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APPLICATION OF AHP METHOD TO ASSESS THE POSSIBILITIES OF USING OF GEOLOGICAL STRUCTURES LOCATED IN THE AQUIFERS AS UNDERGROUND STORAGE SITES

1. INTRODUCTION

Tectonic structures, both those located in aquifers and exploited hydrocarbon deposits may be used for the storage of carbon dioxide, natural gas storage or injection of waste. In Poland, the underground space is used in a relatively small extent compared with other countries. The planned development of the various geological structures requires the determination of the purposes for which they can be most useful. Indication of the ways of the rock mass use for certain activities (geological or mining) should be an important element in deciding whether to grant a concession for its use or not. Due to the possibility of development of the rock mass in a various way, also a conflict of interest, first should be analyze the various possibilities of using the underground space and spend it on priority activities eg. from the point of view of national energy policy or national ecological policy [1].

Deciding on how to develop the rock mass is a process of selection of a number of variants (management methods). It boils down to indicate the best possible variant from the point of view of decision-maker, ie. variant with the highest preferences. Evaluation of uses tectonic structures in aquifer for carbon dioxide storage, natural gas storage or injection of waste can be classified as multi-criteria, hierarchical decision problems. Multi-criteria decision models taking into account the geological conditions as well as

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legal, environmental, spatial, social or political, allow to do a variant assessment of the potential use aquifers.

To solve this problem, the method of AHP – Analytic Hierarchy Process can be used. It allows to bring a complex decision problem to a finite set of several variants of decision-making, using data both quantitative and qualitative. This method has established the theoretical basis and the number of confirmed applications in practice [2–7]. AHP method takes into account the specificity of the psychological evaluation processes, which are especially relational and hierarchical. This method shows particularly useful in situations where there is a hierarchy of evaluation criteria associated with the hierarchy of objectives or expected benefits and most of the criteria is qualitative, and much of assessments is affected by the subjectivity of the evaluation (decision maker). In addition, indicates not only which alternative to choose among the available options, but also justifies her choice (why is the best) [7].

The aim of the article was to present the method of evaluating the potential of tectonic structures located in the aquifer and its validation examples. The work was divided into three parts. The first presents the characteristics of the aquifer (including the general parameters characterizing these structures). The second part of the article describes the method of AHP, based on which, in the final part of the work was carried out hierarchical analysis of the problem of decision-making choice of management structures.

2. CHARACTERISTICS OF THE METHOD OF THE ANALYTICAL HIERARCHISATION

The multi-criteria decision-making methods are the most widely used methods of decision support (MCDM – Multiple Criteria Decision Making). These methods are called multi-criterial, because very rarely made decision is based on a single, clear criterion. Often it is associated one hand with a lot of various factors affecting the decision on the other hand with the participation of many decision-makers having different objectives and value systems. Thus, in the decision-making process there is a need to consider many points of view and conditions.

Analytical hierarchical process over the past 10 years is one of the fastest growing and most popular in the world mathematical methods used to solve multi-criteria decision-making problems. This process combines the concepts of mathematics and psychology.

The AHP method was developed by Saaty [8–12]. The problem of decision-making in the AHP method is presented in the form of a tree. At the top of the hierarchy there is primary (main) objective at the lowest level – considered variants of the decision-making (Fig. 1). Intermediate levels (branches) are considered components of the problem (decision criteria) that affect the level of realization of the primary objective and selection of the best variant [2, 13].

