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Article

Application of Multi-Criteria Analytic Methods in the Assessment of the Technical Conditions of Small Hydraulic Structures

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Abstract: Increasing water demand, combined with unfavourable climate change, creates a need for well-thought-out water management. Such goals are realised thanks to appropriate hydrotechnical infrastructure, the efficiency and functionality of which depend on its technical condition. In the literature, there is no method for the assessment of the technical condition of small damming structures, including sluice gates. The aim of this article was to present the possibility of using the multi-criteria AHP decision support method to assess the technical condition of small damming structures. The assessment included both concrete elements (spillways, abutments, and apron) and steel elements (gates and hoisting equipment). The analyses considered the effects of growing vegetation, the condition of concrete surfaces (e.g., cracks, cavities, exposed rebar) and steel elements (corrosion, deterioration). A hybrid method was used to study the assessment of the technical condition of water structures. It consisted of a modified Zawadzki's method and weights which were determined by different groups of respondents with industry backgrounds (university students and experts) using the AHP method. The obtained results show that the factors related to the holes and corrosion of the gate elements had the highest value of the matrix solution vector. The last level of the tree structure indicated that the condition of the spillway and gate is the most important factor in the technical condition assessment. As the assessment considers commonly available parameters, the proposed method is universal and can be used in the assessment of other structures of this type in different regions of the world, which is important in terms of their functioning, planned repairs, and optimal use in water resource management.

Keywords: water resources; technical condition assessment; weir; irrigation system; AHP

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1. Introduction

The steady increases in water demand in all industries has created the need for rational management of water resources [1]. In addition to the above objectives, new water–economic and water–environmental–economic systems have been designed to preserve them [2,3]. Apart from industry and municipal services, agriculture is a major user of surface water [4]. Agriculture is undergoing a dynamic transformation due to civilisation's changing needs and opportunities. One effect of this transformation is a change in land use patterns. In the long term, the process of the disappearance of grasslands is clearly visible, and those located in river valleys with specific biotopes and special management methods are particularly at risk of transformation. These changes occur due to abandonment, cessation of agricultural activities, or excessive intensification of agricultural production in these areas [5]. Thus, the main goal is to preserve the areas of high natural value into the future, where biodiversity is an asset and should be protected in line with the guidelines of the Convention on Biological Diversity [6].

The key to preserving the existing characteristics of green spaces is to appropriately manage the water resources within these areas or the catchment areas in which they function [7]. The optimal way to effectively reduce flood risks and the movement of matter is to maintain a constant flow of water in ditches on meadows that use the hydrotechnical infrastructure [8]. Water intake and distribution in irrigation systems is done through canals, ditches, irrigation channels, and drainage structures, as well as other structures installed on them such as sluice gates or dam culverts, water intakes, gullies, and others [9]. Depending on the characteristics and structure of the irrigation system, some of these structures are installed permanently, while others are installed according to periodic and local needs that arise [10]. Damming structures should make it possible to maintain the water level at a certain elevation and to regulate and measure the flow rate of the intake water (from the river, ditch, reservoir). It is also important to channel it to the irrigated area, separate plots/fields.

Efficient water management systems are especially significant in modern times, when mankind has to deal with the effects of global warming. According to predictions, there will be a further increase in air temperature by the end of the 21st century; the rate and magnitude of which depend on the adopted scenarios [11,12]. Taking into account the fact that this parameter is of primary importance for all components of the environment (both biotic and abiotic), this situation will cause different reactions, the effects of which are difficult to predict due to their complex characteristics [13]. Research on climate change spans many industries, addressing a variety of threads, e.g., in the case of agriculture, issues concerning water conditions are significant [14–16]. In the context of climate anomalies, it is crucial to develop modern, economically verified technologies that would ensure uninterrupted water supply for agricultural purposes in different regions [17]. In this context, Saccon [18] notes that more efficient irrigation practices can reduce the amount of water applied to crop fields by 30–70% as well as increase crops by 20–90%, and that effective planning and water management for crop production requires in-depth knowledge and effective solutions. Precise management of water resources in the case of individual rivers or entire catchment areas can only be realised if hydrotechnical infrastructure is properly constructed and operating [19,20].

In addition to solutions aimed at building new damming structures, it is important to know how efficiently the existing structures work [21,22]. For example, in Poland, as part of small-scale water retention, damming is currently carried out on 2162 water structures (weirs, sluice gates). This is estimated to store an additional 313 million m^3 of water per year [23]. As part of the implementation of channel retention tasks, the construction and reconstruction of 650 water structures is planned for the years 2020–2023, totalling approximately EUR thirty-four million. At present, the water retention in Poland is about four billion meters cubed, which is 6.5% of the total water outflow. It is planned to achieve 20% of the total outflow in the future. In this context, it is crucial to assess the technical condition of weirs and barrages in terms of safety and optimal efficiency of their operation. Currently, the technical and functional condition of melioration devices in Poland is bad, as most of them were built 50–70 years ago, and were not properly maintained due to insufficient funding. To a large extent, this infrastructure is technically used up and, without additional financial outlays, will only degrade further [24,25]. The importance of this problem is also confirmed by international institutions, including the International Commission on Large Dams (ICOLD). As an international non-governmental organisation, ICOLD is involved in an exchange of professional information and knowledge on the design, construction, maintenance and impact of large dams. ICOLD reports are concerned with dams’ ageing, risk assessments of dams’ failure, hazards, and assessments of the safety of hydrotechnical structures. They also cover the safety assessment that requires changing climatic conditions and an increase in the risk below dams to be considered (as a result of the increasing population density of these regions) [26,27]. According to ICOLD, damming structures up to 2.5 m in height pose a serious problem. The technical condition of such damming structures can be assessed using various methodologies, each of which has its pros and cons. In recognition of the importance of this problem, ICOLD appointed the Committee on Small Dams, which has defined a small dam (reservoir) as one with a dam height Hz = 2.5 ÷ 15 m and a reservoir volume V < 200 million m^3 [28]. Because of the complexity of the factors involved, including the parameters pertaining to the structure itself and to the mechanisms controlling the water flow, the application of an optimal methodology for assessing the technical condition of a structure is difficult [29]. It requires, among others, a comprehensive assessment of possible solutions that take into account many of their features [30]. This approach requires the use of multi-criteria methods that allow for a detailed analysis of a given problem [31].

There is a lot of research showing that using the AHP method facilitates this assessment. The use of multi-criteria decision-making methods for dam ageing issues has been met with increased interest based on an analysis by Zamarr on-Mieza [32]. The AHP method was used to analyse the technical condition of a structure, for example, by Hämmerling [24]. The paper compared the results of field studies obtained by three methods of assessment of the technical condition of the structure located on the Wełna River. The main goal was to identify the differences between certain methods and to indicate the most important assessment elements and criteria. Moreover, research on the assessment of the operational risk of earth-fill dams using various multi-criteria decision-making methods was conducted by Samaras [33]. The risk of three specific dam projects in the Trikala Prefecture, Greece, was assessed using the AHP and ELECTRE I methods.

The aim of this study was to develop a universal method for assessing the technical condition of small water structures, which could be applied to all such structures. Most methods used to assess the technical condition of hydrotechnical structures have been developed for large water structures. Therefore, based on Zawadzki's method [34], as well as their own experience, the authors of this article have identified the elements of sluice gates that determine their safe operation and use. A survey on water structures was prepared to facilitate the assessment. It was conducted among university students, academic staff, and experienced hydraulic engineers. The research hypothesis was that the weights assigned to the answers of experts are more accurate and should be used in the assessment of the technical condition of small damming structures. The AHP multi-criteria decision support method was used to determine the importance of individual elements of a small water structure. The study was carried out on a polder located in western Poland. However, as the parameters being assessed and taken into account are commonly available, the method used is universal and may be implemented on other structures of this type, without any spatial limitations.

2. Materials and Methods

2.1. Description of the Object of Study

The object of study was a section of a polder located in the catchment of the Wyskoć Ditch, which is a right tributary of the Kościański Canal of the Obra River (Figure 1). In terms of hydrology, this region was identified as the area with the highest water demand in Poland (average outflow per unit time is 2.75 (dm^3-s^{-1}-km^2)) [35].

