European Joint Programme on Radioactive Waste Management

Deliverable D10.7: Views of actors on the identification, significance of uncertainties on site and geosphere

Work Package WP10

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Executive Summary

UMAN Deliverable 10.7 has as primary objective to capture and synthesize the views of the three categories of actors (Research Entities (REs), Technical-Support Organisations (TSOs) and Waste Management Organisations (WMOs) participating in EURAD, related to:

- the significance for safety of uncertainties related to site and geosphere,
- the preferences in the characterisation of these uncertainties,
- the uncertainties evolution along the disposal programme implementation.

During the WP implementation, its draft version (Milestone MS 76) has been used in:

- the selection of the uncertainties with a significant relevance for safety, as basis for the discussion and identification of the management options and preferences of different actors regarding site and geosphere related uncertainties (Milestone MS89: UMAN Draft deliverable D10.11 as input to Subtask 4.3 and for the Workshop #1) as part of Subtask 4.3 activity, and in
- the preparation of the dialogue with Civil Society during UMAN Seminar #1, organized under Task 5

This deliverable is therefore based on UMAN Milestone MS76 which provided a first analysis of the views of the three categories of actors (WMOs, TSOs and REs) collected via the 2nd UMAN Questionnaire – Section *Site and Geosphere*, launched on September 15, 2020. In addition, it includes recommendations for further RD&D, knowledge management and strategic studies which resulted as feedback of the UMAN Workshop #1 and Seminar #2 dedicated to uncertainties management options and respectively Civil society views related to site and geosphere.

The 2nd UMAN questionnaire grouped the uncertainties related to site and geosphere in 15 topics, gathering in total 64 parameters and processes considered by the UMAN experts' group to have a potential significance for safety. The 15 topics have been structured in three main categories:

I. Uncertainties to be taken into consideration when conceptualizing natural barriers and aquifers;
II. Uncertainties associated with geodynamics and tectonic perturbations of the site in the long-term;
III. Uncertainties associated with future climate changes.

The analysis was based on the answers received from 22 organisations (representing 11 REs, 4 TSOs and 7 WMOs) running RWM programmes covering all disposal concepts: near surface (NSD), sub-surface (SSD) and geological disposal (DGD). While the views of actors on the significance for safety, characterisation methods and uncertainty evolution are described for all 15 groups of uncertainties, in depth analysis is provided only for the uncertainties with relevant impact on the disposal safety for majority of actors.

The answers compilation revealed that the groups of uncertainties scored with medium and high significance by <u>*all categories of actors*</u> involved in this survey are:

- uncertainties related to site structure and geometry;
- uncertainties related to the host rock properties defining the water and gas flow, and radionuclide migration;
- uncertainties related to tectonics of the site and their future evolution;
- uncertainties related to long term evolution of the climate.

According to the questionnaire results, a lower relevance for disposal safety is associated with:

- uncertainties related to adjacent aquifer properties and processes;
- uncertainties related to seismic and volcanic processes;
- uncertainties related to diapirism and transgression/regression processes.

Uncertainties associated with near surface disposal have been generally evaluated to have lower significance for safety than those related to geological disposal.

A general observation valid both for near surface and geological disposal concepts is that there are differences between the importance degree given by the three categories of actors to the same group of uncertainties. In this study, WMOs and REs generally associate a higher significance to uncertainties and their impact on safety than the technical support organisations (TSOs).

The uncertainties of greatest significance in terms of geological disposal safety, scored as medium to high *by all actors,* are those associated with:

- *the conditions and hydraulic parameters of the host rock* that determine the groundwater flow field (especially hydraulic conductivity, hydraulic heads, gradients in the host rock);
- *the geochemistry and transport properties*, with particular emphasis on groundwater chemistry and host rock-specific sorption parameters;
- *the thermal and mechanical properties* of the host rock in its natural state.

Besides these categories, REs and WMOs consider of high importance the uncertainties related to the site characteristics necessary for the creation of the conceptual model (geological structures, stratigraphic characteristics, homogeneity of geological layers), while *TSOs and WMOs* share the same high concern on the uncertainties associated to:

- tectonic processes;
- hydraulic and geo-mechanical properties of the excavated disturbed area (EDS), including re-saturation of the EDZ area;
- glaciations.

TSOs add to this list the uncertainties related to scaling effects, while WMOs add the uncertainties related to the water flow and transport parameters of radionuclides in adjacent aquifers (sorption, diffusion, colloidal transport).

In the case of near surface disposal, uncertainties of highest significance for both REs and TSOs are associated with the hydraulic properties of the adjacent aquifers. While REs are highly concerned by the uncertainties related to the radionuclide transport properties, TSOs give a greater importance to the tectonics and seismic processes.

Each category of actors uses for the uncertainties' characterisation a diversity of methods, adequate to the uncertainty type (parametric, scenario, conceptual, etc.), which complement each other, with the aim to reduce the uncertainty level. Methods mostly applied by all actors are:

- statistical methods applied on relevant (measured) data;
- quantification by expert judgement;
- modelling (likelihood of events, geochemical databases…).

Generally, all actors' opinions converge on the fact that uncertainties will decrease along the programme phases, as the knowledge of the site and scientific findings evolve.

The uncertainties with a possible high significance for safety considered for a more detailed analysis in this document are:

- uncertainties associated with the site homogeneity;
- uncertainties associated with hydraulic conductivity;
- uncertainties associated with sorption parameters and processes;
- uncertainties associated with faulting;
- uncertainties associated with glaciations, with focus on permafrost.

High significant uncertainties need dedicated actions to be implemented with priority.

Therefore, according to the actors' opinions, further *R&D activities* should be performed to improve knowledge and databases related to the radionuclide transport in different host rocks. Therefore, e*xperimental studies on hydraulic conductivity* would be useful for the investigation of clay re-saturation kinetics taking into account all processes occuring in the disposal system: diffusion/advection in host rock, plugs & seals, hydraulic conductivity of host rock and EDZ, hydrogen production and transport, and counter-pressure build-up.

Large scale and laboratory experiments on sorption of anionic species in clay rocks should be performed for low but non-zero K_d. R&D activities addressing the identification of relevant sorption processes/mechanism for the development of mechanistic sorption models based on a bottom-up approach for improved sorption models, and the upscaling from batch systems on pure phases to the real host rock in confined conditions could bring in-depth understanding and supplementary knowledge on the radionuclide transport mechanisms.

Further works should be done in the *development of computational tools* (such as *geochemical codes* allowing to combine uncertainty components in a non-additive model and *improved glaciations codes* coupling the climate evolution, permafrost and groundwater flow models).

A *strategic study on climate change* could provide additional insight on how to deal with glacial periods in safety case and safety assessment, while a *strategic study on site homogeneity* could clarify the conditions under which a host rock volume can be considered homogeneous.

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Glossary

CS – Civil Society

DGD – Deep Geological Disposal

EURAD – European Joint Programme on Radioactive Waste Management

EDZ – Excavation Damaged Zone

Kd – distribution coefficient of radionuclide

NSD – Near Surface Disposal

RE- Research Entity

RMW – Radioactive Waste Management

RN - radionuclide

SoK – State of Knowledge

SOTA – State of the Art

SSD – Sub Surface Disposal

TSO – Technical Support Organisation

UMAN – Uncertainty Multi-Actor Network

WMO – Waste Management Organisation

WP – Work package

1. Introduction

The UMAN Deliverable 10.7 gathers views of different actors on the characterisation and potential safety significance of the uncertainties related to site and geosphere, collected via the 2nd UMAN Questionnaire launched on September 15, 2020.

It is based on the preliminary list of uncertainties elaborated by the expert group of the UMAN Subtask 3.3 [1], classification schemes provided by the Subtasks 2.1 [2] and strategies options developed in Subtask 4.2 [3].

The categories of actors included in this survey are: Research Entities (REs), Technical Support Organisations (TSOs) and Waste Management Organisations (WMOs). The views of Civil Society (CS) organisations, an important actor in the decision-making process, have been collected as part of the Seminar #2 organized under UMAN Task 5 and integrated in this deliverable.

This document focuses primarily on the relevance for safety of the site and geosphere uncertainties for the three categories of actors participating in EURAD. Its content evolved during WP UMAN implementation, following the two-fold aims of the work:

- provide input for Milestone *MS89: UMAN Draft deliverable D10.11 as input to Subtask 4.3* and for Workshop #1: *Management options and preferences of different actors regarding site and geosphere related uncertainties*, organized by Subtask 4.3;
- provide relevant input on site and geosphere related uncertainties for the dialogue with Civil Society organisations foreseen in Seminar #2, organized under Task 5.

Based on the answers received to the 2nd UMAN questionnaire – *Section Site and Geosphere,* the expert group of Subtask 3.3 selected 5 uncertainties for which a more detailed analysis of the potential impact on the safety, methods used in their characterisation and their evolution has been developed.

This deliverable was further developed by the members of the expert group which provided details related to the relevance of these uncertainties on the safety of different disposal systems, as compiled from the experience acquired in the national programmes or in other international reports, projects, works.

The views of actors considered in this study covered all phases of the disposal programme, as well as all different types of radioactive waste disposal concepts: near surface, sub-surface and geological

disposal types.

2. Methodology: the identification and characterisation process

2.1 Approach/methodology used for identification

A Group of 4 Experts representing RESs, TSOs and WMOs from 4 Member States (Czech Republic, France, Switzerland and Romania) with different disposal programmes (from the point of view of the repository concepts and implementation stages) established, following a brainstorming organized in the beginning of the UMAN WP, a first list of uncertainties potentially significant for the disposal safety.

This preliminary list reflects the views and experience of the 4 experts gathered in the national RWM programmes, as well as results found in a survey of the literature from advanced RWM programmes in the world (Sweden, Finland, Canada).

In a second step, the preliminary list of uncertainties related to site and geosphere [1] was further completed with new uncertainties identified in IAEA recommendations for Deep Geological Disposal (DGD) [4] and from Strategic Research Agendas for RWM.

In order to complete the list of uncertainties and to have as representative views as possible on how different types of actors perceive the relevance of the identified uncertainties for storage security, a wide survey at EURAD level based on a questionnaire was developed.

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2.2 List of uncertainties

Characterisation of the geosphere surrounding a radioactive waste repository is an important issue for the site selection process and for the safety case associated with such facilities. The possible significance for safety of uncertainties associated with site and geosphere of such facilities, their characterisation and possible evolution along the disposal programmes, have been addressed via the questionnaire for the following three groups of uncertainties:

- uncertainties to be taken into consideration when conceptualizing natural barriers and aquifers;
- uncertainties associated with geodynamics and tectonic perturbations of the site in the long-term (including seismic events and faulting);
- uncertainties associated with future climate changes, such as potential future glaciations and other possible processes (e.g. flooding and desertification, subglacial erosion and permafrost formation).

The processes and parameters related to these uncertainties are manifold and their characterisation requires knowledge ranging from information about possible geological and climate evolutions on a larger scale to more detailed information on radionuclide transport in natural barriers and aquifers (mineralogy, hydrology, bio-geochemistry,…) on a smaller scale. All these elements have been considered by the expert group early in drafting the preliminary list of uncertainties, and further on, in designing the questionnaire.

The questionnaire grouped the uncertainties related to site and geosphere in 15 topics, gathering in total 64 parameters and processes considered by the expert group to have a potential significance for safety.

The 64 uncertainties, explicitly addressed by the questionnaire, are:

I. Uncertainties to be taken into consideration when conceptualizing natural barriers and aquifers

A. Uncertainties associated with structural and geometric data of the host rock and surrounding geological layers and aquifers

- Site topography
- Depth, dimensions and topography of geological layers
- Homogeneity
- Geological structures

B. Uncertainties on thermal and mechanical properties of the undisturbed host rock

- Geo-mechanical properties
- Thermal properties
- In situ stress field

C. Uncertainties associated with hydraulic conditions and liquid and gas flow in the undisturbed host rock

- Kinematic porosity
- Hydraulic conductivity
- Hydraulic heads and gradients (including abnormally high pore pressures)
- Gas flow properties and processes

D. Uncertainties associated with EDZ properties

- Water (re-)saturation
- Hydraulic properties
- Geochemistry and microbial activity
- Thermal properties
- Geo-mechanical properties
- Gas flow properties and processes

E. Uncertainties associated with hydraulic conditions and properties of adjacent aquifers

- Recharge and discharge estimates of local and regional hydrogeological units
- Local and regional hydraulic interrelationships between aquifers (connectivity)
- Groundwater flow fields (average flow rates, prevailing directions)

F. Uncertainties associated with geochemistry and solute transport properties in the host rock

- Chemical, radiochemical and mineralogical composition of the rock (porous medium or fracture – matrix system properties)
- Groundwater chemistry
- Solubility limits
- Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)
- Diffusion coefficients
- Colloid (facilitated) transport
- Changes in the transport properties due to precipitation/dissolution reactions

G. Uncertainties associated with geochemistry and solute transport properties in the adjacent aquifers

- Chemical, radiochemical and mineralogical composition of the aquifers (porous medium or fracture – matrix system properties)
- Groundwater chemistry
- Solubility limits
- Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)
- Diffusion coefficients
- Colloid (facilitated) transport

H. Uncertainties associated with data and model representativeness

- Scale effects – uncertainties associated with upscaling of lab data to field scale
- Scale effects – uncertainties associated with process modelling from micro to macro scale
- Data spatial extrapolation

II. Uncertainties associated with geodynamics and tectonic perturbations of the site in the long-term

I. Tectonic processes and structures

- Tectonic processes: uplift, subsidence, tilting, folding, faulting
- Fault location, length, depth and activity
- Temporal and spatial evolution of faulting
- Detection methods

J. Uncertainties associated with earthquakes

- Historical seismicity
- Epicentre location, earthquake magnitude, seismic wave properties
- Geodynamic properties
- Propagation of the seismic waves with depth
- Pumping effect (i.e. fast water and contaminant vertical movement)

K. Uncertainties associated with diapirisms

- Evidence of Quaternary and late Tertiary diapirism
- Diapiric velocity

L. Uncertainties associated with volcanic occurrence in the regions

- History of volcanic activity, Quaternary and late Tertiary volcanism
- Location and time of potential volcanic eruptions

III. Uncertainties associated with future climate changes

M. Climate changes (other than glaciations)

- Climate history
- Climate changes that may result from the anthropic global warming: type (e.g. wet or dry), duration,…
- Changes in the transfer pathways in the biosphere and to humans

N. Glaciations

- Starting time and duration of the next glacial period
- Extent and location of the ice sheet
- Inter-glacial cycle frequency and duration
- Permafrost depth
- Erosion/sedimentation rates
- Induced stress fields
- Changes in groundwater flow (porosity, permeability, hydraulic gradients, flow directions,…)
- Impact on groundwater chemistry (dilution due to plug flow, increased desorption,…)
- Changes in the transfer pathways in the biosphere and to humans

O. Marine transgression and regressions (i.e. sea level changes)

- Extent, time of occurrence, duration…
- Possible impacts on site landscape, groundwater hydraulics, geochemistry…
- Changes in the transfer pathways in the biosphere and to humans.

2.3 The Questionnaire

The first purpose of the 2nd UMAN Questionnaire was to collect the views of the actors in regards with the significance of each site and geosphere uncertainty proposed by the group of experts.

The second aim was to gather supplementary information/data on their characterisation and evolution over time, and collect missing uncertainties, considering the diversity of national disposal programmes in terms of repository types and implementation phase.

For each of the 15 uncertainties covered in the questionnaire, questions were dedicated to

- Significance for safety, quantified as:
  1. high
  2. medium
  3. low
  4. not known or assessed yet
- Potential impact on safety such as:
  a. impact on the radiological dose or risk during operation
  b. impact on the radiological dose or risk after closure
  c. impact on safety functions (please specify which functions and disposal system components could be impacted)
  d. others potential impact(s) (please specify)
- Uncertainty characterisation (methods, approaches), in which the following pre-set answers have been proposed:
  a. quantification by expert judgement
  b. applying statistical methods on relevant (measured) data
  c. modelling (likelihood of events, geochemical databases…)
  d. accuracy of measurements and detection limit of equipment
  e. exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty)
  f. other (please specify)
- Evolution along the programme implementation, from conceptualization to repository closure)

Note that the 2nd UMAN Questionnaire was common with other subtasks and also included specific sections dedicated to uncertainties about other topics:

- Uncertainties on waste inventory
- Spent fuel related uncertainties
- Uncertainties on human aspects

The 2nd UMAN questionnaire has been sent to all partners participating in the EURAD project but the Civil Society. It was available in two formats: word documents and on-line questionnaire (https://inr-eu.ro/). Answers have been received from 22 organisations (*Table 1*), representing, as illustrated in *Figure 1*, REs (11 answers); TSOs (4 answers) and WMOs (7 answers), covering all disposal concepts: near surface, sub-surface and geological disposal.

Table 1. List of actors answering the questionnaire, with details on the disposal programmes and status in implementation

Affiliation	Country	Type of actor	type of host rock for:			current phase of the programme for:		
			Near surface disposal	Sub-surface disposal	Deep geological disposal	Near surface disposal	Sub-surface disposal	Deep geological disposal
CNRS	FR	RE	Sedimentary		Sedimentary	operation &closure		Site characterisation
CVR	CZ	RE	Sedimentary	Sedimentary	Crystalline	operation &closure	operation &closure	Site evaluation, site selection
BGR	DE	RE			Crystalline Sedimentary			Site evaluation, site selection
TUL	CZ	RE			Crystalline			Site evaluation, site selection
HZDR	DE	RE			other			Site evaluation site selection
Slovak University of Technology	SK	RE				Policy, framework, programme establishment		Policy, framework and programme establishment
LEI	LT	RE	Sedimentary			construction		
RATEN	RO	RE	Sedimentary			Site characterisation		
IC2MP - CNRS	FR	RE			Sedimentary			Site characterisation
SCK CEN (EGA unit)	BE	RE	sedimentary		Sedimentary	facility construction		Policy, framework and programme establishment
GRS	DE	RE			other			Policy, framework and programme establishment
EIMV	SI	TSO	Sedimentary	Sedimentary	Crystalline	Site characterisation	Site characterisation	Policy, framework and programme establishment
SURO	CZ	TSO	Crystalline	Sedimentary Crystaline	Crystalline	operation and closure	Operation& closure	Site evaluation, site selection
Bel V /FANC	BE	TSO			Sedimentary	Site characterisation		Policy, framework and programme establishment
IRSN	FR	TSO	sedimentary	Sedimentary	Sedimentary	operation and closure	site evaluation, site selection	Site characterisation
SÚRAO	CZ	WMO			Crystalline			Site evaluation, site selection
NAGRA	CH	WMO			Sedimentary			Site evaluation, site selection
SKB	SE	WMO		Crystalline	Crystalline		Site characterisation	Site characterisation
BGE-EMO	DE	WMO			salt			operation and closure
BGE-STA	DE	WMO			others			site evaluation, site selection
ENRESA	ES	WMO			Sedimentary			Policy, framework and programme establishment
ANDRA	FR	WMO	sedimentary	Sedimentary	Sedimentary	post-closure	site evaluation, site selection	facility construction

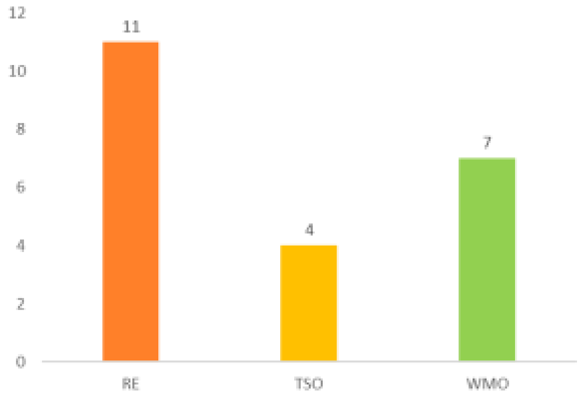


Figure 1. Distribution of the questionnaire answers per type of actor

Significance for safety perceived by each type of actors strongly depends on the current stage of the disposal programmes and the experience already gained in the programmes. As seen in *Figure 2*, compared to geological disposal, for near surface disposal most of the respondents are in more advanced phases of programme implementation (site characterisation, facility construction, operation and closure, and even in post closure). Expensive experience and feedback on the uncertainties related to site and geosphere have thus been gained by the actors for this type of disposal.

At the opposite, answers related to geological disposal show that actors are facing in majority the early phases of disposal programme implementation (policy, framework and programme establishment and site evaluation and siting). Only two answers (from France and Sweden) provide an input from most advanced programmes.

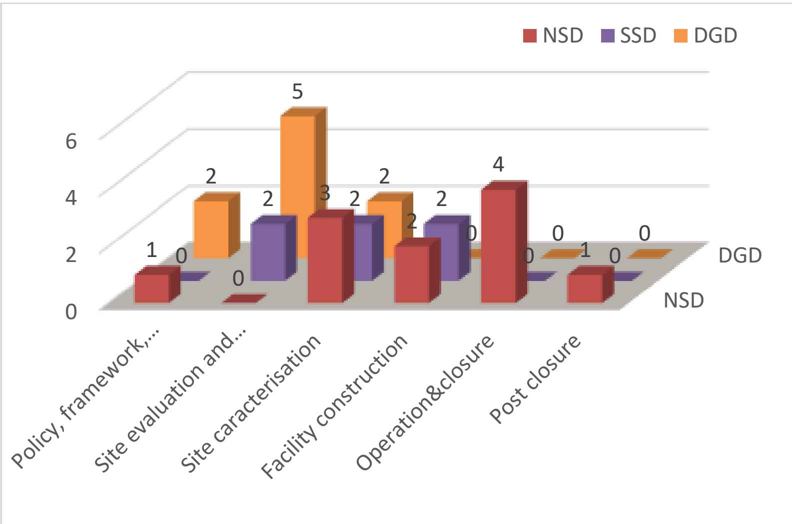


Figure 2. Distribution of the answers per disposal programmes phase and disposal types

(NSD – Near Surface Disposal, SSD – Sub Surface Disposal, DGD – Deep Geological Disposal)

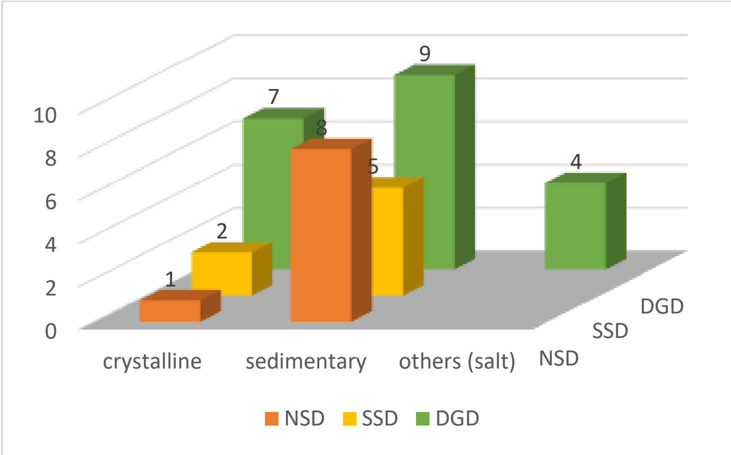


Figure 3. Distribution of the answers per type of rock and disposal

(NSD – Near Surface Disposal, SSD – Sub Surface Disposal, DGD – Deep Geological Disposal)

The answers cover site and geosphere aspects specific to all types of host rocks considered for disposal in Europe (sedimentary, crystalline and salt), with a greater percentage for the sedimentary ones (*Figure 3*).

2.4 Statistical analysis of the answers to the questionnaire

In order to assess the relevance for safety of the uncertainties for each type of actors, the answers have been scored as given below. Then, the score obtained for each uncertainty was normalized for each type of actors by dividing the cumulated score for each type of actors by the number of responses different from 0 (answers "not known or addressed yet" have not been considered in the analysis of the safety-significant uncertainty since being not known or not considered yet, it does not mean that it has no impact).

- 3 points for high significance for safety
- 2 points for medium significance for safety
- 1 point for low significance for safety
- 0 points for "not known or addressed yet"

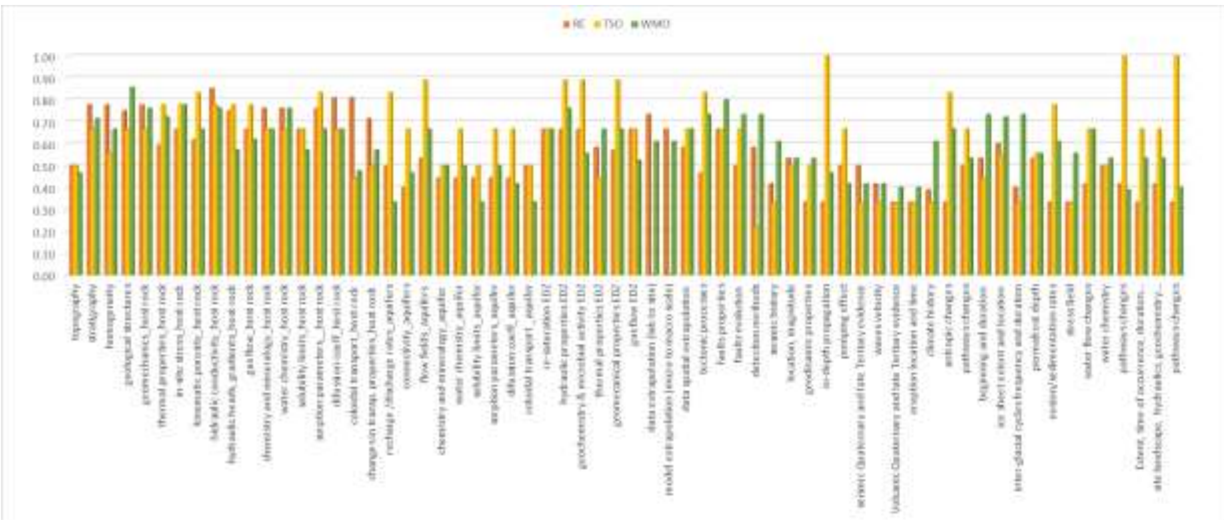


Figure 4. Distribution of "significance for safety" level for geological disposal
("not known or addressed yet" answers excluded)

Figure 4 shows that there are groups of uncertainties scored with medium and high significance for safety of geological disposal by all categories of actors involved in this survey. These are:

- uncertainties related to site structure and geometry;
- uncertainties related to the host rock properties defining the water and gas flow and radionuclide migration;
- uncertainties related to tectonics of the site and their future evolution;
- uncertainties related to long term evolution of the climate

According to the questionnaire results, a lower relevance for safety has been obtained for:

- uncertainties related to adjacent aquifer properties and processes;
- uncertainties related to seismic and volcanic processes;
- uncertainties related to diapirism and transgression/regression processes.

