Comparison of Candidate Sites for installation of Landfill facility at Ignalina NPP Site Using Fuzzy Logic Approach – 8095

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ABSTRACT

There is only one nuclear power plant in Lithuania – Ignalina NPP (Nuclear Power Plant). Two similar units with installed capacity of 1500 MW (each) were commissioned in 1983 and 1987 respectively. But the first Unit of Ignalina NPP was finally shutdown December 31, 2004, and second Unit is planned to be shutdown before 2010.

Operational radioactive waste of different activities is generated at Ignalina NPP. After closure of INPP a waste from decommissioning should be managed also. According to Lithuanian regulatory requirements (1) the waste depending on the activity must be managed in different ways. In compliance with this Regulation very low-level radioactive waste (VLLW) could be disposed of in a Landfill facility. In such case very simple engineered barriers are required. A cap on the top of the repository is necessary from long-term safety point of view.

Experience has shown that the effective and safe isolation of waste depends on the performance of the overall disposal system, which is formed by three major components: the site, the disposal facility and the waste form. The basic objective of the siting process is to select a suitable site for disposal and demonstrate that this site has characteristics which provide adequate isolation of radionuclides from the biosphere for desired periods of time.

The methodology and results on evaluation and comparison of two candidate sites intended for construction of Landfill facility at Ignalina NPP site are presented in the paper. Criteria for comparison are based on the IAEA (International Atomic Energy Agency) recommendations (2). Modeling of the radionuclide releases has been performed using ISAM (Improving of Safety Assessment Methodologies for Near Surface Disposal facilities) methodology (3). For generalization of the information and elaboration of the recommendations Fuzzy Logic approach was used (4).

INTRODUCTION

After survey stage of EGG (Engineering-Geological Geotechnical) investigations two alternative sites respectively called as north and south (Fig. 1) have been proposed as potential for Landfill installation (5). The data concerning environmental conditions of the sites have been collected following IAEA guidelines on siting of near surface disposal facilities (2).
The evaluation of site characteristics (or degree of compliance with the site selection criteria) has been presented as expert judgments (qualitative estimations) in terms of linguistic expressions like good, fair or poor.
The potential radiological impact on environment (human exposure) has been also assessed in case of repository installation in the north site as well as in the south site.

While preliminary estimations of the radiological impact could be attributed to the strictly deterministic (or well quantified) factor that should be used in the comparison procedure of the candidate sites the site characteristics obtained from the survey stage should be referred to kind of information that is not numeric. It is classified as data containing so-called epistemic uncertainties i.e. the uncertainties generated by factors such as lack of data or lack of understanding of relevant processes, high complexity of the system etc. Therefore, to be able to use qualitatively expressed information for purposes of site comparison the Fuzzy Logic technique has been applied. Fuzzy Logic deals with epistemic uncertainties in a proper way and gives to analysts the tool of mathematical representation (in numeric form) of available qualitative data.

The survey of literature demonstrates that such methods have been already used in the site selection process of the radioactive waste repositories. The hierarchy process method was used to siting of geological repository for high-level radioactive waste (6). An application of Fuzzy sets to the safety analysis of radioactive waste disposal facilities is studied in (7)-(9).

The data obtained during EGG investigations in the form of list of site selection criteria, the application of the Fuzzy Logic to representation of the expert judgments through the Fuzzy sets, the derivation of the membership functions as well as weighting factors and calculation of suitability indexes for both candidate sites are provided in the paper. Moreover the methodology and the results of the preliminary estimations of the radiological impact with regard to environmental peculiarities of candidate sites are briefly presented in this work. The results of the assessment of potential radionuclide transport are also included into Fuzzy sets.