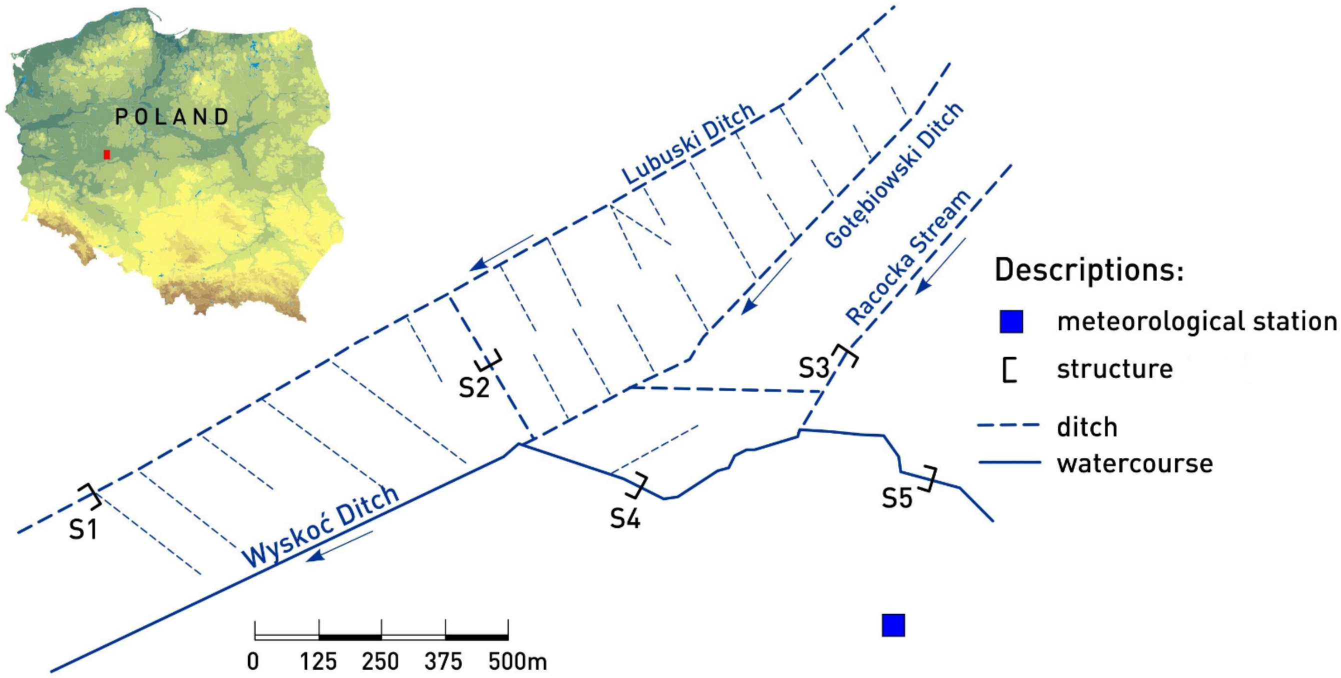


Figure 1. Location of the object of study (where S1–S3 denote the location of sluice gates and S4–S5 denote weirs).

Within the polder, a subirrigation system located in the lower part of the Wyskoć Ditch between km 1 + 300 and km 2 + 700 was implemented. The analysis included five damming structures: two weirs and three sluice gates. Weir S4 enables the damming of water in the Wyskoć Ditch and in the Struga Racocka River. Water is supplied through the damming structures S4 and S5. The sluice gates S1, S2, and S3, which are located on the ditches, are used for damming up water on the individual irrigated plots.

2.2. Applied Method

For the assessment of the technical condition and safety of weirs, sluice gates and bank apron, the method described by Zawadzki [34], with subsequent modifications by Michalec [36], was proposed. This method has been used by Dąbkowski and Jędryka, Tarnawski and Michalec, and Michalec [25,37,38], among others, in studies of damming structures. The method for assessing the technical condition of small damming structures proposed by the authors of this article has been adapted to accommodate for their designs. The new method takes into account the construction elements typically associated with small damming structures. The analyses considered the appearance and condition of both fixed and movable elements. The condition of the structure was assessed based on the presence of cracks, holes, exposed rebar, dripping and seepage, discolouration, and vegetation observed on permanent structures (frame, abutments, apron). This method also assessed the condition of the gates and lifting mechanisms (presence of corrosion and distortion of the moving parts). All the features of the construction elements were assessed based on the occurrence and intensity of unfavourable or harmful processes in the structure, according to the following scale: 5—very good condition (no unfavourable processes); 4—good condition, 3—satisfactory condition, 2—unsatisfactory condition, 1—bad condition (very high intensity of unfavourable processes). The study was based on the material collected during visual inspection, which included detailed photographic documentation in the form of ground photographs of five sample damming structures located in the polder in the Wyskoć Ditch catchment area (Figure 2).

Figure 2. Photos of water structures S4—Weir on the Wyskoć Ditch and S3—water gate on the Racocka Struga River.

Figure 3 shows a diagram of the adopted technical condition assessment research methodology, which used both survey and AHP methods.

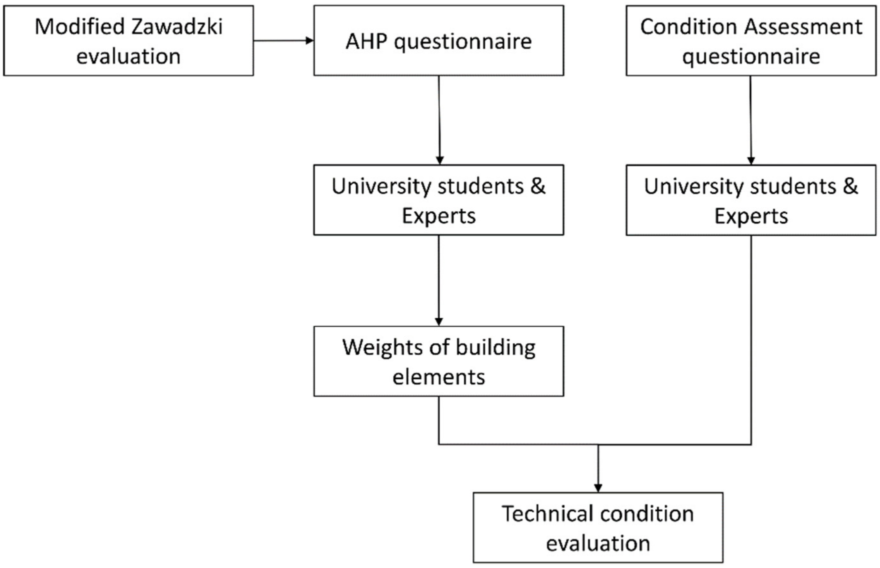


Figure 3. Plan of the adopted research methodology.

2.3. Use of Surveys for Technical Condition Assessment

Results from two surveys were used in the analyses. The first one was related to filling out the comparison matrix for comparing factors and solutions to the AHP method, while the second was closely related to the assessment of the technical condition of sample sluice gates and weirs.

The analysis applied in this article used the AHP multi-criteria decision support method to determine weights for the assessment of the technical condition of small damming structures. Using the AHP method, the importance of individual water structure elements and destructive factors was ranked. Destructive factors are those that cause damage to sluice gates and weirs. We included the following activities: vegetation, holes, corrosion of gate elements, corrosion of concrete elements, distortion, and damage. The weights of the comparisons of factors and solutions were given based on the results of survey 1 (Supplementary S1—questionnaire, Supplementary S2—sample questionnaire responses), which was filled out by two groups of respondents: university students (engineers and Master's students) (Poznań University of Life Sciences) and hydraulic engineering specialists (research staff of Poznań University of Life Sciences and specialists from the

National Water Management Authority Wody Polskie, who manage these type of structures and supervise the technical condition of water structures in Poland). As intended, the questionnaires were completed by both the students and experts. These were the two main groups whose responses were separately analysed and entered into the matrix, which was solved for the AHP method. Survey 1 was filled out by 20 university students and 15 hydraulic engineering specialists.

The second step of the survey was to assess the technical condition of individual structures (S1–S5), to verify the objectivity of the developed methodology, and to analyse the usefulness of photographs for the assessment of the technical condition of structures (Supplementary S3—questionnaire, Supplementary S4—sample questionnaire responses). Survey 2 was conducted online and was based on a modified version of Zawadzki's method [34]. The modification consisted in narrowing the elements to be assessed and assigning appropriate weights to them. The questionnaire was not completed during the field inspection. The authors of this paper took photographs of small damming structures. Then, a questionnaire was prepared with the photos and made available to all the respondents. In the first part of the survey, it was indicated which parts of the structure were subject to assessment, and examples of structures with a very good technical condition (assessment 5) and bad technical condition (assessment 1) were given. The next section of the survey provided photographic documentation of five structures (S1–S5). According to the adopted method, all the elements could be rated from 1 to 5. When an overflow was classified as submerged, the verbal invisible evaluation was given.