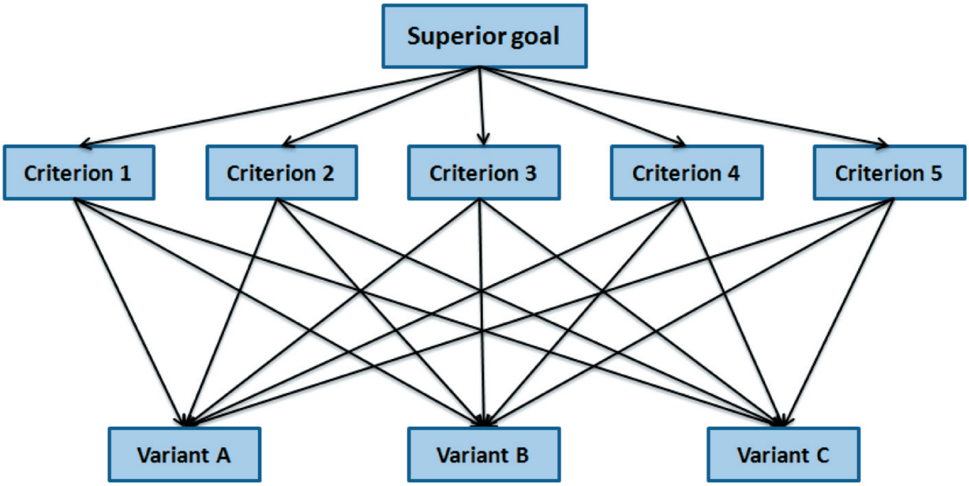

Fig. 1. Hierarchical tree showing the problem of decision-making in AHP method; own elaboration based on [13]

After construction a decision tree a hierarchical representation of the problem is developed. It is based on the generation of ratings of mutual comparison of the selection criteria (global preferences) and the options considered (local preferences). Evaluator (decision maker) makes a series of pairwise comparisons of items on each level of the hierarchical model, which are associated with the element located at a higher level. To determine the dominance nine-point scale is used with ratings from 1 (no dominance) to 9 (absolute dominance) – Saaty scale. This scale assigns individual degrees to natural numbers and verbal description. They express a subjective preference of the expert in relation to one member of the pair as compared with the second [2]. Using this scale, based on expert assessments are created matrixes ratings. Matrices are constructed for each criterion located at the level of the hierarchy directly above currently compared level. The result of the analysis is to determine the ranking of alternatives to the use of subjective evaluations obtained from the analysis of the problems of lower rank.

After comparing all pairs of objects, consistency of evaluations for each matrix comparisons should be checked. This is done on the basis of the maximum eigenvalue λ_{max} it finds the matrix comparisons by calculating the coefficient of cohesion *CR* This coefficient is the quotient of the index of conformity evaluations (*CI*) and random consistency index (*RI*) [14]. Random cohesion index is calculated from the generated random matrix of dimension $n \times n$. Sizes *RI* are estimated on the basis of 10,000 matrix. *RI* index was published for decision-making problems with the maximum number of objects not exceeding 15. When solving bigger problems can be use extrapolation of that index. The *CR* indicates the extent to which pairwise comparisons of the characteristics validity are incompatible with each other [4]. According Saaty value of CR for a 3×3 matrix must be less than or equal to 5%, for 4×4 matrices should be 8%, and for the larger matrix does not exceed 10% [12, 15]. Hence, can be assume that if the value of CR is less than 0.1 (10%) is the compatibility factor is acceptable, comparisons are consistent (compatible), and can be satisfied with the expert assessments [14]. Then it is assumed that the comparisons matrix is consistent.

3. THE DECISION CRITERIA FOR THE EVALUATION OF THE POSSIBILITIES OF USE OF GEOLOGICAL STRUCTURES IN AQUIFERS

The problem in choosing structures within aquifers for underground storage, like most of the decision-making problems, has the nature of multi-criteria. Requires analyzing its structure, define a set of decision alternatives, a set of criteria and decision-making issues.

One of the most important elements is to identify decision criteria, both the main and sub-criteria used in the considered decision problem. Final selection of criteria characterizing the aquifers, has been made taking into account the circumstances and their specifics. Among the criteria for structures in the aquifer layers identified 5 categories:

- environmental,
- socio-political,
- geological,
- technical,
- legal.