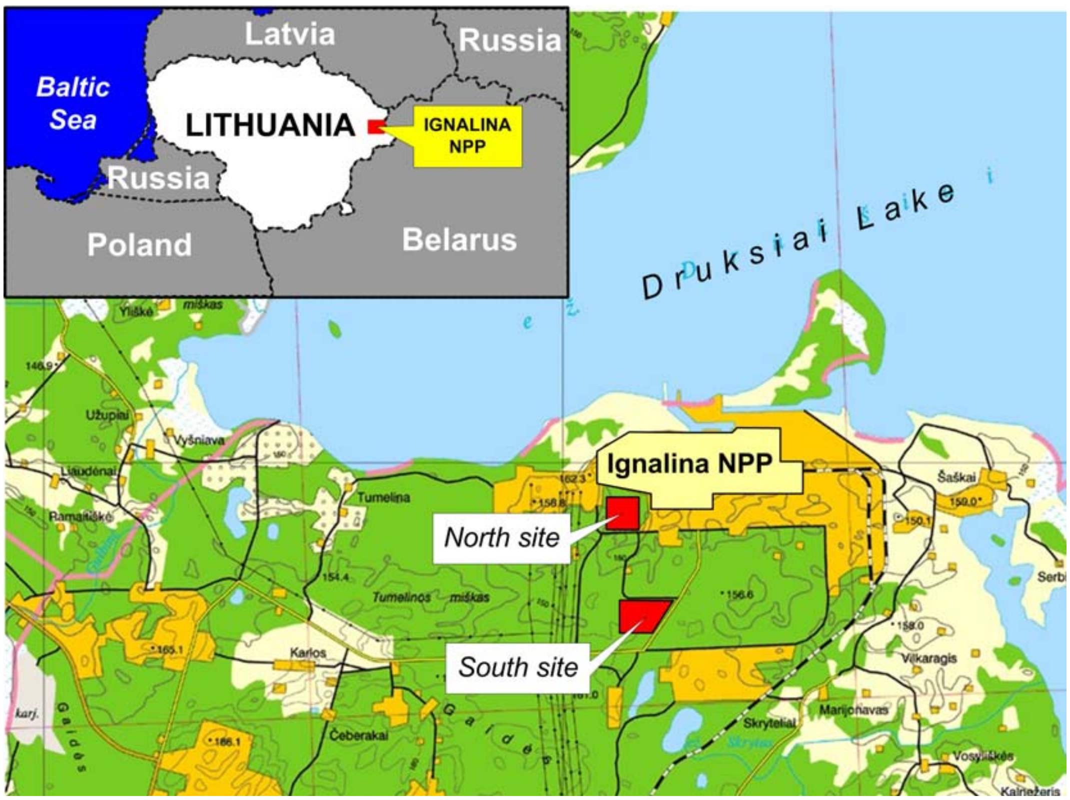

Fig. 1. Surroundings of Ignalina NPP. Two candidate sites proposed for construction of the Landfill facility

SITE SELECTION CRITERIA

The information obtained during survey stage of EGG investigations is presented in the form of the site selection criteria following general guidelines for the assessment of the typical site characteristics recommended by IAEA for near surface facilities intended to contain low and intermediate level wastes (2). Such guidelines for Landfill type repositories intended for disposal of VLLW are not available at the moment. The evaluation of the site compliance with the specific criterion has been carried out in terms of expert opinion (expert judgment). When using Fuzzy Logic approach subjective expert judgments expressed in the linguistic form are described as fuzzy sets and mathematically are represented by a membership functions that give values from real unit interval [0, 1] for each criterion under consideration. The membership function is interpreted as respective degree of truth or degree of compatibility. After processing of available data the list of the site selection criteria with respective expert judgment for some items is provided in Tables I. Three levels of ranking of site compliance with specific criterion are used: ‘High’ (H), ‘Medium’ (M) or ‘Low’ (L).