In the questionnaires, the base elements of sluice gates and weirs were assessed:

- Spillway—concrete elements—technical condition of the spillway was assessed. Surface condition in terms of holes, exposed rebar and leakage.
- Abutments—concrete elements—special attention was given to damage visible on the surface of the element. Any discolouration, cavities or exposed rebar negatively affected the assessment of this item.
- Apron—concrete elements—during the assessment, there being no visible damages such as cracks or fractures on the surface and holes was verified. The score of an apron could also be lowered due to the displacement from its original location caused, for example, by it's being washed away or by the washing out of material. Vegetation growing on the apron in the cracks could further lower the results of the assessment.
- Gate—steel elements—its technical condition was assessed, taking into account corrosion, tightness of the gates, and their completeness. The gates should be free from any doubt as to their functioning and be freely adjustable by a lifting mechanism.
- Lifting mechanism—steel elements—here, the focus was on the completeness of the hoisting system and its efficiency. The mechanisms had to be constantly maintained and had to operate failure-free at all times.
- At the end of the assessment of each structure, the respondents could write their comments on the assessment as a whole. Examples included: no gates, destructive effects of vegetation or maintenance work required.

Survey 2 was filled out by university students (Poznań University of Life Sciences), academic staff (Poznań University of Life Sciences), and specialists from the National Water Management Authority Wody Polskie. A total of 91 people were surveyed, including 26 engineering students, 30 Master's students, 25 members of academic staff, and 10 experts.

The modified Zawadzki's method is given in the form of a table (Table 1), where weights indicating the importance of individual elements could also be added. In Variant I, the weights were all the same, whereas in Variant II and III, the weights were related to the matrix scores that were obtained using the multi-criteria decision support method (AHP). The final score given is the weighted average of the assessed items.

Table 1. List of assessed elements and weights according to the new method of technical condition assessment of small damming structures.

No.	Question:	Answers:						Variant I	Variant II	Variant III
		1	2	3	4	5	Invisible Element			
1.	Concrete elements—spillway							0.2	$W1_{AHPII}$	$W1_{AHPIII}$
2.	Concrete elements—abutments							0.2	$W2_{AHPII}$	$W2_{AHPIII}$
3.	Concrete elements—apron							0.2	$W3_{AHPII}$	$W3_{AHPIII}$
4.	Steel elements—gate							0.2	$W4_{AHPII}$	$W4_{AHPII}$
5.	Steel elements—lifting mechanism							0.2	$W5_{AHPII}$	$W5_{AHPIII}$

2.4. Using the AHP Method to Assess the Weights in the Technical Condition Assessment

Multi-criteria methods are particularly useful for solving problems in which the selection criteria consist of both qualitative and quantitative factors. The method described by Saaty [39,40] has been developed by many researchers [41–43], enabling the solution of deterministic, stochastic, and fuzzy problems.

Problem-solving using multi-criteria methods is conducted in several steps. The first is to create a hierarchical structure, i.e., to decompose the analysed problem [44,45]. The hierarchical tree structure describes the goal, general factors, and at subsequent levels, the increasingly specific factors. The levels of the tree structure in the AHP method can be infinite, but there are always solutions at the last one. The tree structure shows the structure of the discussed problem in a clear and comprehensive way. At level I, the hierarchical tree presents the research problem. Level II describes the factors affecting the research problem. Level III of the hierarchical tree represents the elements covered by the technical condition assessment. The applied method of the assessment of the technical condition should be based on the AHP method, in which the analysis is carried out according to Saaty's [39] 9-point scale. Based on the solution of the tree, the importance values of technical condition assessments of the individual elements of damming structures are obtained. The study addressed the results of survey 1, in which respondents assigned weights when comparing the individual factors and elements of structures. The respondents did not have any criteria. They only used their own knowledge. A minor help was given in the description of the scales used. The numbers obtained in this way filled the matrices, the solution of which allowed the determination of the importance of each element for the assessment of technical condition. This was to be used to determine the order of priority of the individual elements subject to assessment. The results of the study allowed for the development of a proposal for a universal method of the assessment of the technical condition of small damming structures on irrigated areas, which can be used to assess any such areas. Figure 4 shows a tree structure describing the aspects related to the assessment of the technical condition of damming structures, and the water gate elements subject to assessment.

The first level of the tree consists of the goal of the study. At level II, factors affecting the technical condition of individual elements of the analysed water damming structures are identified. The assessment considered aspects such as vegetation, holes, corrosion of gate elements, corrosion of concrete elements, distortion, damage, and ability to control the flow. Level III identifies the individual elements of a small damming structure. The following elements are listed for assessment: spillway, abutments, apron, gates, and lifting mechanism.

The next step was to create the matrices, which were filled out with the results of the comparison of factors and elements (Supplementary S5). The matrices were filled with values from Saaty's linear scale [46]. At level I, there was only one matrix, whereas at level III, the matrix was solved for as many times as there were factors in Level II. The size of the matrix was closely related to the number of elements.

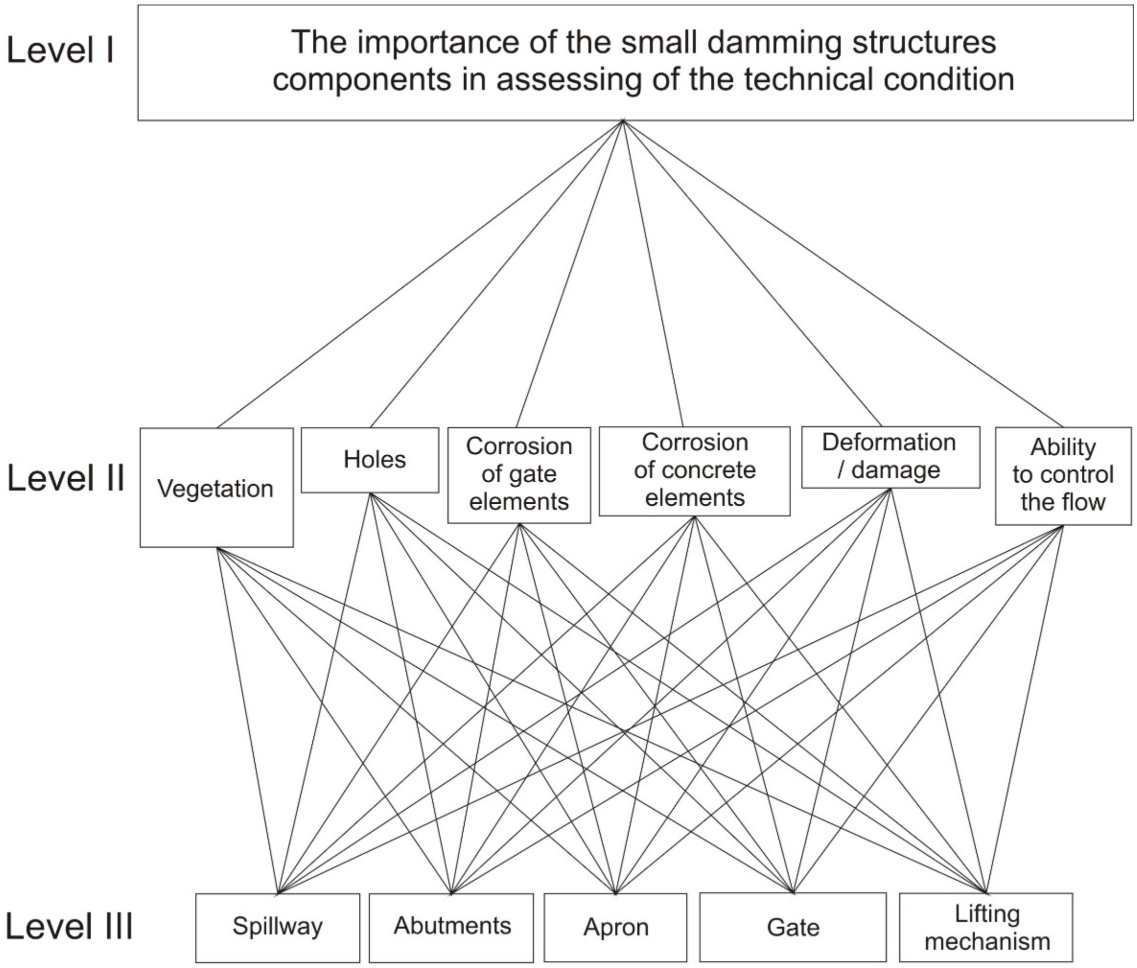


Figure 4. Priority tree of the elements of a small damming structure (level I—the research problem, level II—factors affecting the research problem, level III—elements covered by the technical condition assessment).

Solving a matrix yields a local vector as a result. The global vector is the result of multiplying the local vector from a given level by the global vector from the level above. The resulting local vectors of individual matrices made it possible to hierarchise the factors influencing the technical condition of the structure elements and the individual elements of the sluice gates, in the context of the overall assessment of technical condition. The priority in the final assessment of the technical condition of individual water gate elements was determined by calculating the global vector, which was the product of the local vector from level III and the global vector from level II. The calculated global vectors for the last level of the tree structure were multiplied by the values of the technical condition assessment of the individual water gate elements. This allowed for the overall assessment of the technical condition of the entire structure. At level II, local vectors are always equal to global vectors; at level III, local vectors are different from global vectors. Global vectors are calculated from the result of the local vector of a given level, multiplied by the global vector of the level above. Since it is assumed that, at level I, the global and local vectors are equal to 1, the global vector is equal to the local vector at level II.