When we take into consideration the "not known or addressed yet" answers, the obtained distribution of possible "significance for safety" slightly changes, as shown by a comparison of *Figure 4* and *Figure 5*.

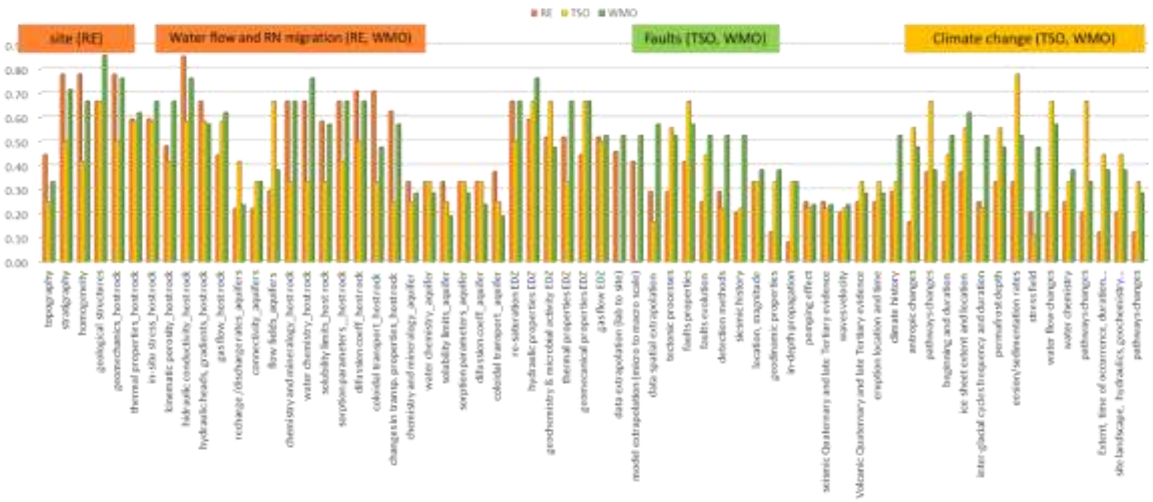


Figure 5. Distribution of "significance for safety" level for geological disposal ("not known or addressed yet" answers included)

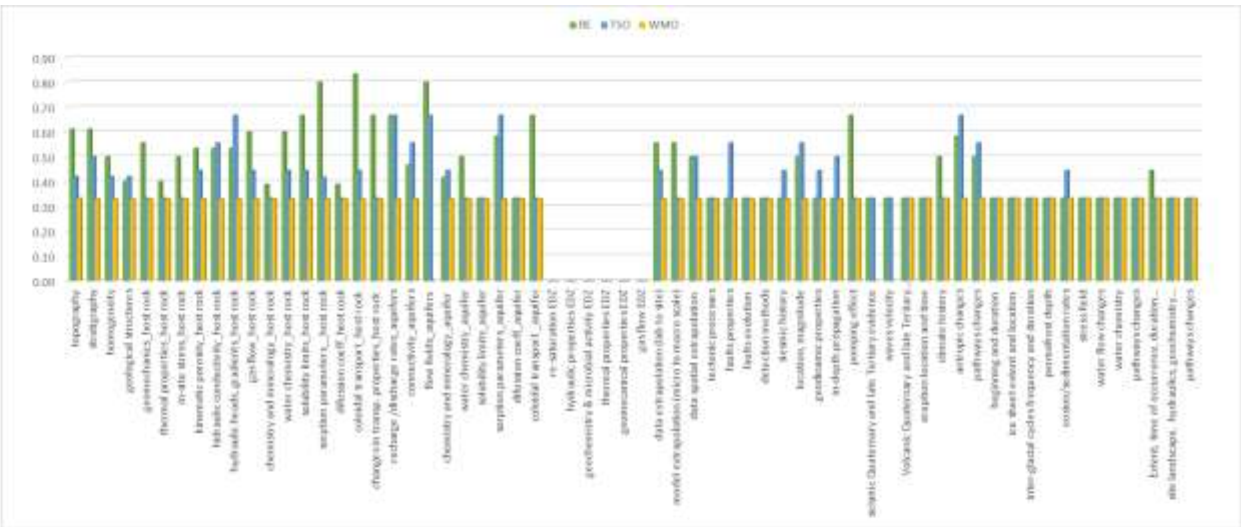


Figure 6. Distribution of "significance for safety" level for near surface disposal ("not known or addressed yet" answers excluded)

It has to be noted that, for near-surface disposal, there is only one answer received from the WMOs group, therefore we cannot perform a statistical analysis for this category. These answers are however relevant, reflecting a vast experience in near surface disposal, including not only construction, operation and closure, but also facility post-closure (*Table 1*), which provided a very useful feed-back on the safety issues.

For sub-surface disposal, the statistics were quite poor: 1 response from the REs group, 3 responses from the TSOs group and 2 responses from the WMOs. The low number of responses may be related with the low number of sub-surface disposals in the EU RWD programmes.

Even so, this statistic is in a good agreement with the other two (Figure 7): it highlights the same four major groups identified as having significant impact on safety in a geological disposal, and adds the uncertainties related to the adjacent aquifers, identified in the near-surface disposal statistic.

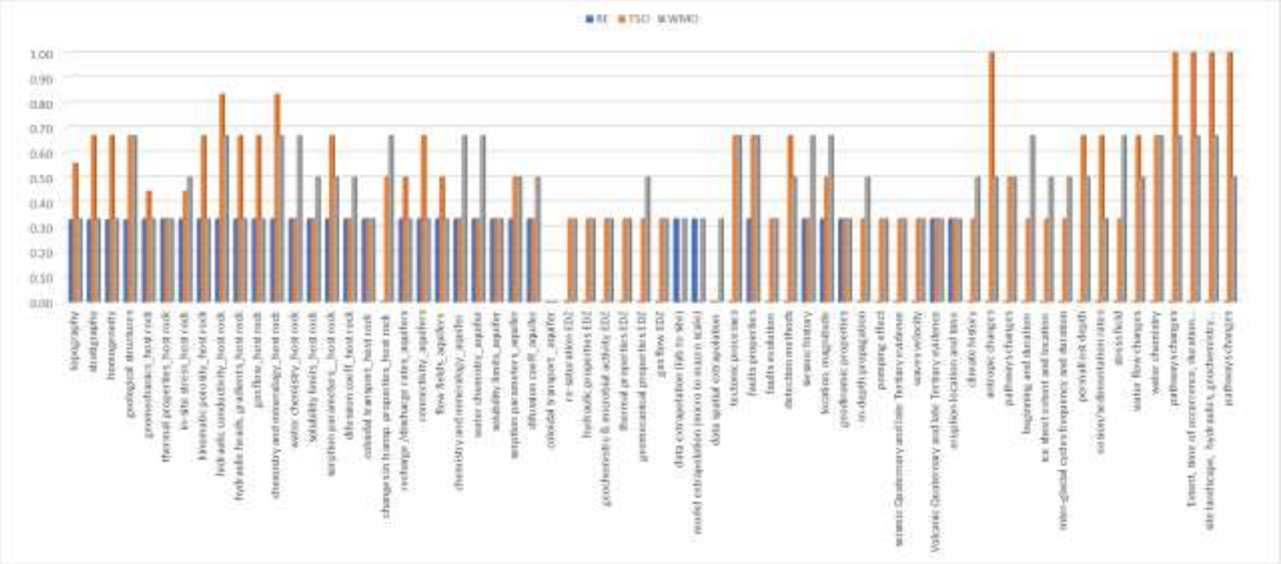


Figure 7. Distribution of "significance for safety" level for sub-surface disposal *("not known or addressed yet" answers excluded)*

3. Uncertainties to be taken into consideration when conceptualizing natural barriers and aquifers

The geosphere is the ultimate barrier of the disposal system. In the safety case and safety assessment, each safety-related aspect of the site and geosphere has to be considered, analyzed, understood and integrated, considering its associated uncertainty.

The uncertainties discussed in this chapter have a potential safety significance and should be considered notably when conceptualizing natural barriers and aquifers in scenario and models.

3.1 Uncertainties associated to structural and geometric data of the host rock and surrounding geological layers and aquifers (needed to create the model of the disposal site) (A)

3.1.1 Significance for safety

Geological disposal

Site topography, stratigraphy and homogeneity are first elements considered when developing a model of a possible disposal site, for evaluating its performance and performing safety analyses. Uncertainties on strata thickness and their homogeneity could influence the accuracy of the model and consequently the radiological impact assessment of the disposal facility.

In the case of geological disposal, uncertainties associated with the structural and geometric data of the site are considered, by all actors involved in the survey, to have a medium and high significance for the disposal safety (*Table 2*).

Table 2. Synopsis of the actors' views on uncertainties related to structural and geometric data of the site for deep geological disposal (h – high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	Score of uncertainty relevance for safety						Impact on		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Site topography	0.50	6l;2h; 1n	0.50	1m; 2n; 1l	0.47	4l; 1h; 2n	xx	xxxxxx	xxxxx
Depth, dimensions and topography of geological layers.	0.78	4m; 4h;1l	0.67	1h; 1m; 1n; 1l	0.71	3h; 2m;2l	xx	xxxxxxxx	xxxxxx
Homogeneity	0.78	6m; 3h	0.56	2l; 1h; 1n	0.67	2h; 3m;2l	xxx	xxxxxxxxx	xxxxxx
Geological structures	0.75	2m; 4h; 2l;1n	0.67	2m; 1h; 1l	0.86	5h; 1m; 1l	xx	xxxxxxx	xxxxxxxx

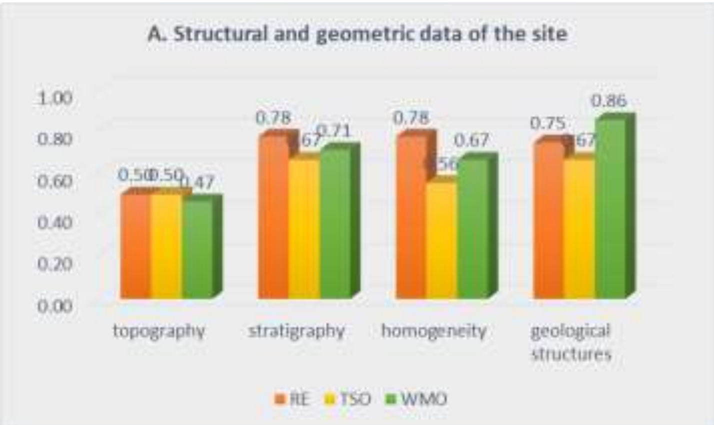


Figure 8. Significance for safety of uncertainties related to structural and geometric data of the site-for geological disposal

Uncertainties associated with the characteristics of the geological strata required for site modelling (depth, dimensions, geometry of geological strata, degree of homogeneity) are of the greatest importance for REs and WMOs (*Figure 8*). This is due to their possible role in radionuclides retention, and especially the impact that these uncertainties may have on the safety functions of the geological environment and the post-closure radiological dose assessment.

Uncertainties on the geological structures cover for instance the possible existence of discrete features (such as septaria) or of rocks with metallic mineralization. Undetected discrete features may affect the radiological impact assessment, while undetected presence of some metallic mineralization (representing potential ores of interest for a future exploitation) could affect the human intrusion scenario, with consequences on the radiological risk estimation.

The importance for safety also lies in the possibility of inaccurate post-closure safety assessments, caused by the lack of information on important geological features of the site. Geological layers play an important role in radionuclide immobilization and retardation, slowing down the contaminant release, reducing therefore the radiological impact on the population and environment.

Uncertainties associated with the size, homogeneity and continuity of the layers may lead to poor estimates of the post-closure safety (REs and TSOs), while uncertainties related to the presence of discontinuity could underestimate the radionuclide transport through the rock (TSOs) due to the creation of faster pathways.

Among the structural data of the site, **homogeneity** is considered of significant importance by all actors when developing conceptual models of a disposal site.

The REs pointed out that the more homogeneous the clay rock layer is, the lower uncertainties in transport properties are. Heterogeneous properties may lead to preferential flows in the matrix domain and may form connections between disconnected faults. Heterogeneity can also induce chemical or other types of gradients, fracture developments, anisotropy, connectivity between sub-units of very different characteristics, with a direct impact on the natural barrier integrity and consequently, on the safe containment function of the geological layers.

The TSOs highlighted the role of faults and inhomogeneity of geological layers, which may produce water conducting pathways resulting in preferential transport routes for radionuclides. Faults can have a drainage function due to the presence of preferential paths of groundwater flow in zones with higher permeability (greater fracturation of rocks on the fault) which could accelerate and increase the contaminant release in the environment.

The WMOs underlined that the importance of these uncertainties lays on role that the geologic layers have on the radionuclides immobilisation, retention and retardation.

Most impacts are associate with the post-closure safety or risk assessment and safety functions of the host rock and surrounding geological layers (*Table 2*), but uncertainties on the site structural and dimensional data could impact also the operational safety, for example due to the potential variations in the mechanical properties of the rock or in water conductivity, which can lead to the collapse or flooding of the galleries.

Near surface disposal

The relevance for safety of these uncertainties seems to be less important, being scored as medium and low (*Figure 9*).

Table 3. Synopsis of the actors' views on uncertainties related to structural and geometric data of the site for near surface disposal ((h – high, m-medium, l-low, n-not known or addressed yet))

Uncertainty	Score of uncertainty relevance for safety			Impact on: (number of answers)		
	REs	TSOs	WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions

Site topography	0.61	3l; 2h; 1m	0.42	1m; 3l	0.33	1l	xx	xxx	xx
Depth, dimensions and topography of geological layers.	0.61	3m; 2l; 1h	0.5	2m; 2l	0.33	1l	xxx	xxxx	xx
Homogeneity	0.50	3m; 3l	0.42	1m; 3l	0.33	1l	xx	xxxx	xx
Geological structures	0.40	4l; 1m	0.42	1m; 3l	0.33	1l	xx	xxx	x

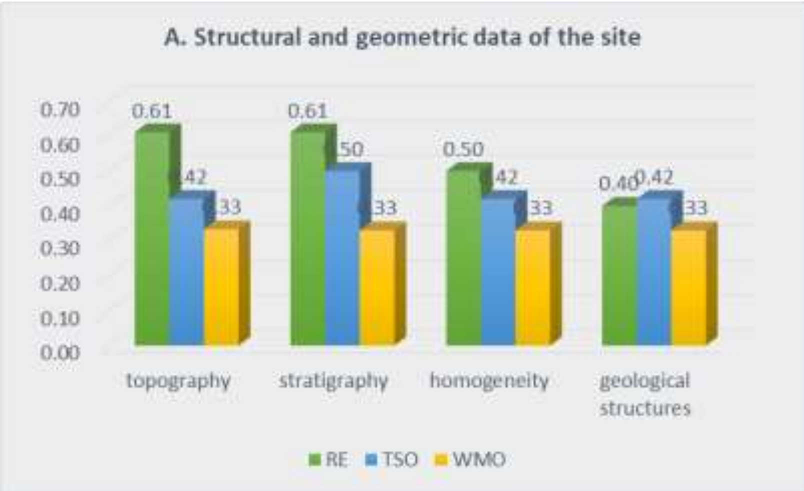


Figure 9. Significance for safety of uncertainties related to structural and geometric data of the site for near surface disposal

From the three categories of actors, only the REs responded that the uncertainties related to site topography and stratigraphy have a significant (medium and high) relevance for safety. These views are connected essentially with programmes in early phases of implementation, when data on the site are missing or are very scarce.

3.1.2 Uncertainties characterisation

There are many methods available and already used in the characterisation of the uncertainty related to the structural and geometric data of the site (*Figure 10. Frequency of the methods used in characterisation of uncertainties related to structural and geometric site dataFigure 10*).

Quantification by expert judgement, applying statistical methods on relevant (measured) data and modelling have been frequently used in the uncertainty characterisation by all actors, especially on uncertainties related to layers depth and thickness, homogeneity and geological structures.

Regarding the uncertainty associated to homogeneity, **REs** pointed out that the statistical analysis is a useful method for its characterisation (*Figure 11*). The "variance of site data can possibly be described from boreholes by statistical analysis of properties of similar rocks in broader region, the power law correlation function describing quite well the self-similar character of the natural rocks".

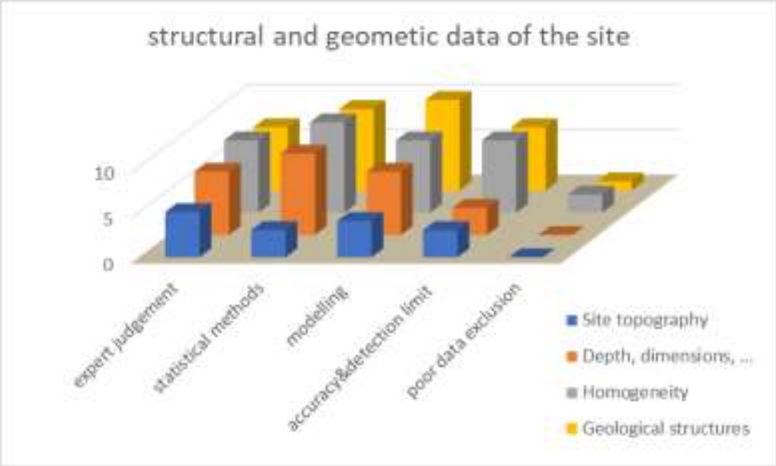


Figure 10. Frequency of the methods used in characterisation of uncertainties related to structural and geometric site data

TSOs mentioned the 3D SGmodels that can be created for a geological repository potential site, underlining however that these models are burdened with a considerable degree of uncertainty (e.g. on the homogeneity of the geological massif at greater depths). Potential faults and inhomogeneities in the host rock can be identified applying geophysical methods simultaneously with geological mapping of critical parts of the site, such as:

- Systematic Mapping of smaller areas based on fragments and supplemented as much as possible by technical works – hand-dug trenches with structural documentation and boreholes to a depth of about 1,000 m;
- Resistivity profiling and electromagnetic profiling, refraction seismic method;
- Electric resistivity tomography (ERT) using a multi-cable for determining the dip and thickness of brittle structures and possibly their other parameters;
- The shallow reflection seismic method in places of the anticipated most important faults;
- Gravimetric measuring and modelling to determine the in-depth extent of the granites.

WMOs highlighted as well the modelling as the most used characterisation method for such uncertainties (*Figure 11* and *Figure 12*). For instance:

- Deterministic modelling of large-scale rock type distribution and heterogeneity based on expert judgement, conceptual understanding and investigation data;
- Stochastic geological simulations of the distribution and evolution of rock types with unfavorable thermal and/or mechanical properties;
- Empirical and numerical studies on acceptable volumes of rocks with unfavorable properties with regard to thermal conductivity and spalling.

The preferences of each category of actors on the methods of uncertainties characterisation depend on the nature of the parameters/processes.

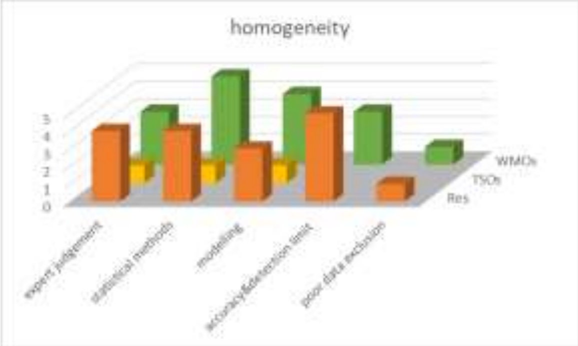


Figure 11. Actors' preferences in the characterisation of uncertainties on site homogeneity

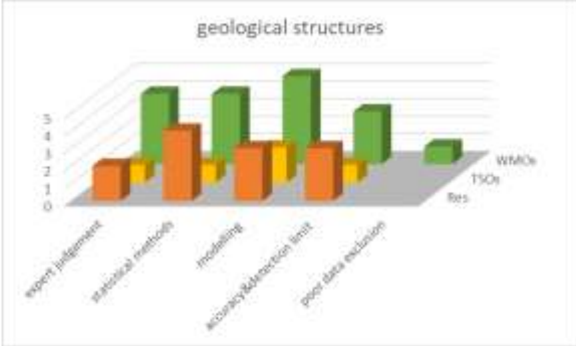


Figure 12. Actors' preferences in the characterisation of uncertainties on geological structures

For example, WMOs tend to use more frequently statistical methods for the characterisation of the uncertainty about homogeneity of the site, and the modelling for the characterisation of the uncertainties associated with the geological structure, and both of them in the characterisation of the structural and geometric data of the site. (*Figure 13*).

Instead, REs prefer to apply statistical methods for characterizing uncertainties on geological structures and accuracy of measurements and detection limit of equipment for the characterisation of the uncertainty associated with homogeneity.

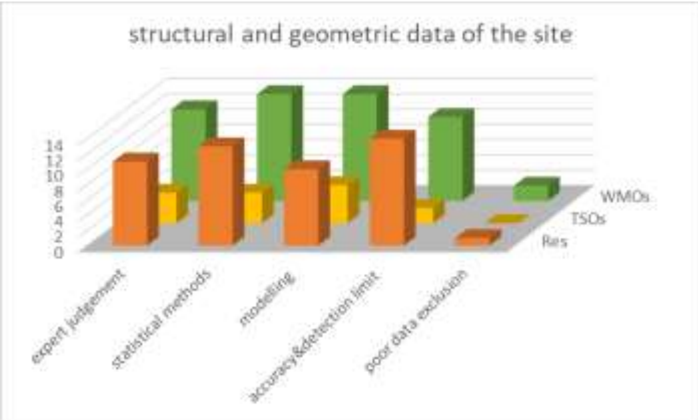


Figure 13. Actors' preferences in the characterisation of uncertainties on structural and geometric data of the site

3.1.3 Uncertainty evolution in time

These uncertainties are higher in the first phases of a disposal programme, when the site is not yet known or is not well characterized *Figure 14*.

Almost all responding **REs'** agree that during the site selection and characterisation stages, information on the site topography, stratigraphy, homogeneity and potential geological structures will be continuously acquired. Site characterisation and activities developed in underground laboratory will bring data improving the knowledge of the properties of the host rock, and surrounding layers and aquifers, reducing therefore the uncertainties until a certain level.

Site monitoring will also help reduce uncertainties by accumulating more site-relevant data, better knowledge, and improved conceptual models.

For geological disposal, new methodologies for the deterministic modelling of site evolution, including more extensive confidence estimates (currently under development in the more advanced programmes) and further adjustments, testing and development of such methodologies (expected during the construction of the geological repository) could reduce the uncertainties on site homogeneity. However, in the WMOs views the uncertainty on site homogeneity is expected to remain high even after the first stages of a disposal programme. In the TSOs vision, remaining uncertainty will be minor and will have no impact on safety.

Figure 14. Significance evolution of the uncertainties associated with structural and geometric data of the site, along the programme

3.2 Uncertainties on thermal and mechanical properties of the undisturbed host rock (B)

3.2.1 Significance for safety

Geological disposal

All three categories of actors consider that uncertainties associated with the geo-mechanical and thermal properties of the disposal site and internal stress field of the host formation have significant impacts (medium to high) on the disposal safety (*Figure 15*), both during the operation and post-closure phases (*Table 4*).

In the pre-disposal stage, the knowledge of the thermal properties is important for the repository design, for defining its structures and the density of waste loading in the disposal galleries, and, in the case of Belgium, even for the waste classification.

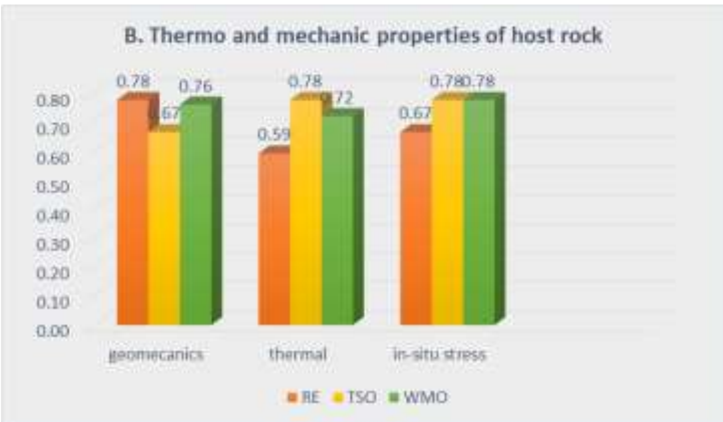


Figure 15. Significance for safety of uncertainties related to thermo-mechanical properties of the undisturbed rocks, in the case of geological disposal

Uncertainties related to the in-situ stress field, associated to the unknown anisotropic behaviour of the host rock formation and the future development of the host rock anisotropy, must be considered in the disposal canister design and the repository loading. It has to be accounted for in defining construction margins of the repository (in supports of galleries and disposal cells, for instance).

Table 4. Synopsis of the actors' views on uncertainties related to thermal and mechanical properties of the undisturbed host rock for geological disposal ((h – high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on: (number of answers)**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Geo-mechanical properties	0.78	4m; 1l; 4h	0.67	1l; 1h; 1m; 1n	0.76	3m; 3h; 1l	xxxxxx	xxxxxxxxx	xxxxxxxxxx
Thermal properties	0.59	4l; 3m; 2h	0.78	1h; 2m; 1n	0.72	3m; 2h;1l;1n	xxx	xxxxxxxxx	xxxxxxxxxx
In situ stress field	0.67	4m; 1n; 2h;2l	0.78	1h; 2m; 1n	0.78	3h; 2m; 1l;1n	xxxxx	xxxxxxxxx	xxxxxxxxx

Near surface disposal

For a near surface disposal, these uncertainties have a low significance for all actors answering the questionnaire (*Figure 16*), with the exception of the uncertainties on geo-mechanical properties, which according to some REs could have a certain relevance for safety (*Table 5*).