Table I. Example of the summary of the assessment of environmental conditions for alternative sites

Site selection criteria group/criterion	Criteria ID	Expert judgment	
		North site	South site
1. Geology			
1.1. Engineering geology conditions	C1	M	M
1.2. Geomorphology	C2	M	M
1.3. Geotechnical conditions	C3	H	H
2. Hydrology			
2.1. Shallow groundwater	C4	M	M
2.2. Groundwater	C5	M	H
2.3. Basic points of discharge	C6	M	M
2.4. Direction of water pathway, velocity of groundwater flow	C7	M	H
2.5. Surface water bodies	C8	M	H
2.6. Feeding of groundwater	C9	H	H
3. Hydro geochemistry			
3.1. Sorption/solubility of radionuclides	C10	M	M
3.2. pH of the groundwater	C11	H	M
3.3. Natural colloids and organic materials	C12	M	M
3.4. Corrosiveness of groundwater towards the concrete	C13	H	L
. . . .			
. . . .			
. . . .			
10. Population distribution			
10.1. Population distribution	C29	H	H
11. Protection of environment			
11.1. Areas of significant public values	C30	H	H
11.2. Public water supplies	C31	H	H

MODELING OF RADIONUCLIDE RELEASES

Further more the list of the site selection criteria has been expanded by adding estimations obtained from the assessment of the potential radionuclide migration for both candidate sites. The assessment of the potential radionuclide migration was carried out using consistent safety assessment ISAM methodology (7) that consists of key components as following:

1. The specification of the assessment context;
2. The description of the disposal system;
3. The development and justification of scenarios;
4. The formulation and implementation of models;
5. The calculations and analysis of the results.

Assessment context

The purpose of the analysis is to assess the impact of potential radionuclide migration out the Landfill facility to the environment by groundwater pathway with respect to the characteristics of the wastes, conceptual design of the facility as well as geological and hydrological peculiarities of the candidate sites.

Disposal system description

Approximately 60 000 m^3 of VLLW (10) from operation and decommissioning of Ignalina NPP are planned to dispose of in the Landfill facility. The Landfill will be installed on the ground surface. Only very simple engineering barriers will be equipped and few meters of top protective layer will be in addition.

Very low level waste intended to dispose off in the Landfill repository will be placed into ISO containers as well as bales (the waste is compacted and wrapped into plastic). The containers will be stacked in few levels and the dome-shaped surface of the repository will be formed. The positioning of the containers and the conceptual design of the repository is showed schematically in Fig. 2.

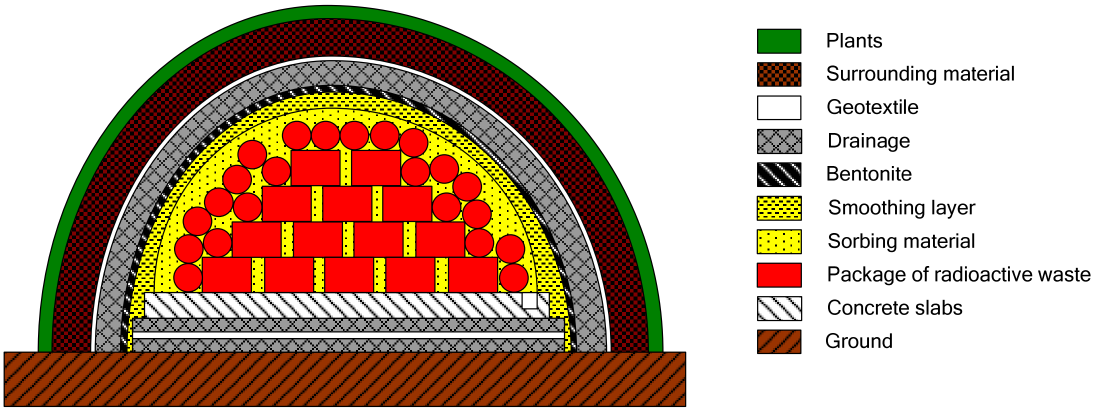

Fig. 2. Conceptual design of the Landfill facility

Based on survey of the available information on characteristics of radioactive waste for Ignalina NPP 33 radionuclides are included into analysis: H-3, C-14, Cl-36, Mn-54, Fe-55, Co-58, Fe-59, Co-60, Ni-59, Ni-63, Zn-65, Sr-90, Zr-93, Nb-93m, Nb-94, Tc-99, Ag-110m, I-129, Cs-134, Cs-135, Cs-137, Ra-226, U-234, U-235, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Pu-242, Cm-244.