Since a comparison of individual factors and solutions may not be entirely objective, parameters that check the consistency of comparisons are required; such parameters can be found in the literature. One of the most important values determined in the AHP method, and one of the measures of consistency of comparisons reflecting proportionality of preferences, is the eigenvalue of the matrix [47]. The maximum eigenvalue of a matrix is calculated from the formula [48]:

$$\lambda_{max} = \frac{\sum_{n}^{i=1} \lambda_i}{n} \tag{1}$$

where:

n—dimension of the matrix;

λ—eigenvalue of the matrix for the i-th row.

Another important measure is the Consistency Index *CI*, calculated according to the formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where:

n—dimension of the matrix;

λ_{max} —maximum eigenvalue.

Because of the partial lack of objectivity of the assessments, the Consistency Ratio *CR* is calculated [44]:

$$CR = \frac{CI}{RI} \tag{3}$$

where:

CI—Consistency Index

CR—Consistency Ratio

RI—value of Random Index

The value of the Random Index *RI* depends on the dimension of the comparison matrix. The priority assessment is considered consistent if the value of the calculated *CR* does not exceed 0.1 [49]. The local vectors determined by the matrix solutions were converted into global vectors using the tree structure. This was especially significant for the last level of the tree structure, for which the determined weights of the individual sluice gates elements were based on. Three types of weights were analysed. In Variant I, only the original results of the technical condition assessment were considered (weights equal to 0.2 were assumed everywhere) (Variant I). For Variant II, the weights derived from the AHP method were used for university students, and for Variant III, the weights from experts were used.

2.5. Statistical Analysis

In the first stage of the statistical analysis, the collected questionnaires (survey 2) were verified in terms of the reliability of answers. For this purpose, the results were analysed separately for each respondent in terms of the minimum value, maximum value, range, and frequency of each response. Thus, two cases were identified where all scores were −1. The remaining surveys were further analysed statistically. In the second stage, the results of the surveys were analysed to determine the technical condition of the structures and to check if there were significant reported differences in their condition and the condition of their elements—this included verification of the differences between the elements of the structures and the structures. The third stage of the analysis of the surveys' results was to answer the question of to what extent the prepared methodology was objective, and whether different groups of people, regardless of their education, are able to assess the technical condition of structures—this included verification of the significance of discrepancies between groups. In order to present the results of the surveys, the percentages—the shares of responses in each group—were calculated. For the presentation of the results, a coding method was adopted, consisting of one letter and two digital indices, Sxy, where S stands for the hydrotechnical structure, x—the first index—stands for the assessed structure's assigned number, and y—the second index—denotes the assessed element's assigned number. Non-parametric Friedman's ANOVA tests with Kendall's concordance coefficient were used to determine the significance of the discrepancies between the assessed structures and elements, and the non-parametric sign test and the Chi-squared test were used to compare pairs of structures and pairs of the same or different structure elements. The non-parametric Kruskal-Wallis test, the Mann-Whitney U test, and the Chi-squared test were used to answer the question of whether survey results between groups differed significantly with regard to structures and the elements of structures. Statistical analysis of the results regarding the presence of differences between the groups, as well as the structure elements and the structures, was performed at the 0.05 significance level in Statistica 13.1. In order to understand the relationship between the technical condition of individual elements of the structure, the Spearman's non-parametric rank order correlation analysis was used.

3. Results

3.1. Results of AHP Analyses

First, the level II matrix of the tree structure was solved. Figure 5 shows a comparison of the solution vector results for factors influencing the technical condition of a structure. Two matrices were prepared for level II of the tree structure based on surveys filled out by university students (Variant II) and experts (Variant III). This allowed for a comparison of the technical condition assessment of the analysed damming structures by two groups of respondents.

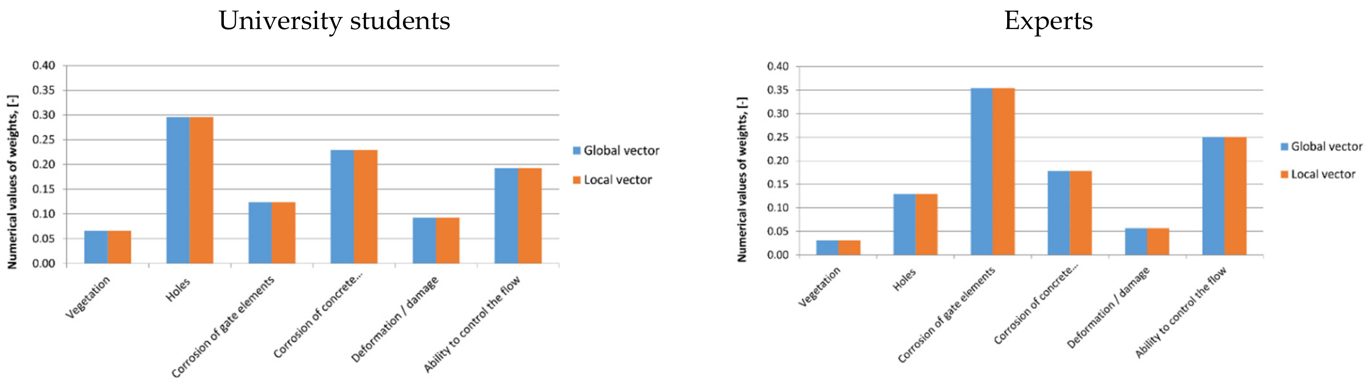


Figure 5. Changes in the values of the matrix solution vectors for level II of the tree structure depending on the variant.

A comparison of the results revealed that for both university students and experts, the lowest value of the solution vector was obtained for vegetation (obtained values of 0.067 and 0.032, respectively). The highest value of the matrix solution vector for university students was obtained for holes (0.296), and for experts for corrosion of the gate elements (0.354). The most similar value of the solution vector for the matrix obtained from the surveys filled out by both university students and experts was that for the vegetation factor (0.03). The largest differences between the values of the solution vector were obtained for corrosion of the gate elements (0.23). In the next step, the matrices for level III of the tree structure were calculated. Figure 6 shows the results of the matrix solutions for level III of the tree structure, which are local vectors.

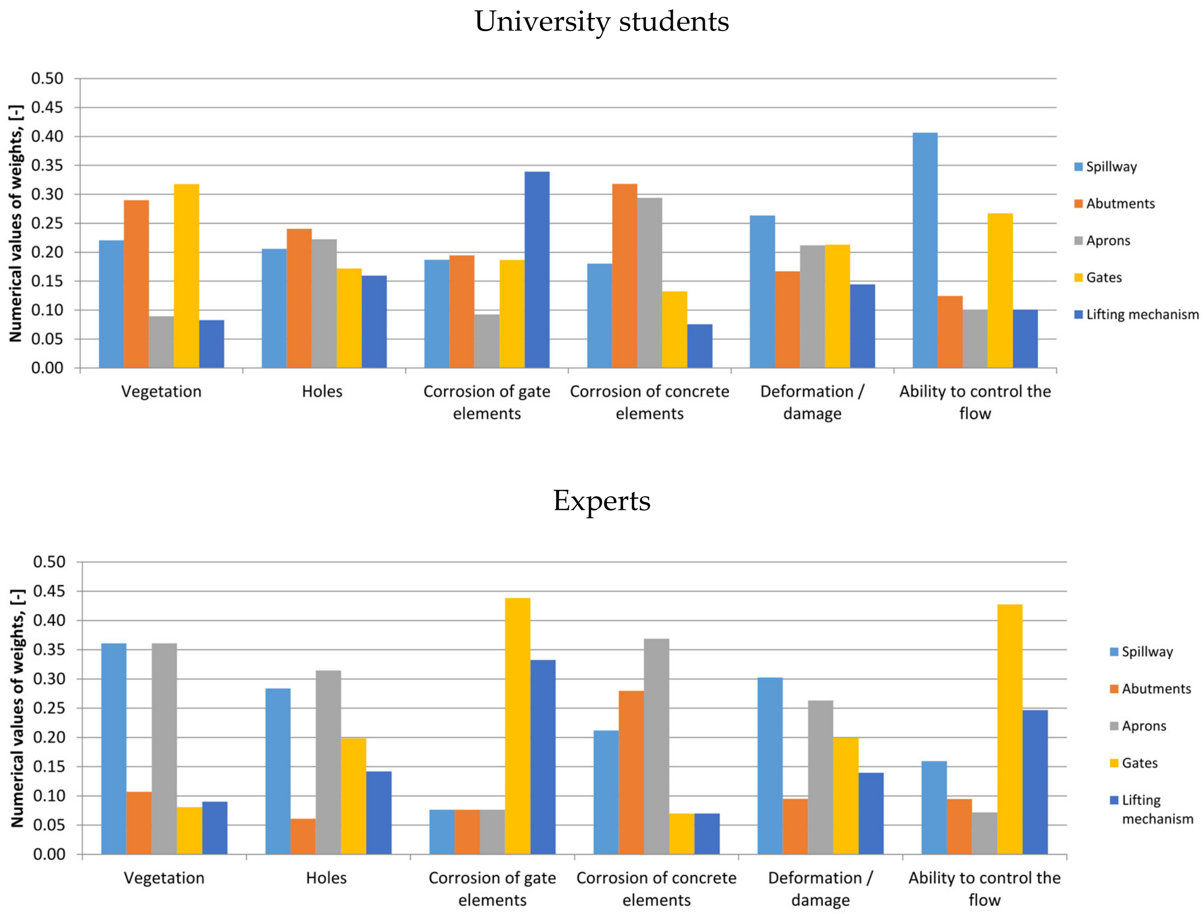


Figure 6. Changes in the values of the matrix solution vectors for level III of the tree structure depending on the variant.