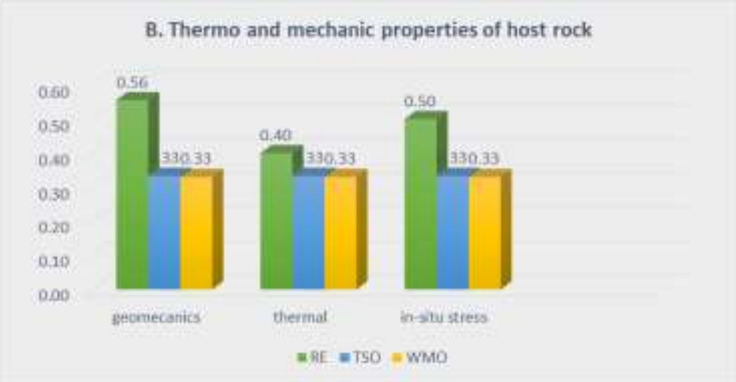


Figure 16. Significance for safety of uncertainties related to thermo-mechanical properties of the undisturbed rocks – near surface disposal

A reason could be, for example, siting the repository on a deposit in a soil susceptible to moisture, which could collapse or suffer differential settlements as the water content in the foundation layer increases. In this case, the integrity of the disposal cell could be lost, causing the loss of its isolation and confinement function and, consequently, leading to a faster release of radionuclides through the new created transport pathways.

Table 5. Synopsis of the actors' views on uncertainties related to thermal and mechanical properties of the undisturbed host rock for near-surface disposal (h-high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	Score of uncertainty relevance for safety						Impact on: (number of answers)		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Geo-mechanical properties	0.56	4l; 2h	0.33	3l	0.33	1l	xxx	xx	xx
Thermal properties	0.40	4l; 1m; 1n	0.33	2l	0.33	1l	x	x	
In situ stress field	0.50	3l; 2n; 1h	0.33	2l	0.33	1l	x	x	x

3.2.2 Uncertainty characterisation

The preferences of the different actors for the characterisation of the uncertainties associated with thermal and mechanical behaviour of the "undisturbed" host-rock are given in *Figure 17* and *Figure 18*. No important differences between these preferences were noted.

Statistical methods seem to be the most frequent used in the parametric uncertainty characterisation by all actors. Modelling and expert judgement are also largely applied in the characterisation of all three types of uncertainties associated with the thermal and mechanical properties of the undisturbed host rock.

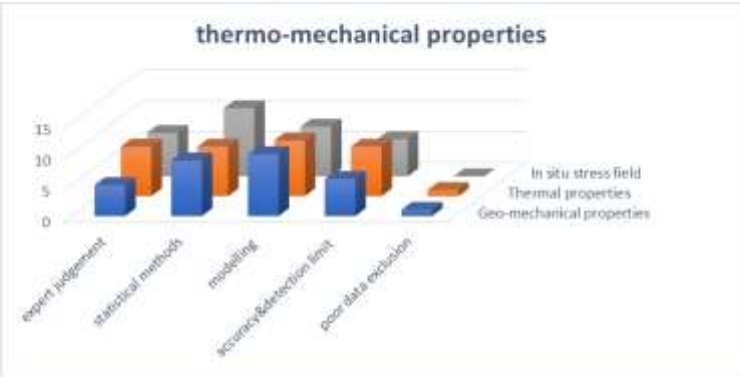


Figure 17. Frequency of the methods used in characterisation of uncertainties related to thermo-mechanical properties of the site

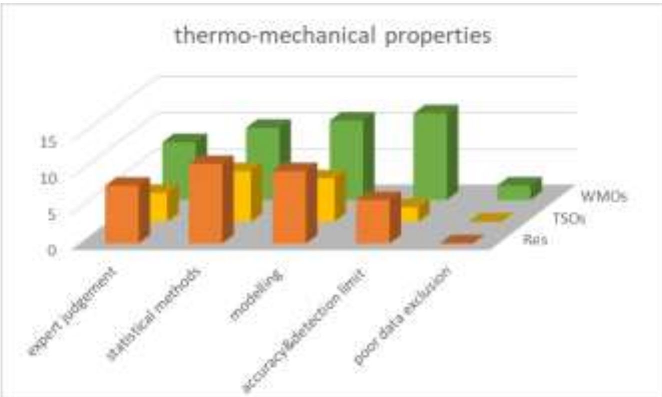


Figure 18. Actors' preferences in the characterisation of uncertainties on thermo-mechanical properties of the host rock

3.2.3 Uncertainties evolution in time

All actors agree that all these uncertainties will decrease during programme implementation. The uncertainty will reduce as host rock and site are selected and more data (especially from reproductible tests) on geo-mechanical properties are collected (*Figure 19*).

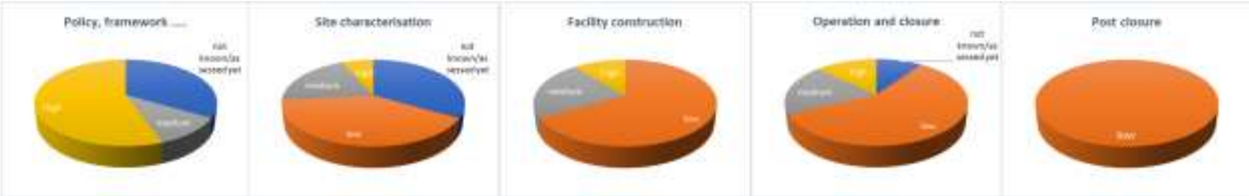


Figure 19. Significance evolution of the uncertainties associated with thermo-mechanical properties of the host rock, along the programme

The selection of a homogenous site could reduce the variability and therefore the uncertainty. For example, uncertainty on geo-mechanical properties, including stress field, relevant for geological disposal, will decrease with site characterisation and in situ measurements. Similarly, uncertainty on thermal properties of the host rock will progressively decrease combining in-situ measurements and modelling. However, there is a need to adapt the design (space the disposal cells of exothermic waste from each other) to account for this uncertainty.

3.3 Uncertainties associated with hydraulic conditions and liquid and gas flow in the undisturbed host rock (C)

3.3.1 Significance for safety

Geological Disposal

Liquid and gas flow in the undisturbed host rock is the main process contributing to the radionuclide transport from the repository to the biosphere. Kinematic porosity, hydraulic conductivity, hydrostatic pressure and hydraulic gradients, together with the gas phase properties, are the main parameters defining the water and gas flow fields, the key vectors of the radionuclide transport.

According to the three types of actors (REs, TSOs and WMO), the uncertainties on these parameters and processes have a great relevance for the disposal safety (medium to high) (*Figure 20*), due to their possible impact on the safety functions of the natural barriers.

Of all these uncertainties, hydraulic conductivity of the host rock has been rated with the highest score for its significance-for-safety (*Table 6*), and will be discussed in more detail below.

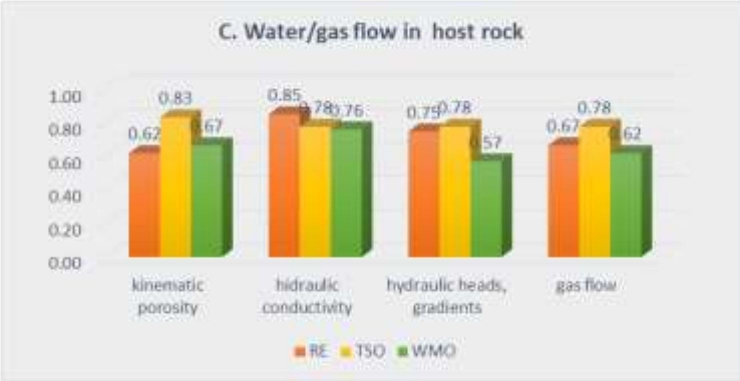


Figure 20. Significance for safety of uncertainties related to the hydraulic conditions and liquid and gas flow in the undisturbed host rock - geological disposal

Table 6. Synopsis of the actors' views on uncertainties related to hydraulic conditions and liquid and gas flow in the undisturbed host rock for geological disposal (h-high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	Score of uncertainty relevance for safety						Impact on: (number of answers)		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Kinematic porosity	0.62	4m; 2l; 1h; 2n	0.83	1h; 1m; 2n	0.67	1m; 3h; 3l	xxx	xxxxxxxxxx	xxxxxx
Hydraulic conductivity	0.85	6h; 2m; 1l	0.78	1h; 2m; 1n	0.76	4h; 1m; 2l	xx	xxxxxxxxxx	xxxxxxxxxx
Hydraulic heads and gradients (including abnormally high pore pressures)	0.75	4m; 3h;1l; 1n	0.78	1h; 2m; 1n	0.57	2h; 1m; 4l	xx	xxxxxxxxxxx	xxxxxxx
Gas flow properties and processes	0.67	3h; 3n; 3m	0.78	2h;1l;1n	0.62	2h; 3l;2m	x	xxxxxx	xxxxx

The high level of significance **for REs** is justified by the uncertainty associated to the time for the re-saturation of the host rock affected by repository construction. Hydraulic conductivity governs the advective flow responsible for filling the void pores with the underground water. Hydraulic conductivity is also a key parameter of the migrations pathways to the surface, even in the absence of a fracture system. In clay rocks with low hydraulic conductivity, where the radionuclide transport is controlled by diffusion, the uncertainty on hydraulic conductivity is recognized as being less important.

For TSOs, hydraulic conductivity is one of the factors influencing the flow of groundwater through the rock mass. Water flow in the repository may become significant if hydraulic conductivity of the host rock and hydraulic heads are underestimated.

WMOs underlined as well the role of hydraulic conductivity in governing the Darcy and flow-related transport resistance fluxes, with a direct impact on the radionuclide transport rates and advective travel times.

As noticed by **all actors,** hydraulic conductivity of the host rock is important for the safety functions of the disposal system related to radionuclides immobilization, retention and slow release. A low hydraulic conductivity is important in limiting the water flow in the host rock, reducing the radionuclide transport rate.

Both **REs** and **WMOs** noticed the governing role played by the hydraulic conductivity in the rate of the erosion of the bentonite buffer and copper canisters corrosion.

Near surface disposal

In the case of near surface disposal, uncertainties related to hydraulic conditions and liquid and gaseous flows are estimated to a low-to-medium impact by all actors (*Table 15*).

Table 7. Synopsis of the actors' views on uncertainties related to hydraulic conditions and liquid and gas flow in the undisturbed host rock for near-surface disposal (h-high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Kinematic porosity	0.53	3m; 2l	0.44	2l; 1m;1n	0.33	1l	xxx	xxxxxxxxxx	xxxxxx
Hydraulic conductivity	0.53	1m; 3l; 1h	0.56	2m; 1l	0.33	1l	xx	xxxxxxxxxx	xxxxxxxxxx
Hydraulic heads and gradients (including abnormally high pore pressures)	0.53	3m; 2l	0.67	3m	0.33	1l	xx	xxxxxxxxxxx	xxxxxxx
Gas flow properties and processes	0.60	3l; 2h	0.44	2l;1m;1n	0.33	1l	x	xxxxxx	xxxxx

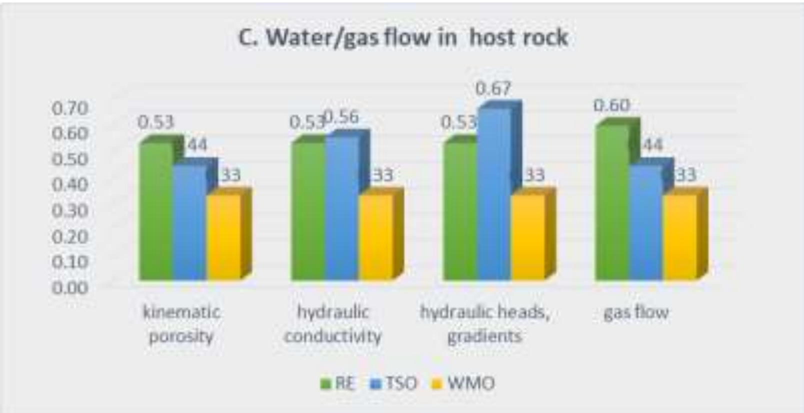


Figure 21. Significance for safety of uncertainties related to the hydraulic conditions and liquid and gas flow in the undisturbed host rock – near surface disposal

Of all uncertainties related the water and gas flows, those on hydrostatic pressure and hydraulic gradients in the host rock are rated by the TSOs with the highest significance for post-closure safety, while uncertainties on the gas flow received the higher score from REs (

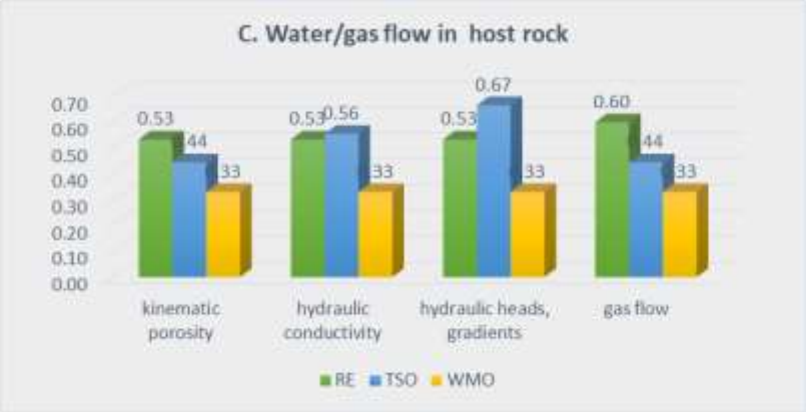


Figure 21).

3.3.2 Uncertainties characterisation

There is a variety of methods which can be used for the characterisation of the uncertainty associated with hydraulic conductivity (*Figure 22*). **WMOs** indicated a statistical analysis of relevant/measured data, based on laboratory and in-field measurements, modelling and accuracy of measured data and detection limit as the most applied methods for such uncertainty characterisation.

REs underlined that extrapolation from laboratory scale to a larger scale is difficult, and that little information about associated uncertainty is available. Large scale values determined indirectly need to consider uncertainty propagating from the original data. This is usually not directly supported by the tools, and REs recommend the use of a combination of practiced conductivity estimates with non-intrusive stochastic methods.

TSOs noticed that the hydraulic conductivity of the host rock can be quantified based on lab testing and data (which however need to be upscaled) and model calibration. It was also pointed out that, depending on the values considered for the hydraulic conductivity, the impact of local overpressure (0.5MPa more than expected at this depth) may become not negligible.

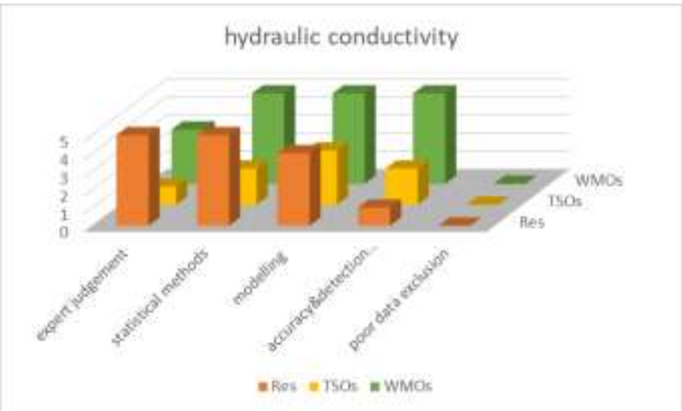


Figure 22. Actors' preferences in the characterisation of uncertainties on hydraulic conductivity

Uncertainty characterisation may be covered by scenarios or sensibility analyses.

Methods for the characterisation of uncertainties associated with hydraulic conductivity have been established by the most advanced programmes and are available (for example SKB TR-11-01 [5] and R-09-20 [6]).

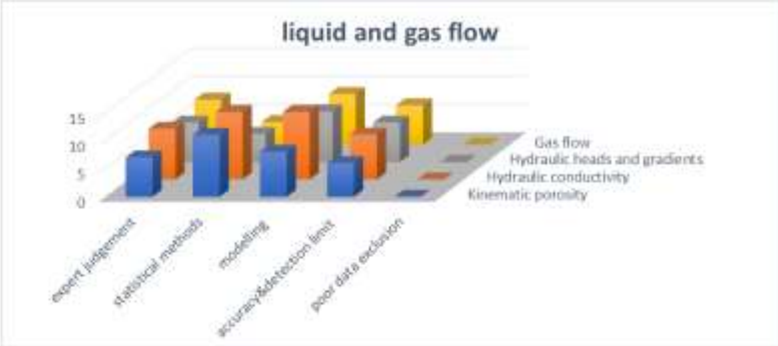


Figure 23. Frequency of the methods used in characterisation of uncertainties related to liquid and gas flow in undisturbed host rock

Preferences for the other types of uncertainties related to liquid and gas flow in the host rock are illustrated in *Figure 23* and *Figure 24*.

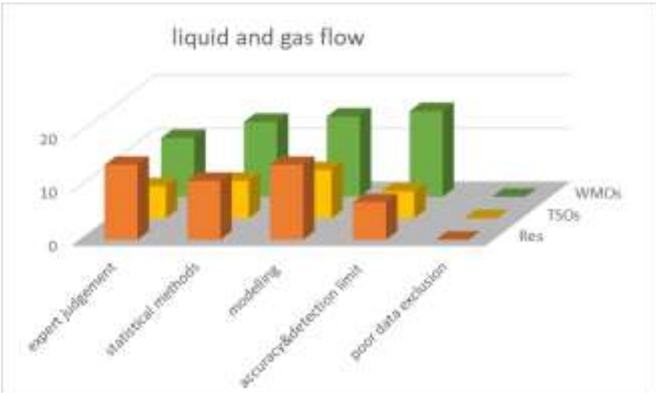


Figure 24. Actors' preferences in the characterisation of uncertainties on liquid and gas flow in host rock

3.3.3 Uncertainty evolution in time

The uncertainty on hydraulic conductivity of the host rock will reduce as the host rock and site are selected, and as more data on hydrogeology and hydraulic properties are collected (*Figure 25*). The selection of a homogenous site will reduce the variability and therefore the uncertainty. This view is shared by all types of actors.

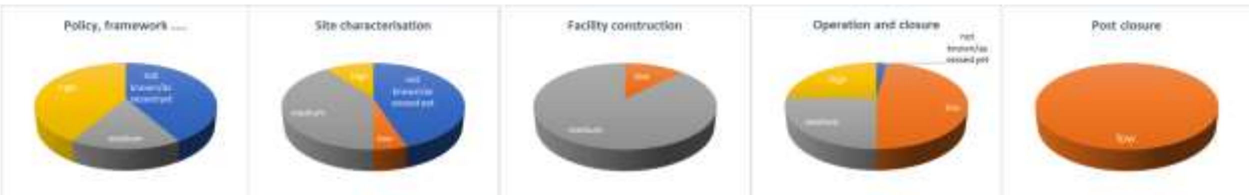


Figure 25. Significance evolution of the uncertainties associated with on liquid and gas flow in host rock, along the programme

However, uncertainties on hydraulic conductivity associated with future conditions of the site are large and difficult to be evaluated.

3.4 Uncertainties associated with EDZ properties (D)

3.4.1 Significance for safety

Geological disposal

The uncertainties associated with the EDZ properties, such as the hydraulic, geochemical, geo-mechanical and thermal properties, microbial activity, as well as the gas flow properties and processes, have been evaluated, with few exceptions, as having a medium significance for the geological disposal safety.

Among the parameters and processes governing the EDZ evolution, the highest significance for safety has been given by TSOs to the uncertainties related to hydraulic properties, geochemistry and microbial activity, and geo-mechanical properties of the EDZ (*Figure 26*).

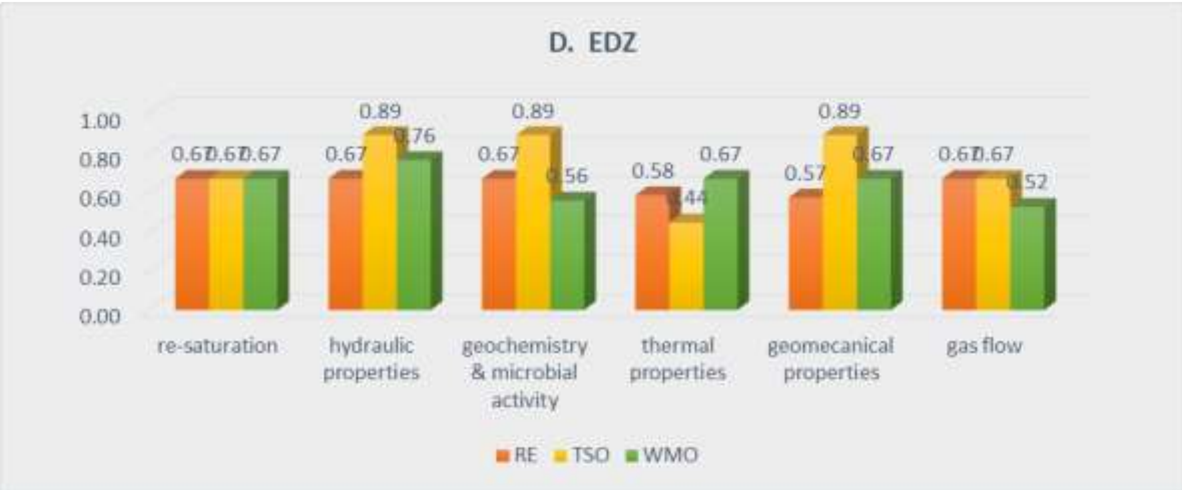


Figure 26. Significance for safety of uncertainties related to EDZ properties – geological disposal

The impact of these uncertainties, either high or medium, is mostly associated with the post-closure dose/risk assessment and safety functions of the host rock, and in a very little extend with the operational safety (*Table 8*).

Table 8. Synopsis of the actors' views on uncertainties related to EDZ properties for geological disposal (h-high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Water (re-) saturation	0.67	5m; 2h; 2l	0.67	3m; 1n	0.67	3h; 1m; 3l	xx	xxxxxxx	xxxxxxx
Hydraulic properties	0.67	4m; 2h; 2l; 1n	0.89	2h; 1m; 1n	0.76	4h; 1m; 2l	x	xxxxxxxx	xxxxxxx

Geochemistry and microbial activity	0.67	3m; 2l; 2h; 2n	0.89	2h; 1m; 1n	0.56	1h;2m; 3l;1n	x	xxxxxxx	xxxx
Thermal properties	0.58	2m; 2h; 4l;1n	0.44	1m; 2l; 1n	0.67	1m; 3l; 3h	x	xxxx	xxxxx
Geo-mechanical properties	0.57	3m; 3l; 1h; 2n	0.89	2h; 1m; 1n	0.67	1m; 3l; 3h	xxx	xxxxx	xxxxxxxx
Gas flow properties and processes	0.67	3m; 2l; 2h; 2n	0.67	1h; 1m; 1l;1n	0.52	2m; 4l; 1h	x	xxxxx	xxx

3.4.2 Uncertainties characterisation

Methods mostly used in the EDZ uncertainties characterisation by all actors are: modelling, statistical methods applied to the parametric uncertainties and use of the accuracy and detection limits (Figure *27*).

The preferences by each type of actors are shown in *Figure 28*.

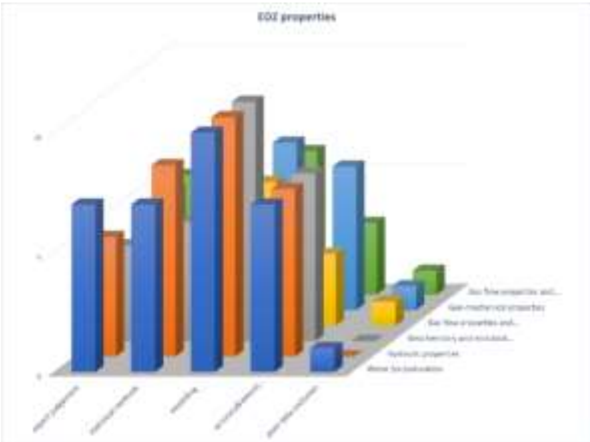


Figure 27. *Frequency of the methods used in characterisation of uncertainties related to EDZ properties*

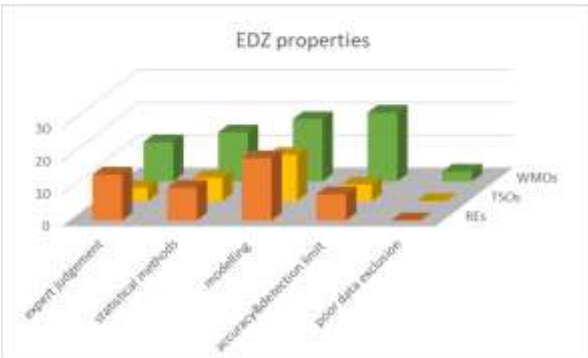


Figure 28. Actors' preferences in the characterisation of uncertainties on EDZ properties

3.4.3 Uncertainty evolution in time

All actors consider that the uncertainty will reduce as more data on EDZ characterisation will be available and more knowledge in gas flow processes will be developed (*Figure 29*). Long term measurements in underground laboratories, as well as measurements during disposal operation, can considerably reduce these uncertainties. Indeed, re-saturation is a very complex process, but modelling and experiments carried out by advanced geological disposal programmes (as for example those in the Cigéo Pilot phase) can contribute in decreasing this uncertainty.

Some uncertainties will certainly remain, especially with regards to the long-term evolution of the unsealed parts of the EDZ.

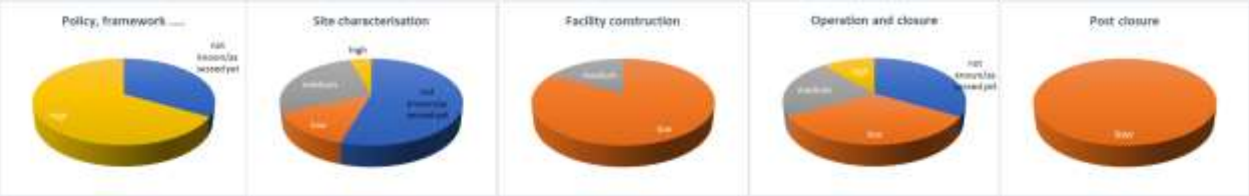


Figure 29. Significance evolution of the uncertainties associated with the EDZ properties, along the programme

3.5 Uncertainties associated with hydraulic conditions and properties of adjacent aquifers (E)

3.5.1 Significance for safety

Geological disposal

Uncertainties associated with the hydraulic conditions and the properties of adjacent aquifers showed a low-to-medium significance for the safety aspects of the geological disposal in the view of REs and WMOs (*Figure 30* and Table 9), while the TSOs answers give a higher significance to the uncertainties on the parameters defining aquifer recharge and discharge and the groundwater flow field: flow rates, dominant directions. The uncertainty on the connectivity between aquifers has only a medium relevance for the disposal safety for all actors.