Under the first criterion next three sub-criteria were separated: location outside protected areas, the location outside the NATURA 2000 network and location outside Protection zones of waters intakes. These criteria have been combined into one sub-criterion called “location in relation to protected areas”.

In the socio-political criteria there are issues related to social awareness and acceptance. They constitute one sub-criterion called “acceptance and public awareness”.

Further building the architecture of the hierarchy tree in the geological criterion, distinguished ten sub-criteria:

- type of tectonic structure,
- sealing horizons, which is divided into two sub-criteria: “seal lithology” and “thickness of the seal structure”,

- faults,
- depth,
- the size of the pore space, which is divided into two sub-criteria: “the thickness of the pore space” and “the volume of pore space”,
- petrophysical properties, which are divided into two sub-criteria: “permeability” and “porosity”,
- the water mineralization,
- hydrodynamic conditions (water flow rate),
- the presence of mineral deposits,
- hydraulic contact with potable water.

In the technical criteria, were separated four sub-criteria: transport infrastructure, the existing infrastructure for pumping, the location near a large issuer or pipeline and use of the terrain.

In the last criterion – legal was separated one sub-criterion, compliance with local development plan called “compliance with the LDP”.

In total, 20 sub-criteria for the geological structures in the aquifers were received. These are quantitative criteria, such as the porosity, thickness of the seal or mineralization of water, as well as qualitative criteria:

- Extensive linguistic (for example, the criterion “location in relation to protected areas,” which are defined possibilities as follows: in the national parks, in landscape parks, in the protected landscape areas and lagging, in the NATURE 2000 network, outside the protection areas).
- “Zero – one” (for example, the criterion of “acceptance and public awareness,” in which a choice of options: yes/no).

The final element in the hierarchical decision-making structure are variants of the decision. Includes four variants of the exploitability of the geological structure of these are: storage of natural gas, carbon dioxide storage, waste storage and the structure is not suitable for use for any of these purposes.

4. METHODOLOGY FOR EVALUATING THE POSSIBILITIES OF USING OF GEOLOGICAL STRUCTURES IN AQUIFERS

Analysis of the decision problem using the AHP method to determine the possible use of tectonic structures in the aquifers for injection waste or underground storage is carried out in four phases [2, 16]:

1. Development of a hierarchical representation of the problem (indication of the principal aim, defining options and decision criteria).
2. To generate ratings of each other comparison of criteria and options considered, the result of these comparisons are matrices ratings.
3. Determination of global and local preferences that is weights to each criterion and variant in hierarchical model. Assess the compatibility matrices ratings resulting from paired comparison.
4. Classification of decision variants.

In the first stage was made the decomposition of the problem of decision-making and the goal of parent was set (selection of the best application for the selected geological structure of the aquifer). The main criteria and sub-criteria of structures evaluation were determined and four possible options for decision-making were defined.

In the next stage was determined the evaluation matrix for the criteria by comparison of individual elements in pairs. Assessment of the validity of items on each level of the tree was made by comparing pairs. Define the matrix, comparing the ratings criteria been established on the basis of expert authors of the article. Determining the validity of individual elements proceeded in accordance with the method of comparison criteria by determining the degree of dominance of one over the other.

For the geological criteria it was assumed their strong dominance over the other groups of criteria, with the exception of criteria – contact with drinking water where, depending on the considered criterion, there is a balance or dominance of the last one. In the group of geological criteria it was assumed strong dominance of the size of the structure and quality of the sealing horizon. This follows from the assumption that these properties are the prerequisites to qualify the structure for any development.

The second in importance the group criteria – in the opinion of the decision-maker – it is the environmental criteria, which may (in extreme cases) eliminate the possibility of structure development (location of the property in a protected area with large restrictions or shallowly occurring drinking water).

Other criteria are characterized by a lack of domination of the above-mentioned criteria groups. Factors such as social acceptance, planning conditions or technical conditions may change over time.

