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Monitoring of the Technical Condition and Optimisation of the Functioning of Small Hydraulic Structures in Poland: The Case Study of the Oświecim Weir

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Abstract: Successively conducted monitoring and inspections allow for the detection of emerging issues and their elimination. The objective of this study is the analysis of the administrative procedures related to the monitoring of the technical condition of small hydraulic structures in Poland. The case study of the Oświecim Weir on the Prosna River presents the parameters subject to assessment and further activities aimed at the elimination of the detected defects. The obtained results showed damage to its concrete structures, including cracks and cavities. The undertaken activities related to the complete remodelling of the Oświecim Weir and the incurred costs generally result from the environmental conditions (water flows in the Prosna River), directly causing the necessity for the stabilisation of water conditions in the area. In the context of the observed climatic changes, the problem is faced by more and more regions around the globe. The proper technical condition of hydraulic structures, resulting from diligent monitoring, provides the basis for the mitigation of this unfavourable situation.

Keywords: monitoring of hydraulic structures; life cycle assessment; hydrological low flows; agricultural irrigations; Poland

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1. Introduction

Adjusting the water conditions to human needs is a common activity aimed at its optimal use [1,2]. According to Yamada [3], civilisation has developed along rivers, allowing for the development of cities and agriculture. It is important to provide the appropriate amounts of water for different economic purposes [4,5], an increasingly complex task. The observed climatic changes result in the disturbance of the course of precipitation and evaporation and, consequently, reduced possibilities of obtaining access to water for agriculture [6]. According to Misra [7], water and food safety are the key challenges related to such changes. More and more efficient methods for the management of water resources are, therefore, sought after in the context of climate change [8,9]. Information on the spatial distribution and range of irrigated areas is important for increasing efficiency in agriculture and the management of water resources [10]. Hydraulic structures with different size classes (damming height) and functions play a key role in this context. Dams on large rivers [11] are obviously the most significant, although smaller structures also play an important role. Owusu et al. [12] recommend support for small water bodies to strengthen the local capacity for sustainable management.

Hydraulic structures are included among dangerous objects and require rapid action in terms of the elimination of the problems recorded as a result of visual and instrumental observations [13]. Next to the processes affecting their aging, they are exposed to the permanent impact of the environment in which they function (water erosion, frost, etc.). Their response to particular situations such as floods can be of impulsive, destructive character. A failure of the earth dam of the Sardoba reservoir caused the flooding of a large area in Uzbekistan and Kazakhstan, including residential and agricultural areas [14]. The breakage of the Niedów dam after a high water flow in the Witka River resulted in damage to roads, bridges, a wastewater treatment plant, etc. [15]. The hydrogeological conditions in the vicinity of hydraulic structures may also lead to their subsidence [16,17]. On the other hand, economic losses also occur in the situations of improperly operating hydraulic structures built for a reduction in water deficits, among others, in the context of conducted agricultural irrigations [18].

The hydraulic structures existing for many years may not meet the currently binding provisions considering the changing hydrological conditions [19]. Hydraulic structures have currently lost their appeal [20], and many of them are in bad technical condition [21]. Considering the cycle of the functioning of hydraulic structures and the effects of their collapse, the effectiveness and reliability of the monitoring of these types of objects should be ensured, during both their construction and operation, to meet the most rigorous requirements [22]. The monitoring of hydraulic structures provides the basis for the analyses and assessments of predictions regarding negative processes, and the formulation of guidelines regarding the elimination of reported infringements, the prevention of failures, and the provision of the conditions necessary for safe maintenance [23].

In Poland, the management of the existing hydraulic facilities is largely within the competence of the State Water Holding Polish Waters. The activities are conducted based on the relevant legal documents constituting the Acts of Construction Law [24] and Water Law [25]. In short, as the administrator, the State Water Holding Polish Waters should maintain and use objects in accordance with their purpose and environmental protection requirements and maintain their proper technical and aesthetic condition to avoid the excessive deterioration of their useful properties and technical efficiency. Moreover, the safe use of the objects should be provided in case of the occurrence of external conditions affecting the objects, related to either human activities or natural forces. The assessment of the technical condition of hydraulic structures should be performed by persons with special expertise in terms of hydrotechnical construction. In the Polish nomenclature, hydraulic structures fall into four classes, determined by the function of the structure, the damming height, the capacity of the reservoir created through water damming, the size of the flooded area, and the size of the population residing in the flooded area in case of the destruction of the structure. The objects of classes I and II (with the consideration of, among others, the water damming height, the volume of the reservoir, the area flooded by the wave resulting from the regular damming level, the size of the population in the area flooded as a result of the destruction of the structure, the irrigated or meliorated area, and the protected area) are of the greatest importance, although the objects of lower orders are important at a local scale, particularly in the context of improvement in water relations in those zones falling outside the valleys of large rivers [18].