Uncertainties on these parameters could impact both the post closure dose assessment due to underestimation of the radionuclides release in the biosphere, and, more generally, the safety functions of the geologic environment concerning the radionuclide immobilization, retention and slow release.

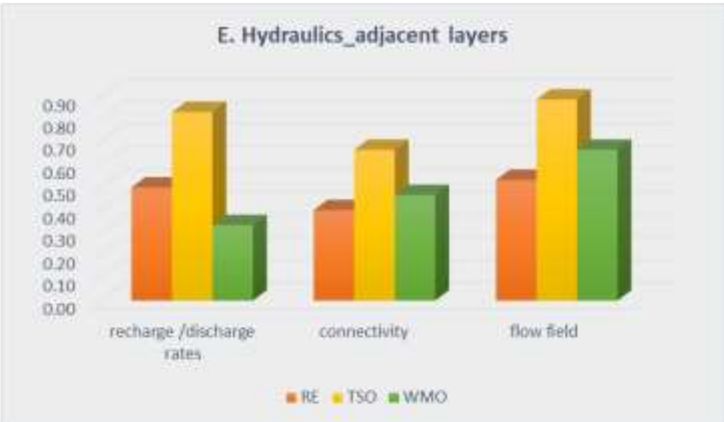


Figure 30. Significance for safety of uncertainties related to hydraulic conditions and properties of adjacent aquifers (DGD)

Table 9. Synopsis of the actors' views on uncertainties related to hydraulic conditions and properties of adjacent aquifers for geological disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Recharge and discharge estimates of local and regional hydrogeological units	0.50	1m; 5n; 1h;2l	0.83	1h; 2n; 1m	0.33	5l; 2n	x	xxx	xxxx
Local and regional hydraulic interrelationships between aquifers (connectivity)	0.40	4l; 4n; 1m	0.67	1h; 2n; 1l	0.47	1h; 4l;2n	x	xxx	xxx
Groundwater flow fields (average flow rates, prevailing directions)	0.53	1h; 1m; 3l;4n	0.89	2h; 1m; 1n	0.67	1h; 2m; 1l;3n	x	xxxxxx	xxxx

Near surface disposal

With the except of the uncertainty on the flow field parameters, all the other uncertainties have been rated with a low and medium significance for a near-surface disposal safety by all actors answering the questionnaire (*Figure 31* and *Table 10*) *Figure 31. Significance for safety of uncertainties related to hydraulic conditions and properties of adjacent aquifers (NSD)*.

Uncertainty on flow field in the aquifer is of high concern for the majority of the responding REs due to the impact on the radionuclide transport pathways and their travel time towards the biosphere, and consequently, on the post-closure dose assessment. The lower the depth of the aquifer the higher the impact of the flow field uncertainties on the radionuclides release estimations.

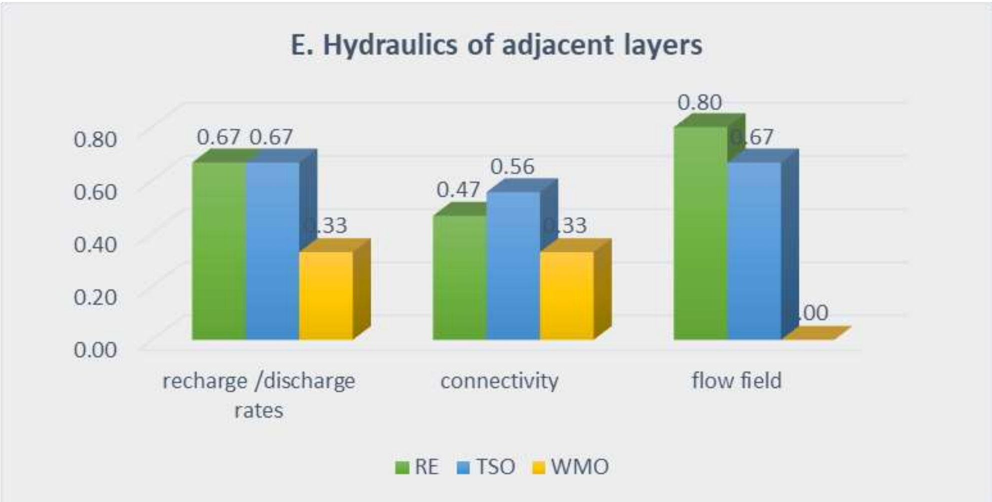


Figure 31. Significance for safety of uncertainties related to hydraulic conditions and properties of adjacent aquifers (NSD)

Table 10. Synopsis of the actors' views on uncertainties related to hydraulic conditions and properties of adjacent aquifers for near surface disposal (h-high, m-medium, l-low, n-not known or addressed yet)

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on: (number of answers)**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Recharge and discharge estimates of local and regional hydrogeological units	0.67	1l;3m; 1h; 1n	0.67	1h; 1m;1l;1n	0.33	1l	x	xxxx	xx
Local and regional hydraulic interrelationships between aquifers (connectivity)	0.47	3l; 2m	0.56	1h; 2l; 1n	0.33	1l	x	xx	x
Groundwater flow fields (average flow rates, prevailing directions)	0.80	1l; 1m; 3h	0.67	2m; 1h; 1l	0		x	xxxx	xx

3.5.2 Uncertainty characterisation

The methods used for the characterisation of the uncertainties associated to hydraulic conditions and properties of adjacent aquifers and the actors' preferences are similar with those used for the uncertainties associated with host rock (*Figure 32*, *Figure 33*).

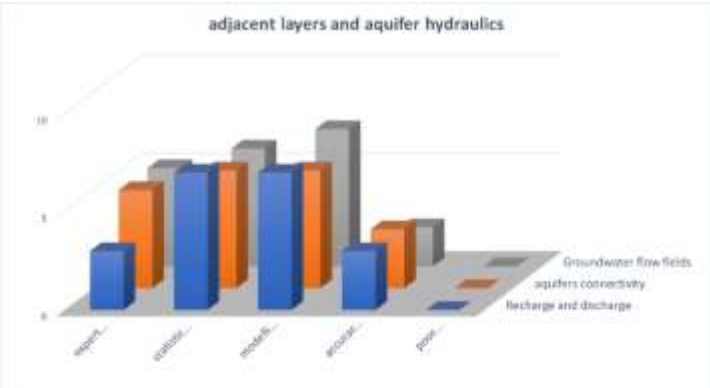


Figure 32. Frequency of the methods used in characterisation of uncertainties related to hydraulic properties of adjacent layers and aquifers

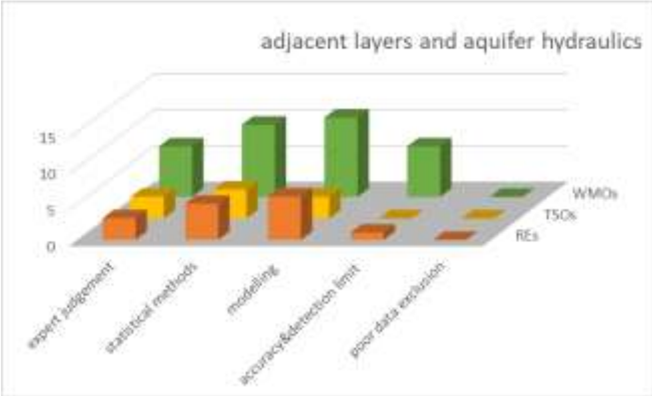


Figure 33. Actors' preferences in the characterisation of uncertainties on hydraulic properties of the adjacent layers and aquifers

3.5.1 Uncertainty evolution in time

The uncertainties related to the hydraulic properties of the adjacent layers are of higher importance in the safety case of near surface and sub-surface disposal. Connectivity between the aquifers, hydraulic heads and flow parameters in the adjacent aquifers are either unknown or only little information is available at the beginning of the programme. Site characterisation will bring data and evidences which will confirm hypothesis and models, reducing progressively the uncertainties. As *Figure 34* shows, there is a clear trend in increasing the share of low significance in the actors' views, as the programme evolves.

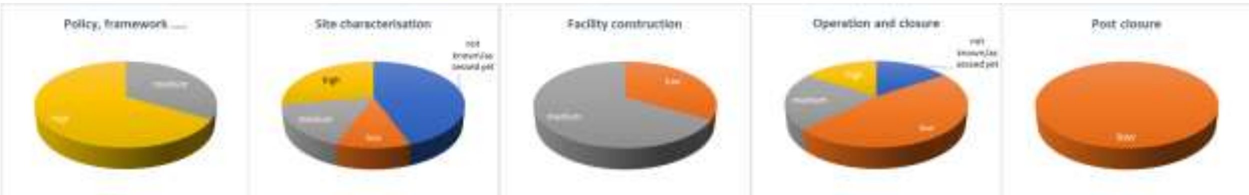


Figure 34. Significance evolution of the uncertainties on hydraulic properties of the adjacent layers and aquifers, along the programme

3.6 Uncertainties associated with geochemistry and solute transport properties in the host rock and EDZ (F)

3.6.1 Significance for safety

Geological disposal

Radionuclide transport is a very complex process involving a large number of geochemical and transport properties of the host rock: mineralogy, rock and water chemistry, solubility limits of the radionuclides, sorption parameters, diffusion coefficient, colloids, which could change over the long-term period considered for the geological disposal safety assessment, either due to the repository presence, or climate evolution.

The geochemistry of the host rock and radionuclide transport properties are those characteristics of the site determining the behaviour of radionuclides in the geological environment and their migration to local aquifers. Uncertainties associated with these parameters could generate uncertainties on the radionuclide speciation, interaction with the host rock and their mobility, which might lead to underestimation of contaminant release into the biosphere, with consequences on the estimation of the dose or risk in the post-closure phase. In parallel these uncertainties could also mislead in the evaluation of the safety function of the rock related to immobilization, retention and slow release of radionuclides.

Geochemical and solute transport properties in the host rock and the EDZ are predominantly collected from samples – drill cores, water samples – taken directly from the site-specific rock, or from "similar" rocks, where samples are easier to be taken, and investigated in laboratory experiments. Therefore, safety relevant properties such as transport porosity, sorption properties, etc. are determined based on these samples. For an evolved site investigation, an underground laboratory might be used to confirm initial sampling and sample analysis through onsite characterisation and experiments.

The questionnaire included 7 types of uncertainties associated with geochemistry and solute transport properties in the host rock and EDZ:

- Chemical, radiochemical and mineralogical composition of the rock (porous medium or fracture – matrix system properties)
- Groundwater chemistry
- Solubility limits
- Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)
- Diffusion coefficients
- Colloid (facilitated) transport
- Changes in the transport properties due to precipitation/dissolution reactions

It has to be mentioned that none of the respondents to the questionnaire indicated a missing uncertainty issue for this group of uncertainties.

Figure 35 shows a summary input of all actors on all 7 items related to parameter and process uncertainty for geochemistry and radionuclide transport in the host rock and EDZ with respect to relevance for safety for deep geological disposals. Responds related to deep geological disposal might be looked at as the most representative, because here was by far the largest input from the respondents. The three categories of actors agree on the relative high significance (medium to high) for safety of all these uncertainties (*Figure 35*). A lower significance is given, in average, to uncertainties on the colloidal transport and, respectively, changes in the transport properties which, in the view of TSOs and WMOs, have mostly a low relevance (*Table 11*). However, they remain of interest for REs.

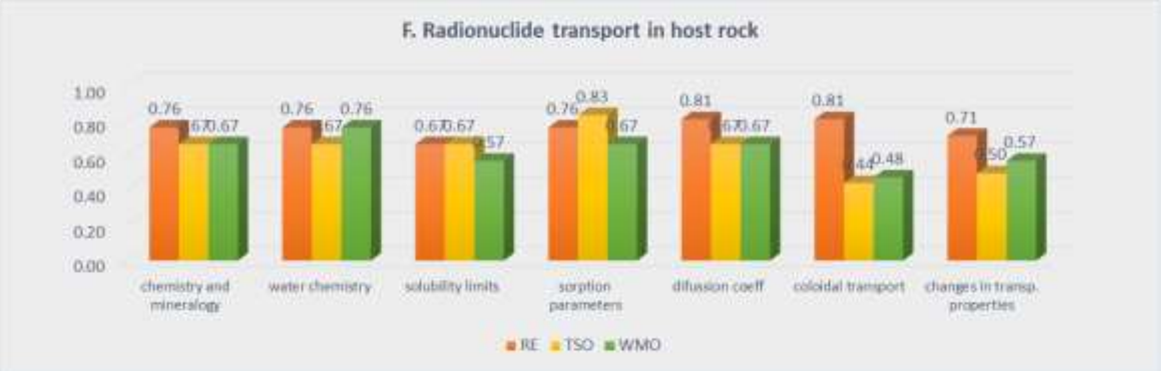


Figure 35. Significance for safety of uncertainties related to geochemistry and solute transport properties in the host rock and EDZ

The significance for safety was justified by some of the respondents who provided explanations to their indication.

Therefore, in the view of a RE from a more advanced programme, mineralogical composition of the reference host formation is well known, but larger uncertainties are associated with the type and amount of the organic matter and, consequently, its complexation potential, with pyrite content, which affects the redox conditions and (after oxidation in the near field) with the potential presence of sulphates/thiosulphates.

The **REs** views converge on the impact of geochemical properties on the radionuclides speciation and transport properties. Uncertainty in sorption parameters is associated with uncertainty on transportable fraction of RN. Due to strong sorption, the most toxic nuclides (Actinides and Tc) move only few meters before decay. However, some RN (like U^{VI}) may form anionic ternary carbonate complexes leading to low retention. Sorption of actinides may also be low in the vicinity of salt and organic containing wastes like bitumen, not only due to complexation, but also to potential oxidation by nitrates.

In clay rock, uncertainties on mineralogy and chemistry have a high significance for safety because they influence porewater chemistry and deviation between anionic and total porosity. These characteristics influence as well the redox state and carbonate partial pressure.

Also, **REs** answers pointed out the uncertainty associated to the reversibility of the sorption process. Partial irreversible sorption can strongly reduce the transportable RN fraction. Also competition with natural elements is important, for example between RN and Fe^{+3} arising from container.

High significance for safety of the uncertainties on pore water chemistry are associated with carbonate, redox, small transportable organic molecules, pH and ionic strength. Even in the overall reducing water, local oxidation might occur by waste components, even in low ionic strength, high values can be caused for example by salts containing waste like bitumen. This will have strong impacts on RN solubility and sorption.

Uncertainties on host mineralogy has also impact on colloid formation, complexation, redox reactions, solid solution formation are all considered highly significant for the disposal safety.

- High uncertainty on rock composition could however have a medium importance due to the concept-dependent significance.

For **TSOs**, uncertainty on sorption parameters is important because the Kd model and sorption parameters for most radionuclides are chosen by analogy with few RNs, and this has indirect impact on the dose estimates. Uncertainties on the sorption of some radionuclides in the host rock (e.g. uncertainties on Kd of U in clay due to the presence of organic matter) can have a significant impact on radionuclide concentration in the aquifer.

Beside the impact of host rock composition on the transport properties, WMOs bring new views such as capsule failure as result of the copper corrosion via sulphide.

High significance of uncertainties on rock microstructure and composition is associated by all actors (especially for those in an advanced phase of implementation) with the impact on post closure dose and with the safety function of the host rock related to immobilisation, retention and slow release of radionuclides.

High to medium relevance for safety of the uncertainties on groundwater chemistry is linked to its impact, on the RN speciation, which in turn affects the solubility and transport properties, recognized by all actors.

- Minor effect on bentonite saturation and mineralogical changes. Strong effect on retention (item of sorption below) but possibly hidden, if non-sorbing radionuclides dominate; uncertainty also relates to taking data from laboratory samples in different conditions than in-situ.

Table 11. Synopsis of the actors' views on uncertainties related to geochemistry and solute transport properties in the host rock and EDZ for geological disposal

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on: (number of answers)**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Chemical, radiochemical and mineralogical composition of the rock (porous medium or fracture – matrix system properties);	0.76	2h;5m; 1n	0.67	1h; 1l; 2n	0.67	3h; 3l; 1m	x	xxxxxxxx	xxxxxxx
Groundwater chemistry	0.76	3h; 3m; 1l; 1n	0.67	1h; 1l; 2n;	0.76	4h;1m;2l	x	xxxxxxx	xxxxxxxx
Solubility limits	0.67	2h; 3m; 2l; 1n	0.67	2m; 2n	0.57	1h; 3m; 3l	x	xxxxxx	xxxxx
Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)	0.76	3h; 3m; 1l; 1n	0.83	1h; 1m; 2n	0.67	2h; 3m; 2l	x	xxxxxxx	xxxxxxx
Diffusion coefficients	0.81	3h; 4m; 1n	0.67	1h; 1m; 1l; 1n	0.67	2h; 3m; 2l	x	xxxxxxxx	xxxxxx
Colloid (facilitated) transport	0.81	4h; 2m; 1l;1n	0.44	1m; 2l;1n	0.48	3m; 4l	x	xxxx	xxxxxx
Changes in the transport properties due to precipitation/dissolution reactions	0.71	2h; 2m; 3l;1n	0.50	1m; 1l; 2n;	0.57	2h;4l; 1m	xx	xxxxxx	xxxxx

Of all these uncertainties, the uncertainty about the sorption parameters distinguishes by the high safety relevance given by the three categories of actors, as shown in *Table 11* and illustrated in *Figure 36* for deep geological disposal and *Figure 37 Figure 37*for near surface disposal, respectively (comparison to sub surface disposal has been ignored due to a few respondents to this option only). Again, replies were sorted depending on the college (RE, TSO, WMO) and on the individual categories of uncertainties associated with geochemistry and solute transport properties in the host rock, but without weighting them in order to compare directly the individual college shares of replies to the different topics (and options).

What is in common is that high importance for safety is more often expressed from REs than from WMOs and TSOs for Deep Geological Disposal and Near Surface Disposal. It is also a bit astonishing that there is no topic with the same significance distribution for all colleges (the same colours in one row) for the Deep Geological Disposal (*Figure 36*). The reason might be that the respondents are in different programme phases.

REs noticed that there are many sources of uncertainties associated to sorption. Uncertainties on sorption parameter (Kd) propagate to uncertainties on the radionuclide transportable fraction. However, the impact is not the same for all radionuclides: for example, in sedimentary rocks, due to strong sorption properties, the most toxic nuclides (Actinides and Tc) move only few meters before decay. Complexation of some radionuclides could also reduce their retention on the host rock minerals (for example U^{VI} may form anionic ternary carbonate complexes leading to low retention).

Sorption of actinides or other radionuclides may also be decreased if the host rock contains dissolved organic matter (acting as vector and sink) which translates in a larger uncertainty due to the oxidation process.

Another uncertainty associated to sorption is the question of reversibility. Partial irreversible sorption can strongly reduce the transportable fraction of radionuclides. Also competition with natural elements is important, for example between radionuclides and Fe^{+3}.

Uncertainty could also come from the possible changes in the groundwater chemistry.

There are also cases when uncertainty on sorption is determined by the uncertainty on the speciation of the migrating species (metastable elements or mixture of species).

For **TSOs**, the uncertainty source is associated to the Kd model used in the estimation of the sorption parameters. For most radionuclides, the sorption data are chosen by analogy with a small number of radionuclides for which this parameter has been measured, and this method has an impact on the dose estimates. The uncertainties on the sorption of some radionuclides in the host rock (e.g. uncertainties on Kd of U in clay due to the presence of OM) can have a significant impact on radionuclide concentration in the aquifer. Chemical retention in the host rock could as well introduce uncertainties on the sorption values.

WMOs mentioned as well the impact in transport properties of the sorption related uncertainties as well as the impact on the safety functions of the geosphere related to immobilization, retention and slow release of radionuclides, which in the presence of these uncertainties could be overestimated.

Figure 36. Relevance for safety as given by all respondents from the different actors to all individual safety relevant topics on geochemistry and solute transport properties in the host rock and EDZ for geological disposal (RE - left, TSO - middle, WMO - right)

(■ Not answered, not known or assessed yet ■ low importance ■ medium importance ■ high importance)

Near surface disposal

In the case of near surface disposal, the significance of these uncertainties for safety is generally low, falling within a medium level range, except for the uncertainty on the sorption parameters and colloidal transport, which are considered to have a high significance for safety for majority of the REs answering the questionnaire (Figure 37 and Table 12). This is also the case of the safety analysis of the Romanian near surface disposal. The radionuclide transport model is extremely sensitive to Kd values; therefore, variations in the Kd value led to high impact on the value of the post-closure radiological dose.

Figure 37. Significance for safety of uncertainties related to geochemistry and solute transport properties in the host rock (NSD)

Table 12. Synopsis of the actors' views on uncertainties related to geochemistry and solute transport properties in the host rock for near surface disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Chemical, radiochemical and mineralogical composition of the rock (porous medium or fracture – matrix system properties);	0.39	3l; 2m	0.33	2l; 1n	0.33	1l	x	xx	x
Groundwater chemistry	0.60	4m; 1l;1n	0.44	2l;1m;1n	0.33	1l	x	xx	x
Solubility limits	0.67	3n; 1h; 1m; 1l	0.44	1m; 2l; 1n	0.33	1l	x	x	x
Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)	0.80	3h; 1m; 1l; 1n	0.42	2m; 1l	0.33	1l	x	xxx	x
Diffusion coefficients	0.39	4l; 1h	0.33	3l; 1n	0.33	1l	x	x	x
Colloid (facilitated) transport	0.83	4n; 1m; 1h	0.44	1m; 2l; 1n	0.33	1l	x	x	x

Changes in the transport properties due to precipitation/dissolution reactions	0.67	3n; 1l; 1m;1h	0.33	3l; 1n	0.33	1l	x	xx	

Figure 38. Relevance for safety as given by all respondents from the different actors (RE, TSO, WMO) to all individual safety relevant topics on "geochemistry and solute transport properties in the host rock and EDZ" for near surface disposal (*11* replies, 6 *RE (left), 4 TSO (middle), 1 WMO (right)* not shown).

(Not answered, not known or assessed yet low importance medium importance high importance)

Sub surface disposal

For the sub-surface disposal, there are only 5 answers to the questionnaire (1 RE, 2 TSO, 2 WMO), which does not give good statistical information. The only pattern, which seems to be consistent for all considered uncertainties, was that “high importance” was indicated only for those respondents which are in the phases of site characterisation (1) and site evaluation (2). From those being in the phase of facility operation (2), a few indicated medium but most of them indicated low importance for all the different categories of uncertainties (see *Figure 39*).

Figure 39. Screen shot of all 5 responses on uncertainties relevant for safety (all F, G, H – topics of the questionnaire) on sub surface disposal

(- high, – medium, – low, white – not known/not assessed yet)

3.6.2 Uncertainties characterisation

Characterisation of the uncertainty associated to sorption parameters and processes have been performed combining (*Figure 40*, *Figure 41*):

- modelling, equally used by all actors;
- quantification by expert judgement applying statistical methods on relevant (measured) data, mostly preferred by TSOs;
- accuracy of measurements and detection limit of equipment, used especially by WMOs and REs;
- exclusion of poor quality/inappropriate data (in reducing the order of magnitude).

Detailed experimental sorption studies, in situ studies for Kd, looking for desorption of natural trace elements representing key radionuclides can all contribute in acquiring information on the sorption processes and sorption parameters.

Figure 40 and *Figure 41* show that there are no clear preferences in the characterisation methods for any of the different actors. All methods proposed by the questionnaire have been used in uncertainty characterisation more or less equally for the different processes/parameters. However, a preference for “modelling (likelihood of events, geochemical databases…)” could be observed; at the same time, it seems that “exclusion of poor quality/inappropriate data (in reducing the order of magnitude)” is less often used, which may point out that a lot of poor quality data are (still) used.

REs recommend batch sorption experiments, which are well known techniques used in the estimation of the sorption parameters, from simple Kd to thermodynamic sorption constants. In this case the uncertainty of sorption parameters is given by the accuracy of the measurements and detection limits of the equipment, by the assumptions of model used in data computation and it is difficult to be quantified truthfully and deserve to be assessed.

Another method suggested by the **TSOs** is the component additivity approach, in which sorption is considered as the sum of radionuclide sorption on the individual (dominant) mineral components.

In addition, uncertainty characterisation can take benefit of the ranges of Kd values provided in different national safety cases (see e.g. NAGRA or ANDRA documents).

WMOs mentioned as a useful characterisation method the modelling of upper and lower bounding values, considering the upper and lower bounding values for the relevant parameters.

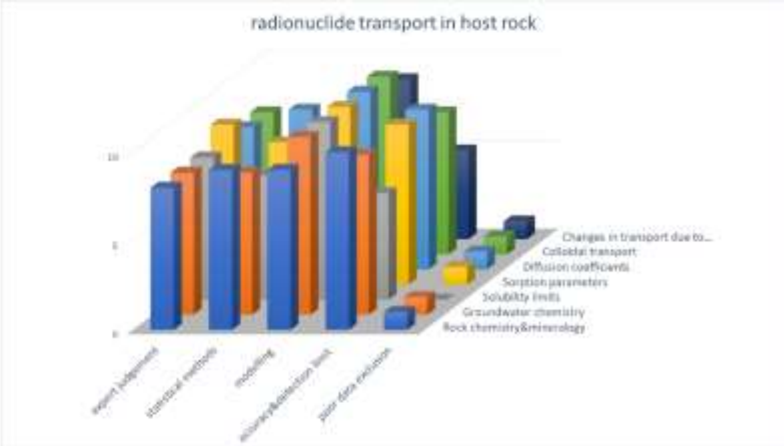


Figure 40. Frequency of the methods used in characterisation of uncertainties related to radionuclide transport in the host rock

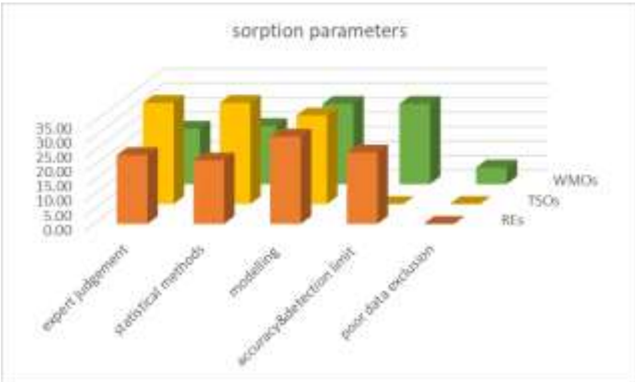


Figure 41. Actors' preferences in the characterisation of uncertainties on radionuclide transport in host rock

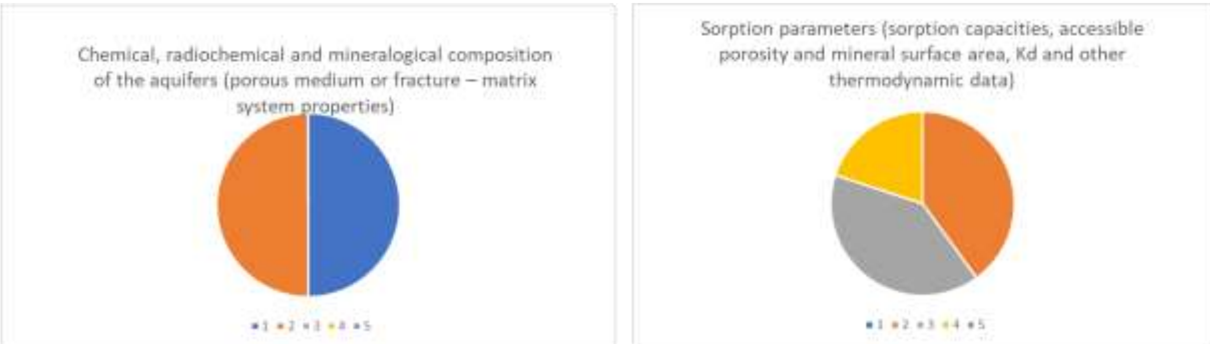


Figure 42. Options for characterisation methods of uncertainties for processes/parameters for Near Surface Disposal (2 replies on chemical composition, 5 replies on sorption).