Weights for decision-making criteria according to the method AHP developed by Saaty [8], were determined by comparing them in pairs and finding the approximate eigenvector of the comparisons matrix. Weight vector criteria was calculated using the average values of the elements in each row of the normalized comparisons matrix.

As a result of the calculation for a matrix of comparisons obtained ranking of criteria for geological structures in aquifers (Fig. 2). It was found that the most important factors are the geological criteria. The least important criteria: "the existing logistics infrastructure", "the way of land use" and "existing infrastructure for pumping."

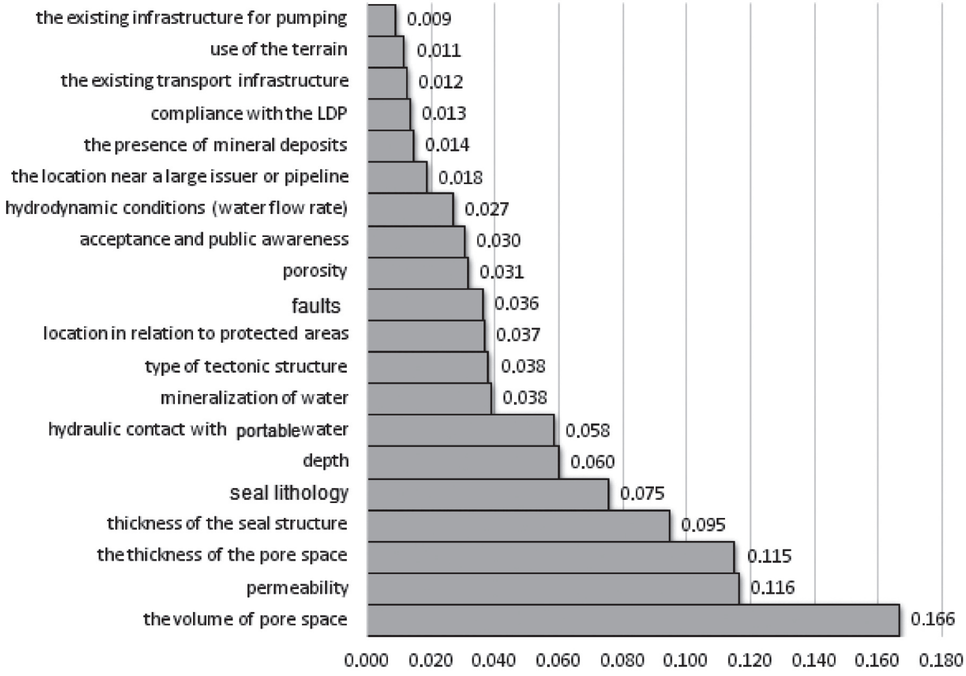

Fig. 2. Position of criteria in the hierarchy tree for structures in aquifers; based on [17]

Found weight vector, has been verified on the basis of the calculated for matrices comparisons cohesion factor (*CR*), in accordance with the method of AHP. Verifying the consistency of evaluations is made on the basis of the maximum eigenvalue (λ_{max}), obtained for the matrix comparisons by calculating the coefficient of cohesion *CR* [14]:

$$CR = \frac{CI}{RI} \cdot 100\%$$

where:

$CI = \frac{\lambda_{max} - n}{n-1}$ – index of compliance of evaluations, which is an indicator of consistency, which shows the lack of consistency of comparisons and a deviation from compliance [4];

n – the size of the comparisons matrix;

RI – random consistency index.

The maximum eigenvalue is calculated using the formula [14]:

$$\lambda_{max} = \sum_{i=1}^{n} \left(p_i \cdot \sum_{j=1}^{n} r_{ji} \right)$$

The coefficient *CR* determines the extent to which pairwise comparisons of characteristics validity are incompatible with each Rother [4]. If the value of *CR* is less than 0.1 (10%) coefficient of compliance is acceptable, comparisons are compatible and we can be satisfied with the expert evaluations [14]. It is assumed then, that the comparisons matrix is consistent. If the value of *CR* exceeds 10%, the evaluation should be reviewed and all or some of the comparisons repeated, in order to eliminate incompatibilities ratings [18].