The monitoring of hydraulic structures covers systematic observations, measurements, and research on such objects, aimed at the assessment of their technical condition and safety [26]. The detailed determination of the technical condition is key for undertaking corrective measures aimed at the repair of the deterioration of their condition, or a construction disaster, and consequently, the prevention of a potential threat to the life or health of people, infrastructure, and the environment. Moreover, inappropriate monitoring guidelines may generate higher costs related to undertaking renovation work in the event of their delay.

The primary objective of this paper is to present the administrative and legal procedures, the scope of activities, and the degree of detail for the conducted inspections in Poland in the context of reporting defects in the conditions of hydraulic infrastructure.

The implementation of the aforementioned assumptions was based on the case study of the Oświecim Weir on the Prosna River in central Poland. The objective of the paper is also to determine the hydrological changes in the analysed river that justify the undertaken measures and point to the potential benefits resulting from the implemented repair measures.

2. Materials

The Oświecim Weir was constructed in 1970 on the upper course of the Prosna River (Figure 1), constituting a right tributary of Warta, the third largest river in Poland. The Prosna River catchment above the weir covers an area of 1581 km^2. The analysed area is dominated by agricultural land. The Prosna River catchment is located within one of the areas with the smallest water resources in Poland [27]. According to the classification of structures applied in Poland, the Oświecim Weir is a structure of class IV (Figure 2). The basic properties of the weir are presented in Table 1.

For each damming structure, guidelines for water management are developed, providing the basis for its exploitation in normal as well as extreme conditions. In the case of the Oświecim Weir, the normal water damming height on the Prosna River determined for the ordinate of 135.20 m a.s.l. is maintained in the growing season from 1 April to 30 October (each year). Exceptions result from the current hydrological situation and the needs regarding irrigations and the maintenance of environmental flows in the river. Moreover, it is acceptable to exceed that level by 0.15 m and implement periodical damming to an ordinate of 135.35 m a.s.l. In the autumn–winter period, from 1 November to 30 March (each year), the flaps of the structures remain open, resulting in restoring the free flow of flood waters.

Figure 1. Location of the study area.