(■ *quantification by expert judgement,* ■ *applying statistical methods on relevant (measured) data,* ■ *modelling,* ■ *measurements accuracy and detection limit of equipment,* ■ *exclusion of poor quality/inappropriate data)*

For Near Surface Disposal responses *Figure 42*, where only a small number of respondents answered, an equal distribution of the characterisation methods "quantification by expert judgement", "modelling (likelihood of events, geochemical databases…)" and "accuracy of measurements and detection limit of equipment" is observed. Due to the much smaller number of respondents, the variety of characterisation methods might be not representative.

3.6.3 Uncertainty evolution in time

The importance of uncertainty according to the indicated status of the individual programmes of the respondents yields about an indication how importance of uncertainty may change with the progressing programme. Within the questionnaire, the programme status could be chosen in between six different phases:

- Policy, framework and programme establishment
- Site evaluation and site selection
- Site characterisation
- Facility construction
- Facility operation and closure
- Post-closure

The indication of uncertainty significance has been assess based on the total number of the following types of answers:

- Not answered or uncertainty unknown or not assessed
- Uncertainty of low importance with regards to safety
- Uncertainty of medium importance with regards to safety
- Uncertainty of high importance with regards to safety

The number of replies is not enough large to have good statistics with respect to the different programme phases, or to identify trends of different colleges. However, generally, the indications vary from low to high importance for the different phases and the different colleges. The *Figure 43*, *Figure 44* and *Figure 45* are related to all replies, independent on the college (RE, TSO, WMO) for three different repository options.

Deep Geological Disposal

From 19 replies to Deep Geological Disposal, 5 respondents are in the phase of *Policy, framework and programme establishment*, 8 in the phase of *Site evaluation and site selection*, 3 in the phase of *Site characterisation* and 1 in the phase of *Facility construction*. There was no feedback from respondents being in the phases of *Facility operation* and *Post closure*.

From *Figure 43*, one can get the impression that importance of uncertainty related to safety is decreasing with the evolving phases. However, there are less respondents to later phases – in case of facility construction only one respondent from the WMO college, with an obvious reply. And high importance of uncertainty is indicated by about 1/3 of the respondents of the initial three phases underlining the importance of uncertainty of processes and parameters in the host rock and EDZ.

Figure 43. Importance of uncertainty related to all individual safety relevant topics on "geochemistry and solute transport properties in the host rock and EDZ" for Deep Geological Disposal according to the indicated status of the individual programmes

(■ not answered, unknown or not assessed, ■ low importance ■ medium importance, ■ high importance)

Near Surface Disposal

From 11 replies to Near Surface Disposal, 1 corresponds to *Policy, framework and programme establishment* phase, 3 to the *Site characterisation* phase, 2 to *Facility construction* phase, 3 to *Facility operation* phase, 1 to *Post closure* and none to *Site evaluation and site selection* (1 had no indication of phase),

Here again, *Figure 44* suggests that importance of uncertainty related to safety decreases with the evolving phases. However, there are even less respondents here compared to Deep Geological Disposal and representativeness might be not ensured. The larger number of respondents indicating “Not answered or uncertainty unknown or not assessed yet” hopefully does not indicate that related significance of uncertainties was not considered in these phases (yet).

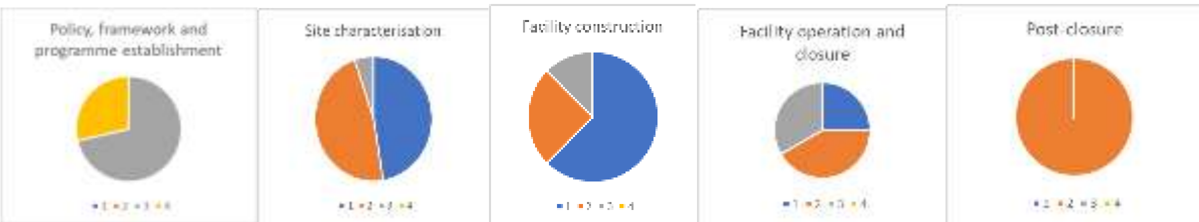


Figure 44. Importance of uncertainty related to all individual safety relevant topics on “geochemistry and solute transport properties in the host rock and EDZ” for Near Surface Disposal according to the indicated status of the individual programmes
(■ not answered, unknown or not assessed, ■ low importance ■ medium importance, ■ high importance)

Sub-Surface Disposal

From only 5 replies to Sub Surface Disposal (*Figure 45*), none respondent is in the phase of *Policy, framework and programme establishment*, 2 in the phase of *Site evaluation and site selection*, 1 in the phase of *Site characterisation*, none in the phase of *Facility construction*, 2 in the phases of *Facility operation* and none in the phase of *Post closure*. The importance of uncertainty ranges from predominantly high importance to predominantly low importance for the different phases and no trend could be identified due to the small number of replies.

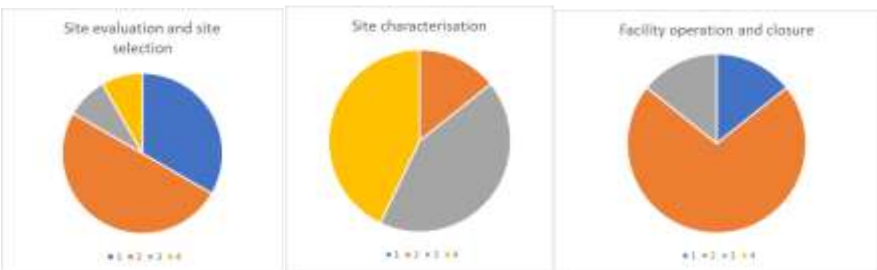


Figure 45. Importance of uncertainty related to all individual safety relevant topics on “geochemistry and solute transport properties in the host rock and EDZ” for Sub Surface Disposal according to the indicated status of the individual programmes
(■ not answered, unknown or not assessed, ■ low importance ■ medium importance, ■ high importance)

Summarizing, all actors agree that the uncertainty related to the radionuclide transport in the host rock will decrease along the programme implementation.

REs noticed that there is a continuous effort in achieving high quality sorption data for an ever-growing number of radionuclides, on different substrates, with the aim of establishing thermodynamic sorption values to be used in geochemical modelling codes. This will enable the estimation of sorption based on mineralogical composition and thermodynamic sorption constants. Estimation of sorption for a series of radionuclides can be performed based on available mineralogical data.

However, a certain level of uncertainty will remain.

TSOs and WMOs share the same opinion as the **REs**, considering that with a better characterisation of the porewater chemistry and chemical conditions at the actual site, and ongoing work on better defining sorption competition effects, these uncertainties will decrease. After adequate site characterisation, this uncertainty is expected to be small so as not to impact safety anymore, uncertainties will reduce.

There are also opinions that a possible increase of uncertainty could happen due to climate change and its impacts on the surface system.

3.7 Uncertainties associated with geochemistry and solute transport properties in the adjacent aquifers (G)

Topics for the geochemical and solute transport properties in the adjacent aquifers are the same as indicated for the host rock and the EDZ (F), which are collected similarly from samples – drill cores, water samples – taken directly from the site specific rock, or from "similar" rocks, where samples are easier to be taken, and investigated in laboratory experiments to measure/determine safety relevant properties such as transport porosity, sorption properties, etc. However, for an evolved site investigation, no underground laboratory might be available to confirm initial sampling and sample analysis.

Adjacent aquifer heterogeneity may play a role as well as assumption on mixing of radionuclide fluxes out of the host rock with the non-contaminated water fluxes in the adjacent aquifers, since heterogeneity and long-term evolution might by difficult to estimate (see also influence of climate changes below).

Same as for host rock and EDZ, the questionnaire included the same 7 different topics to be associated with their uncertainties associated with geochemistry and solute transport in the adjacent aquifers and significant for safety, their characterisation and their evolution in time:

- Chemical, radiochemical and mineralogical composition of the rock (porous medium or fracture – matrix system properties)
- Groundwater chemistry
- Solubility limits
- Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)
- Diffusion coefficients
- Colloid (facilitated) transport
- Changes in the transport properties due to precipitation/dissolution reactions

It has to be mentioned that also here none of the respondents to the questionnaire indicated a missing uncertainty in this group (G in the questionnaire).

3.7.1 Significance for safety

Geological disposal

Uncertainties associated with geochemistry and transport properties in adjacent aquifers have shown to have a low impact on geological disposal safety in the views of WMOS and REs (*Figure 46*).

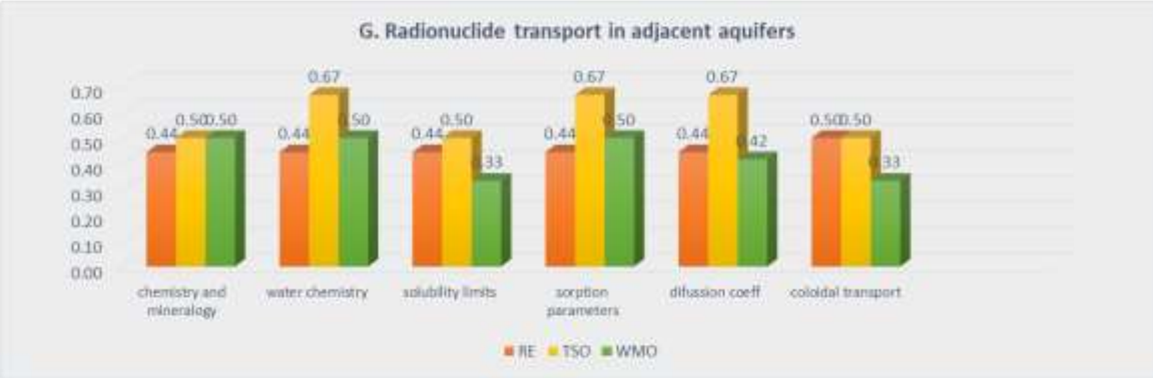


Figure 46. Significance for safety of uncertainties related to geochemistry and solute transport properties in the adjacent aquifers (DGD)

In contrast, **TSOs** tend to give a higher significance to the uncertainties associated with the water chemistry, sorption and diffusion parameters of the porous medium or the fracture-matrix system, and to the sorption parameters in the aquifer (*Table 13*).*Table 13*

Table 13. Synopsis of the actors' views on uncertainties related to geochemistry and solute transport properties in the adjacent aquifers for geological disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Chemical, radiochemical &mineralogical composition of the aquifers (porous medium or fracture – matrix system properties)	0.44	5l; 1h; 2n	0.50	1m; 2n; 1l	0.50	3l; 1h;3n	x	xxx	xxx
Groundwater chemistry	0.44	5l; 1h; 2n	0.67	1h; 2n; 1l	0.50	3l; 1h;3n		xxx	xx
Solubility limits	0.44	5l; 1h; 2n	0.50	1m; 2n; 1l	0.33	4l; 3n		xx	x
Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)	0.44	5l; 1h; 2n	0.67	1h; 2n; 1l	0.50	2l; 2m;3n		xxx	xx
Diffusion coefficients	0.44	4l; 2m; 2n	0.67	1h; 2n; 1l	0.42	3l; 1m; 3n		xxxx	xx
Colloid (facilitated) transport	0.50	4l; 1h; 1m;2n	0.50	1m; 2n; 1l	0.33	4l; 3n		xxx	x

Figure 47 gives an in-depth illustration of the significance for safety of all uncertainties associated with the radionuclide transport parameters in the adjacent aquifer, for category of actors, related to deep geological disposal. Responds related to deep geological disposal might be looked at as the most representative, because here was by far the largest input from the respondents.

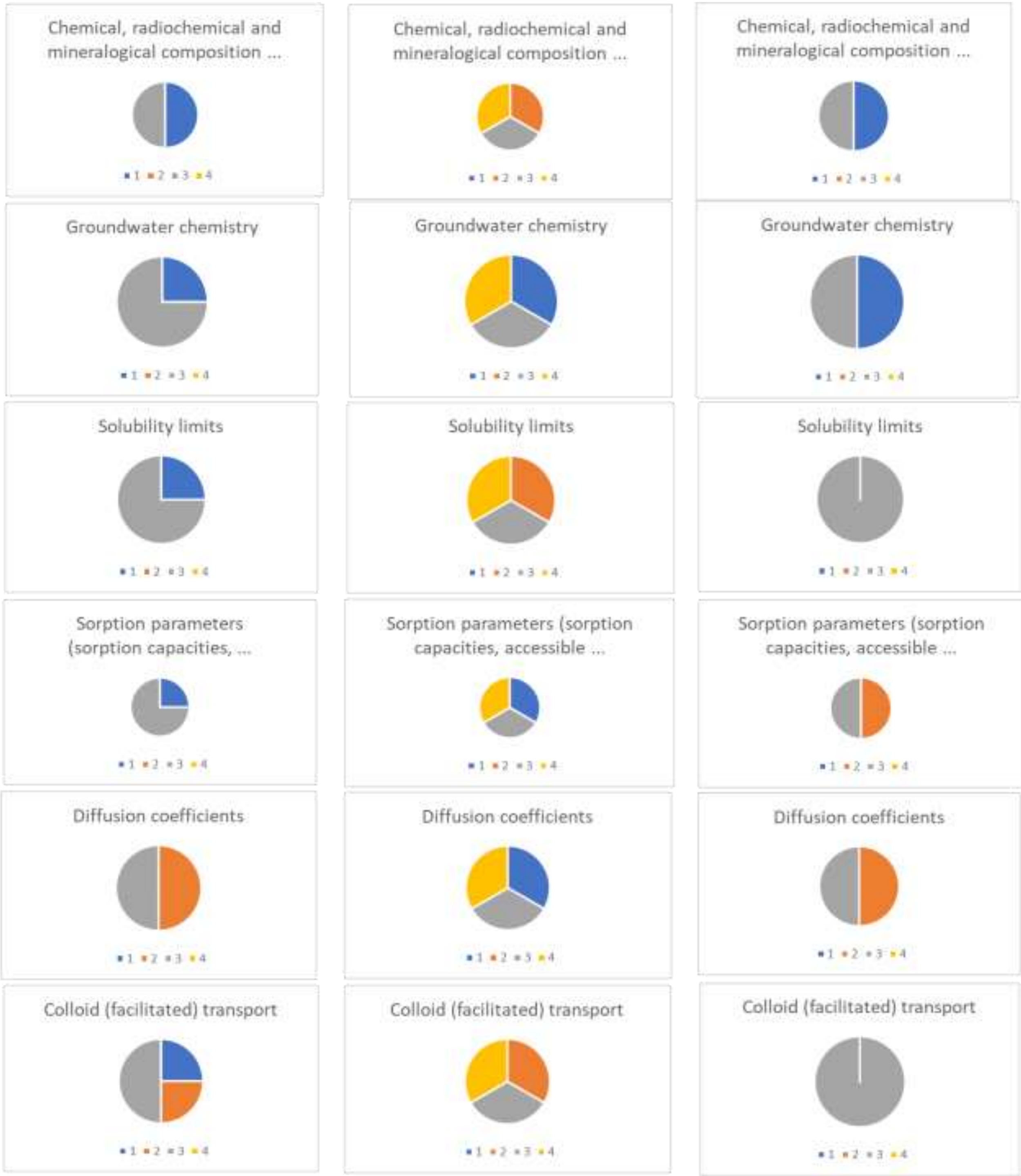


Figure 47. Relevance for safety as given by all respondents from the different actors) to all individual safety relevant topics on "geochemistry and solute transport properties in adjacent aquifers" for Deep Geological Disposal

19 replies, 8 from *RE (left), 4 from TSO (middle), 7 from WMO (right).*
■ Not answered, unknown or not assessed, ■ low relevance ■ medium relevance ■ high relevance

Also here, a nearly general pattern is noticed, significantly different from the one observed for the same processes in the host rock and EDZ (*Figure 35*). REs indicated always the largest parameter relevance for safety for the different processes in the adjacent aquifers, followed by TSOs, whereas WMOs mostly indicated a much lower safety relevance for these parameters, except for "chemistry and mineralogy" parameters, which were a little bit less relevant for TSOs. A conclusion would be that for WMOs adjacent aquifer processes and parameters uncertainties are less safety relevant than for REs and TSOs. Such an actor specific pattern is not observed for all the other processes parameters (A-E and G-O) keeping in mind that only little input came from TSO's side. In addition (and again), it has to be mentioned that some of the answers by the respondents seemed to be inconsistent, either due to misunderstanding of individual questions or due to missing knowledge of details.

What is obvious is that high importance for safety is expressed only from 1 RE, 1 TSO and 1 WMO, whereas all others, independent from their college, indicated only low importance – ignoring perhaps the large dilution factors for radionuclides concentrations, which are implemented in safety analysis diluting radionuclide fluxes from the host rock into the non-contaminated water fluxes within the adjacent aquifers (remark by author). Also here, there is no topic with the same significance distribution for all colleges (the same colours in one row) for the Deep Geological Disposal (*Figure 47*) The reason might be that the respondents are in different programme phases.

Near surface disposal

For near surface disposal, the same general picture with low significance for safety for REs and WMOs (*Figure 48*), and a slightly higher concern of the TSOs, this time for sorption parameters and colloidal transport (*Table 14*) could be observed.

In the case of the Romanian near surface disposal, the low level of relevance for safety is justified by the rapid advective transport of radionuclides through the altered upper part of the main aquifer, which makes sorption processes having a very low impact in the safety analysis.

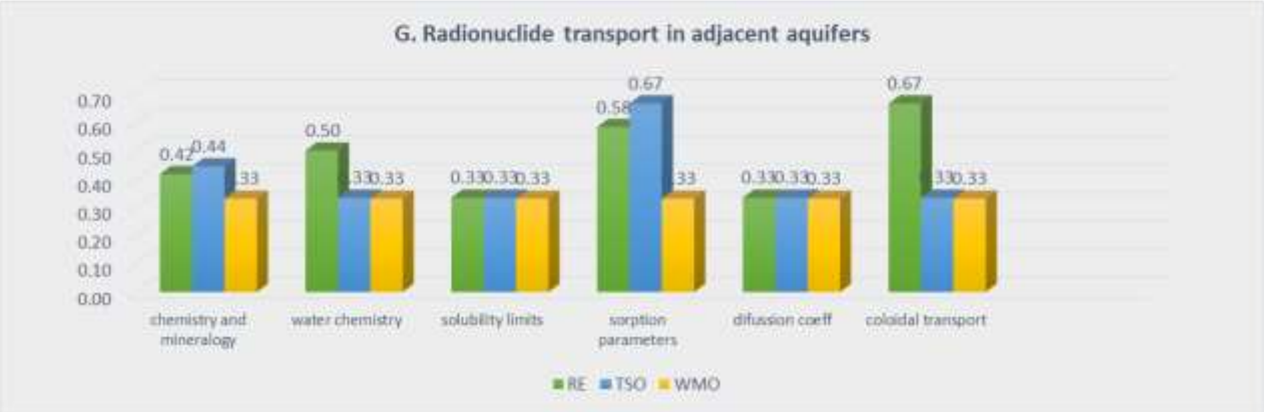


Figure 48. Significance for safety of uncertainties related to geochemistry and solute transport properties in the adjacent aquifers (NSD)

A graphical representation of the significance for safety per category of actors is given in *Figure 49*. It shows same degree of medium to high concern of REs and TSOs for the uncertainty associated with sorption parameters, and the full agreement on the low significance for safety of the diffusion coefficient in the adjacent aquifers.

Table 14. Synopsis of the actors' views on uncertainties related to geochemistry and solute transport properties in the adjacent aquifers for geological disposal

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Chemical, radiochemical and mineralogical composition of the aquifers (porous medium or fracture – matrix system properties)	0.42	3l; 1m; 2N	0.44	1m; 1n; 2l	0.33	1l		x	
Groundwater chemistry	0.50	2m; 2l; 2n	0.33	4l	0.33	1l			
Solubility limits	0.33	4n; 2l	0.33	4l	0.33	1l			
Sorption parameters (sorption capacities, accessible porosity and mineral surface area, Kd and other thermodynamic data)	0.58	1h; 1m; 2l; 2n	0.67	2m; 1h; 1l	0.33	1l		xx	
Diffusion coefficients	0.33	4l; 2n	0.33	4l	0.33	1l			
Colloid (facilitated) transport	0.67	5n; 1m	0.33	4l	0.33	1l			

Figure 49. Relevance for safety as given by all respondents from the different actors to all individual safety relevant topics on "geochemistry and solute transport properties in adjacent aquifers" for Near Surface Disposal

11 replies, 6 *RE (left), 4 TSO (right), 1 WMO (not shown)*.
■ Not answered, unknown or not assessed, ■ low relevance ■ medium relevance ■ high relevance

3.7.2 Uncertainties characterisation

Methods mostly used in the characterisation of the uncertainties related to radionuclide transport in the adjacent aquifers, and preferences of each actor are illustrated in *Figure 50* and *Figure 51*

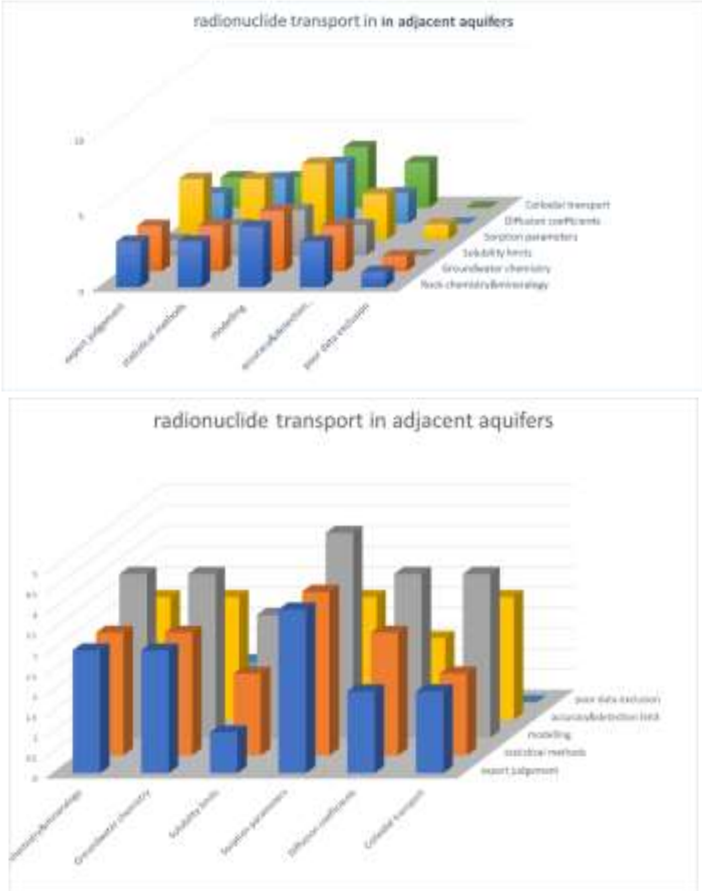


Figure 50. Frequency of the methods used in characterisation of uncertainties related to radionuclide transport in adjacent aquifers

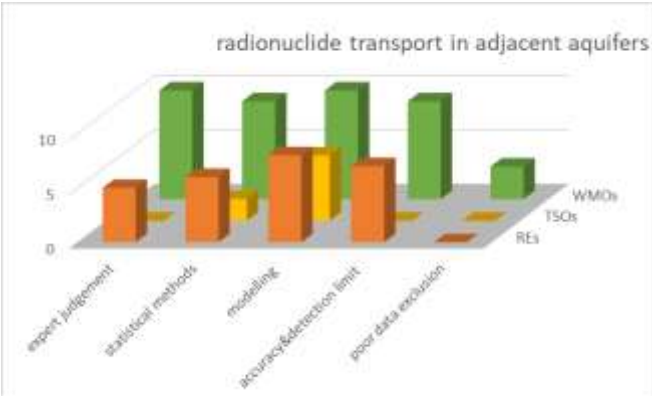


Figure 51. Actors' preferences in the characterisation of uncertainties on radionuclide migration in adjacent aquifers

In *Figure 50* and *Figure 51* options for characterisation of uncertainties for processes/parameters are shown for Deep Geological Disposal. All uncertainty characterisation methods were used for the Deep Geological Disposal, more or less equal for the different processes/parameters. However, preference for modelling could be observed – same as for the characterisation of uncertainties for the host rock and EDZ. (see 3.6.2). Similarly, "exclusion of poor quality/inappropriate data (in reducing the order of magnitude)" is less often used.

3.7.3 Uncertainty evolution in time

The number of replies was not enough large to have good statistics with respect to the different programme phases, or to identify trends of answers from different colleges. Generally, the indications vary from low to high importance for most of the different phases and the different colleges. The Figure 52, Figure 53 and Figure 54 are related to all replies, independent on the college (RE, TSO, WMO) for three different repository options.

Deep Geological Disposal

From 19 replies to Deep Geological Disposal, 5 respondents are in the phase of Policy, framework and programme establishment, 8 in the phase of Site evaluation and site selection, 3 in the phase of Site characterisation and 1 in the phase of Facility construction. There was no feedback from respondents in the phases of Facility operation and Post closure.