For a matrix of criteria for structures in aquifers was calculated the approximate eigenvalue of matrix comparisons (λ_{max}), which equals 22.221 and the consistency ratio *CR* – 0.072 (which is equal to 7.2%). The calculated coefficient is smaller than the accepted threshold of 0.1. It can be stated that the presented expert evaluation in the comparisons matrix for decision-making criteria are consistent and the resulting weight vector can be used in further analysis of the decision.

The next step was the evaluation of individual decision variants due to the accepted criteria. In effect (based on the ratings of the matrix) were calculated the priorities representing the individual schedules of validity variants due to additional criteria. Matrix ratings for variants was determined also by comparison of individual elements in pairs. As a result, it was created 20 ratings matrix, and then was set for them vectors of usability. This stage was associated with parameters corresponding to all the criteria for a specific geological structure within the aquifer. Having calculated all the partial vectors usability of variants against the criteria, can be find a aggregated vector of variants usability, which lineup decision (ways of managing geological structures) in the ranking.

5. VALIDATION OF METHOD

Based on the presented methodology, were validated selected anticline structures located in aquifers in the Mesozoic formation within the Szczecin Basin (Huta Szklana) and the Mogilno-Lodz Basin (Tuszyn) (Fig. 3) [17]. Analyzed structures, lie in the area dominated by diapirs and salt pillows, which surrounds the central area of salt tectonics [19].

Anticline of Tuszyn is situated on the south-eastern outskirts of Tuszyn, about 17 km south-east of Pabianice, in the Łódź Basin This structure is asymmetric. The west wing is steeper from the east wing. Within the analyzed anticline are faults that limits the structure and cross rocks from the Zechstein down to the Lower Cretaceous (Fig. 3). Rocks identified as perspective to use for waste injection or storage are rocks at the age of Lower Cretaceous of Mogilno Formation lying at a depth from 737 to 966 m. The thickness of this formation ranges from 81 to 95 m in the top part of the anticline to 120.5 m in the east wing (Fig. 4). The porosity of these rocks is about 25%, and permeability from a few dozen times 10^{-9} to about $3.5 \cdot 10^{-6}$ m^2 (a few dozen – about 3500 mD). Sealing rocks are carbonated marls of Upper Cretaceous with a thickness from 602 to 935 m [19, 20].

