RADIOACTIVE WASTE DISPOSAL SITE SELECTION [1, 2]

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Summary*: The present paper treats the application of the approach and methods of system analysis and Analytical Hierarchical Process (AHP) for the solution of a typical problem of the decision-making theory – the site selection problem. The specific features of site selection for highly radioactive waste repository is the high degree of uncertainty, as well as the high responsibility of the choice itself – "responsibility for the future generations". The hierarchical structuring, the multi-model approach and the adequacy analysis overcome the uncertainty. A procedure has been developed including a set of AHP models - relative and ranking ones, applied to a different degree of detail and to different elements of the decision-making process. The analysis is performed and a choice is realized in a set of 30 potential sites according to 28 criteria distributed in 5 groups, the sites being evaluated using the criteria and 5 typical non-linear scales of preference.*

1. Introduction

The problem of site selection for the construction of a permanent repository for highly radioactive waste disposal is one of the basic elements of the system for radioactive waste management. This is a typical **decision-making problem** – the available data are given namely a set of variants (sites), a set of criteria and experts, as well as the goal – ranking and selection of prospective sites. The problem contains some uncertainty that could be regarded as objective and subjective one (Vachev, 1987). For example, while most of the criteria are characterized by subjective uncertainty, the processes of the climatic, tectonic and seismotectonic development are described by objective uncertainty.

For this reason, the definition and diminution of uncertainty is the main concern when solving similar types of problems. The following approach and tools are applied for their solution:

- **hierarchical structuring** (special type of structure of the sets of criteria and sites);
- **adequacy analysis** (including the sensitivity analysis, adequate system for obtaining and assessing the statistical and experimental data and expert considerations, scenario analysis, etc.);
- **multi-model approach** (use of different types of decision-making models and comparative analysis of their results).

A number of approaches and methods exist for the solution of similar decision-making problems, one of the most suitable and efficient being the Analytical Hierarchical Process (AHP), developed in the end of the eighties by Prof. Thomas L. Saaty (Saaty, 1990). This approach has already been used for the

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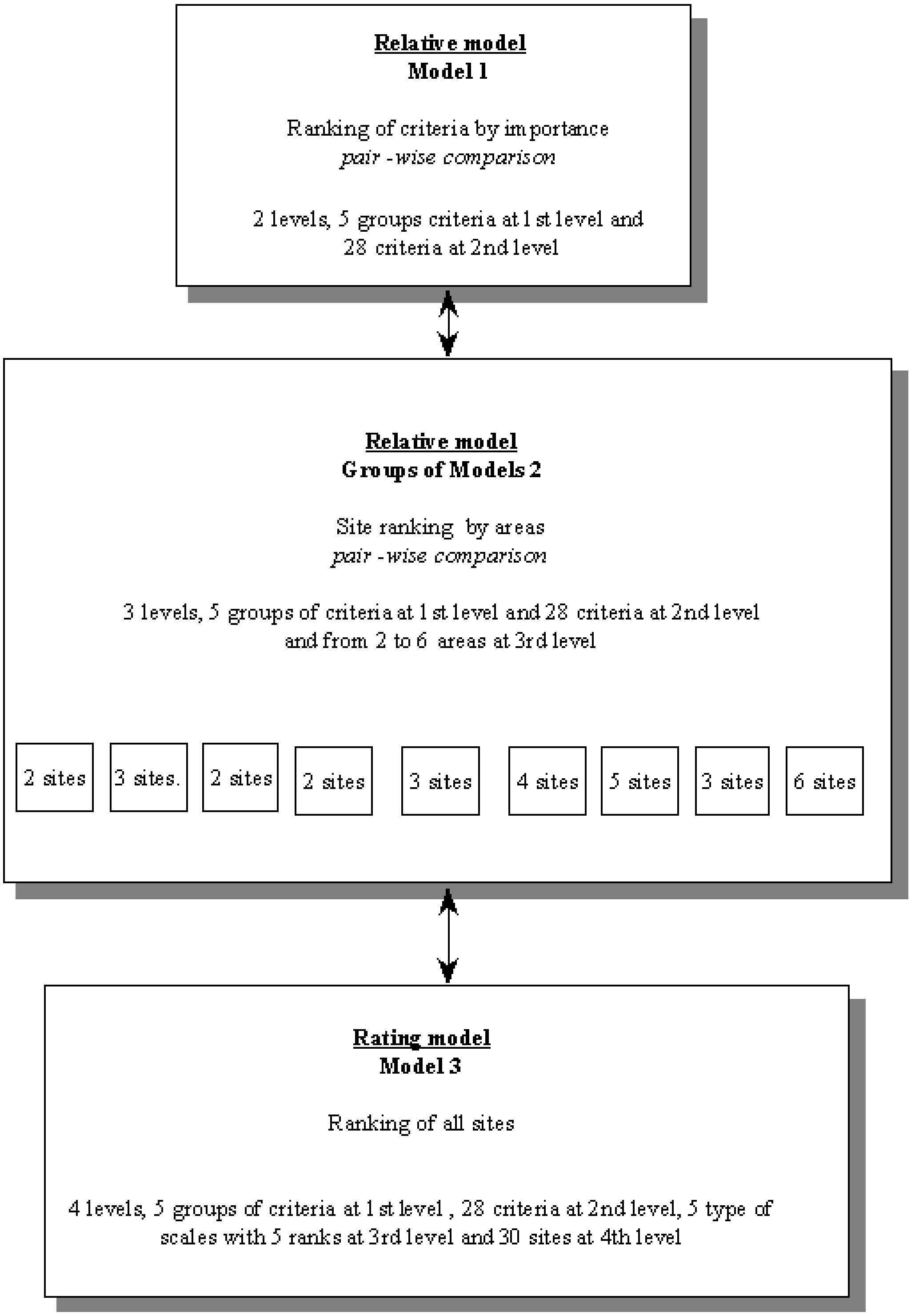
development of the Concept of the Bulgarian Academy of Sciences (BAS) for a National Radioactive Waste Repository (Vachev et al., 1983; Vachev, 1987; Vachev and Evstatiev, 1994) and has been approved by the PHARE Project (Radioactive Waste Management in Bulgaria, 1997) and in (Kozhoukharov et al., 2000).