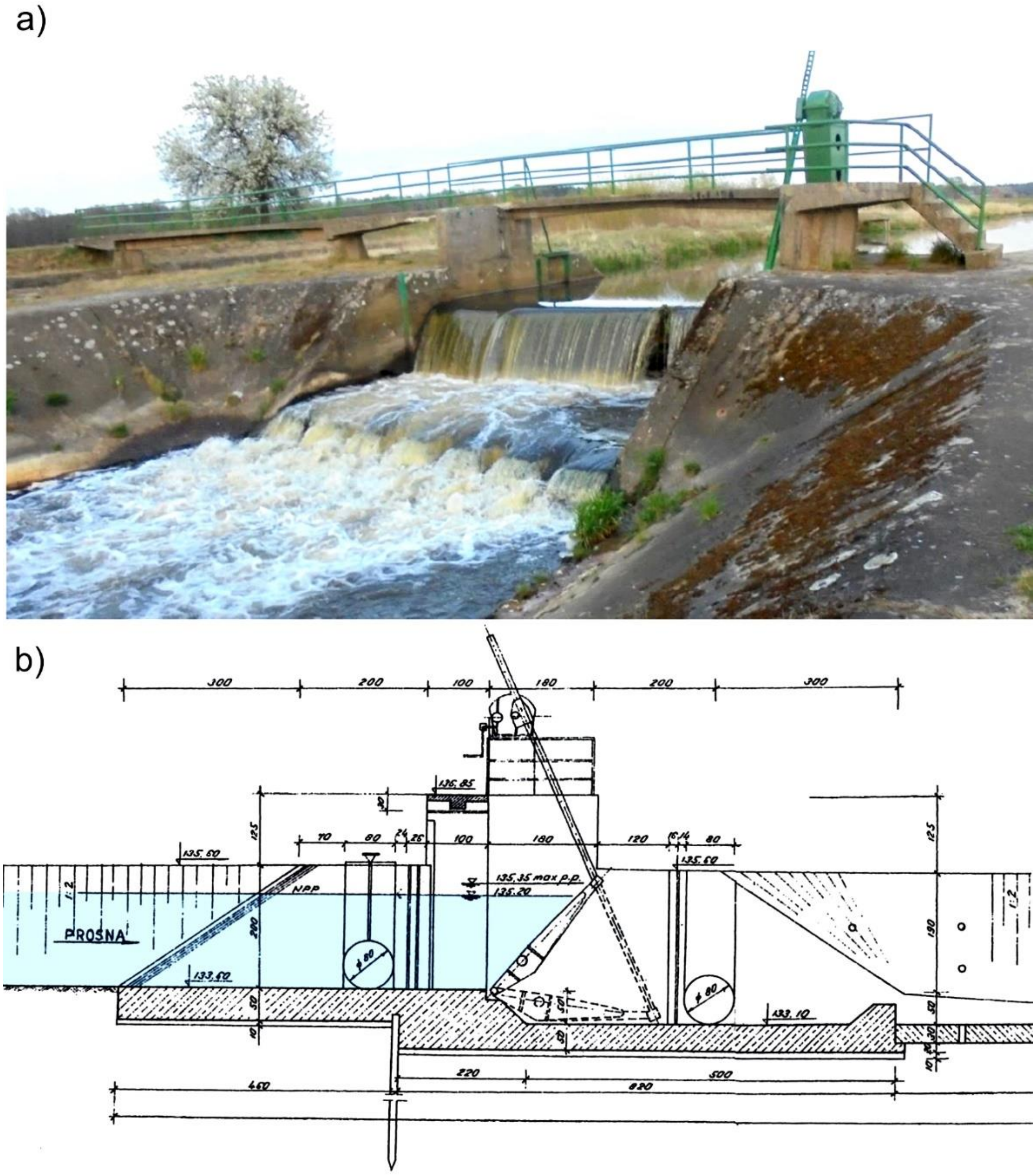

Figure 2. Oświecim Weir: (**a**) view of the structure subject to the assessment of the technical condition (before renovation); (**b**) longitudinal section of the weir (source: State Water Holding Polish Waters).

In periods of the occurrence of low water levels (drought) with open flaps, the passage of at least the water flow not affected by lowering the flap through the weir, is ensured. The level of water flow in the weir's cross-section is Qb = 0.88 m^3/s. In the case of water flows lower than 1.00 m^3/s (reading on the water gauge Mirków H = 65 cm), the flap is completely lowered. The situation is similar after reaching a water level of H = 160 cm in Mirków, signifying a warning level. The weir flap is then lowered (laid down). In the case of water flows higher than 38 m^3/s, water fills the entire cross-section of the embankments.

Next to the surface water level regulation function and retention in the Prosna River channel and its tributaries, the primary purpose of the weir is to dam water for the purposes of agriculture. Through the Struga Bobrowska and Kanał Dębicze streams, and a system of valves and melioration ditches, water damming on the weir allows for the irrigation of several hundred hectares of agricultural land. Each of these streams again flows into the Prosna River in its lower course, simultaneously allowing for the drainage of agricultural land in periods of high groundwater levels. Moreover, the weir threshold allows the correction of the river bottom by approximately 40 cm, slowing down the water flow in periods of low flow.

Table 1. Basic properties of the Oświecim Weir.