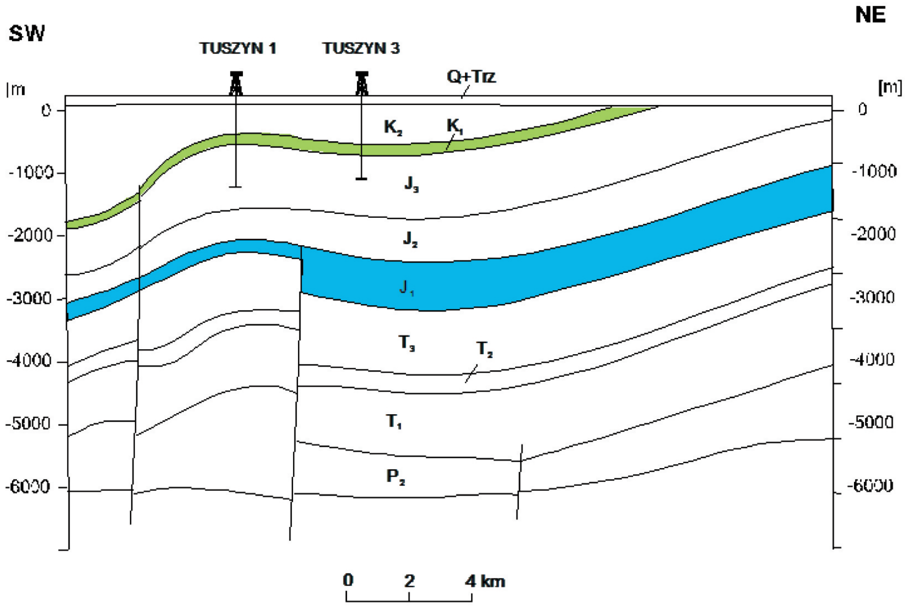

Fig. 3. Geological cross section through the Tuszyn Anticline [19]: P_2 – Upper Permian, T_1 – Lower Triassic, T_2 – Middle Triassic, T_3 – Upper Triassic, J_1 – Lower Jurassic, J_2 – Middle Jurassic, J_3 – Upper Jurassic, K_1 – Lower Cretaceous, K_2 – Upper Cretaceous

A	B	C	D	E	F	G	H	I	J	K

The computer system to assess the potential of geological structures using AHP hierarchical multi-criteria c

Considered geological structure:	**aquifer**
Name of geological structure:	**The Tuszyn Anticline**

The table of entered values for each criterion for consideration geological structure:

criterion	type of tectonic structure	seal lithology	thickness of the seal structure	faults	depth	the thickness of the pore space	the volume of pore space	porosity	permeability	mineralization of water
value	anticline	claystone, shale	55 m	single faults in the structure	737 m	95 m	72000000 m^3	25%	$3{,}5 \cdot 10^{-6}$ m^2 (3500 mD)	0,25 g/l

criterion	the presence of mineral deposits	compliance with the LDP	location in relation to protected areas	acceptance and public awareness	the existing transport infrastructure	the location near a large issuer or pipeline	the existing infrastructure for pumping	use of the terrain	hydraulic contact with portable water	hydrodynamic conditions (water flow rate)
value	no	no	outside the protected areas	yes	yes	10 - 20 km	no	forests, arable fields	yes	meter / hundreds of years

Fig. 4. The parameters used to analyze the possibilities of the development of the Tuszyn Anticline; based on [17]

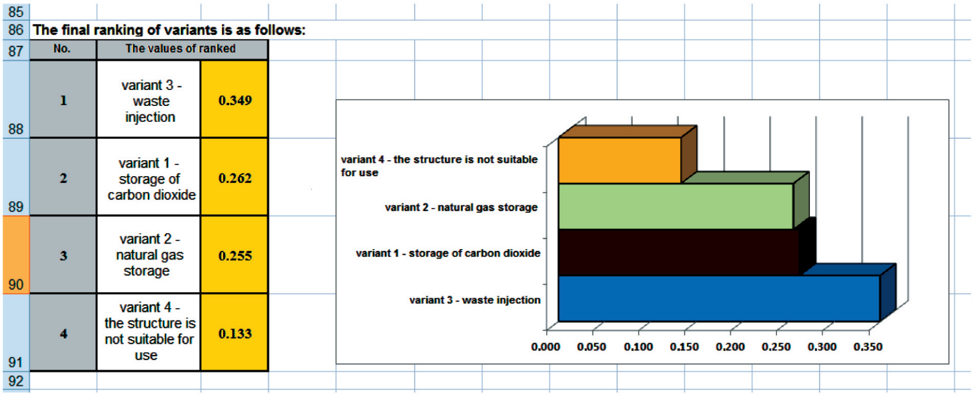

Fig. 5. The ranking of the possibilities of development of the Tuszyn Anticline; based on [17]

On the basis of the weight vector which is the result of the calculation made with AHP method (Fig. 5) can be stated that the choice of waste injection is the best possible way to use the Tuszyn anticline with definite advantage over the other (rank 0.349). The next two positions are: storage of carbon dioxide and natural gas storage, the difference between the ranks of these alternative solutions is relatively small. Option four – the structure is not suitable for use, obtained last place with the rank of 0.133. Proves that some criteria for this anticline received low ratings due to weaker parameters for variants storage, or waste injection.