Figure 1. Block – scheme of common procedure for ranking of potential sites for high radioactive waste disposal



2. Model for Site System Analysis and Assessment

2.1. Structure and Characteristics of the Model

The model for system analysis and assessment of sites is developed on the basis of the assumed hierarchical structure of the criteria for assessment and selection, the set of sites, the site selection process (the stage of regional investigations) and the AHP approach and the Expert Choice 8.0, 9.5 software product.

The model includes 5 levels:

- level 0 contains the top – the goal of the model – "Analysis, assessment and selection of sites for the construction of a National Repository for Radioactive Waste Disposal"
- level 1 contains 5 groups of criteria
- level 2 contains 28 independent criteria
- level 3 consists of the assessment scales for each criterion and their ratings
- level 4 includes a set for selection, consisting of 30 sites, classified in 9 areas

Both relative and rating models are used (see Figure 1), the use of the latter being imposed by the great number of variants for selection and not by the usual practice of absolute assessment of site variants according to the corresponding scales.

2.2. Procedure for Analysis, Assessment and Selection of Sites at the Current Stage of the Selection Process

The procedure includes the following main stages (the realised main stages are shown schematically in Figure 1):

E1. Development of a rating model (based on absolute site comparison):

E1.1. Measurement of importance by means of binary comparisons of:

a) the groups of criteria

b) the criteria in each group

E1.2. Creation of absolute scales with rating of intensities;

E1.3. Assessment of the sites according to each criterion (in a rating table), using the created absolute scales.

E2. Ranking and analysis of site ranking.

E3. Development (preceding the rating model) of a group of relative models for arranging the sites within the framework of each area, using comparison in pairs.

E4. Development of a relative model (for the first group of most prospective ranked sites).

E5. Sensitivity analysis.

E6. Comparative analysis

E7. Adequacy analysis

E8. Analysis of results.

3. Ranking of the Potential Sites

3.1. Assessment of the Importance of the Groups of Criteria and of the Criteria - Model 1

The mutual importance of the groups of criteria and of the single criteria in each group is evaluated using relative comparisons in pairs (binary assessment of preference) (see Figure 1) among the set of criteria (see Table .1).

The assessments are made using a verbal scale of preference (with degrees respectively 1,3,5,7,9 and their intermediate 2,4,6,8). Questionnaires generated by the Expert Choice software product have been used.

