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# Operational Evaluation of a Small Hydropower Plant in the Context of Sustainable Development

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**Abstract:** Proper design of hydrotechnical structures should meet the basic principles of sustainable development, i.e., the investment should be designed and made in technical terms, in accordance with the applicable standards and regulations, provide certain economic benefits and guarantee the absence of environmental hazards. The article examines the work of a Small Hydropower Plant (SHP) in Jaracz in technical and hydraulic terms. It also provides the analysis of the effect of changes in parameters such as water head, flow rate velocity, and shape of trash rack bars on expected SHP profits. The assessment of hydraulic performance consisted of investigating the impact of reduced flow rate and water head on power output and energy production. The analyses were carried out for the Francis turbine installed in the facility. Since the loss of channel capacity is shaped by plant debris accumulated on trash racks, the hydraulic performance assessment was extended to include the analysis of the species and weight composition of such accumulation on fine trash racks located in the inlet channel. Field research involved collecting organic material from the growing season (spring, summer) and post-growing season (autumn). Technical conditions were developed on the basis of the current technical condition of the inlet channel; there were also made simulations of its deteriorating state, as well as its impact on the received energy and economic benefits.

**Keywords:** small hydropower plant (SHP); plant debris; hydraulic losses; energy losses

## 1. Introduction

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In accordance with the obligations resulting from, i.a., the 3 × 20 climate package, it appears that by the year 2020, Poland will have been obliged to raise the share of renewables (RES) in its energy consumption to 15% [1]. The 3 × 20 strategy consists in cutting greenhouse gas emissions by 20%, increasing the share of energy from renewable sources to 20% and improving energy efficiency to 20% [2]. The concept of sustainable development is the overarching objective of the European Union and assumes an increase in the level and quality of life by reaching a compromise in economic, social and environmental development. Global resources of fossil fuels, including solid, liquid and gaseous reserves, are gradually being depleted, leading to an increase in their prices. On one hand, the desire to reduce greenhouse gas emissions and, on the other hand, the search for energy sources alternative to fossil fuels, make the use of renewable energy sources increasingly common. Consequently, hydropower is recognised as very important in many countries [3], because it reduces pollution and greenhouse gas emissions; and in addition, it may have a positive global impact on the quality of life [4]. It should be emphasised that the development of Small Hydropower Plants (SHPs) in European Union countries is practically possible only with the support of government policy through various solutions, such as legal, administrative and economic. Turkey is a perfect example of such a country, since it increased its energy potential from renewable water energy by four times in one year [5]. The major concern of international importance is alignment of the definition of a small hydropower plant. In China, it can refer to installed capacities (P) of up to 25 MW, in India up to 15 MW, and in Sweden, a SHP is assumed to be a facility with a capacity of up to 1.5 MW. According to the European Small Hydropower Association (ESHA), the European Commission (EU) and the International Union of Producers and Distributors of Electrical Energy (UNIPEDE), a small hydropower plant is a power plant with a capacity of up to 10 MW. It is estimated that SHPs, due to their high popularity, will be widely used in the production of electricity in the EU and in other regions of the world. However, they also have some negative effects on the environment, usually associated with fauna and flora [6]. Valero [7] indicated that the greatest negative impact of SHPs on water quality and habitat conditions of riparian vegetation can be observed during the construction of hydropower facilities and up to two years after their completion. After this period, both the temperature and the oxygen content dissolved in water return to normal development conditions appropriate for aquatic life. The pH value also stabilises around acceptable limits. At the same time, SHPs affect such variables as flow velocity and water depth, which—in turn—affect fauna and flora [8–13]. Vougioukli et al. [14] made an environmental impact assessment for small hydropower plants using the Life Cycle Assessment method (LCA). Its basic elements are: (1) identifying and quantifying the loads introduced into the environment, (2) assessing the potential impacts of these loads, and (3) estimating the options available to reduce them. The main parameter used by the authors in this model was the weight of components used for the construction and operation of SHP: concrete, aggregates and steel. The aim of the analysis was to indicate that the environmental cost must be included in the total investment cost, because it can affect the financial evaluation indicators of the project. Vougioukli et al. [14] stated that despite the disadvantages of this methodology (mainly related to the quality of source data), it can be used as a supporting solution in the decision-making process of SHP construction. At the design stage of a new facility, the environmental impact of small hydropower plants should also be carefully considered [15], preferably using GIS tools [16]. When designing new SHPs and LHPs, it is equally necessary to take into account the spatial arrangement of already existing hydropower objects. Too dense an infrastructure, especially in one river, may lead to unfavourable processes, i.e., the reduction in flow velocity, and loss of hydraulic continuity of the watercourse, which may trigger its eutrophication [17]. Researchers suggest that optimising the use of existing hydroelectric infrastructure would be beneficial for energy, water and environmental security. Overall assessment or optimisation of SHPs is a particularly challenging issue because, as a rule, SHPs are located at smaller reservoirs or on rivers, and there are therefore problems related to nonuniformity and seasonal variability of flow conditions. Anagnostopoulos and Papantonis [18] made such an attempt by optimising two SHPs equipped with Francis turbines. The research and performance analysis of these two power plants were carried out using an evaluation algorithm that simulated in detail their operation throughout the year and calculated their production results and economic indicators. Anagnostopoulos and Papantonis found that the use of two turbines can sufficiently increase both the energy production of the power plant and the economic outcome of the investment. Proper evaluation of investment costs is crucial in any project, and renewable energy source investments, with particular emphasis on small hydropower plants, certainly do not constitute an exception to this rule. In the case of small hydropower plants, the investment costs can be divided into two parts. The first component is the cost of electromechanical equipment, which, as the literature study indicates, can be quite accurately estimated [19–25]. The cost of electromechanical equipment for new SHPs is usually around 30–40% of the total expenditure [20], and is the major component in the case of modernisation of existing small hydropower plants. The second component of the investment budget of SHPs is the additional costs resulting from land purchase, cost of infrastructure and manpower, which are extremely difficult to estimate, because they are too dependent on local conditions, such as the location of hydropower facilities (more specifically possible difficulties with access to the planned location) and closely related local costs of building materials [22,26]. Santolini et al. [23] presented a technical-economic analysis of a small hydropower facility in Turkey on the basis of the flow variability curve. The research included five technical parameters of SHPs (type of turbine, dimensions of turbine, annual energy production, maximum installation height and turbine purchase cost) and two economic parameters of the investment (net present value—NPV, and internal rate of return—IRR). The method applied was aimed at estimating the impact of SHP design operating conditions on its performance and profitability. Santolini et al. noticed that the simultaneous consideration of technical and economic aspects allows the selection of appropriate SHP design operating conditions based on the desired performance, cost-effectiveness and feasibility of the installation. Social aspects should also be taken into account when planning this type of investment. In some cases, the construction of SHP or other hydroelectric system may cause some misunderstandings and socio-ecological problems, particularly when there is no appropriate policy based on sustainable development. In a situation where the overall level of SHP awareness is low, there may be problems resulting from the lack of full satisfaction, electricity production and employment [27]. Another consideration that should not be disregarded is the influence of SHPs, in particular a larger group of several hydropower facilities, on the Medium Voltage Distribution Grid [28]. One of the main negative consequences of connecting numerous SHPs to the network is a significant increase in active power losses, which can be compensated by connecting the appropriate number of recipients in the area under consideration. The pursuit of increasing the share of renewable energy sources in the electricity production balance requires the use of appropriate support systems that guarantee their systematic development. These are the conclusions of the government in Nigeria that not only indicate the greater stability of renewable energy systems with a small hydropower plant but also highlight its smaller negative environmental impact [29].