The highest values of the local vector for level III were obtained for Variant II for the factor—ability to control the flow and spillway (0.407). The highest values of the local vector were obtained for Variant III for the factor corrosion of gate elements and gate elements (0.439). A slightly lower value was obtained for the ability to control the flow and gates (0.427).

The next step in the calculation was to use the global vectors from Level II and the local vectors from Level III to calculate the final solutions. Figure 7 shows the comparison of the results of global vectors for individual elements of sluice gates and weirs obtained from calculations for variants II and III.

According to university students (Variant II), the highest weight for technical condition assessments should be given to the spillway (0.242), and the lowest to the lifting mechanism (0.145). According to experts (Variant III), when assessing small damming structures, the highest priority should be assigned to the condition of the gate (0.314) and the lowest to the abutments (0.117). The obtained weights allowed for the values of the technical condition assessment to be calculated and for the differences to be compared.

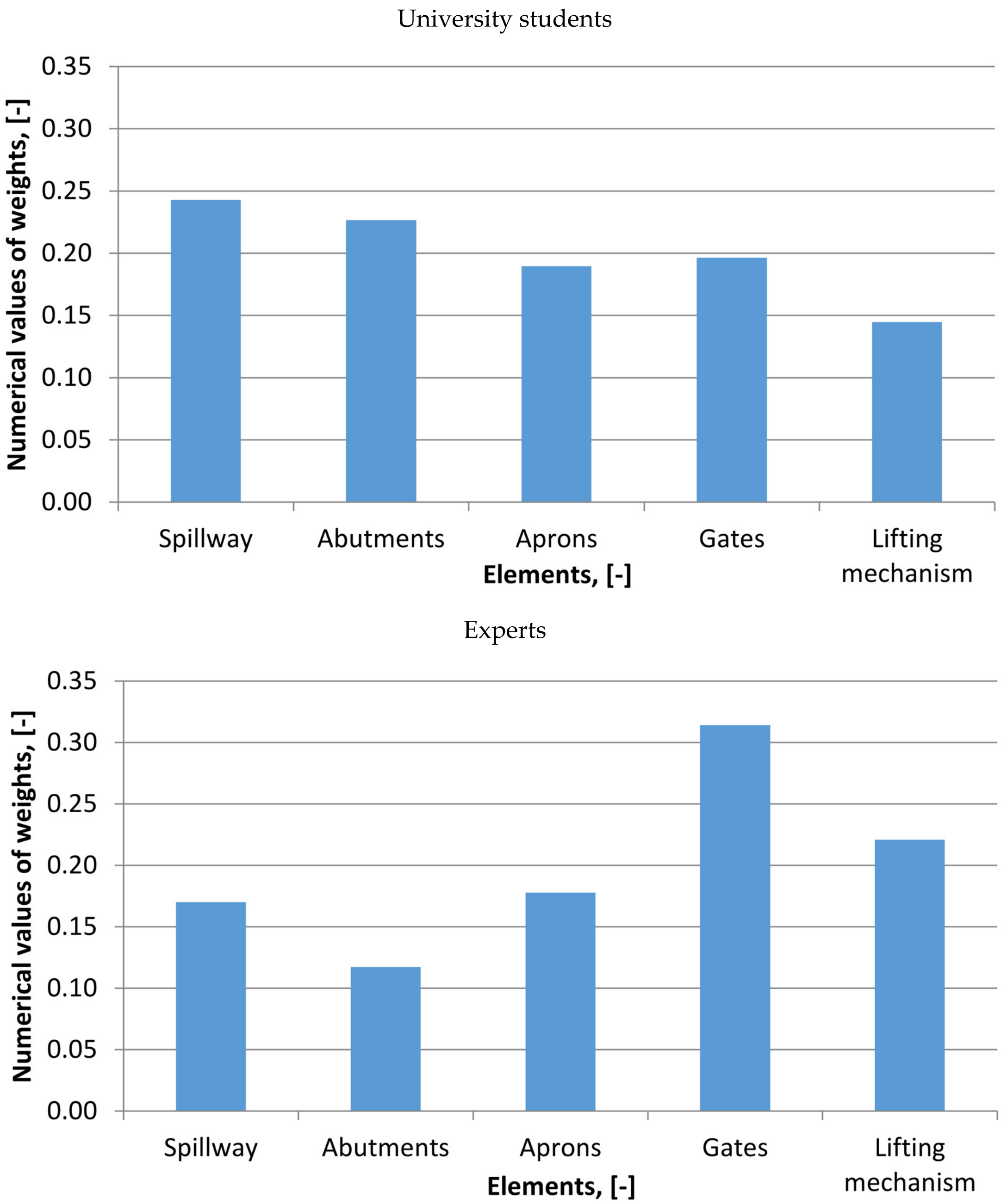
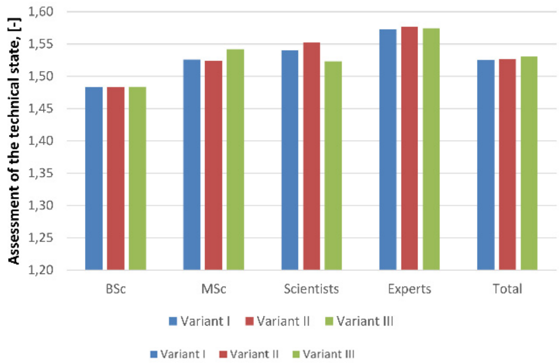


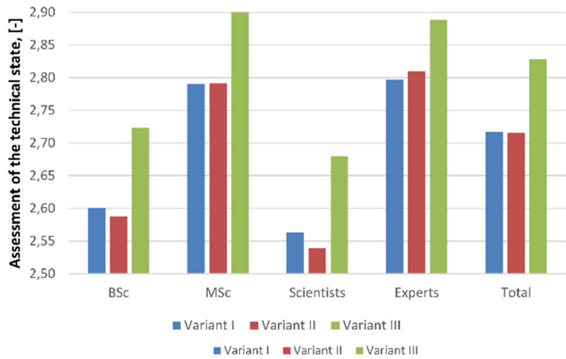
Figure 7. Changes in the values of global vectors for different elements of the structure depending on the variant.

3.2. Assessment of the Technical Condition of Individual Structures

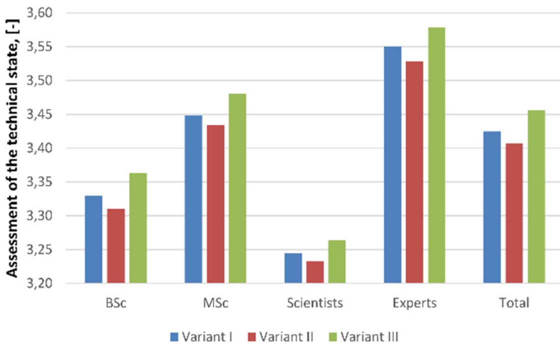
Based on the collected questionnaires (survey two), the results of the technical condition assessment of five sluice gates and weirs were compiled. Each structure was assessed by individuals belonging to four groups with different competencies. Based on the scores assigned by the study participants, averages were calculated for each element of the structure. Each item was rated on an ordinal scale from 1 to 5. Moreover, if assessment based on the attached photos was difficult because of vegetation obscuring the construction elements, a possibility of assigning a score of 0—invisible element—was introduced. Next, after taking into account the weights obtained through the AHP method, weighted scores were calculated for individual elements as well as for the entire structure (Figure 8).