Table 1. Site selection criteria set structure

E	**Host formation geological conditions safety**
E1	Geological structure
E2	Litological type and mineralogical content
E3	Geo - chemical properties
E4	Physical properties
E5	Hydro - geological conditions
F	**Environment stability**
F1	Climate development
F2	Tectonic development
F3	Neo - tectonic activity
F4	Regional stress field
F5	Volcanism and diapirism
F6	Floods hazard
G	**Engineering reliability**
G1	Mining and geo technical conditions
G2	Seismic conditions
G3	Topographical conditions
G4	Exogeodynamic processes
G5	Drilling and mining
G6	Hazard of technogenic origin
G7	Construction and operating expenses
H	**Environmental impact**
H1	Water and mineral resources
H2	Land use
H3	Radioactive wastes transportation
H4	National heritage
H5	Flora and fauna impact
H6	Population radiological impact
I	**Socio-economic permissibility and acceptability**
I1	Population and settlement density
I2	Nuclear experience and compensations for citizens
I3	Communication infrastructure
I4	Adverse effect on other economical activities
I5	Proximity to country borders

The assessments of this model and of the rest models are made by a group of leading experts.[3] The procedure for lowering the inconsistency index values has been applied. A distributive mode is used for the synthesis. The sorted according to their importance results are shown in Figure 2.

The more significant conclusions from assessing the importance of the groups of criteria and of the single criteria for each group are as follows:

- the highest coefficient of importance belongs to the group of criteria H “Environmental impact”, that corresponds to the international practice;
- the next important group of criteria is E “Host formation geological conditions safety”. The influence of the natural barriers against radionuclide migration is taken under consideration in this way;
- the most important of the single criteria is the criterion H6 “Population radiological impact”.

[3] Group of experts from the Geological Institute of the Bulgarian Academy of Sciences: Dimitar Kozhoukharov, Dimcho Evstatiev, Doncho Karastanev and Krastyo Todorov

3.2. Assessment and Ranking of Sites for each Area separately by Comparison in Pairs – Group of Models 2

Model 1 has been applied for ranking of the prospective sites for each area separately (see Figure 1).
The main idea of using a relative model for the single sites is the maximal involving of expert competence and knowledge for a given territory. The obtained result is much more precise than that obtained using the site comparison according to absolute scales because of the substantial uncertainty of some of the criteria. The only disadvantage of this approach is that local optima are obtained for each single area, so excluding the possibility of regarding them as most prospective sites. The results for this group of models are used later during the third stage of analysis and assessment to precise the obtained ranking of the rating model, applied for all the 30 sites simultaneously.

The results of the 9 models run (consisting of 3 levels and containing: 5 groups of criteria, 28 criteria grouped in sets of 5,6,6,6,5 and comparing respectively 2, 3, 2, 2, 3, 4, 5, 3, 6 sites) are presented in Table 2.

Table 2. Sites ranking for every area

					%TOT	%MAX	
N	Site N	Site N	Area name	Site name	Rank 1	Rank 2	1st
1	1	010S	Severozapadna Bulgaria	Deleina	0,562	100%	010S
2	4	040S	Severozapadna Bulgaria	Dalgodeltzi	0,438	78%	
3	8	080S	Dolnocredni tereni	Sumer	0,413	100%	080S
4	9	090S	Dolnocredni tereni	Varbitza	0,305	74%	
5	15	150S	Dolnocredni tereni	Zlatar	0,282	68%	
6	13	130S	Belene	Oresh	0,563	100%	130S
7	12	120S	Belene	AEC-Belene	0,437	78%	
8	23	230S	Avren	Oreta	0,637	100%	230S
9	24	240S	Avren	Devisilovo	0,363	57%	
10	25	250S	Jalti chal	Vangelova chuka	0,419	100%	250S
11	27	270S	Jalti chal	Kerezliiska reka	0,326	78%	
12	26	260S	Jalti chal	Kurbanlaka	0,255	61%	
14	29	290S	Belorechka struktura	Chomakovia kladenec	0,295	100%	290S
13	28	280S	Belorechka struktura	Sveta Elena	0,241	82%	
15	31	310S	Belorechka struktura	Pojarite	0,236	80%	
16	30	300S	Belorechka struktura	Kodja guile	0,228	77%	
17	35	350S	Harmanliiski blok	Orlina	0,229	100%	350S
18	35a	35AS	Harmanliiski blok	Kumtarla	0,229	100%	35AS
19	34	340S	Harmanliiski blok	Ratiovitza	0,197	86%	
20	33	330S	Harmanliiski blok	Huhla	0,194	85%	
21	32	320S	Харманлийски блок	Giklidja	0,151	66%	
22	36	360S	Iugoiztochen Sakar	Aiazmoto	0,455	100%	360S
23	37	370S	Iugoiztochen Sakar	Bialata cheshma	0,298	65%	
24	38	380S	Iugoiztochen Sakar	Kachulka	0,247	54%	
25	39a	39AS	Sakar	Garvanski kamak	0,224	100%	39AS
26	39	390S	Sakar	Stanchovo pladniste	0,208	93%	
27	40	400S	Sakar	Sakartzi	0,191	85%	
28	41	410S	Sakar	Kushlovetz	0,149	67%	
29	42	420S	Sakar	Iukpazar	0,117	52%	
30	42a	42AS	Sakar	Gospodinovi dabichki	0,111	50%	