Since Poland joined the European Union, the intensive promotion of renewable energy sources has started, which arises from the need for environmental protection and enhancement of energy security. The number of small hydropower plants being launched has been constantly growing, from 681 in 2007 to 739 in 2011 [30]. In 2017, 770 installations generating hydropower, with a total rated power output of 989.447 MW, were registered and covered by the Energy Regulatory Office concession (status as of 31 December 2017). Additionally, technological and innovative development in this area is supported in various parts of the world [31], which may translate into an increase in regional growth and better guarantees of energy supply. Currently, the location of small hydropower plants is based on searching for existing, often damaged, hydrotechnical facilities. Such proceedings reduce the negative impact on the environment through the reconstruction of damaged elements of barrages. It is possible to use modern geographic information techniques, i.e., GIS, to indicate the best locations for SHPs [16,32]. This is characterised by exceptional efficiency, because these techniques can use topographic and meteorological data sets to optimise the location of designed facilities [33]. The latest achievements in GIS technology and the increased availability of high-quality topographical and hydrological data allows for quick and wide evaluation of hydropower potential while maintaining a relatively high level of detail [16]. In addition, there is a possibility of reducing economic losses through cutting down ecological costs. De Almeida et al. [34] pointed out that the use of SHP improves the quality of air in cities in Portugal (Coimbra) and complies with the provisions of the Kyoto Protocol.