The Huta Szklana Anticline is located about 7.5 km NE of the Krzyż. Geologically anticline lies in the Szczecin Basin. This is a elongated structure, and its south-west wing is limited by the fault, which cuts through the Zechstein and Triassic rocks (Fig. 6) with throw SW wing about 400 meters in the Triassic formations. Formations perspective and proposed for use as storage are sandstones of Połczyn Formation Middle Buntsandstein (Lower Triassic). These formation lies at a depth of 2491 to 2700 m, their thickness ranges from 112 to 116 m (average thickness of 114 m). Share of sandstones in this horizon is about 30%, their porosity about 10%, and permeability-dozens times $10^{-9} m^2$ (dozens mD) (Fig. 7). Rocks sealing Połczyn Formation are represented by clay--mudstone and carbonate-evaporite rocks of Buntsandstein of the Upper Ret and the Muschelkalk with a thickness of approximately 400 m [19, 21].

Calculated using the AHP method (Fig. 8) weight vector indicates the selection of carbon dioxide storage as the best possible way of the development the Huta Szklana Anticline (rank 0.310). The advantage over the second place – natural gas storage is very low (rank 0.303) – you can even consider both decisions itself as almost equivalent.

At the third place there is the underground waste injection, the difference between the ranks in relation to the first two places is still small. Option four – the structure is not suitable for use, obtained last place, with the rank of 0.090.

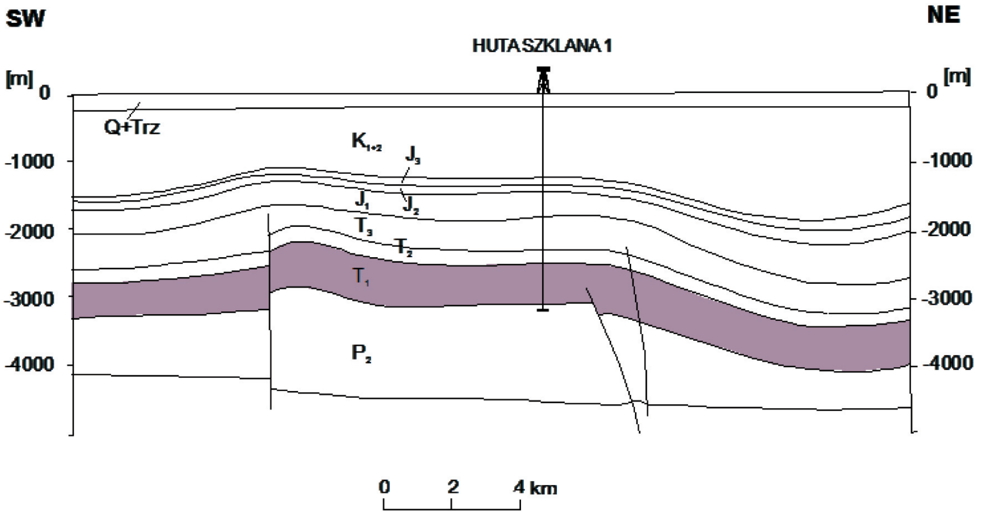

Fig. 6. Geological cross section through the Huta Szklana Anticline [19]: T_1 – Lower Triassic, T_2 – Middle Triassic, T_3 – Upper Triasic, J_1 – Lower Jurassic, J_2 – Middle Jurassic, J_3 – Upper Jurassic, K_1 – Lower Cretaceous, K_2 – Upper Cretaceous, P_2 – Upper Permian