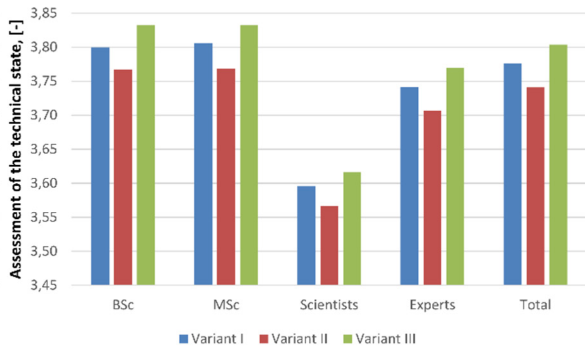
Structure S1



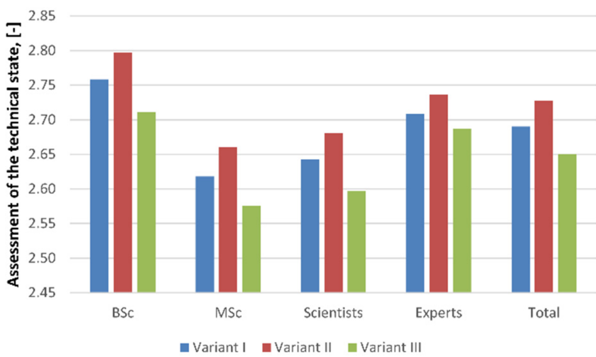
Structure S2



Structure S3



Structure S4



Structure S5

Figure 8. Comparison of the technical condition assessments for structures S1, S2, S3, S4, and S5.

Based on the results obtained for structure S1, it was concluded that the discrepancies between the assessments made by the different groups of respondents were small and amount to about 0.089, 0.093, and 0.091 for the averages, students, and experts, respectively. An overall analysis of all the responses for the average and for individual variant weights obtained using the AHP method also showed little difference in the scores. The largest difference was observed among the specialists—0.030. The smallest difference was observed in the engineering students group—0.001. The discrepancy between the lowest and the highest average for all survey respondents amounted to 0.006. The values of the technical condition assessments varied from 1.483 to 1.573, from 1.483 to 1.567, and from 1.484 to 1.575 for Variants I, II, and III, respectively. The analysis of the listed values classified the condition of structure S1 as unsatisfactory. The same steps were taken for all the five structures.

An analysis of the scores obtained for Structure S2 reveals that the smallest discrepancies were obtained among the responses given by the scientists. The differences ranged from 0.111 to 0.117 for all other groups of respondents, except for the engineering students (0.123). The discrepancies in the individual variants related to the different weights obtained using the AHP method and were as follows: for Variant I—0.234, for Variant II—0.271, and for Variant III—0.222. The smallest discrepancies between weighted scores for a given method were observed in Variant III. The technical condition assessment scores for Structure S2 varied from 2563 to 2797 for Variant I, from 2539 to 2810 for Variant II, and from 2680 to 2902 for Variant III. Therefore, according to all the respondents, structure S2 was in satisfactory condition.

The technical condition assessment scores for structure S3 indicate that the smallest differences were observed among the specialists (0.019), and the largest among the engineering and Master's students (0.033 and 0.032, respectively). An analysis of the different variants indicated that the largest differences could be observed for Variant III (0.315), while the smallest were observed for the university students (0.296), Variant I (0.305). The technical condition of structure S3 was described with the following values: from 3.245 to 3.550 for Variant I, from 3.232 to 3.528 for Variant II, and from 3.264 to 3.579 for Variant III. In conclusion, structure S3 was in satisfactory technical condition.

When analysing the results of the technical condition assessment for structure S4, the smallest differences were observed in the group of specialists (0.019), and the largest for that of engineers (0.037). An analysis of all the responses across different variants revealed that the smallest discrepancy was that for Variant II (0.203), and the largest was for that of Variant III (0.216). The values of the technical condition assessment varied from 3.595 to 3.806, from 3.566 to 3.769, and from 3.616 to 3.821 for Variants I, II, and III, respectively. The analysis of the listed values classified the condition of structure S4 as good.

The technical condition assessment values for structure S5 show the smallest differences for scientists (0.028) and the largest for BSc students (0.048). The smallest differences in scores were observed in Variant III (0.135), and the largest for Variant I (0.140). The lowest and the highest recorded values in Variant I were 2.618 and 2.759, respectively. In Variant II the lowest value was 2.660, and the highest was 2.797. In Variant III, the lowest score was 2576 and the highest was 2711. Based on the assigned scores, it can be concluded that the structure was in satisfactory condition.

3.3. Statistical Analysis of the Surveys

An analysis of the survey results showed that structure S1 was in the worst technical condition and structure S4 in the best condition. Analysing all of the survey results for these structures without specifying individual elements revealed that, in the case of structure S1, as many as 48% of the results indicated a very bad condition (assessment 1) and 28% a bad condition (assessment 2). For structure S4, 17% of the results indicated very good condition and 49% a good condition. Statistical analysis showed that there were significant differences at the level of 0.05 in the scores obtained by individual structures (Figure 9). In Figure 9, the dashed lines between structures indicate no significant differences in the technical condition of structures, while solid black lines indicate significant differences in the technical condition, with the arrow indicating structures for which the technical condition is better.

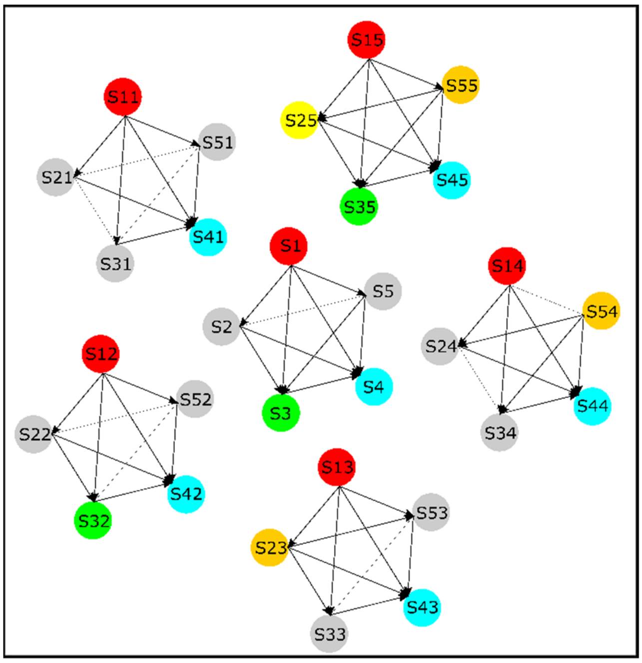


Figure 9. Comparison of the technical condition of structures and individual elements of structures.

The technical condition of the structures on the polder can be arranged in a descending order as follows: S4 > S3 > S2 = S5 > S1. The differences in conditions between structures S2 and S5 were statistically insignificant. When the individual elements of the structures were taken into account, in each case, the lowest score was for structure S1 (i.e., S11, S12, S13, S14, and S15). The condition of the individual elements of Structure s1 was significantly lower than that of the corresponding elements of other structures. The only exception was the condition of the gate of structure S1 (S14), which was in a similar condition as that of structure S5 (S54) (no significant differences at the level of 0.05). The highest score was given to the technical condition of the individual elements of structure S4 (Figure 9—colour blue). Figure 10 summarizes the results of the questionnaires obtained from the selected groups of respondents regarding the structure technical condition rating.