Small hydropower plants, like most investments, can moderately affect the environment. The obvious fact is that such projects will generate both positive and negative effects. Başkaya et al. [35] carried out research on the negative impact of SHPs on the environment in Turkey and found that the deterioration of habitat conditions was ranked first among the negative factors. The remaining ones were: reduction in environmental flows, impediment of free passage for fish and wild animals, inappropriate protection and restoration of natural habitat, creation of additional waste, dust and noise, illegal hunting and formation of high voltage lines. Retention reservoirs, due to the accumulation of water, are very often complemented with hydroelectric power plants. Reservoirs then perform two functions: flood protection and energy production, i.e., by providing an adequate water head for a hydroelectric power plant, thus enabling the production of electricity. The handling of weir-shutters allows for prolonged water retention in the upper sections of rivers and the maximum slowdown of flow, in order to, i.a., prevent the accumulation of flood waves. It is worth remembering that, to some degree, the operation of hydroelectric power plants contributes to the removal of waste (plant debris and trash) from the fluvial environment, which is carried downstream with the flow, thus increasing the cleanness of rivers. Waste accumulates on trash racks that protect turbines and other elements of power plants, from where it is periodically removed. The main objection to small hydropower plants is their negative impact on ichthyofauna as a result of interrupting the morphological continuity of rivers and causing damage to fish flowing through turbines [11,36]. However, currently, the vast majority of hydropower plants are created almost exclusively on already existing dams, and the construction of fish passes is obligatory. Therefore, such investments do not interrupt the continuity of rivers; on the contrary, they unblock them. The negative impact of turbines is limited by the introduction of environmentally friendly technologies, e.g., Archimedes' screws. It has been seen in recent years that significant technological progress has been made in the SHP industry, and positive impacts outweigh the negative ones. The work of a small hydropower plant takes place in an annual cycle covering growing and post-growing seasons—including autumn and winter with lower temperatures. Each of these seasons faces different operational problems related to the work of a small hydroelectric plant, particularly to inlet trash racks. Some threats, e.g., the reduction in inlet channel capacity due to blocking of the inlet space with plant debris, are easily manageable by the facility's host. In contrast, the hazards expected in winter might cause more difficulty, because when the air temperature decreases, the phenomena of frazil and ice action can be observed in rivers. Ice pulp floating in water literally stains everything and clogs hydropower facilities, preventing them from normal operation. This can lead to the shutdown of SHP and even to equipment damage [37].

The purpose of this article is to indicate the risks of losing specific profits through improper operation of a SHP located in Jaracz on the Wełna River. The biggest threat is the reduction in flow rate or water head due to the loss of inlet channel capacity caused by accumulated plant debris. Due to its biodiversity, plant debris was evaluated in terms of its seasonal variability, which allowed for the determination that the dominant forms are macrophytes and deciduous trees. Spring is mostly associated with the occurrence of aquatic vegetation, e.g., yellow water lily and great manna grass. In autumn, the share of leaves is significant, whereas winter plant debris is a mixture of previously occurring species.

## 2. Study Area

The assessment of the work of a small hydropower plant under sustainable development conditions was based on the SHP of the Jaracz barrage located on the Wełna River, a right-bank tributary of the Warta River (Figure 1). Water is supplied to the turbine chamber through an open inlet channel. The channel in the upper part of the 90 m has an unsupported bottom and escarpments with an inclination of 1:2, sown with grass. In the lower part, the channel is made of reinforced concrete slabs. The width at its inlet decreases linearly from 5.60 m to 5.25 m. This is the place where the channel branches out into the inlet part of the power plant (3.05 m wide) and the side rinsing vent (1.6 m wide) is connected to the lower outflow channel. The inlet to this channel is equipped with wooden stop logs. The average water depth value in the reinforced concrete channel is $h$ = 0.66 m.

The channel at its inlet is equipped with coarse trash racks, with 0.5 cm wide flat bars and 3 cm spacing. The facility features a working footbridge and a repair gate with a manual opening and closing mechanism installed in front of the inlet to the turbine chamber. Ordinarily, panels with bars are assembled in parallel and made of stainless steel or black steel.