Properties	Units
Operational	
Reinforced concrete dock structure	-
Weir closure—steel flap	2.15 × 7.25 m
Flap drive	ręczny
Time needed for opening weir	0.45 h
Weir opening	7.25 m
Weir length	12.85 m
Damming height	1.60 m
Normal damming height NDH	135.20 m above sea level
Maximum damming height MaxDH	135.35 m above sea level
Hydraulic	
Average high water flow	44.30 m^3/s
Average annual water flow	6.34 m^3/s
Average low water flow	1.36 m^3/s

In this paper, we employed legal documents and detailed documentation concerning the monitoring of the technical condition of the Oświecim Weir. The materials included:

- The Act of 7 July 1994 Construction Law [24];
- The Act of 20 July 2017 Water Law [25];
- The report from the five-year periodical inspection of the Oświecim Weir as of 5 September 2019 [28];
- The decisions of the Building Supervision Authority (Wielkopolska Voivodeship Building Supervision Inspectorate) mandating the elimination of irregularities in the technical condition of the Oświecim Weir [29];
- The technical expertise regarding the Oświecim Weir on km 121 + 350 of the Prosna River and the Grabów Weir on km 110 + 300 of the Prosna River [30].

With regard to the issue of the proper functioning of hydraulic structures in a broader context referring to the hydrological conditions in the study area, the daily data on the flow rate in Prosna collected for the Mirków water gauge were analysed (Figure 1). The water gauge functions under the purview of the measurement observation network run by the Institute of Meteorology and Water Management—National Research Institute. The data covered the hydrological years 1970–2021. In Poland, the monitoring of water flows is conducted in reference to the period of a hydrological year (1 November of the preceding year–31 October of the analysed year). The collected data provided the basis for the determination of characteristic water flows, i.e., the minimum flow, the average low flow, the average flow, the average high flow, and the highest flow. Moreover, the values of water flow $Q_{90\%}$ were determined and used for the designation of periods of the occurrence of hydrological drought. The variability of the following water flow properties was analysed: the 7-day minimum water flow, the 30-day minimum water flow, and the average annual water flow. Moreover, for the purpose of showing the effect of climate change on the duration of water deficits in the river, the duration of the flows below the threshold flow of $Q_{90\%}$ was determined for each year. The variability of the described properties was analysed by means of a Mann–Kendall test [31] and a Sen test [32]. The Mann–Kendall test (MK) allows for the determination of the trends of changes in water flows in the river. The level of changes in particular flows was determined by means of a non-parametric Sen test. For the purpose of the removal of autocorrelation from the data series, the trend-free pre-whitening (TFPW) procedure was applied [33]. The analysis employed the modified versions of Mann–Kendall and Spearman's Rho trend tests developed by Patakamuri and O'Brien [34]. The analysis was performed at a significance level of 0.05. The described procedure is usually applied in the analysis of long-term changes in hydrological data [35–37].

3. Results

Pursuant to the provisions binding in Poland, hydraulic structures are subject to periodical inspections covering the assessment of the technical condition of the structures, conducted once a year pursuant to Art. 62 Par. 1, point 1 of the Act of 7 July 1994 Construction Law. In addition, once every 5 years, periodical inspections are carried out covering the assessment of the technical condition and the useful value of the structures, together with the assessment of installations and facilities, pursuant to Art. 62 Par. 1, point 2 of the aforementioned act. The obligation is on the part of the administrator of the object. In those cases in which it is determined that the object may pose a threat to safety or is in inappropriate technical condition, the fact is reported to a territorially competent building supervision authority that can mandate the elimination of the reported irregularities based on a decision, and specify the term of the execution of such an obligation. Moreover, in terms of hydraulic structures, the national services for the safety of damming structures [38] perform periodical assessments of the technical condition and state of the safety of damming structures pursuant to the provisions of the Act of 20 July 2017 Water Law. Based on the aforementioned inspections and expert opinions on their technical condition, the objects are approved for operation. The stages of the process, considering the positive as well as negative inspection results, are presented in Figure 3.