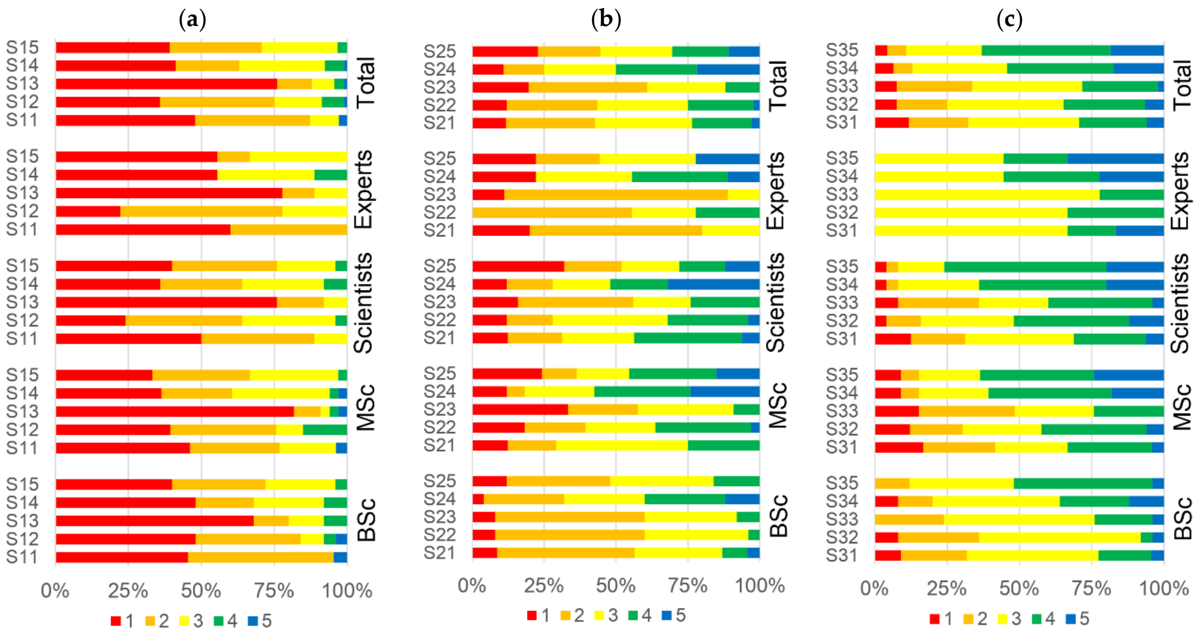


Figure 10. *Cont.*

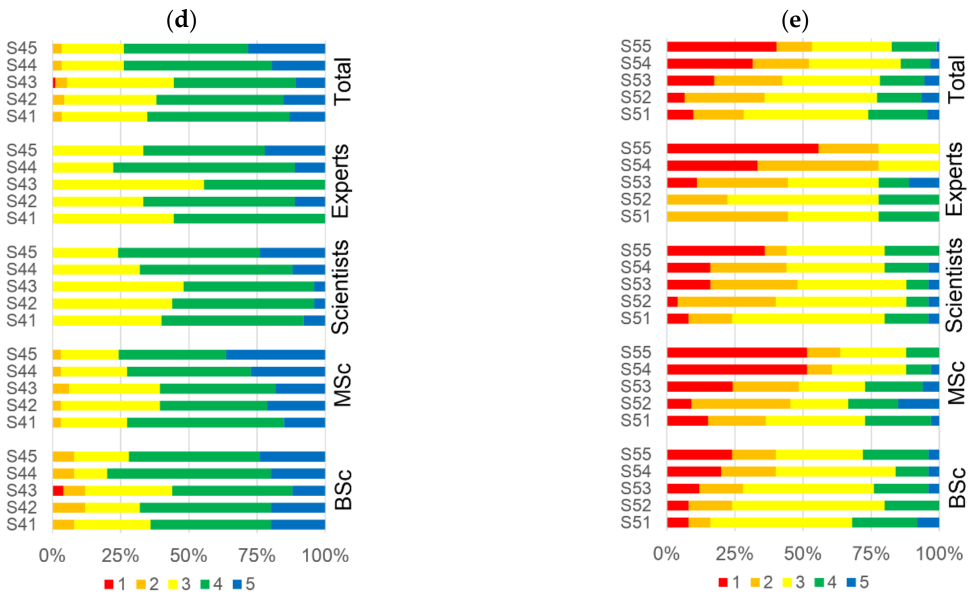


Figure 10. Questionnaire scores regarding of the technical conditions of individual structure (S1—(**a**), S2—(**b**), S3—(**c**), S4—(**d**), S5—(**e**)) obtained from selected groups of persons (BSc, MSc, Scientists, Experts) and in general by all respondents (Total).

Taking into consideration the individual elements within respective structures, the worst scores were given to the concrete apron S13, S23, S43, as well as the steel gates and hoisting devices S54 and S55, while the highest scores were assigned to the steel gates in structures S1, S2, S3 and S4, and the steel gate mechanisms in structures S3 and S4. The results of the analysis of the differences between the technical condition of the individual structure elements are shown in Figure 11. The results of the analysis show that, within the structure, there are significant differences between the technical condition of its individual elements. Based on 50 benchmarking analyses, in 17 cases, the analysis showed no significant differences—value zero. In case of four structures, the technical condition of concrete elements—spillway (Sx1) and abutments (Sx2)—did not differ significantly.

		V				
	v vs V	S11	S12	S13	S14	S15
>	S11		1	-1	1	0
	S12	-1		-1	0	0
	S13	1	1		1	1
	S14	-1	0	-1		0
	S15	0	0	-1	0	

		V				
	v vs V	S21	S22	S23	S24	S25
>	S21		0	-1	1	0
	S22	0		-1	1	0
	S23	1	1		1	1
	S24	-1	-1	-1		-1
	S25	0	0	-1	1	

		V				
	v vs V	S31	S32	S33	S34	S35
>	S31		0	0	1	1
	S32	0		0	1	1
	S33	0	0		1	1
	S34	-1	-1	-1		1
	S35	-1	1	1	1	

		V				
	v vs V	S41	S42	S43	S44	S45
>	S41		0	0	1	1
	S42	0		-1	1	1
	S43	0	1		1	1
	S44	-1	-1	-1		0
	S45	-1	-1	-1	0	

		V				
	v vs V	S51	S52	S53	S54	S55
>	S51		0	0	-1	-1
	S52	0		0	-1	-1
	S53	0	0		-1	-1
	S54	1	1	1		0
	S55	1	1	1	0	

Figure 11. Differences in the technical condition assessments of individual elements of a structure (if V > v or v > V then 1, if V < v and v < V then −1, if the differences are insignificant then 0).

In the third stage of statistical analysis, the assessment results were compared between the different groups participating in the surveys, i.e., the experts, scientists, Master's, and engineering students. Detailed results for individual structure elements are shown in Figure 10. The results compiled for structures (Figure 12a), structure elements (Figure 12b) and overall (Figure 12c) show in a generalised way the variation between the groups of people surveyed. An analysis of the results of the assessments made by the different groups surveyed and compiling the results by structure showed significant differences for structure S3 between the results of the surveys filled out by the group of experts and engineering students, and scientists and engineering students. In the case of structure S5, there were differences in the results between experts and engineering students, and Master's and engineering students. For structure S2, differences existed between survey results obtained from Master's students and engineering students. An analysis of the results of the assessments made by the individual groups surveyed, compiling the results by individual structure elements, showed that there were no significant differences. In terms of the assessment of individual structure elements, there were no significant differences between the surveyed groups. Also, when compiling the results by groups surveyed, the differences in their assessment were not statistically significant. The above results indicate that, regardless of the group performing the technical condition assessment of a structure, the adopted methodology allows for obtaining comparable results. Individual differences occur within structures. The group whose assessment results differed most from other results were the engineering students i.e., persons with the least theoretical knowledge and practical experience.

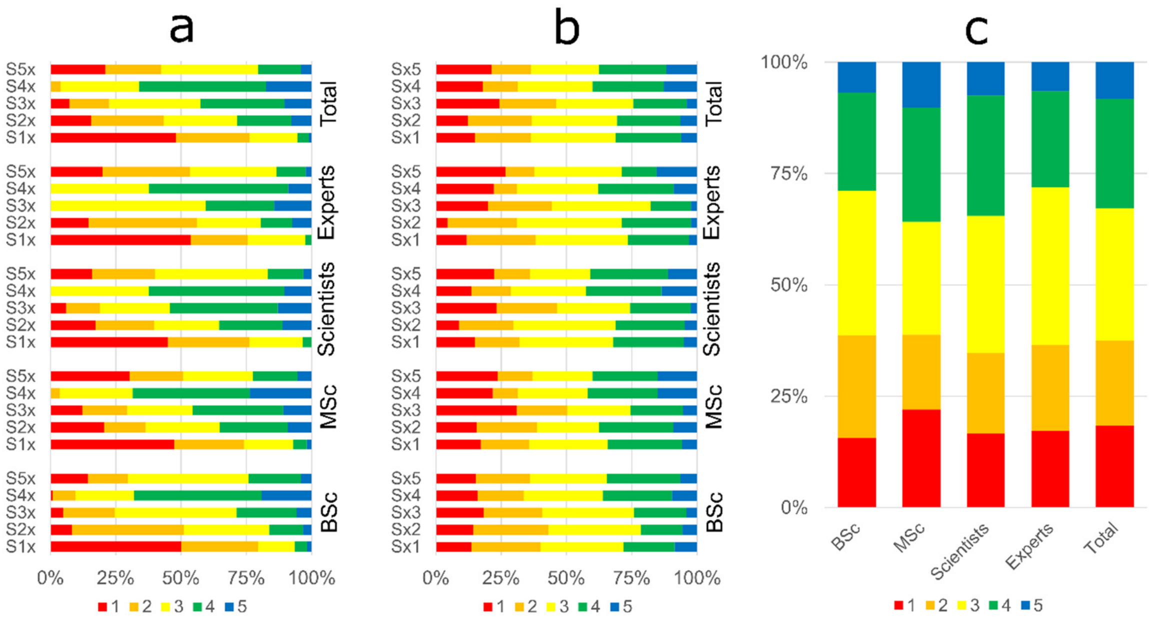


Figure 12. Scores obtained by individual structures (**a**) structure elements, (**b**) total scores without breakdown by structure and structure elements, (**c**) scores obtained from the respondents (the technical condition assessment scale is 1–5).