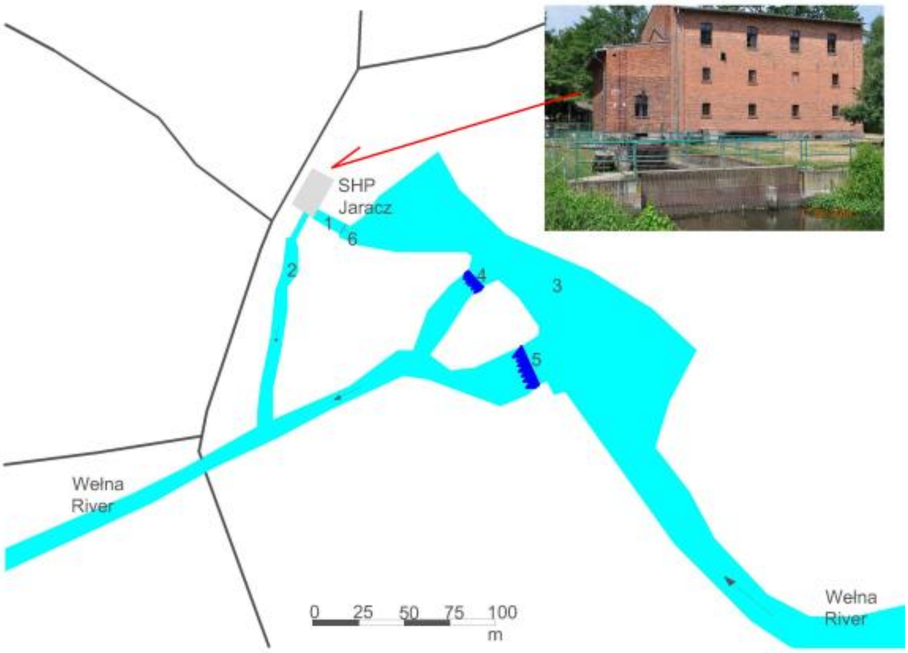


**Figure 1.** Situational plan with SHP in Jaracz.

## 3. Methods

### 3.1. Determination of SHP Power

Power output generated in a hydroelectric power plant with the use of river energy depends on water head (the difference in levels below and above the turbine) and flow rate. Hydraulic power output is also affected by the efficiency of turbine aggregate. It should be noted that the parameters can be changed by, e.g., the reduction in inlet channel capacity on trash racks caused by accumulated plant debris. Decrease in any value has specific economic consequences. To indicate the exact financial losses resulting from the reduction in flow rate and water head, the authors carried out a financial analysis of SHP profits for the installed Francis turbine with a power output of 60 kW, water head of 2.35 m and flow rate of 3.3 $m^3 s^{-1}$. The analysis included simulations involving the reduction in water head to 2.2 m and 1.95 m, respectively, and the systematic decrease in flow rate by max 10%. In each analysed case, the output value—taking into account the efficiency of the SHP devices equal to $\eta$ = 0.7—was determined from the following equation,

$$P = 9.81 \cdot Q \cdot H \cdot \eta \tag{1}$$

where:

$P$—power of the power plant, $Q$—flow rate, $H$—water head and $\eta$—efficiency coefficient of the turbine aggregate being the product of turbine, transmission and generator efficiency. For small hydropower plants, the value is estimated as between 0.5 and 0.7; for bigger facilities, it starts at 0.75–0.85 [38]. Generally, it is assumed that the efficiency coefficient of modern hydropower plants (turbine, generator, drive, transformer) ranges approximately 75–85%, while the coefficient of renovated older-generation hydropower plants is approximately 55–70%. Over the years, efficiency decreases regularly due to, e.g., material wear and fatigue [39].

Profit ($Z$) has been defined as the product of the capacity of the power plant, the working time of the power plant and the unit price per kWh.

$$Z = P \cdot n \cdot c \tag{2}$$

where:

$P$—power of the power plant,

$n$—time of operation of the power plan,

$c$—unit price per kWh.

A 3-h SHP working time was assumed, because it is located on a lowland river with a small flow-through reservoir. A time of 3 h is the smallest number of operating hours for a power plant a the partial annual compensation tank.

### 3.2. Measurement of Plant Debris

For the purpose of this research, the authors determined the composition of plant debris accumulated on the trash racks of the inlet channel. The composition of plant debris was analysed in the two-year period taking into account its seasonal variability. The organic matter was collected 8 times per 4 samples, respectively, during and after the growing season. During field measurements, the collected plant material from the SHP trash racks was weighed on site, and then a sample of several kilograms (as representative) was subjected to further detailed testing. After drying the material under natural conditions, the dominant plant fractions were determined.

### 3.3. Technical Condition of the Channel and Trash Racks

The technical condition of the inlet channel can also cause the loss of certain financial profits by increasing the hydraulic losses resulting from the increase in flow resistances. Hydraulic losses ($\Delta H_{wl}$) of water flowing through an obstacle in the form of trash racks can be determined empirically from the equation:

$$\Delta H_{wl} = \Delta H_{we} + \Delta H_k + \Delta H_t + \Delta H_{wn}(m) \tag{3}$$

where:

$\Delta H_{we}$—input losses at the inlet to the channel,

$\Delta H_k$—losses on bars and supporting structures of trash racks,

$\Delta H_t$—loss due to water friction against the inlet wall,

$\Delta H_{wn}$—loss caused by the presence of side cavities.