3.3. Assessment and Ranking in the Set of Sites Using a Rating Model – Model 3

The relative model cannot be applied when there is a great number of variants (as in the present case - 30) because of the great number of comparisons (Figure 1). A rating model is constructed in similar cases (Figure 4), a scale with several levels of different degree of preference being formed for each criterion. The scale is non-linear as a rule.

Taking under consideration the use of quality assessments for some of the criteria, as well as the great differences in their importance (see Figure 2), a decision has been made for the application of several typical scales with non-linear relationship between the levels and degrees of preference. This relationship is represented by a monotonous concave or convex curve depending on the criteria importance – the more important criteria are characterized by a convex curve and the less important - by a concave one (like fuzzy sets membership function). The scales reflect verbally the adjective "favorable" (unfavorable - 1, low favorable - 2, moderate favorable - 3, high favorable - 4, extremely favorable - 5) and have 5 levels (Table 3 and Figure 1).

Table 3. Creation of non-Linear Typical Scales

Normalized	0	0,25	0,5	0,75	1	b
Levels	1	2	3	4	5	
Scale 1 (series 1)	0,00	0,71	0,84	0,93	1,00	0,25
Scale 2 (series 2)	0,00	0,50	0,71	0,87	1,00	0,50
Scale 3 (series 3)	0,00	0,35	0,59	0,81	1,00	0,75
Scale 4 (series 4)	0,00	0,09	0,30	0,60	1,00	1,75
Scale 5 (series 5)	0,00	0,03	0,18	0,49	1,00	2,50
levels (verbal)	UNFAVS#	LOWFAVS#	MODFAVS#	HGHFAVS#	EXTFAVS#	
S# - scale number						

The general expression of the scales is P=F(K), where P is the degree of suitability of the corresponding sites according to a given criterion - $P \in [0,1]$:

$$P=((K_i - K_{min})/(K_{max}-K_{min}))^b,$$

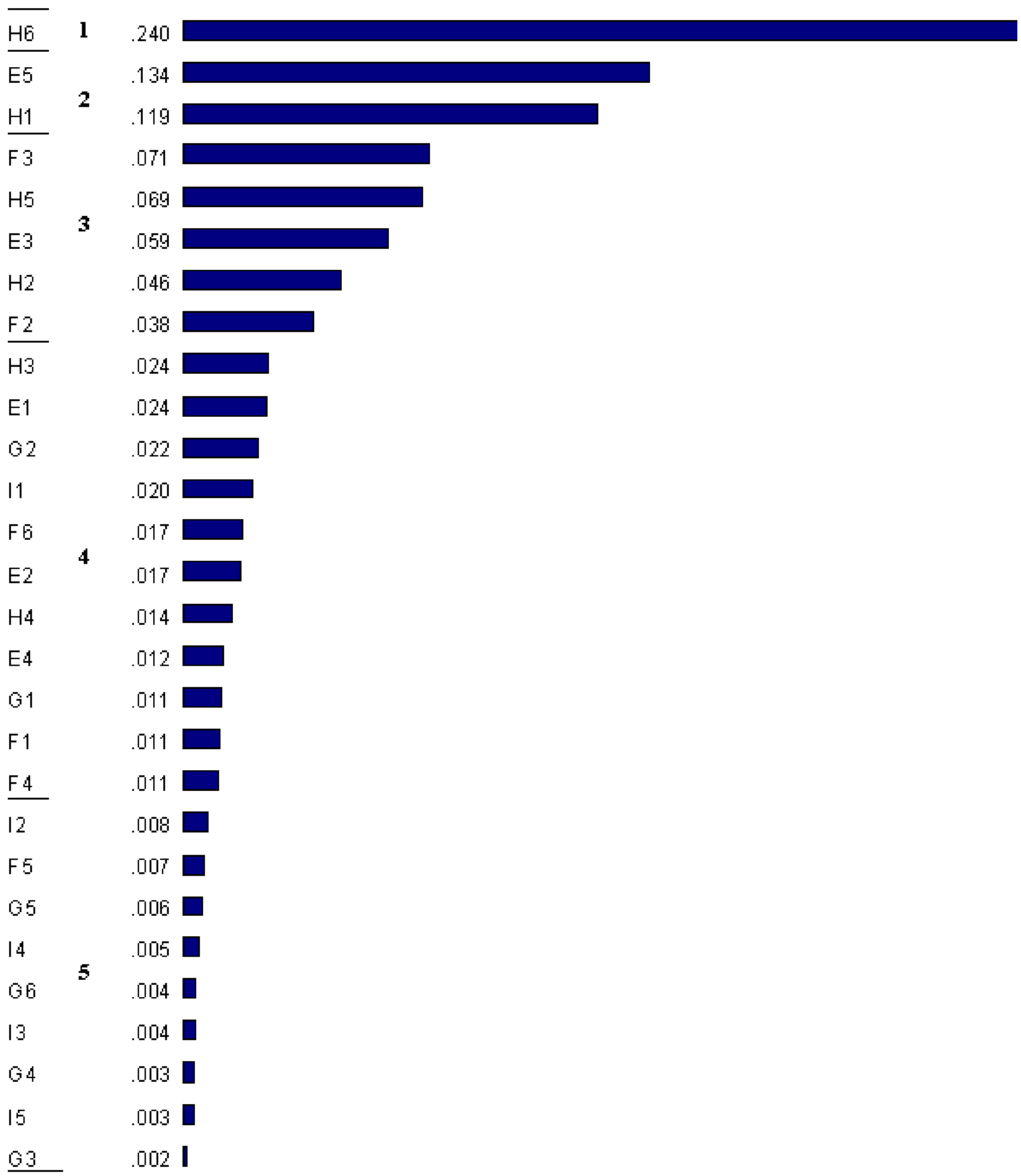
where: $K_i \in [1,5]$ are the scale levels, and $b \in [0,\infty]$ is a coefficient of non-linearity depending on the importance of the corresponding criterion and forming the convex curve for $b \le 1$ and a concave curve for $b > 1$ (see Table 3 and Figure 3).

The results from the synthesis of model 1 – the ranking of models (see Figure 2) are used for grouping the criteria according to their importance. Five groups of criteria have been distinguished:

Groups	Range of Priority	Criteria	Priority
Group 1	≥ 0.200	H6	0.240
Group 2	[0.120, 0.200]	H1, E5	{0.119, 0.134}
Group 3	[0.030, 0.120]	F2, H2, E3, H5, F3	{0.038,...,0.119}
Group 4	[0.010, 0.030]	F4, F1, G1, E4, H4, E2, F6, I1, G2, E1, H3	{0.011,.., 0.024}
Group 5	≤ 0.010	G3, I5, G4, I3, G6, I4, G5, F5, I2	{0.002,...,0.008}

A rating model is developed, the priorities of the single levels being determined in accordance to the above mentioned considerations, and the comparison of sites is made by the experts for each of the 28 criteria using the corresponding scale in the questionnaires.

Figure 2. Ranking and classification of criteria



The results of the ranking are presented in Figure 4. As a rule, they are not so precise as the results obtained by pair comparisons for each area because of the uncertainty of some of the criteria. For this reason the results from the site ranking are used for each area by comparison in pairs.

A group of 6 more favorable sites from 2 areas - "Sakar" and "Dolnocredni Tereni" has been formed: 090S "Varbitza", 39AS "Garvanski Kamak", 400S "Sakartzi", 080S "Sumer", 390S "Stanchovo Pladniste" and 410S "Kushlovetz". Two areas "Severozapadna Bulgaria" and "Belene" are more unfavorable.