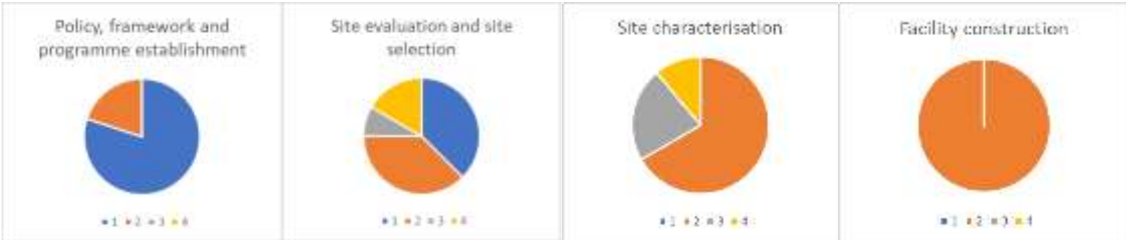


Figure 52. *Importance of uncertainty related to all individual safety relevant topics on "geochemistry and solute transport properties in adjacent aquifers" for Deep Geological Disposal according to the indicated status of the individual programmes of the respondents*
■ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance.*

According to Figure 52, it seems that importance of uncertainty related to safety is decreasing along the programme implementation. However, as already mentioned, there are less respondents in later phases – (in case of Facility construction only one WMO). High importance of uncertainty is indicated by about 1/3 of the respondents in the initial two phases of the programme, underlining the importance of uncertainty associated with processes and parameters in the adjacent aquifers in these phases.

Near Surface Disposal

From 11 replies to Near Surface Disposal, 1 respondent is in the phase of *Policy, framework and programme establishment*, none in the phase of *Site evaluation and site selection*, 3 in the phase of *Site characterisation*, 2 in the phase of *Facility construction*, 3 in the phases of *Facility operation* and 1 in the phase of *Post closure*. Figure 53 leaves no identification of a trend, even though one can get the impression that importance of uncertainty related to safety is decreasing with the evolving phases. However, there are even less respondents here compared to Deep Geological Disposal and representativeness might be not given.

Figure 53. *Importance of uncertainty related to all individual safety relevant topics on "geochemistry and solute transport properties in adjacent aquifers" for Near Surface Disposal according to the indicated status of the individual programmes of the respondents*
■ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance.*

Sub-Surface Disposal

The only 5 replies to Sub Surface Disposal, with 2 answers in the phase of *Site evaluation and site selection*, 1 in *Site characterisation*, and 2 in *Facility* operation do not provide enough information for a consistent trend in the uncertainty evolution. The importance of uncertainty seems to range from predominantly high importance to predominantly low importance for the different phases and no trend could be identified due to the small number of replies (Figure 54).

Figure 54. *Importance of uncertainty related to all individual safety relevant topics on "geochemistry and solute transport properties in adjacent aquifers" for Sub Surface Disposal according to the indicated status of the individual programmes of the respondents*

■ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance.*

Concluding, the general opinion of the three categories of actors is that the uncertainties associated to geochemistry and radionuclide transport properties in the adjacent aquifers trend to decrease along the programme implementation, as data, information and knowledge accumulate.

It has been mentioned that uncertainties on rock composition and water chemistry are most likely to reduce as construction of the repository begins and groundwater will be drawn in from the surrounding area, and the old boreholes for site characterisation can catch more data.

Uncertainty on sorption is also expected to decrease during the site characterisation and subsequent phases as more knowledge becomes available on soil properties and sorption of safety-relevant radionuclides in biosphere soils.

An increase of uncertainty is also possible due to climate change that could affect the surface system.

3.8 Uncertainties associated with data and model representativeness (H)

Uncertainties associated with data and model representativeness concerns –in principle– all processes and related parameters described in all the other sections (3.1-3.7). Although the issues of

- scale effects –uncertainties associated with upscaling of lab data to field scale
- scale effects –uncertainties associated with process modelling from micro to macro scale
- data spatial extrapolation

are known, new experimental techniques and modelling approaches (including upscaling procedures) are proposed to be applied in radioactive waste management [7, 8]. However, uncertainties associated with these new techniques and procedures have not been investigated in depth. They may lead to better process and system description and understanding. Having this in mind, the results of the questionnaire may help to identify specific needs to improve their applicability for radioactive waste management.

3.8.1 Significance for safety

Geological disposal

As a general remark, the uncertainties associated with the representativeness of the data and models are considered to have a medium significance for the geological disposal safety for the REs and WMOs, and low significance for TSOs.

REs and WMOs are almost equally concerned by the potential impact that the uncertainties related to the scale effects might have on the disposal safety: the uncertainties associated to data extrapolation from laboratory scale to the scale of site, uncertainties related to extrapolation models from micro scale to macro scale and uncertainties associated to the spatial extrapolation of the data (*Table 15*).

Figure 55 shows a summary input of all actors on the uncertainties associated with data and model representativeness with respect to relevance for safety for deep geological disposals. Again, responds related to deep geological disposal might be looked at as the most representative, being by far the largest input from the respondents.

A fact that might partly explain this discrepancy between TSO and the other two categories of actors (WMO and RE) is the small number of answers received from the technical support organisations (only 4). In addition, it has to be mentioned that some of the answers seemed to be inconsistent, either due to misunderstanding of individual questions or due to missing knowledge of details.

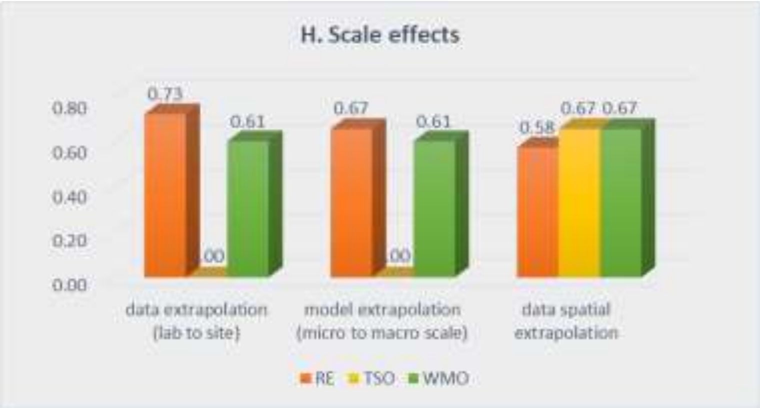


Figure 55. Significance for safety of uncertainties related to data and model representativeness (DGD)

Another representation of the input on significance for safety is given in the *Figure 56* for each category of actors. What is in common is that high importance for safety is more often expressed from REs and WMOs than from TSOs for the Deep Geological Disposal.

The diversity of answers could be associated to the fact that they are reflecting different phases of the programmes. But again, the very limited number of responses does not yield a representative picture about preferences for the different colleges.

Table 15. Synopsis of the actors' views on uncertainties related to data and model representativeness for geological disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Scale effects – uncertainties associated with upscaling of lab data to field scale	0.73	2h; 1l; 2m;3n	0.00	4n;	0.61	1h; 3m; 2l;1n	x	xxxx	xxxx
Scale effects – uncertainties associated with process modelling from micro to macro scale	0.67	5m; 3n	0.00	4n	0.61	1h; 3m;2l;1n		xxxx	xxxx
Data spatial extrapolation	0.58	1m; 1h; 2l; 4n	0.67	1m; 3n	0.67	2h; 2m; 2l;1n		xxxx	xxxxx

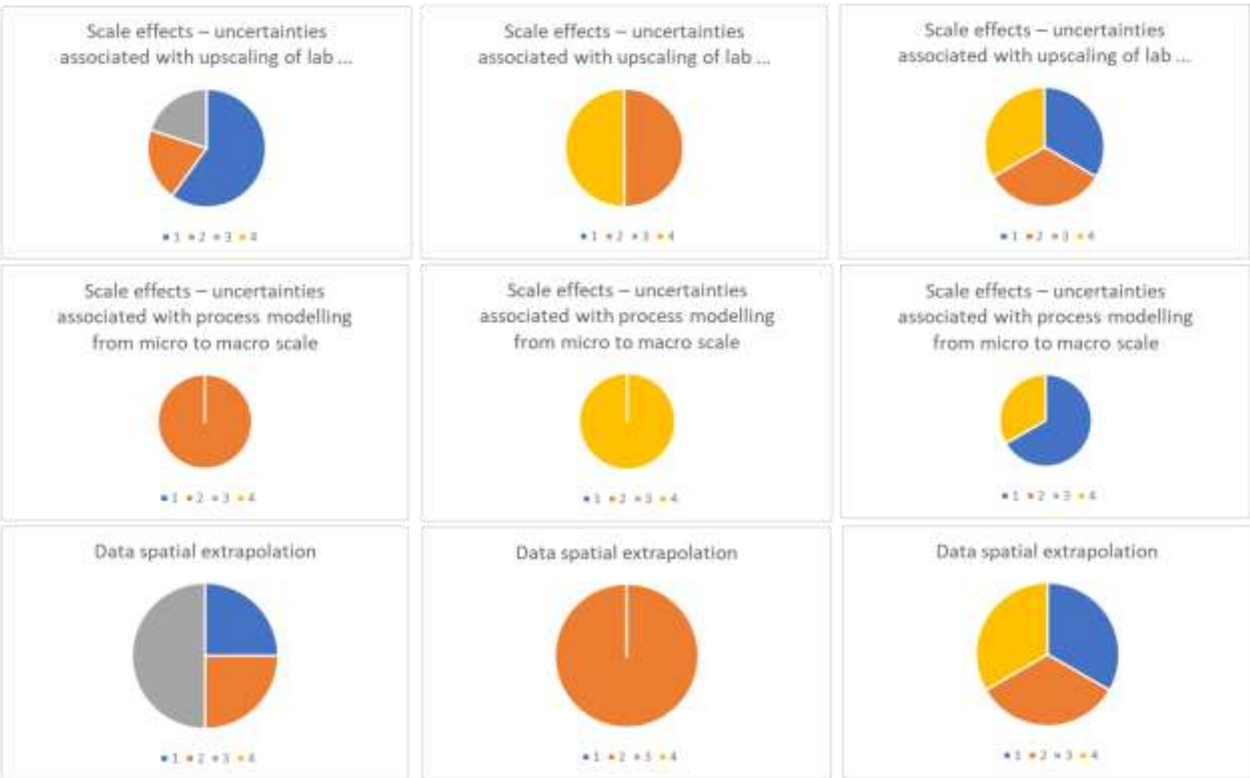


Figure 56. Relevance for safety as given by all respondents from the different actors (RE, TSO, WMO) to all individual safety relevant topics on "uncertainties associated with data and model representativeness" for Deep Geological Disposal.

19 replies (7 relevant), 4 from *RE (left), 1 from TSO (middle), 2 from WMO (right).*
■ Not answered, unknown or not assessed, ■ low importance, ■ medium importance, ■ high importance

Near surface disposal

In the case of near surface disposal, however, the significance for safety remains low for TSOs and WMO, and slightly higher for the REs (*Figure 57* and *Table 16*). Distribution of the uncertainties significance for safety for WMOs and REs is illustrated in *Figure 58*.

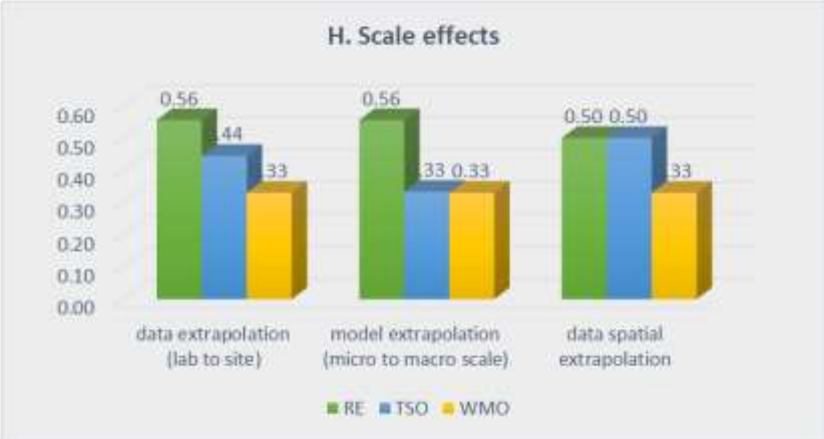


Figure 57. Significance for safety of uncertainties related to data and model representativeness (NSD)

For **REs**, impact of the uncertainties associated with *upscaling of lab data to field scale* are mainly related to the effective transport properties and changes of the parameter basis for migration paths due to unpredictable heterogeneities and connectivity between different sub-units, which could underestimate the radiological dose.

Impact on the radiological dose could also arise if not all aspects of field environment (such as: redox, presence of competing ions, carbonate partial pressure, mineralogical heterogeneity) are simulated.

A RE particularly concerned by the uncertainties associated with conductivity, pointed out that there it is largely agreed that conductivity is due to fractures of wide range of scales, obeying the power law distribution. This can be used in upscaling, but there are no studies comparing this process with the field data.

Table 16. Synopsis of the actors' views on uncertainties related to data and model representativeness for near surface disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Scale effects – uncertainties associated with upscaling of lab data to field scale	0.56	2l; 1h; 3n	0.44	1m; 2l; 1n	0.33	1l	x	xxxx	xxxx
Scale effects – uncertainties associated with process modelling from micro to macro scale	0.56	2l; 1h; 3n	0.33	2l; 2n	0.33	1l		xxxx	xxxx
Data spatial extrapolation	0.50	1l; 1m; 4n	0.5	1m; 1l; 2n	0.33	1l		xxxx	xxxxx

Figure 58. Relevance for safety from different actors to all individual safety relevant topics on uncertainties "associated with data and model representativeness" for Near Surface Disposal

11 replies (3 relevant), 1 *RE (left), 2 TSO (middle), non from WMO (right)* not shown

■ Not answered, unknown or not assessed, ■ low importance, ■ medium importance, ■ high importance

According to the **REs**, *uncertainties on process modelling from micro to macro scale* could be related in some cases to the missing reliable inputs for modelling. Also, at microscale, reversibility is typically assumed in models, while this is not the case at macroscale. Couplings, as well, are more complicated at large scale. None of the systems modelling today uses reactive transport, but only potentially space dependent lookup tables for solubility, sorption and diffusion. The functional dependency is ignored. This is acceptable as long as the geochemical environment is uniform, but can lead to large errors if there are gradients, like it could be expected in the near field. For example, while there are sorption data on clay and on concrete, there is no model describing the behaviour of the radionuclides at the clay/concrete interface. All these could have a medium impact on the radiological dose after repository closure.

There is also the opinion that the effect of simplification can be strong but can be evaluated through model comparison on synthetic cases (RE, medium impact on safety functions).

Uncertainties on *data spatial extrapolation,* could have a medium to low impact on the radiological dose after repository closure since, in the REs views, they may influence the calculation of dilution and hence the concentration of radionuclides in the aquifer. Mineralogical variability limits spatial applicability of Kd values: leading to larger uncertainties. However, a comparison of Kd values for a clay rock borehole log and those accounting for detailed mineralogical heterogeneity showed only small differences.

These uncertainties could have also an impact on the safety functions of the host rock due to uncertainties on its performance associated with the limitation of water flow and chemical retention (RE, WMO).

3.8.2 Uncertainties charcaterisation

Methods mostly used in the characterisation of the uncertainties related to scaling effects and data spatial extrapolation, as well as the preferences of each actor are illustrated in Figure 59 and Figure 60.

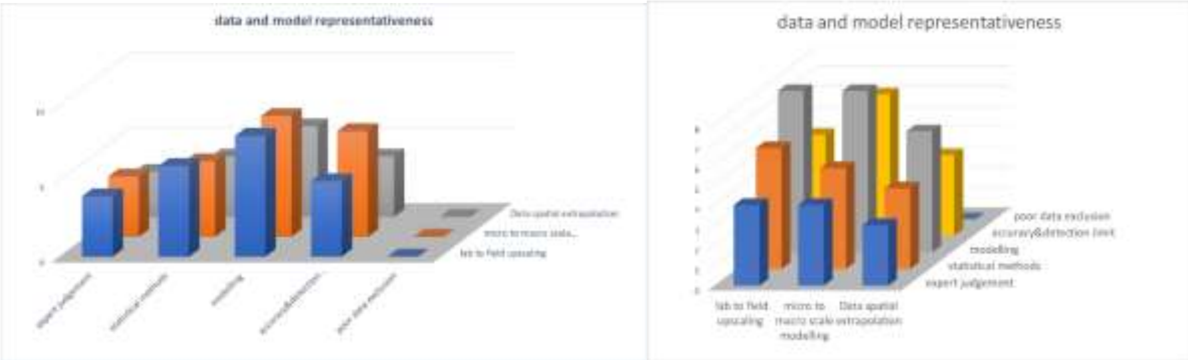


Figure 59. *Frequency of the methods used in characterisation of uncertainties related to scaling effect*

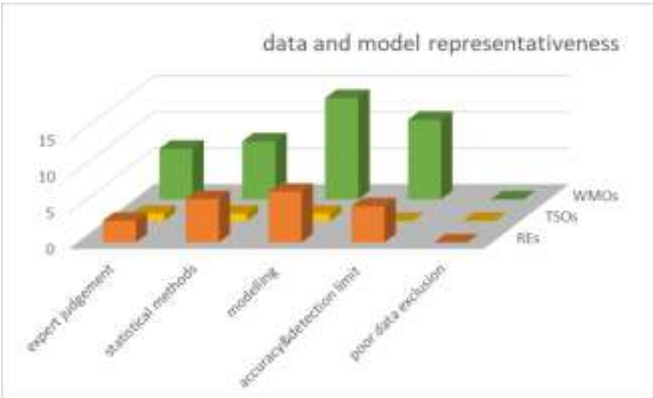


Figure 60. Actors' preferences in the characterisation of uncertainties on scaling effects

In Figure 59 and Figure 60 methods used in characterisation of uncertainties for processes/parameters are shown for Deep Geological Disposal. Excepting the poor data exclusion, all other options were used, more or less, for the different processes/parameters uncertainty characterisation. However, preference for "modelling (likelihood of events, geochemical databases…)" could be observed.

An interesting additional methos was suggested by a RE: uncertainties characterisation by comparison, taking for example "in situ Kd" from the field obtained by desorption tests. If, for example, porewater solution concentrations of sparingly mobile or mobile trace elements (like Fe, REE, Th, U, Se, Mo etc.) are compared with lab data of homologues elements, and modelled using the same models. It is often the case that only a fraction of the elemental content of the natural clay rock is exchangeable. Similar for diffusion data of the lab which can be compared with characterisation of natural diffusion profiles of non-sorbing tracers like natural Cl36, oxygen isotopes, He etc.

3.8.3 Uncertainty evolution in time

Unfortunately, the number of replies was not that large to have good statistics with respect to the different programme phases, or to identify trends of answers from different colleges. Generally, the indications vary from low to high importance for the different phases and the different colleges. The Figure 61, Figure 62Figure 63 are related to all replies, independent on the college (RE, TSO, WMO) for three different repository options.

Deep Geological Disposal

From 19 replies to Deep Geological Disposal, 5 respondents are in the phase of *Policy, framework and programme establishment*, 8 in the phase of *Site evaluation and site selection*, 3 in the phase of *Site characterisation* and 1 in the phase of *Facility construction*. There was no feedback from respondents being in the phases of *Facility operation* and *Post closure*. From *Figure 61*, there is no general trend to be identified. Most of the input is on "no" or "low importance" This gives the impression that there is not that much focus on uncertainties related to scaling.

Figure 61. Importance of uncertainty related to all individual safety relevant topics "associated with data and model representativeness" for Deep Geological Disposal according to the indicated status of the individual programmes of the respondents

■ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

Near Surface Disposal

From 11 replies to Near Surface Disposal, 1 respondent is in the phase of *Policy, framework and programme establishment*, none in the phase of *Site evaluation and site selection*, 3 in the phase of *Site characterisation*, 2 in the phase of *Facility construction*, 3 in the phases of *Facility operation* and 1 in the phase of *Post closure*. Figure 62 leaves no identification of a trend, even though one can get the impression that importance of uncertainty related to safety is decreasing with the evolving phases.

Figure 62. *Importance of uncertainty related to all individual safety relevant topics "associated with data and model representativeness" for Near Surface Disposal according to the indicated status of the individual programmes of the respondents*

■ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

Sub-Surface Disposal

From only 5 replies to Sub Surface Disposal, none respondent is in the phase of *Policy, framework and programme establishment*, 2 in the phase of *Site evaluation and site selection*, 1 in the phase of *Site characterisation*, none in the phase of *Facility construction*, 2 in the phases of *Facility operation* and none in the phase of *Post closure*. The importance of uncertainty not or just indicated with low importance for the different phases and no trend could be identified due to the small number of replies (Figure 63).

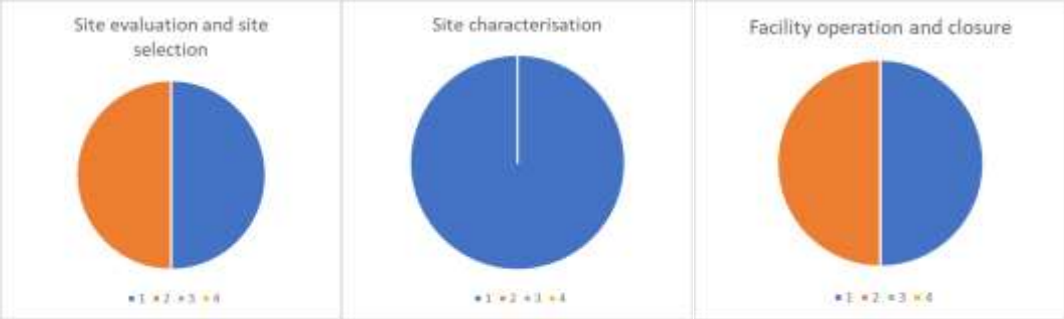


Figure 63. *Importance of uncertainty related to all individual safety relevant topics "associated with data and model representativeness" for Sub Surface Disposal according to the indicated status of the individual programmes of the respondents*

■ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

In early programme phases, these uncertainties are very much dependent on the ability to extrapolate from one host/site to another. Later on, uncertainties are more dependent on the ability to extrapolate from test locations to other locations within the site. The extent of the uncertainties is very much dependent on the geology and homogeneity of the host rock/aquifers (RE).

These uncertainties may decrease during the site characterisation phase and subsequent phases as more data become available on hydrogeological properties and stratigraphy, and hydrogeological models are further validated (especially for near field disposal).

In geological disposal, uncertainties associated with the transposition of safety-relevant host rock/aquifer properties from one site/host rock to another will also decrease during site selection and subsequent phases as more data about these properties are collected during site characterisation, monitoring and construction.

Uncertainties on the upscaling lab data can be decrease based on model validation versus in-situ tests, while those on data spatial extrapolation could be reduced by refining the 3D model of the site.

4. Uncertainties associated with geodynamics and tectonic perturbations of the site in the long-term

Possible future natural changes of the site and geosphere can be identified starting from present state and based on their past evolution.

Geodynamic effects caused by tectonic events, earthquakes, climate changes, volcanism, diapirism, etc. may affect the overall disposal system due to disturbances of the site integrity and of the stress field or modifications of groundwater flow and pathways.

When gathering all provided answers on uncertainties associated with geodynamics and tectonic perturbations by all types of actors and whatever the types of disposal facilities, we can see on the pie charts from *Figure 64* that (i) the knowledge on the importance of uncertainties increases (the number of "not answered" diminishes) and (ii) the level of importance of uncertainties decreases with evolution of the program:

1- Not answered or uncertainty unknown or not assessed (white)
2- Uncertainty of low importance with regards to safety (green)
3- Uncertainty of medium importance with regards to safety (yellow)
4- Uncertainty of high importance with regards to safety (red)

Figure 64. Global uncertainties significance along the disposal programme phases
☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

4.1 Uncertainties associated to tectonic processes and structures (I)

4.1.1 Significance for safety

When considering all disposal types and stages of development of the project, more than a quarter of answers consider uncertainties associated with tectonic processes and structures as of medium or high importance for safety (*Figure 65*). Such answers exceed a third for uncertainties associated with fault location.

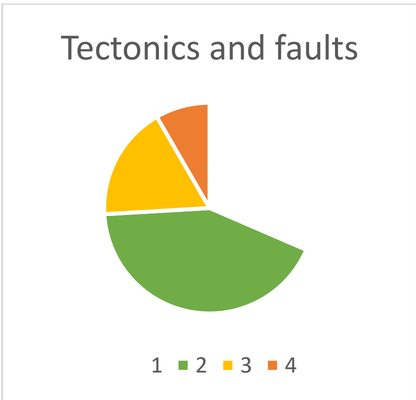


Figure 65. Overall significance for safety of uncertainties related to tectonic and faults (for all actors, repository concepts and programme phases)
☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

As further illustrated below (chapter 4.1.3), the uncertainty is assessed as low by organisations in countries having the most advanced disposal programmes: this does not mean that the topic is not important but that the remaining uncertainty, thanks to (sometimes) tens of years of fieldwork, research or changes of disposal design, is now of low impact on safety.

Geological disposal

Tectonic processes could affect the long-term integrity of the storage system by raising or sinking geological strata, tilting or creasing, by modifying existing faults or creating new ones. Faults are rapid pathways of transport of radionuclides to the surface aquifers and, from aquifers to the environment and the population, therefore contributing significantly to the value of the radiological dose, especially in the case of geological disposal.

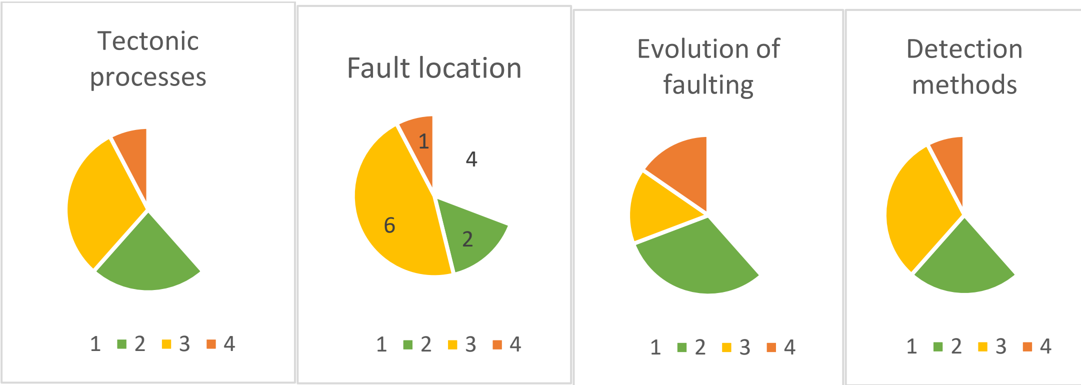


Figure 66. Answers distribution per safety relevance for all actors (DGD)
Not answered, unknown or not assessed, low importance, medium importance, high importance

All uncertainties associated to the tectonic processes and structures addressed by the questionnaire are highly relevant for the **WMOs. REs** give more importance to the uncertainties on faults properties and detection methods, while for **TSOs** indicate higher significance for the uncertainties related to the specific processes: uplifting, subsidence, tilting, folding, faulting (*Figure 66*, *Figure 67*), the all others being evaluated with medium significance (*Table 17*).