The structural elements of a small hydropower plant cause water energy losses at the inlet ($\Delta H_{we}$). These losses depend on the frontal profiles of the pillars' surfaces. The highest hydraulic loss values are caused by rectangular profiles, the lowest by parabolic profiles. Losses on trash racks ($\Delta H_k$) depend on the shape of bars and the angle of trash racks. The highest hydraulic loss values are caused in trash racks with rectangle profiles, the lowest in trash racks with elliptical profiles. Another partial loss is the loss due to water friction against the wall of the inlet ($\Delta H_t$), which is determined by the Manning-Strickler formula, taking into account the technical condition of the inlet channel using the Strickler coefficient $k_{st}$. Additionally, the total hydraulic loss value is also affected by losses due to the presence of side cavities and weir gate openings ($\Delta H_{wn}$). The value of losses depends on the dimensions of cavities and openings. These losses might be easily and totally avoided by applying closings for cavities and upper openings.

## 4. Results and Discussion

### 4.1. Losses Associated with Reduction of Water Level and/or Flow

Table 1 lists SHP power outputs determined from Equation (1) with different variations in flow rate and water head.

**Table 1.** SHP power outputs depending on changes in flow rate and water head.

| SHP Power Outputs in kW | | | | | | | |
|---|---|---|---|---|---|---|---|
| Water Head (m) | Flow Rate ($m^3 s^{-1}$) | | | | | | |
| | 3.30 | 3.25 | 3.20 | 3.15 | 3.10 | 3.05 | 3.00 |
| 2.35 | 53.25 | 52.45 | 51.64 | 50.83 | 50.03 | 49.22 | 48.41 |
| 2.20 | 49.85 | 49.10 | 48.34 | 47.59 | 46.83 | 46.08 | 45.32 |
| 1.95 | 44.19 | 43.52 | 42.85 | 42.18 | 41.51 | 40.84 | 40.17 |

SHP could achieve 75% power output for the variant in which both flow rate and water head are reduced. The highest losses of power output were obviously obtained for the lowest water head combined with the lowest flow rate. The power output declined accordingly to approximately 24.5% in relation to its nominal value. As a result, this could translate into the largest financial losses (Table 2), amounting to approximately €1800.

Table 2 presents the expected values of annual profit in euro calculated empirically, assuming that the plant operates only 3 h a day.

**Table 2.** Annual profit estimate of SHP electricity production depending on changes in flow rate and water head.

| Profit €/year | | | | | | | |
|---|---|---|---|---|---|---|---|
| Water Head (m) | Flow Rate ($m^3 s^{-1}$) | | | | | | |
| | 3.30 | 3.25 | 3.20 | 3.15 | 3.10 | 3.05 | 3.00 |
| 2.35 | 7459 | 7346 | 7233 | 7120 | 7007 | 6894 | 6781 |
| 2.20 | 6983 | 6877 | 6771 | 6665 | 6559 | 6454 | 6348 |
| 1.95 | 6189 | 6095 | 6002 | 5908 | 5814 | 5720 | 5626 |

### *4.2. Covering the Cross-Section with Debris*

The economic value of a hydropower investment also includes the cost of cleaning the trash racks and neutralising the accumulated plant debris. According to the regulations of the Minister of Economy of 16 July 2015 regarding the admission of waste for landfills [40], only waste with a total organic carbon content (TOC) of less than 5% of the total sediment can be stored in landfills for non-hazardous waste. Therefore, plant material and other solids accumulated on trash racks must be subject to appropriate disposal processes. The analysed facility is characterised by naturally floating plant debris of various natures, and its composition depends on the season of the year (Table 3). This material may consist of: leaves, moss, grass, and tree branches (Figure 2). It was observed that during warm seasons the river carries a greater amount of material in comparison to winter periods. In fact, in spring and summer, the riverbanks are overgrown by various types of vegetation, which, after the vegetation period, flow along with the current of the river and accumulate on the encountered obstacles. In autumn, plant debris is mainly composed of leaves from trees growing along the riverbanks.

**Figure 2.** Plant debris collected from SHP trash racks (5 November 2014, 2 January 2015).

**Table 3.** Weights of wet and dry plant debris for the Wełna River.

| Measurement | Season | Wet Plant Debris (g) | Dry Plant Debris (g) |
|---|---|---|---|
| 1 | growing | 240.16 | 106.83 |
| 2 | growing | 260.92 | 110.51 |
| 3 | post-growing | 757.78 | 114.09 |
| 4 | post-growing | 1078.01 | 165.88 |
| 5 | post-growing | 806.79 | 233.48 |
| 6 | post-growing | 1648.64 | 697.80 |
| 7 | growing | 788.90 | 227.84 |
| 8 | growing | 503.69 | 81.15 |