The analysis of the correlation between the different elements of a structure showed that the strongest relationship could be observed between the technical condition of the Sx4–Sx5 steel elements (Figure 13). The Spearman correlation coefficient values ranged from 0.68 to 0.84 with an average value of 0.75. The weakest relationship of the technical condition of a structure was found between the concrete apron and the condition of steel elements, i.e., the gate and the lifting mechanism; however, when considering the concrete elements on each of the structures, the relationships were slightly different. In general, however, the strongest relationships were found between the technical condition of the spillway and abutments (Sx1–Sx2), with an average Spearman correlation coefficient of 0.64.

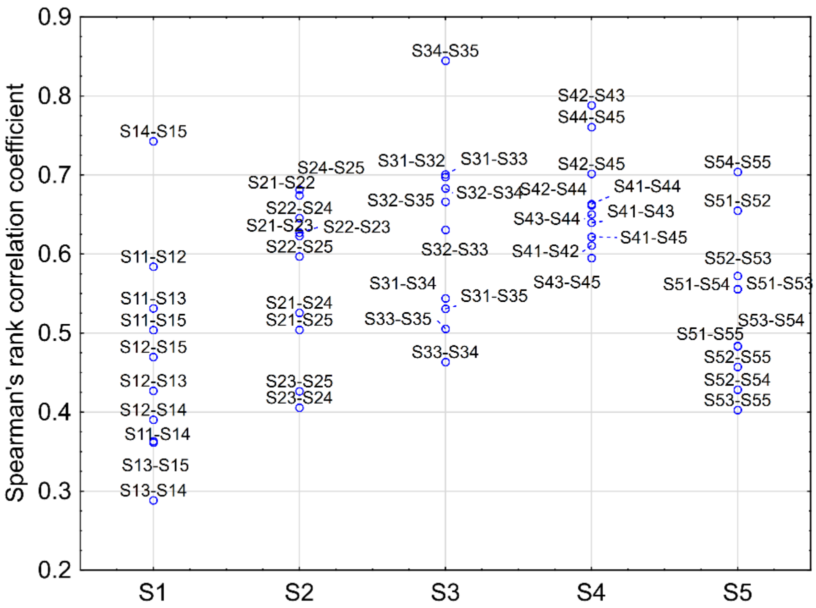


Figure 13. Analysis of the correlation between the results of the technical condition assessment of individual elements of the structure.

4. Discussion

In the context of the safe use of water structures, the subject of the proper condition of damming structures is of great importance.

Most of the popular methods for assessing the technical condition of hydrotechnical structures have been developed for large water structures. Against this background, only the method of Kaca and Interewicz [50] is widely used in Poland for small drainage structures such as reseed irrigation systems and drainage buildings, where it is mainly used to assess the parameters of ditches, sluice gates and culverts [51,52]. It can also be successfully used to assess the technical condition of structures on watercourses and buildings of small-scale water retention in forest areas [53]. To compare the results obtained by this method with others known from the literature, three currently available methods (Kaca, Michalec, and Zawadzki) were juxtaposed in this publication [24]. The analysis showed that results from these methods differ significantly from each other. The subjectivity of the factors used for assessment was also pointed out. Another method used to assess the technical condition of small dams is the Dam Safety Index (DSI), which provides a balanced approach to this problem. This indicator also allows the administrators of damming structures to prepare a maintenance schedule [54]. Due to the ageing of dams, safety issues have become more important. Having analysed various dam risk classifications, Zhou [55] concluded that the five-stage scale should be used to assess the risk of dam failure.

However, to assess the technical condition of small water structures, Jing et al. [56] used the Fuzzy AHP method. The authors claimed that the method they used allows one to assign weights to different risk factors, so that the results of the assessment are more accurate and reliable. The method used by Jing et al. [56] requires only several parameters when compared to the full assessment of the risk magnitude. A similar approach to the issue of technical condition assessment was presented in [57]. The authors presented a developed model for evaluating the engineering conditions of small dams using an analytical hierarchy process. A series of surveys were conducted to collect and analyse the opinions of experts with relevant experiences and expertise on inspection and maintenance of dams.

Shin et al. [57] used the AHP method to simplify the assessment of the technical condition of small water structures by limiting the number of elements taken into consideration to three. The improved model simplified the five-stage assessment of technical conditions, and increased the capability and speed of assessments.

The results presented be Shin et al. [57] indicate that the significantly simplified process by AHP and the concise checklist of the improved model are expected to enable practical applications of the maintenance of small dams and on-time renovation and reinforcement works as required. As the importance of each item of a dam's structure is reflected for inspection, the improved method is regarded as more realistic and practical for representing the actual field conditions.

In the method proposed in this paper, specially prepared surveys were used, similarly to Michalec [32]. Michalec has carried out studies in the context of comparing technical condition assessments, implemented by different groups of people. He compared the results of the assessments made by experts and students. Students assessed the technical condition in two stages: without training and after training. The analysis of the results obtained by Michalec showed that student training had an excellent effect and made their results of the technical condition assessment more similar to those provided by experts.

Most damming structures on irrigation systems dam the water below 2.5 m. That is why the universal assessment of the technical condition of small damming structures was prepared in the paper based on the well-known and frequently used Zawadzki's method. In the proposed method, five elements were assessed, similarly to Samaras [33]. Custom-designed surveys were used in the assessments. Students and experts (employees of the Faculty of Environmental and Mechanical Engineering, as well as experts working in the hydrotechnical engineering industry) prepared the assessment of the technical condition of five sample water structures. In the next step, the importance of certain elements of small hydrotechnical structures was defined using the AHP multi-criteria, decision-making method. While analysing the last level of the hierarchical tree, according to students, the highest weight in the assessment of the technical condition should be given to the spillway and the lowest to the lifting mechanism. According to experts, in the assessment of small damming structures, the most important is the condition of the gate, and the least important are the abutments. The results derived from the AHP calculations made it possible to recalculate the obtained assessments in Variant I and to obtain two other variants of the results (II and III). Table 2 summarises the values of parameters determining the consistency of respondents' answers.

Table 2. Parameters calculated for each matrix depending on survey results.

Respondents	Values of Parameters	Level II	Level III					
			Vegetation	Holes	Corrosion of Gate Elements	Corrosion of Concrete Elements	Distrortion/ Damage	Ability to Control the Flow
experts	λmax.	6.29	5.06	5.12	5.06	5.14	5.22	5.36
	CI	0.06	0.01	0.03	0.01	0.03	0.05	0.05
	CR	0.05	0.01	0.03	0.01	0.03	0.05	0.05
university students	λmax.	7.46	6.56	5.45	8.52	5.24	5.30	5.27
	CI	0.29	0.39	0.11	0.88	0.06	0.07	0.07
	CR	0.24	0.35	0.10	0.79	0.05	0.07	0.07

The CR parameter value for all the matrices filled out by experts was less than 0.1, so the answers given by this group of respondents were consistent. However, in the group of surveyed students, the CR parameter value exceeded 0.1 both for level II matrices and level III matrices, in the context of vegetation and corrosion of gate elements. This confirms the research hypothesis that the weights assigned to experts' answers are correct and should be used in the assessment of the technical condition of small damming structures. This also indicates, as in the study by Michalec [56], the importance of practical expertise needed to make subjective assessments of technical conditions.

5. Conclusions

This paper analysed the technical condition of small damming structures. The method of hybrid assessment of the technical condition of water structures was used in the analysis.

A modified Zawadzki's method was proposed and adapted to the characteristics of the analysed structures. The assessment was focused on the concrete elements of the spillway, abutments, and apron, as well as on the steel elements of the gate and hoisting equipment. In the proposed method, the weights determined by the AHP method play an important role. Surveys completed by different groups of people with industry backgrounds (students and experts) were used to determine them. Based on the analysis of the weights, it was found that for both for students and experts, the lowest value of the solution vector was obtained by the vegetation surrounding the structures. The highest value of the matrix solution vector for students was obtained for the factor holes, and for experts, for corrosion of gate elements. An analysis of the surveys showed that in the assessment of the technical condition, not only students' knowledge (often only theoretical) but also the experience and practice of engineering experts are essential.

In the end, the weights obtained from the experts' surveys were considered to be important in the assessment of the technical condition of the structures, and so, for the spillway, the weights were 0.17, for abutments 0.12, for apron 0.18, for gates 0.31, and for the lifting mechanisms 0.22. Given that the assessment was based on commonly available parameters, the proposed method is universal and can be used for other structures of this type in different regions of the world, which is important from the perspective of their operation and planned repairs for their optimal use in water resource management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings12020115/s1, Supplementary S1—A questionnaire connected with the assessment of the technical condition of small damming structures. Supplementary S2—A questionnaire connected with the assessment of the technical condition of small damming structures—sample questionnaire responses. Supplementary S3—A questionnaire connected hierarchization of elements of small structures. Supplementary S4—A questionnaire connected hierarchization of elements of small structures- sample questionnaire responses. Supplementary S5—A sample matrix for AHP method.

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