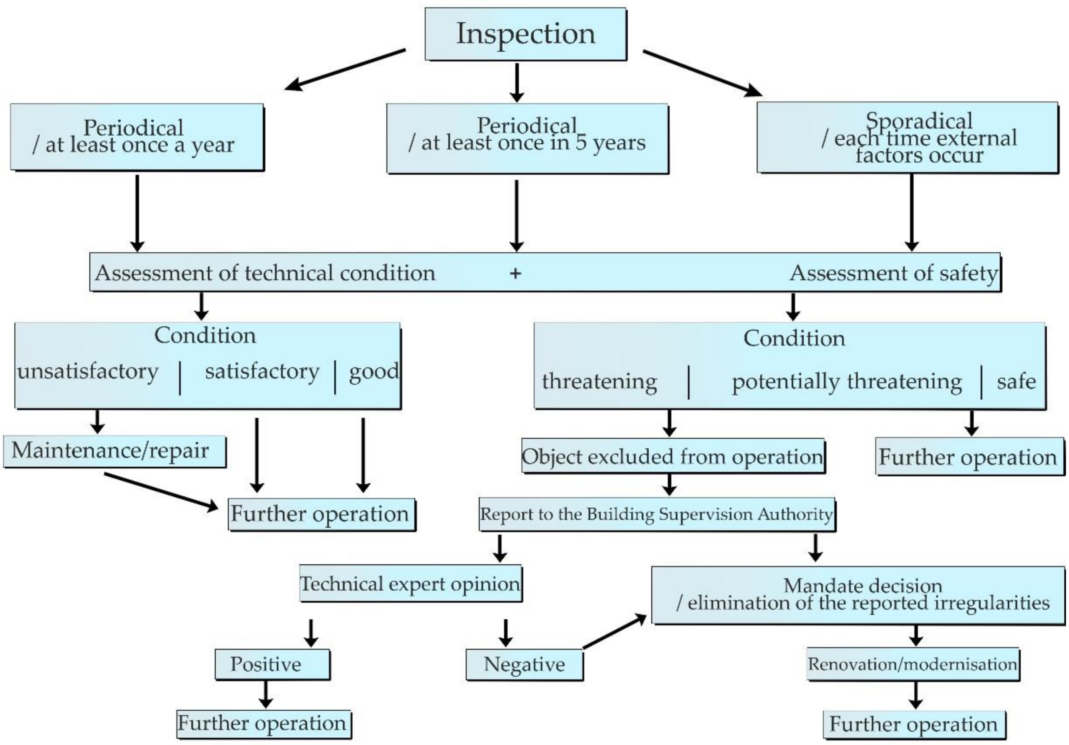

Figure 3. Diagram of the inspection procedure for the assessment of the state of hydraulic structures in Poland.

In reference to the aforementioned procedures (Figure 3), relevant steps are undertaken for the provision of safety in the terms of the functioning of hydraulic structures. The starting point is conducting an assessment of the condition of the structures that will determine further procedures. In reference to the weir analysed in this paper, the inspection [28] was conducted on 05 September 2019. By standard, it covered the assessment of the following features:

- The elements exposed to damaging atmospheric effects and the damaging effects of factors occurring during operation;
- The aesthetic condition of the structure and its surroundings.

The inspection showed the inappropriate technical condition of the object, determined by, among others, the degradation of concrete elements over the entire surface, the degradation and deformation of the reinforcement of the left flood spillway, the degradation of the concrete of the footbridge, the delamination of the right and left retaining wall, the cracking of the right retaining wall, the failure of the outlet of the right drainage and the burying of the left drainage, the deformation of wooden elements of the lower site, the technical lack of the possibility of conducting test runs of the gate valve on the bypass channel.

On 23 January 2020, the Construction Supervision Office ordered the submission of a detailed technical expert opinion on the condition of the structure by 30 June 2020. Its preparation [30] covered the assessment of the particular elements of the hydraulic structure for which an inappropriate condition was reported in reference to the following components:

(a) Walls of the weir:
  - Local cavities in concrete with a depth of up to 15 cm over the entire surface of the walls;
  - Numerous shallow cracks in the concrete structure, visible evident frost corrosion of the wall surface (Figure 4);
(b) Bottom slab:
  - Cavities in concrete with a depth of up to 20 cm over the entire surface;
(c) Service footbridge:
  - Numerous damages, cavities, and cracks in the concrete structure;
  - Exposed reinforcement of the footbridge pillar;
  - (Frost) surface corrosion of the concrete elements of the footbridge;
(d) Strength of the concrete in the weir structure:
  - Our evaluation by means of a non-invasive method with a type N Schmidt sclerometer revealed the compressive strength of the concrete in the left wall of the weir to be at an average level of fcm = 27.02 MPa (with the consideration of the age of the concrete, 18.16 MPa), and in the right one at a level of fcm = 26.72 MPa (with the consideration of the age of the concrete, 17.95 MPa);
(e) The steel elements of the weir:
  - Gates and maintenance gate guides at the level of water level fluctuations, showing visible signs of corrosion;
  - The exhaust system; difficulties with its efficient operation potentially resulting from flap deformation;
(f) The reinforcements of the bottom and the scarps of the river at the upper site:
  - Numerous damages and cracks in concrete slabs;
(g) The reinforcements of the bottom and the scarps of the river on the lower site:
  - Numerous cavities and cracks in concrete surfaces, the lack of filling in concrete slabs, the faulty surface of reinforcements in concrete slabs, the degradation of the bottom reinforcements from fascine mattress, and the degradation of a palisade and wooden tight walls;
(h) The reinforcements of the lateral outflow:
  - The outflow surface on the right bank—partially covered with soil;
  - The reinforced concrete elements forming an outflow channel showed numerous cracks and small cavities;
  - The surface of the outflow on the left bank—numerous deformations with cavities, the surface partially covered with soil, obstructed drainage outflow, and