Due to the fact that the study was carried out in different periods (late summer, late autumn and spring), some differentiation of the fraction was found depending on the collection time (Table 4). During late summer, aquatic vegetation was that group that predominated the species composition by weight of the collected plant debris. The composition was as follows: hornwort, awl-leaf arrowhead, bur-reed and reed. Oak and alder leaves predominated in the tree fraction. The total sample of plant debris taken from SHP trash racks also included material in a state that did not allow for accurate identification due to advanced putrefaction processes. Late autumn was dominated by the tree fraction. It was most widely represented by deciduous tree leaves: oak, poplar and alder. The period was definitely characterised by a smaller amount of aquatic vegetation (reed, bur-reed). During the collection in early spring, the lowest diversity of organic material was observed. Due to thermal conditions (higher temperature in winter) and high humidity, the organic material collected from the trash racks was not suitable for more accurate analysis in terms of fraction.

**Table 4.** Identified species of plant debris and their measurement dates, collected from SHP trash racks on the Wełna River.

| **Plant Debris** | **Year** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **2014** | | | | **2015** | | | |
| | **Growing** | | **Post-Growing** | | **Growing** | | **Post-Growing** | |
| | (a) | (b) | (a) | (b) | (a) | (b) | (a) | (b) |
| Herbaceous | | | | | | | | |
| *Ceratophyllum demersum* L. | | | ■ | ■ | | ■ | | |
| *Sagittaria subulata* L. | | | | | ■ | | | |
| *Nuphar lutea* L. | ■ | ■ | | | ■ | ■ | ■ | ■ |
| *Sparganium* L. | ■ | | | | | | | |
| *Sparganium* spp L. | ■ | ■ | | | | | | |
| *Phragmites australis* | ■ | ■ | ■ | ■ | ■ | | ■ | ■ |
| *Phalaris* L. | ■ | ■ | ■ | | ■ | ■ | ■ | ■ |
| *Glyceria maxima* | ■ | | | | | ■ | | |
| *Rorippa amphibia* L. | | | | ■ | | | ■ | |
| *Veronica beccabunga* L. | | | | | ■ | | | ■ |
| *Myosotis scorpioides* L. | | | | | ■ | ■ | | |
| *Cicuta virosa* L. | | | | | ■ | ■ | | |
| *Lemna minor* | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| woody | | | | | | | | |
| *Pinus sylvestris* | | | | | | | | ■ |
| *Elementa nemorosa* | | | | | ■ | | ■ | ■ |
| deciduous | | | | | | | | |
| *Quercus* | | ■ | | ■ | ■ | | | ■ |
| *Alnus*Mill. | | | | ■ | ■ | | | |
| *Betula* L. | | ■ | ■ | ■ | ■ | | | |
| *Acer* L. | | | | ■ | | | | |
| *Tilia* | | | | ■ | | | | |
| *Ulmus* L. | | | | ■ | | | | |
| *Fraxinus* L. | | | | ■ | | | | |

An increase in the value of the sum of losses should be expected in the case of plant debris and other floating contaminants gathering on the trash rack. Despite the assumption that plant debris is a small and flexible element, in the case of larger quantities, it can block a large part of the trash rack. The water then acts as a pressure force. Table 5 presents the loss value at a constant flow rate resulting from blocking the cross section in the range of 0 to 35%. A loss of capacity of 35% causes an increase of hydraulic loss by 0.1 m.

**Table 5.** Juxtaposition losses resulting from a decrease in the flow capacity of trash rack.

| **Flow ($m^3$ $s^{-1}$)** | 3.3 | | | | | | |
|---|---|---|---|---|---|---|---|
| **Degree of blocking of the cross-section (%)** | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| **Loss (m)** | 0.05 | 0.06 | 0.06 | 0.07 | 0.08 | 0.09 | 0.10 |

### *4.3. Technical Condition of the Channel and Trash Racks*

The structural elements of a small hydropower plant cause water energy losses at the inlet ($\Delta H_{wl}$). The correctly constructed inlet, the sum of losses should not exceed 1% of the water head, whereas in an inlet built without loss-minimising improvements, the total hydraulic loss value can reach 4% of the water head. The biggest component of the total hydraulic loss value is $\Delta H_k$ [41].

Table 6 summarises the hydraulic losses of the inlet channel and trash racks of SHP Jaracz. For the purposes of this study, the authors adopted the widths of a single bar $\beta$ = 2.4 as $S$ = 0.05 m with spacing $b$ = 0.03 m as the parameters of the installed trash racks. In addition, the study included a simulation of trash racks with a much better shape factor $\beta$ = 0.76 (Table 7) as for, e.g., elliptical bars.