Figure 3. Relationships between scale levels and their degree of preference

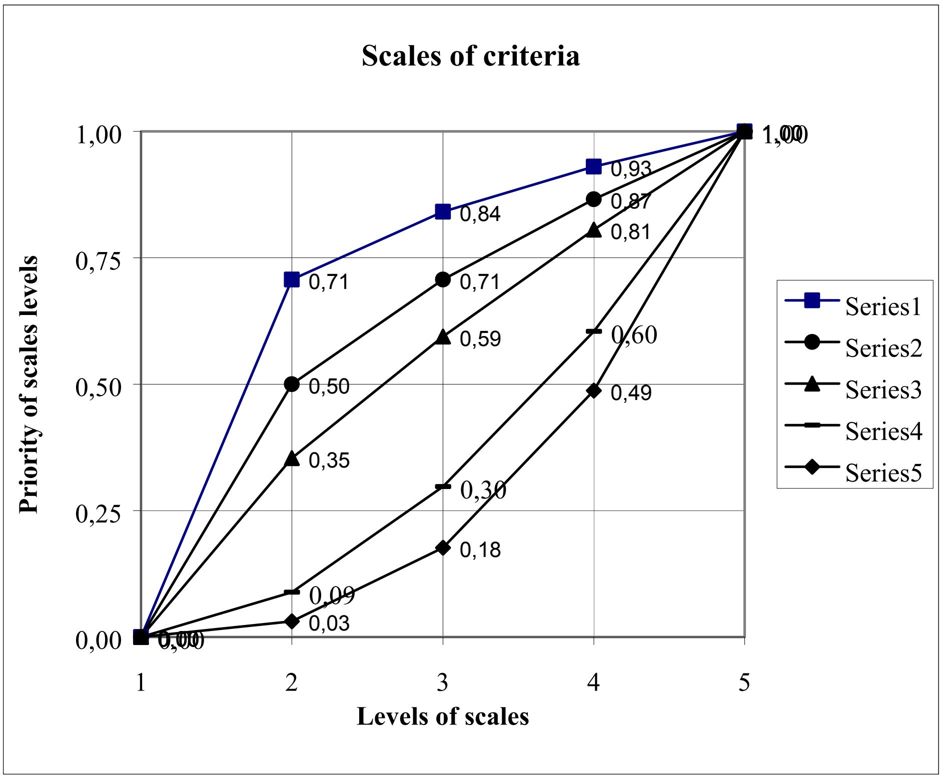


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Table 4. Sites ranking by each criterion

					global	local
group	H	**Criter.** H6	Population radiological impact	Importance:	0,24	0,468
N	Site N.	Site N.	Area name	Site name	rating	
1	1	010S	Severozapadna Bulgaria	Deleina	1	
2	4	040S	Severozapadna Bulgaria	Dalgodeltzi	1	
3	8	080S	Dolnocredni tereni	Sumer	4	
4	9	090S	Dolnocredni tereni	Varbitza	5	
5	15	150S	Dolnocredni tereni	Zlatar	4	
6	12	120S	Belene	AEC-Belene	2	
7	13	130S	Belene	Oresh	3	
8	23	230S	Avren	Oreta	3	
9	24	240S	Avren	Devisilovo	3	
10	25	250S	Jalti chal	Vangelova chuka	3	
11	26	260S	Jalti chal	Kurbanlaka	3	
12	27	270S	Jalti chal	Kerezliiska reka	3	
13	28	280S	Belorechka struktura	Sveta Elena	3	
14	29	290S	Belorechka struktura	Chomakovia kladenec	3	
15	30	300S	Belorechka struktura	Kodja guile	3	
16	31	310S	Belorechka struktura	Pojarite	3	
17	32	320S	Harmanliiski blok	Giklidja	3	
18	33	330S	Harmanliiski blok	Huhla	3	
19	34	340S	Harmanliiski blok	Ratiovitza	3	
20	35	350S	Harmanliiski blok	Orlina	3	
21	35a	35AS	Harmanliiski blok	Kumtarla	3	
22	36	360S	Iugoiztochen Sakar	Aiazmoto	3	
23	37	370S	Iugoiztochen Sakar	Bialata cheshma	3	
24	38	380S	Iugoiztochen Sakar	Kachulka	3	
25	39	390S	Sakar	Stanchovo pladniste	4	
26	39a	39AS	Sakar	Garvanski kamak	4	
27	40	400S	Sakar	Sakartzi	4	
28	41	410S	Sakar	Kushlovetz	4	
29	42	420S	Sakar	Iukpazar	3	
30	42a	42AS	Sakar	Gospodinovi dabichki	3	

Figure 4. Sites ranking as a % of site with maximal priority.