For REs, the impact of tectonic processes is presumably small in a plastic host formation, and therefore the associated uncertainty can have only a medium significance on safety.

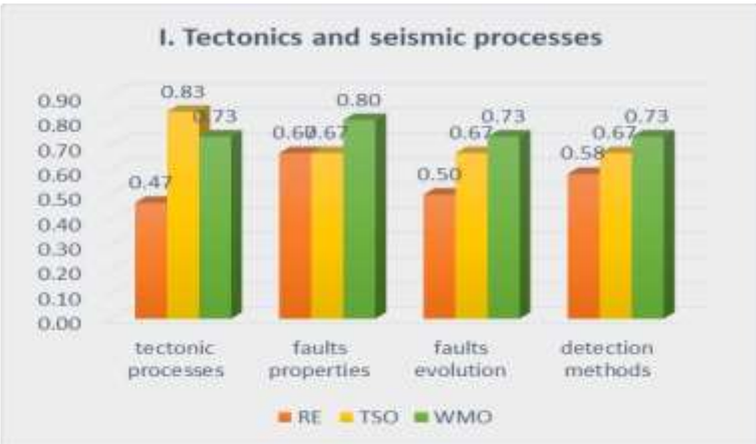


Figure 67. Significance for safety of uncertainties related to tectonic processes and structures (DGD)

Such uncertainty is assessed as high by those concerned with disposal in crystalline rock. For disposal in sedimentary rock, it is most generally considered as low when the project is in site characterisation or construction phase (and unknown when at the “policy” stage).

Organisations who answered consider that the uncertainty on tectonic processes, on faults properties and evolution of faulting will likely be reduced over time. However, some uncertainty will surely remain.

Sub-surface disposal

For sub-surface disposal, several types of uncertainties associated with tectonics and faults are more or less the same as for deep geological disposal (*Figure 68*) because of the need to assess long term post-closure safety or because the facilities are underground (detection methods). The uncertainties on tectonic processes and fault location are considered as high for the projects in early phases of development.

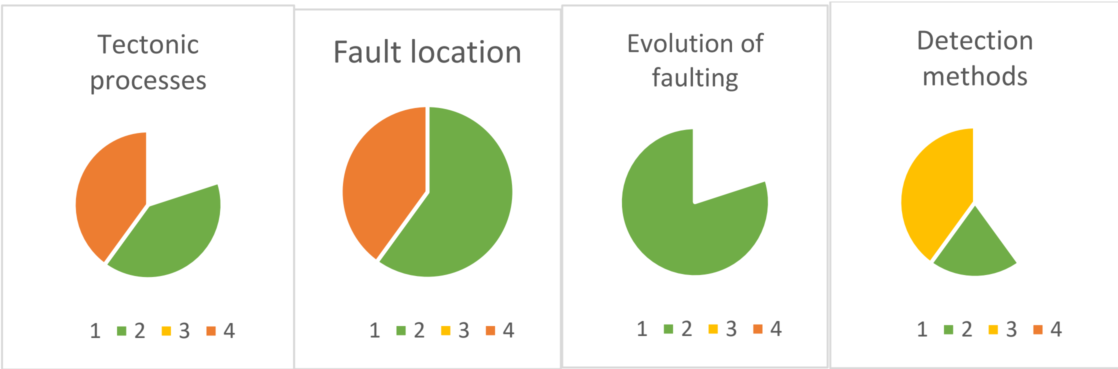


Figure 68. Answers distribution per safety relevance for all actors (SSD)
☐ Not answered, unknown or not assessed, ■ low importance, ■ medium importance, ■ high importance

Table 17. Synopsis of the actors' views on uncertainties related to tectonic processes and structures for geological disposal

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Tectonic processes: uplift, subsidence, tilting, folding, faulting	0.47	3l; 2m; 3n	0.83	1h; 1n; 1m	0.73	2m; 2h; 1l;2n		xxxxx	xxxxxxx
Fault location, length, depth and activity	0.67	1h; 3m; 1l;3n	0.67	3m	0.80	3h; 1m; 1l; 2n	x	xxxxxx	xxxxxxxx
Temporal and spatial evolution of faulting	0.50	4n; 2m; 2l	0.67	1h; 1n; 1l	0.73	3h, 2l;2n	x	xxxx	xxxxx
Detection methods	0.58	4n; 1h; 1m; 2l	0.22	2n; 1m	0.73	2h; 2m;1l;2n		xxx	xxxx

The high significance for safety is associated with the radiological dose/risk during operation and after closure. Undetected active faults could have an impact on the seismic hazard of the repository. Occurrence of a tectonic event during operation could affect the integrity of the disposal system, galleries collapse, flooding, etc. Therefore, active faults should be identified and avoided.

Undetected or activated faults, not considered in the safety analysis, can provide fast pathways for contaminants, alterating significantly the predictions of the radiological dose and increasing the actual risk after repository closure, as noticed by the TSOs and WMOs.

Tectonic processes impact as well the safety functions of the disposal system. As pointed out by WMOs and TSOs, long-term stability of the geosphere could be affected, the safety function limitation of water flow could be lost, and the yield in immobilisation, retention and slow release of radionuclides can be reduced due to the hydraulic flow along the fault zones. Canisters could fail, therefore affecting the safe containment function.

In addition, as mentioned by a WMO, tectonic features of the site play a role even in the early phase of the geological disposal programme, in establishing the degree of utilisation (i.e. the required space for the repository) and consequently the repository layout.

Near surface disposal

In the case of near surface disposal (Figure 69 and

Table 18), neither REs, WMO nor TSOs consider that the uncertainties associated with the geodynamic processes of the site pose major problems in the safety assessment, associating a low significance for both the impact on dose or risk and on the safety functions, with the exception of uncertainties on faults properties, which represent a medium concern for the TSOs in the case of near surface disposal.

The uncertainties associated with tectonics and faults are generally considered as low for all near-surface disposal projects (*Figure 70*). This is due to the fact that:

- the difficulty of fault detection methods at depth is less a challenge given that the disposal facility is near the surface
- such disposal concept does not require demonstration of very long-term post-closure safety: decrease of radioactivity is expected in few centuries. Thus, evolution of faulting is not feared for such short times. When the faults are identified and tectonic processes characterized, since the beginning of the site selection process, the associated uncertainties become low.

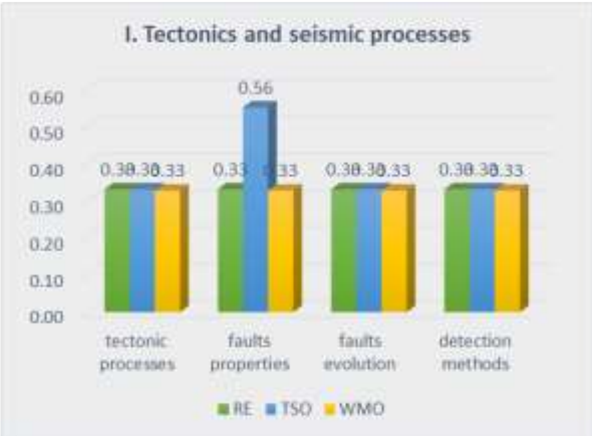


Figure 69. *Significance for safety of uncertainties related to tectonic processes and structures (NSD)*

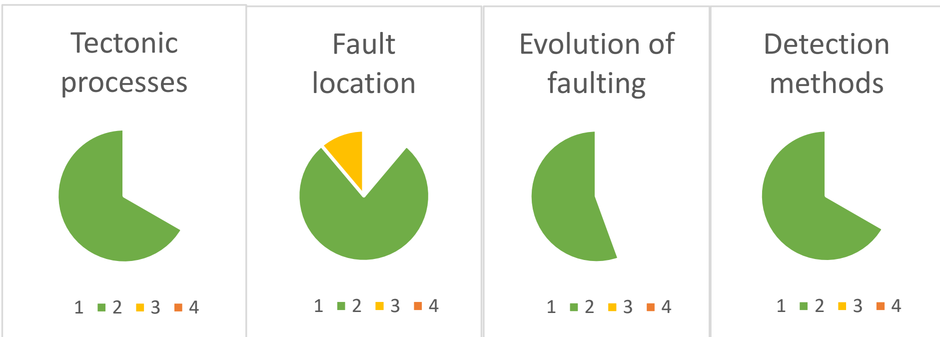


Figure 70. Answers distribution per safety relevance for all actors (NSD)
Not answered, unknown or not assessed, low importance, medium importance, high import

Table 18. *Synopsis of the actors' views on uncertainties related to tectonic processes and structures for near surface disposal*

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Tectonic processes: uplift, subsidence, tilting, folding, faulting	0.33	3l; 2N	0.33	2l; 1n	0.33	1l		xx	x
Fault location, length, depth and activity	0.33	4l; 1N	0.56	1m; 2l	0.33	1l	x	x	xx
Temporal and spatial evolution of faulting	0.33	2l; 3n	0.33	2l; 1n	0.33	1l			
Detection methods	0.33	3l; 2n	0.33	2l; 1n	0.33	1l		x	

4.1.2 Uncertainties characterisation

For deep geological disposal programmes, all the available options of uncertainty management are used. Modelling and quantification by expert judgement seem to be the two preferred options for uncertainties associated with tectonic processes fault location and evolution (*Figure 71*).

For first preference for REs is quantification by expert judgement, while WMOs indicated (*Figure 72*):

- deterministic modelling of structures, including fault zones with inferred potential of seismic reactivation, based on expert judgement, conceptual understanding and investigation data
- treating faults outside the repository by Discrete Fracture Network (DFN) modelling, or
- empirical and numerical studies on acceptable fracture size with regard to seismic reactivation

ANDRA carried out detailed structural mapping and numerous geophysical investigations on the geological disposal site, and IRSN tested methods of structural mapping by fieldwork [9] and integrated results in its hydrogeological model.

The other options chosen for uncertainties associated with fault location and fault evolution are the altered evolution scenarios.

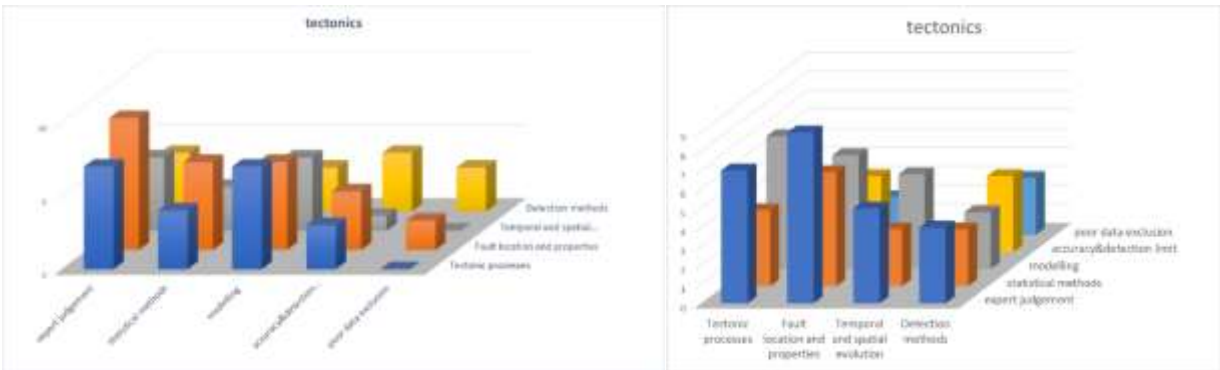


Figure 71. Frequency of the methods used in characterisation of uncertainties related to site tectonics

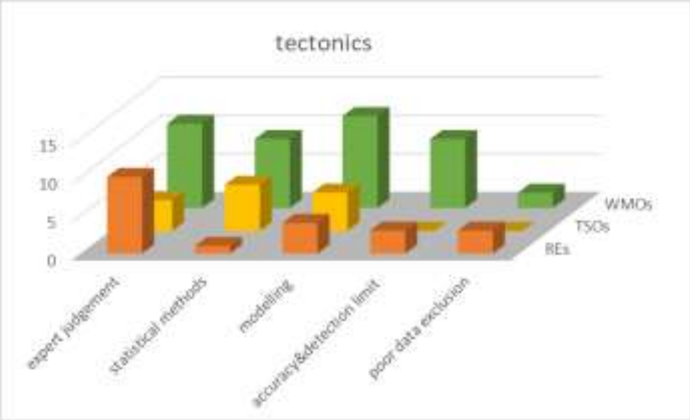


Figure 72. Actors' preferences in the characterisation of uncertainties on site tectonics

4.1.1 Uncertainty evolution in time

Applying site selection criteria could help to avoid presence of local faults, therefore minimizing the risk of future fault formation.

In the **REs** view, uncertainty on the fault's evolution will remain high until the site and host formation selection, when faults characterisation actually starts.

According to the **TSOs** opinion, the uncertainty is expected to reduce as the host rock and site are selected and characterized. Structural mapping of the site leaves minimal uncertainty on potential undetected fault. However, small uncertainty with potential impact on the disposal safety remains and it has to be accounted for by the repository design. Thus, it is necessary to develop a scenario of fault crossing the disposal facility or altered evolution scenario of fault propagation.

WMOs added that new methodologies for deterministic and Discrete Fracture Network modelling, including uncertainty and confidence estimates are under development. Further adjustments, testing and development of the methodology are to be expected during the construction of the repository.

The understanding of faults evolution will definitely increase and the uncertainty estimates will hopefully be more accurate during the repository construction (*Figure 73*). Therefore, WMOs consider as well that a better understanding of the system, will likely significantly reduce these uncertainties over the time.

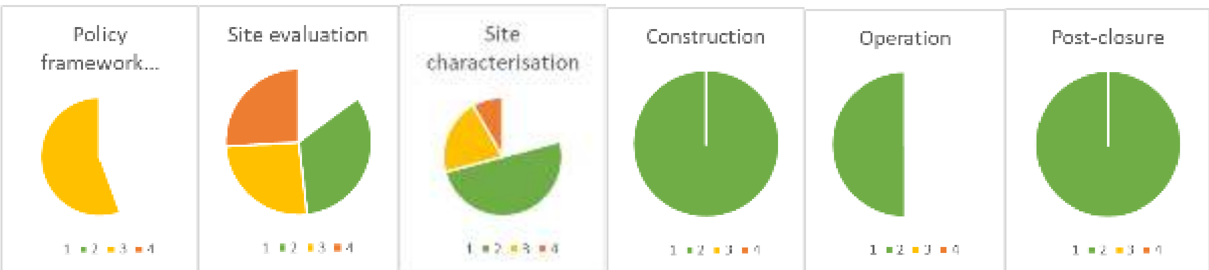


Figure 73. Global uncertainties significance along the disposal programme phases
☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

4.2 Uncertainties associated with earthquakes (J)

4.2.1 Significance for safety

Geological disposal

Disposal sites are as far as possible selected in a low seismic area, but given the long timescales during which the radiotoxicity of the waste may remain significant, earthquakes cannot be excluded. Earthquakes can affect the stability and integrity of the disposal system during operation or post-closure. The consequences of an earthquake can also increase the flow of water through the disposal system (e.g. as a result of the seismic pumping).

When gathering all answers provided on uncertainties associated with tectonic processes and structures by all types of actors and whatever the types of disposal facilities, we can see on the pie charts in *Figure 74* that (i) the knowledge on the importance of uncertainties increases (the number of "not answered" diminish) and (ii) the level of importance of uncertainties decreases with evolution of the program:

1. Not answered or uncertainty unknown or not assessed (white)
2. Uncertainty of low importance with regards to safety (green)
3. Uncertainty of medium importance with regards to safety (yellow)
4. Uncertainty of high importance with regards to safety (red)

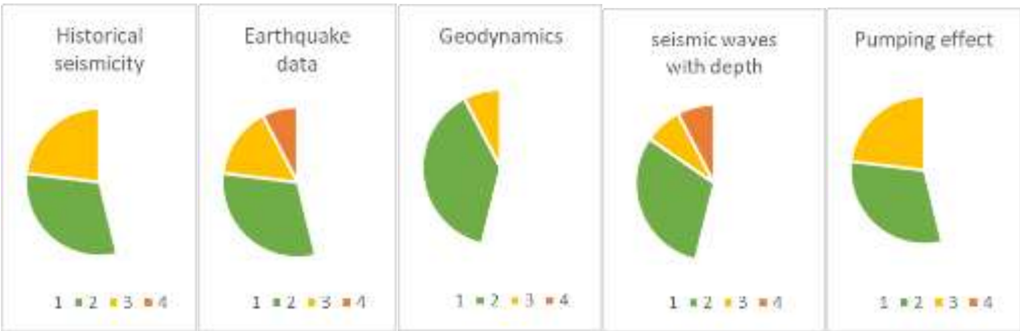


Figure 74. Answers distribution per safety relevance for all actors
☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

Uncertainties regarding the historical seismicity of the site, which may not record events of large magnitude, could have, in the **WMOs** view, a medium to high impact on the disposal safety, being associated with the operational and post-closure risk assessment, as well as with the safety functions of the disposal system (Table 19).

The opinions on the relevance for safety of uncertainties on epicentre location, earthquake magnitude and seismic wave properties, as well as on the geodynamic properties of the site are quite spread among the actors from the same category, but in average, they are considered do not significantly affect the geological disposal safety, by any of the actors involved in this investigation (*Figure* 73).

Uncertainty on pumping effect, which could produce a fast water and contaminant vertical movement, has been evaluate to a medium relevance, at most, by all actors.

In the TSOs' view, the highest significance for safety in this series is associated to the uncertainties on propagation of the seismic waves with depth (*Figure 75*).

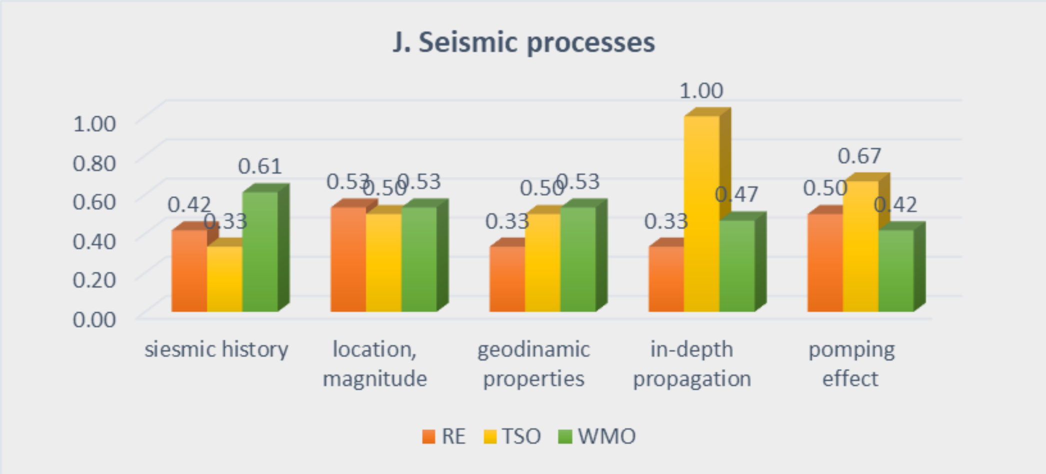


Figure 75. Significance for safety of uncertainties related to seismic processes (DGD)

Table 19. *Synopsis of the actors' views on uncertainties related to seismic processes for geological disposal*

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Historical seismicity	0.42	1m; 3l;4n	0.33	2l;1n	0.61	2h; 2m;1l;2n	xx	xxx	xxxx
Epicentre location, earthquake magnitude, seismic wave properties	0.53	1h; 3l; 3n;1m	0.50	1m; 1l; 1n;	0.53	1h; 1m; 3l; 2n	xxxx	xxx	xxxx
Geodynamic properties	0.33	3l;5n	0.50	1m; 1l; 1n	0.53	3m; 2l; 2n	x	xxxx	xxxx
Propagation of the seismic waves with depth	0.33	2l; 6n	1.00	1h; 2n	0.47	2m; 3l; 2n	x	xx	xx
Pumping effect (i.e. fast water and contaminant vertical movement)	0.50	2m; 2l; 4n;	0.67	1m; 2n;	0.42	1m; 3l; 3n	-	x	x

Near surface disposal

In contrast, for the near surface disposal, significance for safety of the all uncertainties but the one for pumping effect (*Figure 76*), is considered by all actors to have a low to medium impact associated to the safety functions of the disposal system (

Table 20).

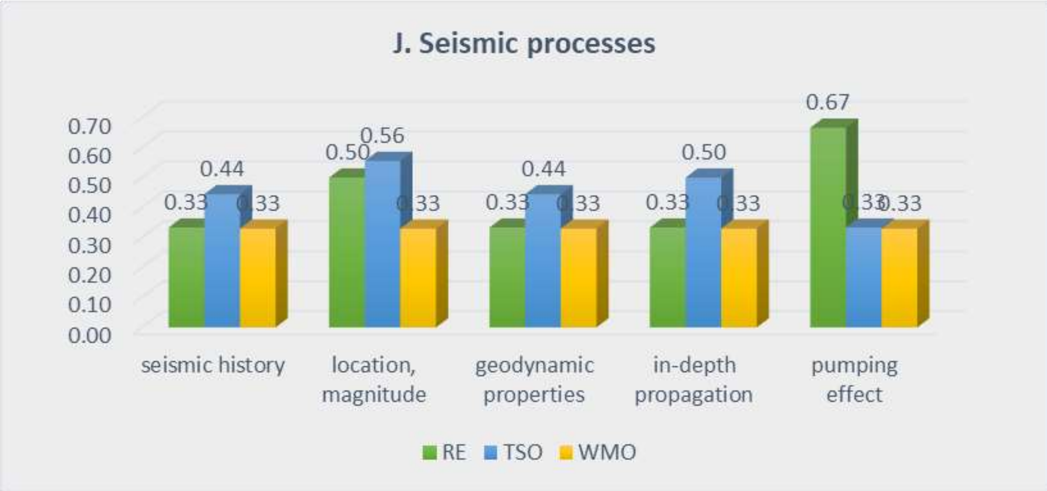


Figure 76. Significance for safety of uncertainties related to seismic processes (NSD)

Table 20. Synopsis of the actors' views on uncertainties related to seismic processes for near surface disposal

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
seismic history	0.33	2l	0.44	1m; 1l	0.33	1l	x		x
location, magnitude	0.50	1m; 1l	0.56	2m	0.33	1l			x
geodynamic properties	0.33	1l	0.44	1m; 1l	0.33	1l			x
in-depth propagation	0.33	1l	0.50	1m; 1n	0.33	1l			x
pumping effect	0.67	1n	0.33	2n	0.33	1l			x

4.2.2 Uncertainties characterisation

For deep geological disposal programmes, the four chosen uncertainty management options are quantification by expert judgement (notably for historical seismicity, geodynamics and pumping effects), modelling (notably for geodynamics and pumping effects), applying statistical methods (notably for seismic data and evolution of seismic waves with depth) and accuracy of measurements and detection limits (notably for earthquake data) (*Figure 77*, *Figure 78*).

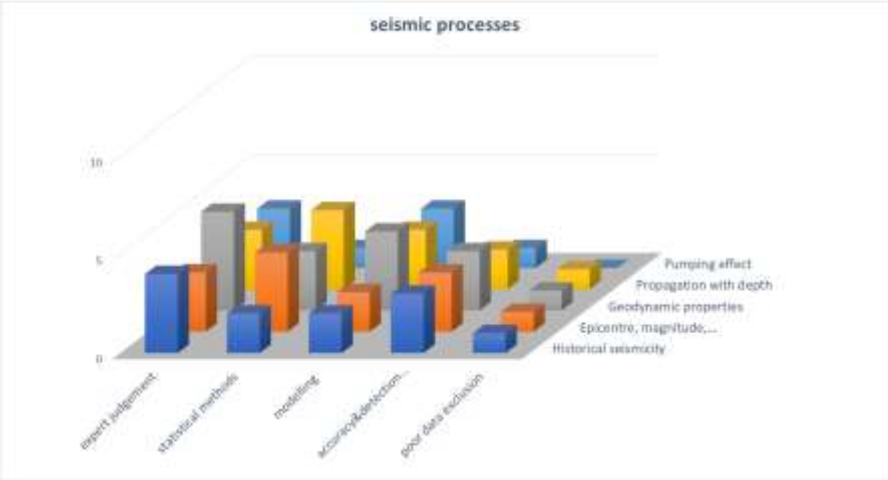


Figure 77. Frequency of the methods used in characterisation of uncertainties related to seismic processes

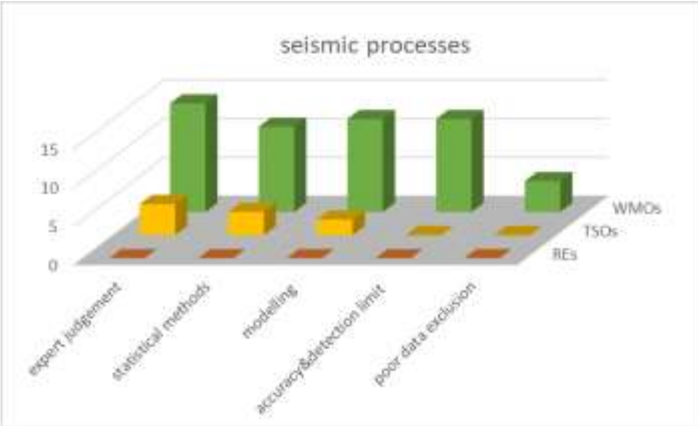


Figure 78. Actors' preferences in the characterisation of uncertainties on seismic processes

4.2.3 Uncertainty evolution in time

When gathering all answers provided on uncertainties associated with earthquakes by all types of actors and whatever the types of disposal facilities, we can see the same tendency as for tectonic processes with evolution of the program:

1- Not answered or uncertainty unknown or not assessed (white)
2- Uncertainty of low importance with regards to safety (green)
3- Uncertainty of medium importance with regards to safety (yellow)
4- Uncertainty of high importance with regards to safety (red)

Figure 79. Global significance along the disposal programme phases of uncertainties related to earthquakes

☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

In the case of deep geological disposal, uncertainty on historical seismicity will decrease during the development of the programme but some will remain for sites located in an intraplate zone with low and diffuse seismicity (*Figure 79*).

