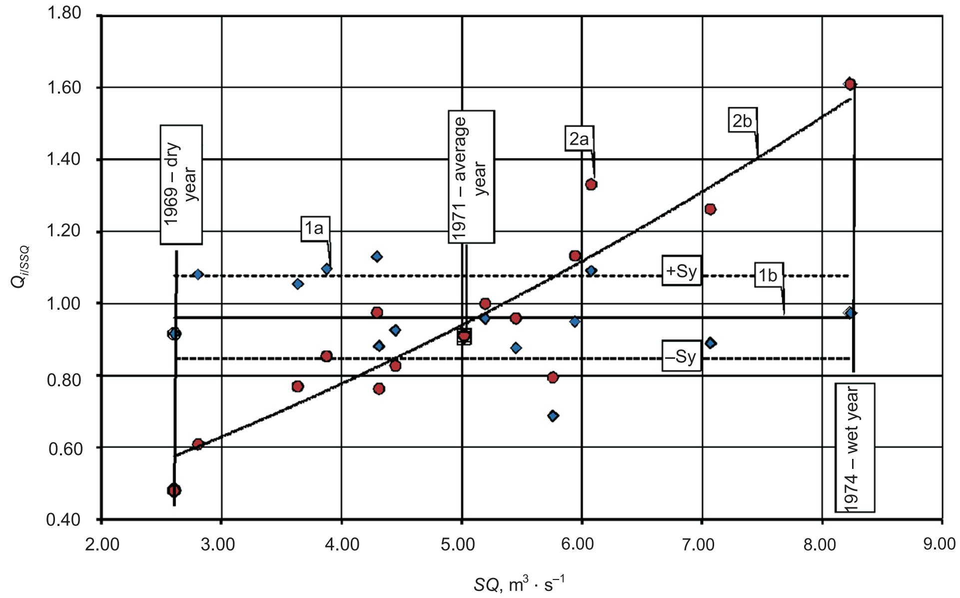

Fig. 5. Dimensionless values of installation flows: 1a – measurement points Q_i/SQ, 1b – mean value Q_i/SQ, 2a – measurement points Q_i/SSQ, 2b – regression curve Q_i/SSQ

SUMMARY OF FINDINGS

1. The flow time curves determine the mutual correlation between the hydrological parameters of the rivers (flow and time) used in the assessment of power resources. The resulting head stream is a value that is shaped by the designing and operational parameters of the installation.
2. The power curves for the specified flows, used for the selection of the installation flow, allow us to determine the energy, and then the flow, at which – for the determined impoundment conditions – the high growth trend of the energy obtained is still maintained. This criterion defines the parameters for the selection of water turbines that allow for the optimal use of hydroelectric resources of rivers.
3. Energy at the specified flows was calculated as effective power, taking into account the capacity of the future installation, whereas daily values of base flows were assumed to be equal to the specified or the observed flows. When the observed flow was greater than the specified base flow, it was assumed equal to the specified one. This interpretation indicates that in periods of high flows, a significant volume of water in power plants flows unproductively, and is not used for energy production. The only way to use it is to collect it directly in dam reservoirs, or to slow down its flow from the catchment area. When the observed flows were smaller than the assumed ones, the amounts of available energy were determined for the daily flow.
4. In the analyses, we have introduced specified flows, the values of which can be close to the installation flows (*SQ*, *SSQ*,). The study has yielded Q_i = (0.961 ± 0.116) *SQ* and Q_i = 0.48 · *SSQ* for the dry year; Q_i = 0.91 · *SSQ* for the medium year; and Q_i= 1.61 · *SSQ* for the wet year. Other flows are not taken into account when selecting the turbine outlet in run-of-river power plants. The flows of $Q_{50\%}$ and $Q_{95\%}$ are taken into account for the assessment of energy resources, whereas the *NTQ* flow determines the longest-lasting operating condition.

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WYKORZYSTANIE KRZYWYCH SUM CZASÓW PRZEWYŻSZENIA PRZEPŁYWÓW WRAZ Z WYŻSZYMI W OBLICZENIACH HYDROENERGETYCZNYCH

ABSTRAKT

Krzywe opracowywane przez hydrologów wykorzystywane są do oceny zasobów energetycznych rzek i ustalenia parametrów instalacyjnych elektrowni wodnych. Pozwalają one na określenie wartości przepływów, ich wieloletniej, rocznej oraz sezonowej zmienności. Przepływy instalacyjne małych przepływowych nizinnych elektrowni wodnych wyznaczane są na podstawie zasobów energetycznych cieków, wartości spadów i kryteriów ekonomicznej efektywności inwestycji. W artykule przedstawiono sposób wykorzystania krzywych czasowych przepływów do określenia przepływu instalacyjnego małych elektrowni wodnych. Analizę przeprowadzono dla założonych przepływów oraz wykorzystywanych przy opracowywaniu katastru energii wodnej. Spad obliczeniowy ustalano jako wielkość stałą jednostkową w założeniu takich samych zmian poziomów wody górnej i dolnej. Uzyskane wartości rocznych przepływów instalacyjnych odniesiono do średnich wartości natężeń przepływu w latach obliczeniowych oraz średniego przepływu w wieloleciu. Tempo wzrostu oraz ilości dostępnej energii stanowią dobre kryteria wyboru przepływu instalacyjnego małych przepływowych elektrowni wodnych.

Słowa kluczowe: zasoby energii wodnej, mała elektrownia wodna, przepływ instalacyjny