numerous cracks and cavities in the reinforced concrete elements forming the outflow channel;

(i) Flap gates:
- A trial run of the gate revealed considerable difficulties in raising the flap, with the time of raising of 1 h;
- Bent gate flap;

(j) Embankment crowns at the object:
- No signs of considerable subsidence.

Figure 4. Technical condition of the Oświecim Weir before renovation [30].

The above expert opinion provided the basis for formulating the guidelines and instructions concerning the necessary renovation work on the Oświecim Weir. Based on the applications derived from the aforementioned expert opinion, the Voivodeship Inspector of the Building Supervision Authority issued a mandated decision on the elimination of the reported irregularities in the technical condition of the object, termed the Decision of the Wielkopolska Voivodeship Building Supervision Inspector [29]. Considering that the term of the implementation of the repairs was specified for 31 December 2023, the thorough modernisation of the weir commenced in the second half of 2021 (Figure 1). The final acceptance of the construction work was performed on 15 December 2021. On 24 February 2022, after inspection, the Voivodeship Building Supervision Inspectorate determined that the owner of the weir had performed the necessary repair, thus meeting the requirements for further operation of the object (Figure 5).

Figure 5. Remodelling (**a**) and functioning (**b**) of the Oświecim Weir (source: State Water Holding Polish Waters).

The incurred costs as a result of the undertaken repair work, resulting from the monitoring of the technical condition of the weir, amounted to EUR 500,000. This investment is undoubtedly justified by the unfavourable hydrological situation characterising the analysed area. The daily discharges of the Prosna River in the hydrological profile of Mirków in the period 1970–2021 were at a level ranging from 0.25 to 84.3 $m^3 s^{-1}$. The average discharge is SSQ = 5.04 $m^3 s^{-1}$, which, in reference to the surface of the catchment area, translates into a unitary outflow of q = 4.06 $dm^3 s^{-1} km^{-2}$. The 7-day minimum discharge values in the analysed period varied from 0.35 $m^3 s^{-1}$ to 3.10 $m^3 s^{-1}$, averaging 1.47 $m^3 s^{-1}$. They decreased in the years 1970–2021 (the decrease was statistically significant at a level of 0.01), by 0.15 $m^3 s^{-1}$ $decade^{-1}$ on average (Figure 6a).

Additionally, the 30-day minimum water flows decreased in the analysed period (the change was statistically significant at a level of 0.01). The changes were even more evident at a level of 0.24 $m^3 s^{-1}$ $decade^{-1}$ (Figure 6b). Not only did the minimum water flows decrease, but the annual flows also showed a decreasing trend, at a rate of 0.47 $m^3 s^{-1}$ $decade^{-1}$ (Figure 6c), which was statistically significant at a significance level of 0.01. A decrease in the minimum and average water flows points to the increasing water deficits in the upper part of the Prosna catchment. The number of days during which the flows in the Prosna River were lower than the flow values of $Q_{90\%}$ also increased (1.33 $m^3 s^{-1}$) (Figure 6d). During the period 1970–2021, no water flows lower than $Q_{90\%}$ were observed for 15 years. During the period of the last 20 years, only 3 years had no flows lower than 1.33 $m^3 s^{-1}$. The number of days with flows below $Q_{90\%}$ increased in the same period, and in 4 years, it exceeded 100 days. These changes were statistically significant at a significance level of 0.01, and their rate of increase reached approximately 10 days per decade.