The analyses were performed for a constant value of inflow velocity equal to 1.0 m $s^{-1}$ and with a variable coefficient $\zeta$ dependent on the shapes of the frontal profiles: pillars, upper beam and threshold (0.06–0.5). The simulations additionally included a variable Strickler coefficient $k_{st}$, which stands for the technical condition of the inlet channel concrete. The angle of inclination of the trash racks was assumed to be $\alpha$ = 70°.

**Table 6.** Hydraulic losses for shape coefficient $\beta$ = 2.4.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Input losses $\Delta H_{we}$** | $\zeta$ | - | 0.06 | 0.065 | 0.075 | 0.09 | 0.1 | 0.25 | 0.5 |
| | $v$ | m $s^{-1}$ | | | | 1 | | | |
| | losses | m | 0.003 | 0.03 | 0.04 | 0.05 | 0.05 | 0.013 | 0.025 |
| **Losses on bars and supporting structures of trash racks $\Delta H_k$** | $\beta$ | ° | | | | 2.4 | | | |
| | $\alpha$ | ° | | | | 70 | | | |
| | $S$ | m | | | | 0.05 | | | |
| | $b$ | m | | | | 0.03 | | | |
| | losses | m | | | | 0.229 | | | |
| **Loss due to water friction against the inlet wall $\Delta H_t$** | $k_{st}$ | $m^{1/3}$ $s^{-1}$ | 100 | 90.9 | 76.9 | 66.7 | 63 | 58 | 50 |
| | $R_h$ | m | | | | 1 | | | |
| | $L$ | m | | | | 90 | | | |
| | losses | m | 0.009 | 0.011 | 0.015 | 0.020 | 0.023 | 0.027 | 0.036 |
| **sum** | | m | 0.241 | 0.270 | 0.284 | 0.299 | 0.302 | 0.269 | 0.290 |

**Table 7.** Hydraulic losses for shape coefficient $\beta$ = 0.76.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Input losses $\Delta H_{we}$** | $\zeta$ | - | 0.06 | 0.065 | 0.075 | 0.09 | 0.1 | 0.25 | 0.5 |
| | $v$ | m $s^{-1}$ | | | | 1 | | | |
| | losses | m | 0.003 | 0.003 | 0.004 | 0.005 | 0.005 | 0.013 | 0.025 |
| **Losses on bars and supporting structures of trash racks $\Delta H_k$** | $\beta$ | ° | | | | 0.76 | | | |
| | $\alpha$ | ° | | | | 70 | | | |
| | $S$ | m | | | | 0.05 | | | |
| | $b$ | m | | | | 0.03 | | | |
| | losses | m | | | | 0.072 | | | |
| **Loss due to water friction against the inlet wall $\Delta H_t$** | $k_{st}$ | $m^{1/3}$ $s^{-1}$ | 100 | 90.9 | 76.9 | 66.7 | 63 | 58 | 50 |
| | $R_h$ | m | | | | 1 | | | |
| | $L$ | m | | | | 90 | | | |
| | losses | m | 0.009 | 0.011 | 0.015 | 0.020 | 0.023 | 0.027 | 0.036 |
| **sum** | | m | 0.084 | 0.086 | 0.091 | 0.097 | 0.100 | 0.111 | 0.133 |

As the results demonstrate in both calculation variants, the input losses $\Delta H_{we}$ have the lowest impact on the total hydraulic loss value (Tables 4 and 5). Also, the losses resulting from the friction of water against the inlet walls is insignificant. Even a concrete channel in very poor technical condition, as determined by the Strickler coefficient ($k_{st}$ = 50), generates only slight losses. The largest share in the total hydraulic loss value is generated by the loss on bars and supporting structures of the trash racks. Therefore, the most important thing in terms of hydraulics is the correct design of the shape of the trash rack bars.

Changing the shape of the track rack bars from rectangular $\beta$ = 2.4 to elliptical $\beta$ = 0.76 would reduce the maximum hydraulic loss by more than 50% (Figure 3). Unfortunately, due to their unusual shape, such trash racks need to be made to order, which raises the investment cost. Bars of this shape are additionally exposed to corrosion in their lower part.