The generalized values of parameters of geosphere components for north and south site are provided in the Table II.

Table II. Parameters of geosphere components of candidate sites (5)

Site	Geosphere component	Prevailing ground type	Thickness, m	Bulk density, kg/m^3	Effective porosity	Hydraulic conductivity, m/s
North	Vadose zone	Clay	2	1 680	0.06	5.8×10^{-9}
		Clay	2	1 970	0.05	4.6×10^{-9}
	Aquifer	Sand	14	1 680	0.32	1.1×10^{-4}
South	Vadose zone	Sand	2	1 480	0.30	1.1×10^{-5}
		Clay	2	1 920	0.05	8.1×10^{-8}
		Sand	2	1 690	0.30	1.1×10^{-5}
	Aquifer	Sand	17	1 640	0.30	5.8×10^{-5}

For the estimation of the radionuclide activities in the groundwater the analysis points are set in flow direction at the distance 100 m (well at boundary of the sanitary protection zone) from the facility edge, at the distance approx. 900 m from north site (discharge point of the aquifer to the lake) and approx. 2 000 m from south site (discharge point to the lake). Corresponding exposure doses for members of critical group consuming water from the well or lake should be evaluated.

As the real radionuclide inventory in the Landfill repository is not yet specified, in order to be able to estimate volumetric activity concentrations in most remote points of the disposal system (at the locations distant to approx. 2 000 m from the Landfill) the initial activity has been set to one terabecquerel (10^{12} Bq) for each radionuclide under consideration.

Scenario

Following the ISAM methodology (3), the formal procedure could be applied for scenarios development. According to the procedure the disposal system is split into components, then possible states of each component are defined and finally scenarios are developed after evaluation of potential states and relationships between components.

Two types of scenarios are presented in the IAEA document (3). First one is for operational period of the facility, second – for post closure period. For the evaluation of the sites from two lists of scenarios have been selected only scenarios concerning geosphere components (unsaturated zone, aquifer) of disposal system that are different for each candidate site.

It is assumed that the scenarios such as direct irradiation, flooding or "bathtubing" relevant to operational period of the facility should occur in the same circumstances for alternative sites or should not be possible at all due to geological and hydrogeological characteristics of the sites taking into account conceptual design of the Landfill.
It is assumed that scenarios of inadvertent intrusion supposed after closure of the facility should also occur in the same circumstances for both sites. Thus the leaching scenario concerning geosphere components (unsaturated zone, aquifer) of disposal system that are different for each candidate site has been selected for radiological assessment. Supposing that the repository design, states of engineered barriers as well as radioactive inventory content and radionuclide transport through the engineered barriers occurs identically for both sites within analyzed period it is assumed that the leaching scenario occurs under the same conditions for both sites.

Conceptual models

Water is penetrating through the engineered barriers of the Landfill facility due to infiltration of precipitation. The leached radionuclides from the wastes out of the bottom of facility are transported to the geosphere (unsaturated zone and aquifer) by diffusion-advection. Further migration of the radionuclides in the aquifer is governed by advection-dispersion mechanisms. The releases of radionuclides to the well or lake should result in the exposure doses to the local people.
For modeling of radionuclide migration the assumptions have been accepted as follows:

1. The protection of engineered barriers against infiltration of precipitation is not taken into account at all. Therefore it is estimated that the infiltration rate through the repository conservatively equals to the difference between precipitation and evapotranspiration.
2. The pores in the waste packages as well as in the backfill are totally saturated by water just after closure of the Landfill facility.
3. Radionuclides are homogeneously distributed in the repository.
4. Dissolution rate of radionuclides is not taken into account. Under conservative assumption the radionuclides dissolve in the pore water immediately (i.e. instant release of the radionuclides into the pore water is assumed).
5. The chemical retention of radionuclides due to sorption is considered for engineered barriers as well as for components of geosphere.
6. The radionuclide concentration in water and sorbing material is in equilibrium.
7. The coefficients of moisture content, diffusion, hydrodynamic dispersion and sorption are constant.
8. Characteristics of geology and hydrogeology remain stable within analyzed period of time.
9. The well is installed at the distance of 100 m (boundary of sanitary protected zone).
10. Discharge point of the aquifer is located at the lake distant approx. 900 m from the north site and approx. 2 000 m from the south site.
11. The local farmer cultivating garden plot is assumed as the member of critical group that consumes the water from the well or lake for everyday needs.
12. The pathways of external exposure resulted from contaminated soil after its irrigation as well as pathways of internal exposure resulted from breathing of dust resuspended from contaminated soil, from the consumption of meat and milk obtained from the cattle watered by contaminated water and from the consumption of vegetables irrigated by contaminated water were taken into account for the estimation of annual dose due to consumption of contaminated water. The consumption of fish cached in the lake is also considered.

Calculations and Results

One-dimensional radionuclide transport analysis was performed for the Landfill facility, vadose zone and aquifer using the DUST-MS computer code (11). The radionuclide migration in biosphere and exposure doses to members of critical group has been assessed using the AMBER software tool (12).
After modeling of radionuclide migration through the disposal system it was revealed that:

1. In case of the consumption of the water taken from the well estimated dose values for most radionuclides are almost the same for both candidate sites with exception for H-3 and C-14. Contribution of tritium to the total

dose is factor of 10 higher for south site in comparison to north site. The impact of carbon is higher by factor 20 for north site in comparison to south site.

2. In case of the consumption of the water taken from the lake it can be observed that the Landfill repository in north site causes higher maximum dose value than in case of the repository constructed in south site for each radionuclide under consideration.

The expert judgment concerning compliance of the radionuclide migration modeling results to the site suitability for the Landfill construction has been estimated as ‘Medium’ in case of the north site and ‘High’ in case of the south site. The list of site selection criteria was expanded by adding criteria with ID code C32 with corresponding expert judgments for each candidate site.

FUZZY SETS

According to the definition of the Fuzzy set it is the representation (occasionally called the map) of the set of available elements (x_i) onto membership values (μ_{Ci}) in the range [0, 1]. In this preliminary study a simple triangle member function (Eq. 1), has been applied to map expert judgments onto Fuzzy set for criteria C_i:

$$\mu_{Ci}(x_{left}, x_{central}, x_{right}, x_i) = \begin{cases} 0, x_i < x_{left} \\ \dfrac{x_i - x_{left}}{x_{central} - x_{left}}, x_{left} \le x_i \le x_{central} \\ \dfrac{x_{right} - x_i}{x_{right} - x_{central}}, x_{central} \le x_i < x_{right} \\ 0, x_i > x_{right} \end{cases} \qquad \text{(Eq.1)}$$

Triangle member functions for three available cases of the expert opinion are represented in Fig. 3.

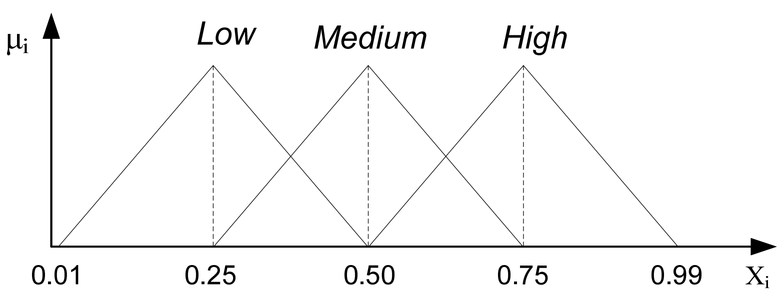

Fig. 3. Triangle member functions used for mapping of the expert judgments onto Fuzzy sets