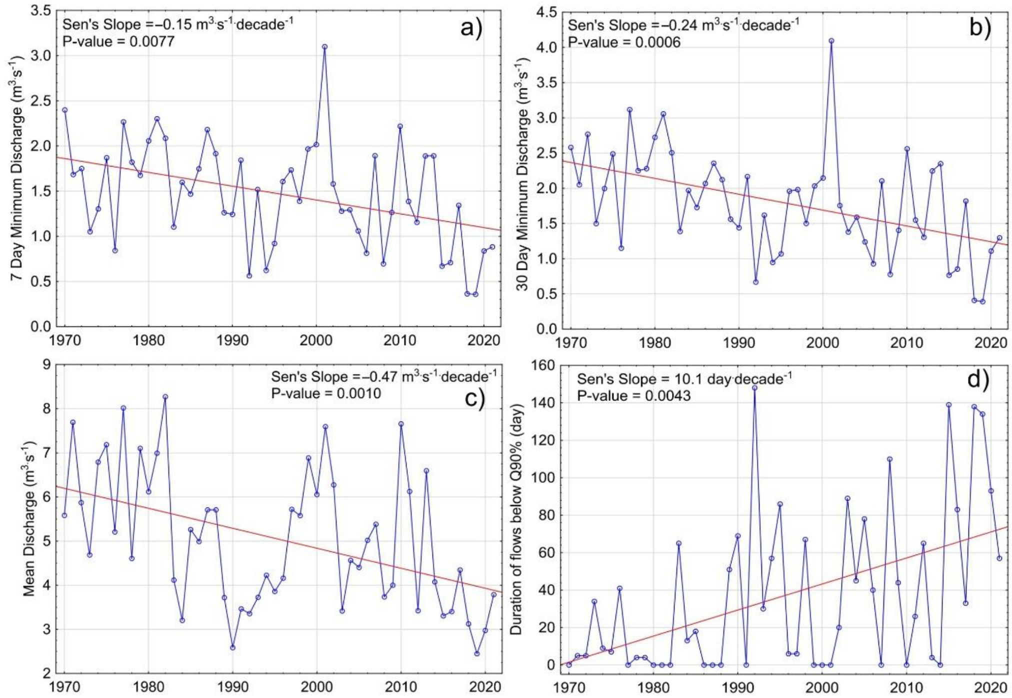

Figure 6. Changes in 7-day minimum water flows (**a**), 30-day minimum water flows (**b**), average annual water flows (**c**), and durations of water flows were below $Q_{90\%}$ (**d**).

4. Discussion

Due to the broad role of hydraulic structures for economic development and the social benefits they offer, it is important to conduct systematic inspections of these structures. Based on the range of knowledge obtained with continuous monitoring, decisions are made regarding the possibilities of repair, reconstruction, and liquidation of hydraulic structures [39]. The long-term operation of these objects increases the possibility of the occurrence and development of different processes that were not originally predicted [40].

According to Su et al. [41], in the case of China, the operation of many hydraulic structures is moving toward discontinuation, and the benefits of their functioning are seriously threatened. The objects constructed at the beginning and in the mid-20th century are subject to the aging process, and only regular inspections, maintenance, and repairs can ensure safety [42]. The situation is analogical to the case analysed in this paper or, in a broader context, to hydraulic structures in the territory of Poland. Hydrotechnical infrastructure has been neglected for decades [43]. This finding is reflected in the case of the Oświecim Weir, built in 1970 and not modernised since then. Its last renovation (before the order of the current modernisation) was performed in 1989. Next to the "natural" process of the aging of the structure, Damulevičius et al. [44], referring to the medium- and small-sized dams built in the second half of the 20th century in Lithuania, draw attention to other issues, namely the inaccuracies in the time of field research, design and construction, as well as the qualitative defects of construction materials. The research conducted by Hossain [45] in reference to the hydraulic structures in Bangladesh showed that structural defects caused serious damage to the structures, leading to their destruction and the main shortcomings concerning the concrete filling.