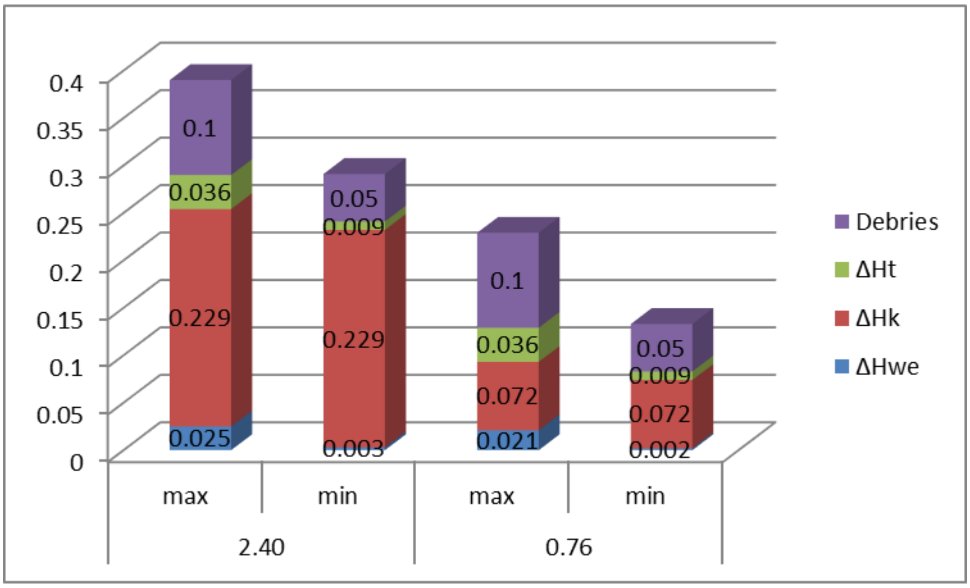


**Figure 3.** Total losses for two different coefficients $\beta$.

Hydraulic losses increase due to the blockage of flow, e.g., by plant debris that should be systematically collected. Trash racks can be cleaned in two ways: mechanically and manually. Manual cleaning is primarily used in small hydropower plants with low budgets and usually depends on the available workforce. Additionally, the service might involve dealing with unsafe working conditions when it is necessary to clean trash racks in extreme weather, e.g., during rain or strong wind.

## 5. Summary

This paper analyses the impact of changes in parameters related to SHP hydraulics on the hydraulic and power losses of power plants. The losses related to changes in hydraulic conditions, e.g., changes in bleed and flow, were analysed in detail. Also analysed was the impact of plant debris on the work of the SHP. For this purpose, a thorough analysis of plant debris in terms of weight and species composition was performed. All analyses were carried out for an existing facility—the Jaracz power plant. The presented analyses may be helpful in the design and operation of similar small hydropower plants. At present, projects concerning renewable energy sources have been widely analysed. Unfortunately, not much has been said about the correct exploitation of objects that guarantee certain profits. In the case of SHPs, the biggest problem is the loss of capacity of the inlet channel. The best way to maintain a constant water level is to pay attention to the correct design and operation of the trash racks.

The risk of losing power plant stability can be divided into hydraulic risks due to fluctuations in the water level, and ecological ones resulting from the development phases of riparian vegetation and other plants growing in the immediate vicinity.

The concept of sustainable development played an important role in shaping the way of thinking about mutual relations between society, the economy and natural environmental resources in the second half of the twentieth century. It is based on the assumption that there is a compromise solution between further economic development and preservation of the environment in the best possible condition. It pays special attention to the interdependence of the economic development of society and the quality of the environment. It also provides the world with the ability to preserve existing environmental values, as well as significantly contributing to the limitation of pollution or degradation of the environment, which was "violated" in the 20th century by man. On the one hand, the implementation of sustainable development is a requirement of our times, and on the other hand it demonstrates our responsibility for future generations.

There is the possibility to reduce the occurrence of plant debris by carrying out appropriate care and maintenance service on green areas located in the immediate vicinity of rivers and SHP. Such treatments include, e.g., mowing grass and introducing protective belts made of perennial and elastic vegetation. This entails certain costs that may affect the total return on investment, yet they should not discourage potential investors.

The maximum losses were estimated at approximately 0.4 m. This translates into a nearly 17% decline in the power output of the power plant and, at the same time, a 17% economic loss for the planned flow rate of 3.3 $m^3\ s^{-1}$. These losses may increase still further due to unfavourable hydrological conditions causing a reduction in flow rate and hydraulic head values. The largest percentage share of losses is attributable to the losses on trash racks related to the selection of their shape and geometry. They can even cover about 59% of all losses, for trash racks with flat bars $\beta = 2.4$, and are practically constant, depending only on the shape of bars. The second-largest component of losses is the loss resulting from the covering of the trash racks with plant debris. Based on the extent of cover, this can range from 0.05 to 0.1 m, for cross-sectional cover equal to 5 and 35%, respectively.

The most important factor affecting hydraulic losses, and thus economic ones, is the adoption of appropriate shapes of trash rack bars at the design stage of new hydropower plants or during the renovation of existing facilities. At the same time, this is a factor that can be affected only at the stage of construction or modernisation.

The results of the analysis indicate that, apart from the losses resulting from the geometry of trash racks $\Delta H_k$, a key factor influencing the economics of SHPs is the systematic cleaning and removal of debris accumulated on trash racks.

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