Because ‘Low’ and ‘High’ judgments are strictly separated, therefore Fuzzy sets do not overlap. However the ‘Medium’ judgment is between ‘Low’ and ‘High’ and the difference between ‘Medium’ and ‘Low’ or ‘Medium’ and ‘High’ can be rather vague. So overlapping of the corresponding Fuzzy sets is allowed. Due to the left point (μ_{left}) of the Fuzzy set for ‘Low’ judgment should result in the final solution its value has been selected slightly above 0. For the sake of symmetry the value of the right point (μ_{right}) of the Fuzzy set for ‘High’ judgment has been selected slightly below 1. As one can see from the picture the equal intervals (in length of 0.5) from the range [0, 1] are assigned for each expert judgment.

An example of the summary of the Fuzzy sets derived from expert judgments to each site selection criteria is presented in Table III for both candidate sites.

Table III. Example of the Fuzzy sets derived to the site selection criteria (C1-C31) and to the results obtained from the assessment of the potential radionuclide migration (C32)

Criteria ID	**Fuzzy set**	
	North site (μ_{Ci})	**South site (μ_{Ci})**
C1	M=(0.25, 0.5, 0.75)	M=(0.25, 0.5, 0.75)
C2	M=(0.25, 0.5, 0.75)	M=(0.25, 0.5, 0.75)
C3	H=(0.5, 0.75, 0.99)	H=(0.5, 0.75, 0.99)
C4	M=(0.25, 0.5, 0.75)	M=(0.25, 0.5, 0.75)
C5	M=(0.25, 0.5, 0.75)	H=(0.5, 0.75, 0.99)
C6	M=(0.25, 0.5, 0.75)	M=(0.25, 0.5, 0.75)
C7	M=(0.25, 0.5, 0.75)	H=(0.5, 0.75, 0.99)
C8	M=(0.25, 0.5, 0.75)	H=(0.5, 0.75, 0.99)
C9	H=(0.5, 0.75, 0.99)	H=(0.5, 0.75, 0.99)
C10	M=(0.25, 0.5, 0.75)	M=(0.25, 0.5, 0.75)
C11	H=(0.5, 0.75, 0.99)	M=(0.25, 0.5, 0.75)
C12	M=(0.25, 0.5, 0.75)	M=(0.25, 0.5, 0.75)
C13	H=(0.5, 0.75, 0.99)	L=(0.01, 0.25, 0.5)
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C29	H=(0.5, 0.75, 0.99)	H=(0.5, 0.75, 0.99)
C30	H=(0.5, 0.75, 0.99)	H=(0.5, 0.75, 0.99)
C31	H=(0.5, 0.75, 0.99)	H=(0.5, 0.75, 0.99)
C32	M=(0.25, 0.5, 0.75)	H=(0.5, 0.75, 0.99)

WEIGHTING FACTORS

The importance of each criterion has been evaluated deriving the weighting factors from the expert judgments in terms of specific criterion contribution to the problem. Five levels of ranking of the criterion importance are used: ‘Very High’ (VH), ‘High’ (H), ‘Medium’ (M), ‘Low’ (L) and, ‘Very Low’ (VL). Triangle member functions, Fig. 4, are also used when converting subjective expert opinion to the Fuzzy sets.