A	B	C	D	E	F	G	H	I	J	K
The computer system to assess the potential of geological structures using AHP hierarchical multi-criteria d										
Considered geological structure:				**aquifer**						
Name of geological structure:				**The Huta Szklana Anticline**						
The table of entered values for each criterion for consideration geological structure:										
criterion	type of tectonic structure	seal lithology	thickness of the seal structure	faults	depth	the thickness of the pore space	the volume of pore space	porosity	permeability	mineralization of water
value	anticline	claystone, shale	1400 m	single faults in the structure	2400 m	114 m	342000000 m^3	10%	$60 \cdot 10^{-9} m^2$ (60 mD)	314 g/l
criterion	the presence of mineral deposits	compliance with the LDP	location in relation to protected areas	acceptance and public awareness	the existing transport infrastructure	the location near a large issuer or pipeline	the existing infrastructure for pumping	use of the terrain	hydraulic contact with portable water	hydrodynamic conditions (water flow rate)
value	no	no	within the network NATURA 2000	no	no	50 - 75 km	no	forests, arable fields	no	meter / thousands of years

Fig. 7. The parameters used to analyze the possibilities the development of the Huta Szklana Anticline; based on [17]

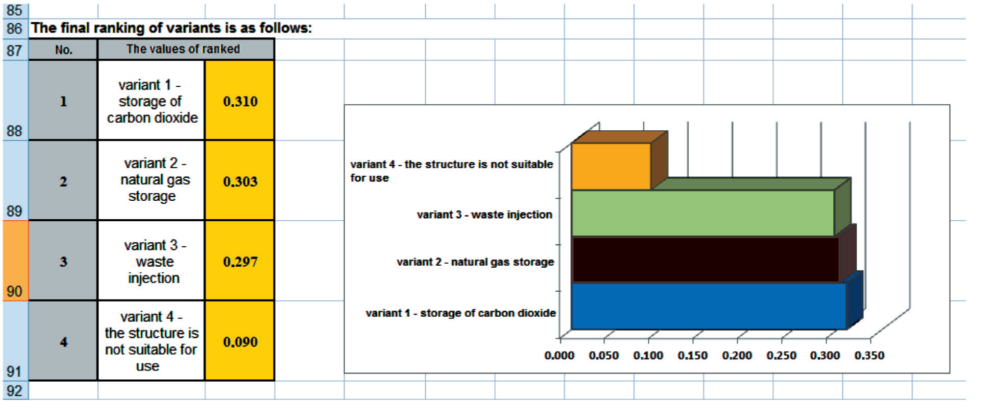

Fig. 8. The ranking of the possibilities of the development of the Huta Szklana Anticline; based on [17]

6. SUMMARY

It was proposed the evaluation of the potential of geological structures in aquifers, using advanced multi-criteria decision support methods (AHP). Allowing selection of the best way of management (use as underground storage or waste injection).

The methodology has been tested on the example of two anticline in the Mesozoic aquifers located in the Polish Lowlands. For these structures, the evaluation was conducted for four variants of decision-making (waste injection, carbon dioxide storage, natural gas storage and the structure is not suitable for use). Variants rated by the use of 5 groups of criteria taking into account aspects and conditions: geological, environmental, socio-political, legal and technical.

Usability of these variants was determined on the basis of the criterion functions for all variants of decision-making. Their usefulness has been studied by comparing pairs of criterion functions for the various options and to determine their degree of dominance in the nine-point Saaty scale. Based on the partial vectors of variants usefulness was found aggregated vector of variants usefulness (lineup decisions in the form of ranking).

The result of the analyzes it was found that for the Tuszyn Anticline the highest preference of the decision maker has the option 3 – underground waste injection, and can be regarded as the most satisfactory from the point of view of all decision-making criteria. Considering the rank obtained for places 1 to 3 can be considered that the Huta Szklana Anticline is suitable for use as a storage or waste injection. The highest preference of the decision maker has the variant 1 – carbon dioxide storage and can be regarded as the most satisfactory from the point of view of all decision-making criteria.

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