The main problems of concrete hydraulic structures are cracks, permeation and erosion, thermal fatigue, and carbonatisation [46]. Cracks substantially affect the resistance, durability, and stability of the structures. The chemical effect of permeating water results in erosional damage and weakens the structural resistance. Thermal variability damages the concrete, and carbonatisation reduces the effective cross-sectional area and corrodes the steel bars [47]. The effect of water itself is magnified by the solid materials (stones, gravel, sand, etc.) transported by the river. Abrasion affects the lifespan of hydraulic structures and results in the need for costly maintenance work [48]. In reference to the resistance of hydraulic structures, the mechanical wear and tear of the concrete are of great importance [49]. The results obtained in this study are confirmed by the monitoring results in the case of the analysed weir. The main damage concerns the concrete structures, including cracks and cavities (Figure 4). Next to the structure itself, the reinforcements of the scarps in the vicinity of the Oświecim Weir are also damaged. According to Kamlov [50], next to the degradation of concrete and the clogging of the drainage system, it is among the main problems related to the operation of hydraulic structures.

The detailed expert opinion on the technical condition of the Oświecim Weir revealed evident frost corrosion of the wall surface, a problem common in cold regions. The degradation of concrete caused by frost is important in reference to the lifespan of concrete structures [51]. The damage caused by freezing and defrosting affects the parameters of cracking in concrete structures [52]. Importantly, repairs to damaged concrete structures are usually complicated and costly [53]. In the analysed case, an optimal solution was the demolition of the existing (degraded) weir and the construction of a new object in its place.

The knowledge of old structures becomes increasingly important. According to Daniel [54], the primary reasons for this include their considerable share in the majority of the functioning objects of this type or an increase in requirements with their aging.

The appropriate management of hydraulic structures is a complex task requiring the consideration of both observing the legal provisions referring to their proper functioning and environmental conditions. The detailed knowledge of the latter provides a substantive basis for the optimal use of hydraulic structures for economic purposes. The hydrotechnical systems regulating water relations are of particular importance in the case of agriculture [55], and weirs constitute an important element in the case of irrigation during periods of water deficits and for a reduction in the risk of floods [18,56]. The normalisation works carried out on the Guntur Weir (Indonesia) provided benefits in terms of a reduction in potential flooding and an increase in the capacity of water supply for the irrigation area [57]. From the point of view of water management, however, the flow regulators situated on ditches play an important role [58,59]. They facilitate water management at the scale of a field or melioration object. The hydrological situation in the upper Prosna catchment area should be considered unfavourable, as observed by, among others, a decrease in the average water flows and, more importantly, the minimum water flows, with a simultaneous increase in their duration (Figure 6). This leads to water deficits and, consequently, drought. This phenomenon in turn considerably affects harvests, particularly in the context of the observed climate change [60]. Research conducted in the USA showed a very strong spatial dependency between greater sensitivity to drought and a lower share of irrigated land, and vice versa [61]. According to the authors, the application of irrigation is an important adaptation strategy aimed at mitigating the effect of drought on agriculture in the USA. The regulation of water relations is an important element in the case of the Prosna River, dominated by agriculture in its land use structure. An inventory of the river catchment showed the existence of 140 hydrotechnical objects (with different classes and sizes) that can dam water [62]. Importantly, based on the example of the analysed Oświecim Weir, their optimal functioning will depend on the proper monitoring of the technical condition, and if necessary, the fast implementation of the necessary repairs. This is of importance for the mitigation of the long-term trend of worsening water relations.

5. Conclusions

The appropriate amount of water supplied to the different branches of the economy provides the basis for the development of a given region, and it is of particular importance in those areas dominated by agricultural activity. Hydraulic structures are key for appropriate water management. They mitigate extreme situations, and their proper functioning depends on their efficiency. This paper presented the procedure regarding the assessment of the technical condition of hydraulic structures in Poland, based on the case of the Oświecim Weir for agricultural irrigation. It provided a detailed overview of the elements subject to assessment, and the administrative–legal course in which a decision on the complete reconstruction of the object was made. The main elements subject to degradation were found to be the concrete structures, covered with cracks and cavities. Moreover, next to the structure itself, we identified damage to the reinforcements of the scarps in its vicinity. The incurred costs were justified in a broader approach referring to the environmental conditions (water flow in the river), directly creating the need for the stabilisation of water conditions. In the context of the observed climatic changes, the problem is faced by increasingly more regions around the globe. The proper technical condition of hydraulic structures based on diligent monitoring provides the basis for mitigating this unfavourable situation.

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