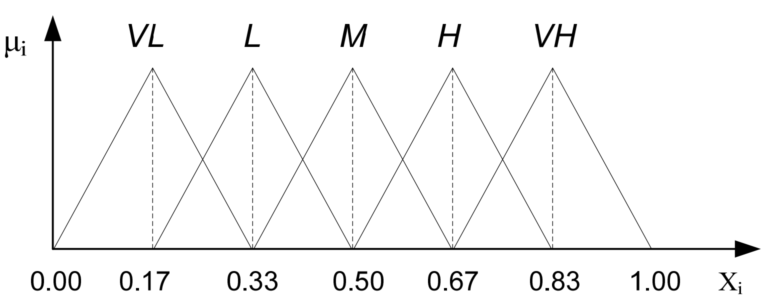

Fig. 4. Triangle member functions used for mapping of the expert judgments onto Fuzzy sets when deriving weighting factors

The judgments of some experts regarding the importance of each criterion have been used. Therefore the weighting factor for specific criterion is derived as the average obtained by summing respective values of the x_{left}, $x_{central}$, x_{right} from Fuzzy sets of each expert and then dividing the sum by *n* (number of the experts):

$$W_{Ci}(w_{i,left}, w_{i,central}, w_{i,right}) = (\sum_{j=1}^{n} x_{j,left})/n, \sum_{j=1}^{n} x_{j,centralt})/n, \sum_{j=1}^{n} x_{j,lright})/n) \quad \text{(Eq.2)}$$

An example of the summary of the derived weighting factors is presented in Table IV.

Table IV. Example of the summary of the weighting factors derived on the basis of expert judgments

Criteria ID	**Weighting factor (W_{Ci})**
C1	(0.67, 0.83, 1)
C2	(0.46, 0.63, 0.79)
C3	(0.63,0.79,0.96)
C4	(0.5, 0.67, 0.83)
C5	(0.63,0.79,0.96)
C6	(0.37,0.54,0.71)
C7	(0.54,0.71,0.87)
C8	(0.37,0.54,0.71)
C9	(0.33, 0.5, 0.67)
C10	(0.63,0.79,0.96)
C11	(0.17, 0.33, 0.5)
. . . .	
C13	(0.21,0.37,0.54)
C29	(0.37,0.54,0.71)
C30	(0.04,0.21,0.37)
C31	(0.46, 0.63, 0.79)
C32	(0.67, 0.83, 1)

SUITABILITY INDICES

Finally on basis of Fuzzy sets and weighting factors the summarized values are calculated that give site suitability indices that are compared in conventional way. The suitability index of the site is obtained by averaging sum of the products of Fuzzy set of specific criterion by corresponding weighting factor of the criterion over all the criteria:

$$F_{site} = (1/N) \times \sum_{i=1}^{N} (\mu_{Ci} \times W_{Ci}) \qquad \text{(Eq.3)}$$

where

N stands for the total number of criteria;
μ_{Ci} is Fuzzy set of the specific criterion;
W_{Ci} is weighting factor of the specific criterion.

The respective suitability indices for the north and south site are estimated as follows:

F_{north} = 1.01;
F_{south} = 1.08.

CONCLUSIONS

Comparison of candidate sites for installation of Landfill facility at Ignalina NPP site using Fuzzy Logic approach is presented in the paper. The list of site selection criteria has been generated on basis of IAEA recommendations on sitting for near surface disposal facilities. Also a criterion on the potential radionuclide migration for candidate sites has been evaluated.

A set of selected criteria have been assessed by application of the Fuzzy Logic techniques. The preliminary estimation of site suitability indices revealed that more favorable conditions for the installation of the Landfill facility are available at the South site.

The merits of the Fuzzy Logic approach as the regarding both qualitative and quantitative parameters, the inclusion of external knowledge (expert judgment) and the relatively simple calculations have assisted in the application of the tool for this specific task. The fuzzy logic-based approach is recognized as a complementary method to deterministic physically-based modeling. However, there always will be a subjective component to defining member functions as well as weightings of the attributes under consideration. This may be improved by ensuring the active involvement of stakeholder groups in contributing to decisions by improving their input towards setting these values.

In the future it is intended to keep on further investigations regarding the choice and the application of the more complicated member functions in the field of the site selection as well as the comparison with the results obtained using other approaches, e.g. AHP (Analytical Hierarchy Process) (13), etc.

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