4.3 Uncertainties associated with diapirism (K)

4.3.1 Significance for safety

Uncertainties associated with diapiric activity in the disposal region are considered to have a low impact on safety by all actors involved in this survey, both for geological and near surface disposal (

Figure *81*, *Figure 82*,

Table 21 and Table 22) when considered in the safety case.

Considering all disposal types and stages of development of the project, uncertainty associated with diapirism is generally not assessed (*Figure 80*).

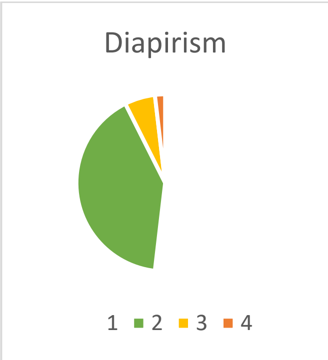


Figure 80. Overall significance for safety of uncertainties related diapirism (for all actors, repository concepts and programme phases)

☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

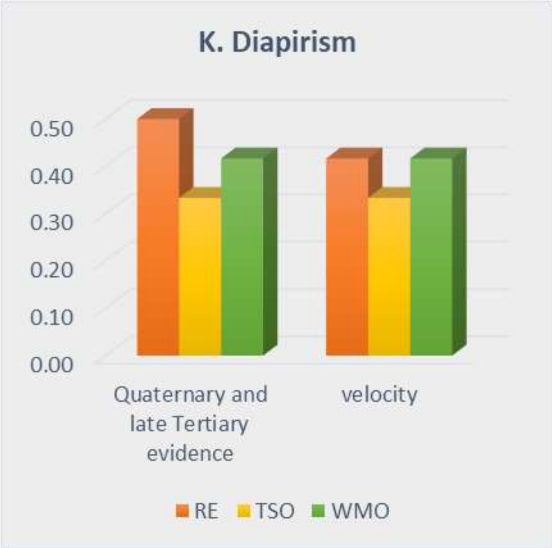


Figure 81. Significance for safety of uncertainties related to diapirism (DGD

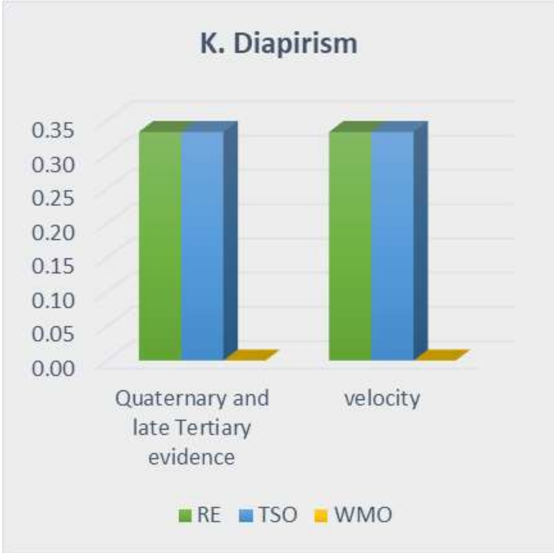


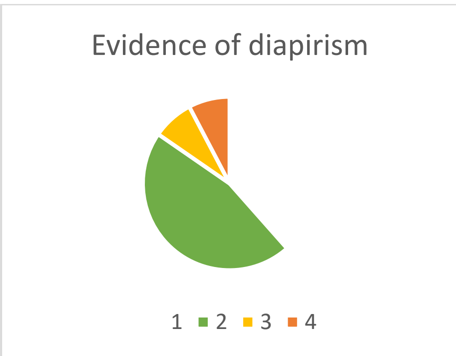
Figure 82. Significance for safety of uncertainties related to diapirism (NSD)

Table 21. *Synopsis of the actors' views on uncertainties related to diapirism for geological disposal*

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Quaternary and late Tertiary evidence	0.50	1n; 1h; 2l	0.33	1n; 2l	0.42	3l		x	x
velocity	0.42	1n; 1m; 2l	0.33	1n; 2l	0.42	3l			

For deep geological disposal, uncertainty associated with diapirism is considered as low for all except:

- assessed as unknown, medium or high by German organisations (GRS, BGE & HZDR) because of the choice of a salt host rock,
- unknown or not answered by several organisations (ANDRA (Fr), TUL, CVR & SURO (CZ), Slovak University (Sk) and ENRESA (Sp))



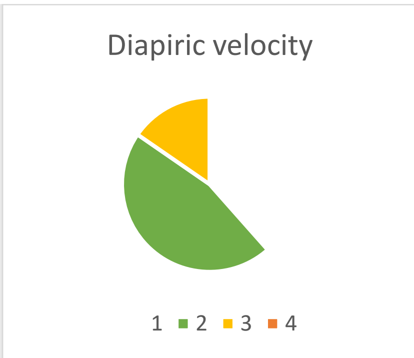


Figure 83. Answers distribution per safety relevance for all actors for uncertainties associated to diapirism (DGD)

☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

Sub-surface disposal

Most of organisation have not answered about the significance of uncertainty, or it is unknown or not assessed. For the others, it is considered as low (*Figure 84*).

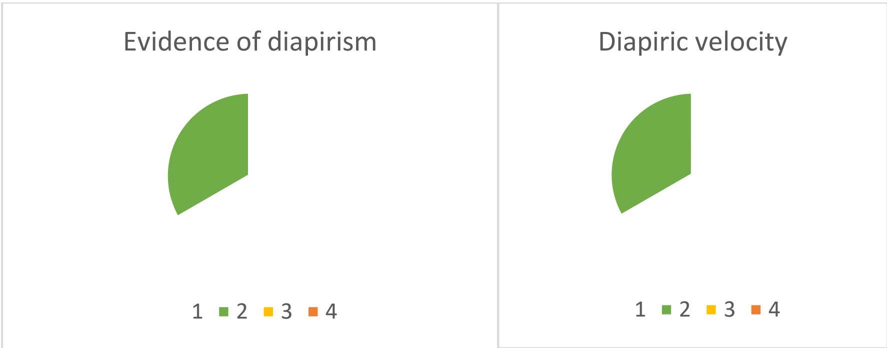


Figure 84. Answers distribution per safety relevance for all actors for uncertainties on diapirism (SSD)
Not answered, unknown or not assessed, low importance, medium importance, high importance

Near-surface disposal

Most of organisation have not answered about the significance of this uncertainty, or it is unknown or not assessed. For the others, it is considered as low (*Figure 85*).

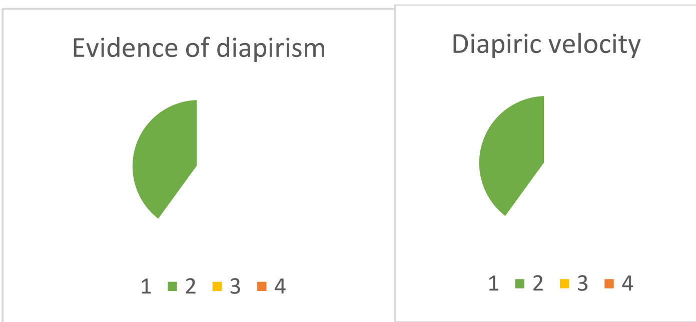


Figure 85. Answers distribution per safety relevance for all actors for uncertainties on diapirism (NSD)
Not answered, unknown or not assessed, low importance, medium importance, high importance

Table 22. *Synopsis of the actors' views on uncertainties related to diapirism for near surface disposal*

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Quaternary and late Tertiary evidence	0.33	2n; 1l	0.33	1n; 1l		-			
velocity	0.33	2n; 1l	0.33	1n; 1l		-			

4.3.2 Uncertainties characterisation

Methods used in the characterisation of the uncertainties related to diapiric process, as well as the preferences of each actor are illustrated in Figure 86 and Figure 87.

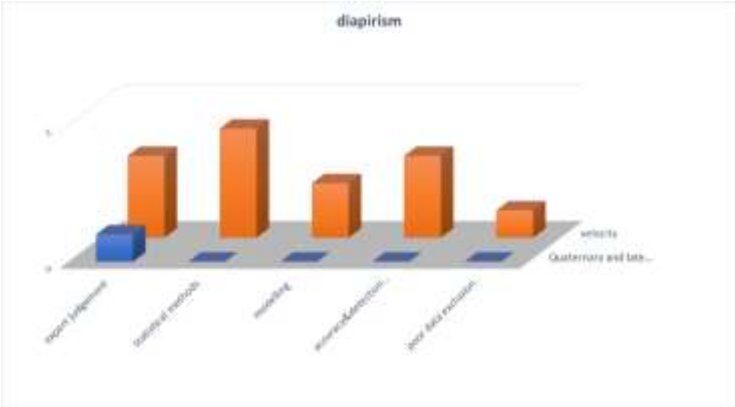


Figure 86. *Frequency of the methods used in characterisation of uncertainties related to diapirism*

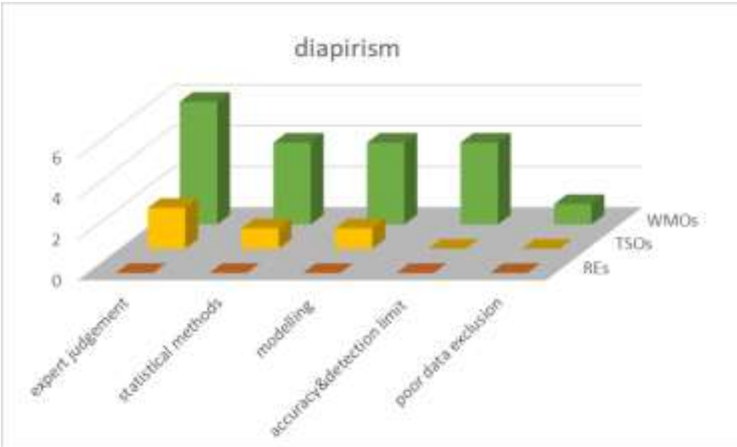


Figure 87. *Actors' preferences in the characterisation of uncertainties on diapirism*

4.3.3 Uncertainty evolution in time

Not really enough numerous data, but the uncertainty remains low during all the programme (*Figure 88*).

Figure 88. Global significance along the disposal programme phases of uncertainties related to diapirism
☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

4.4 Uncertainties associated to volcanic occurrence in the region (L)

4.4.1 Significance for safety

When considering all disposal types and stages of development of the project, uncertainty associated with volcanism is generally considered as low (Figure 89, Figure 90, *Table 23* and Table 24).

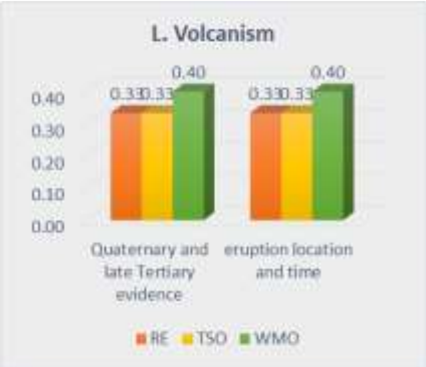


Figure 89. Significance for safety of uncertainties related to volcanism (DGD)

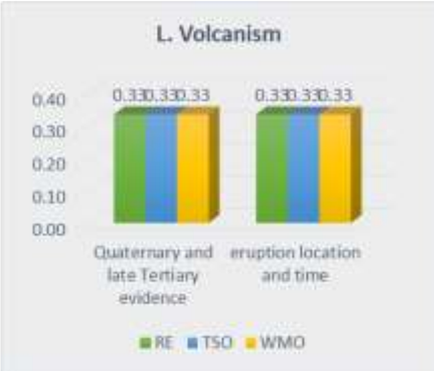


Figure 90. Significance for safety of uncertainties related to volcanism (NSD)

Uncertainty is generally considered as low, but sometimes unknown, not answered or even medium for organisations from countries that are in the very beginning of the deep geological disposal project.

Table 23. Synopsis of the actors' views on uncertainties related to volcanism for geological disposal

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
History of volcanic activity, Quaternary and late Tertiary volcanism	0.33	6l; 2n	0.33	3l	0.40	4l; 1m; 2n		x	x
Location and time of potential volcanic eruptions	0.33	6l; 2n	0.33	3l	0.40	4l; 1m; 2n			

Sub-surface disposal

Uncertainty on volcanic activity and data is considered as low by all (*Figure 91*).

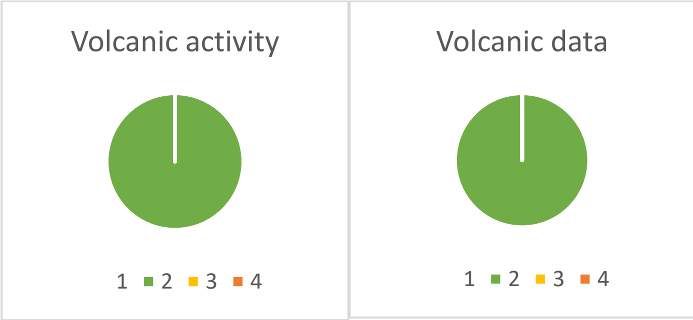


Figure 91. Answers distribution per safety relevance for all actors for uncertainties associated to volcanism (SSD)

☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

Near-surface disposal

Uncertainty on volcanic activity and data is considered as low by all (*Figure 92*) but few organisations did not answer or do not know (Table 24), probably due to the level of progress of the disposal programme in their country (beginning in Slovakia) or has been not considered in the FEPs list, being excluded by the site selection criteria.

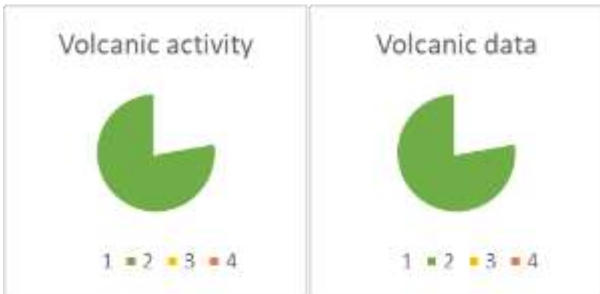


Figure 92. Answers distribution per safety relevance for all actors for uncertainties associated to volcanism (NSD)

☐ *Not answered, unknown or not assessed,* ■ *low importance,* ■ *medium importance,* ■ *high importance*

Table 24. *Synopsis of the actors' views on uncertainties related to volcanism for near surface disposal*

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Quaternary and late Tertiary evidence	0.33	3l;1n	0.33	4l	0.33	1l			
eruption location and time	0.33	3l; 1n	0.33	4l	0.33	1l			

4.4.2 Uncertainties charcaterisation

The only method proposed for uncertainty characterisation is the quantification of a potential volcanic event by the expert judgement (*Figure 93*, *Figure 94*).

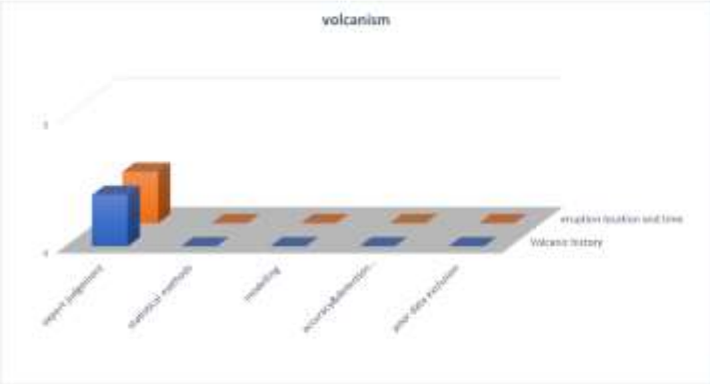


Figure 93. Frequency of the methods used in characterisation of uncertainties related to volcanic processes

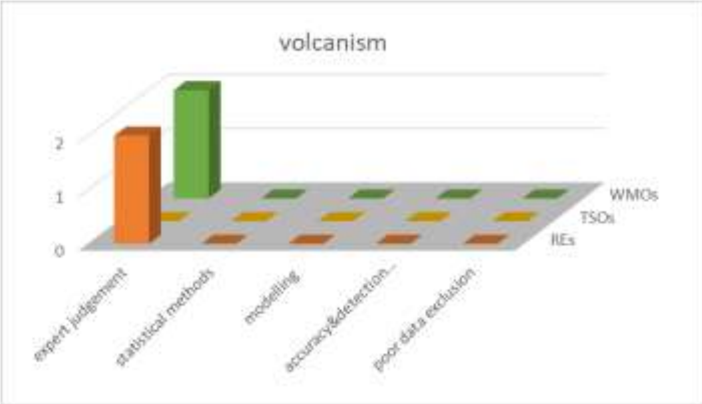


Figure 94. Actors' preferences in the characterisation of uncertainties on volcanism

4.4.1 Uncertainty evolution in time

Answers are not enough numerous to make a thorough analysis but we can see that the knowledge on the importance of uncertainties increases (the number of "not answered" diminish) and the uncertainty remains low during all the programme (*Figure 95*).

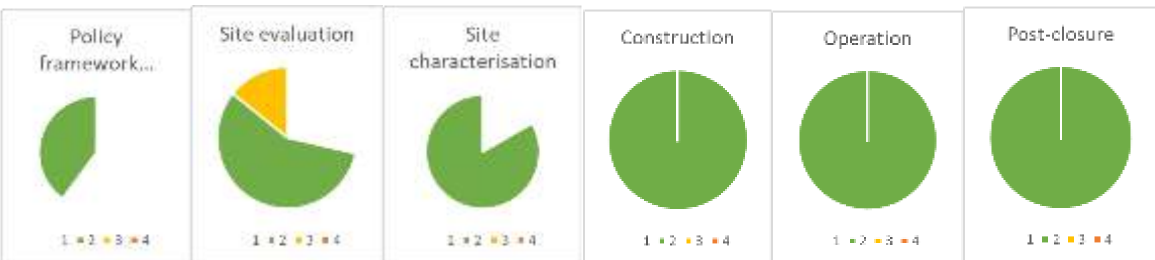


Figure 95. Evolution of uncertainties related volcanism along the programme implementation phases
☐ Not answered, unknown or not assessed, ■ low importance, ■ medium importance, ■ high importance

5. Uncertainties associated with future climate changes

In the near term, climate changes could include global warming, while in the long term a “normal” alternation of glacial and interglacial periods (as in the Quaternary) could be expected. All these natural and anthropic changes can impact safety-relevant processes and parameters, and thus must be taken into account in the safety case and safety analysis.

5.1 Uncertainties associated to climate changes (other than glaciations) (M)

The climate changes on the near term, referring here to the anthropogenic climate changes, could include:

- Wet periods with higher precipitation rates
- Wet tropical climate or hot tropical climate with winter rainfalls, with implications on the erosion rate, probably well documented in countries that undergo these climates nowadays, but poorly studied for being used in modelling in the countries with temperate, oceanic or arctic climate where most repositories are planned to be built.
- Dry climate which could bring desertification and an increased erosion rate, which could become important for the safety of the near-surface disposal.

For coastal areas, climate changes could also lead to shoreline displacement, resulting in significant changes in boundary conditions of a repository in such zone (as in the Forsmark case).

Climate changes could impact some relevant meteorological (precipitation rate, evapotranspiration rate, wind speed and directions) and hydrogeological characteristics (infiltration rate, water table level), with influence on the water flow field and radionuclide release rate in the environment, and on the erosion rate, and consequently on the radiological dose.

Changes in the current climate could also generate modifications of the biosphere (different fauna and flora, other species of vegetables and crops; etc) which will change the habits of the population.

The history of the climate in the region is considered to be helpful in predicting the future evolution of the site, taking into consideration the trends in the last decades.

5.1.1 Significance for safety

Geological disposal

Uncertainties related to the climate changes other than glaciations include uncertainties associated with the climate history of the region, with changes that may occur as a result of anthropogenic global warming and with modifications in the radionuclides transfer pathways to the biosphere and humans. Significance for safety of these uncertainties is seen different by the three categories actors. While the most of the REs appreciate as low their impact on the geological disposal safety, the TSOs and WMOs consider that the type of climate and its characteristics have a higher significance in the safety assessment (Figure 96, Table 25), due to the impact on the post-closure risk estimation (which is function on the scenarios on the future evolution) and on safety functions of the geosphere.

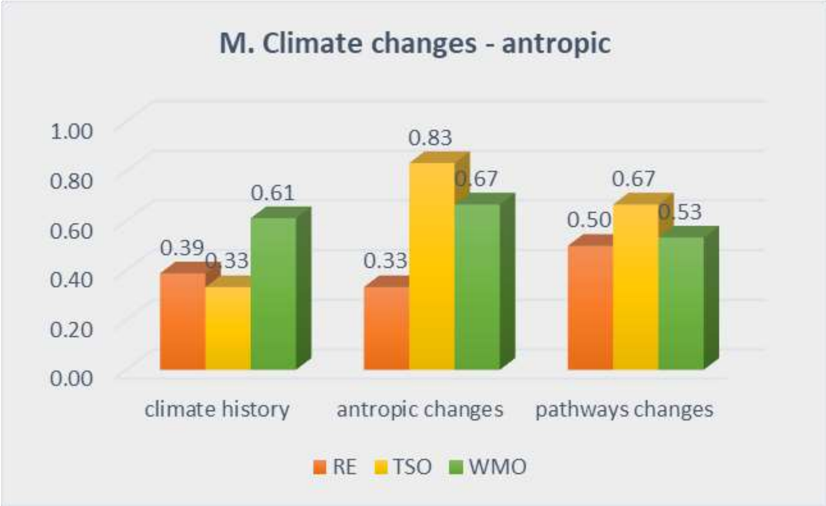


Figure 96. Significance for safety of uncertainties related to anthropic climate changes (DGD)

Table 25. Synopsis of the actors' views on uncertainties related to anthropic climate changes for geological disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
		REs		TSOs		WMOs	Operational dose/risk	Post-closure dose/risk	Safety functions
Climate history	0.39	1m 5l; 2n;	0.33	3l	0.61	2h; 1m; 3l; 1n		xxxx	xxx
Climate changes that may result from the anthropic global warming: type (e.g. wet or dry), duration,…	0.33	4l; 4n;	0.83	1h; 1m; 1n;	0.67	1h; 3m; 1l; 2n	xx	xx	xxx
Changes in the transfer pathways in the biosphere and to humans	0.50	1h; 1m; 4l; 2n;	0.67	1h; 1m; 1l;	0.53	1h; 3l; 1m; 2n	x	xxxx	xx

Near surface disposal

In the case of near surface disposal, the significance for safety of the anthropic climate changes is important both for REs and TSOs. Climatic variations can bring a wetter climate, rich in precipitation that would increase the infiltration rate (one of the parameters to which radionuclide transport models are highly sensitive), or a dry climate, which could increase the erosion rate, leading to the exposure of the repository to the surface, with all the consequences on the post-closure radiological dose and its isolation and confinement functions (*Table 26*, Figure 97).

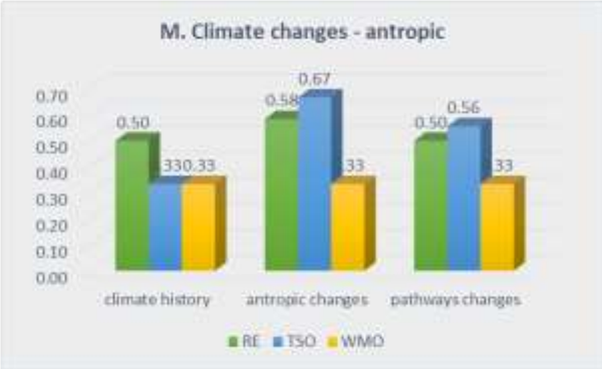


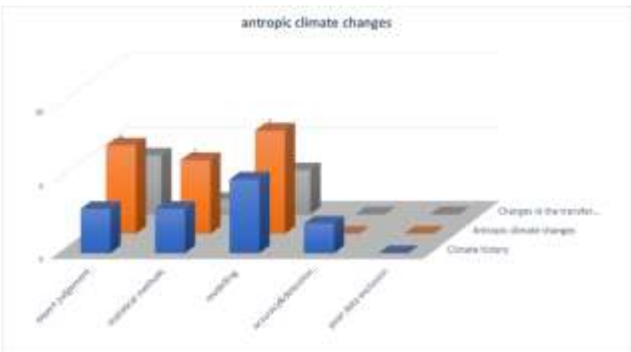
Figure 97. *Significance for safety of uncertainties related to anthropic climate changes (NSD)*

Table 26. Synopsis of the actors' views on uncertainties related to anthropic climate changes for near surface disposal

Uncertainty	**Score of uncertainty relevance for safety**						**Impact on:**		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
climate history	0.50	1h; 3l; 1n;	0.33	3l	0.33	1l			
anthropic changes	0.58	1h; 2l; 1m; 1n	0.67	1h; 1l; 1n;	0.33	1l		x	x
pathways changes	0.50	2m; 2l; 1n;	0.56	1h; 2l;	0.33	1l		x	

5.1.2 Uncertainties characterisation

Modelling is from far the most method used by all actors in the characterisation of the anthropic climate changes (*Figure 98* and *Figure 99*); it is complemented by quantification by expert judgement and statistical analyses on existing data, used especially by TSOs and WMOs.



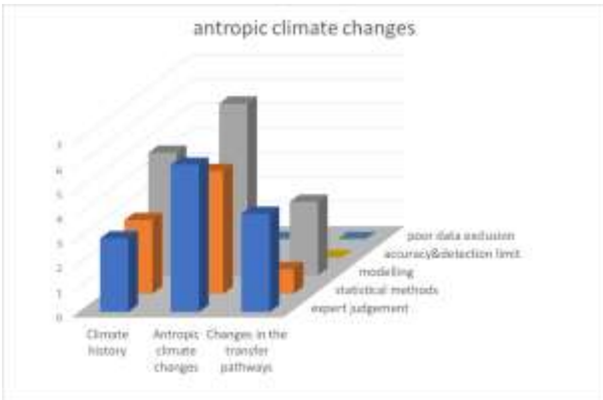


Figure 98. Frequency of the methods used in characterisation of uncertainties related to antropic climate changes

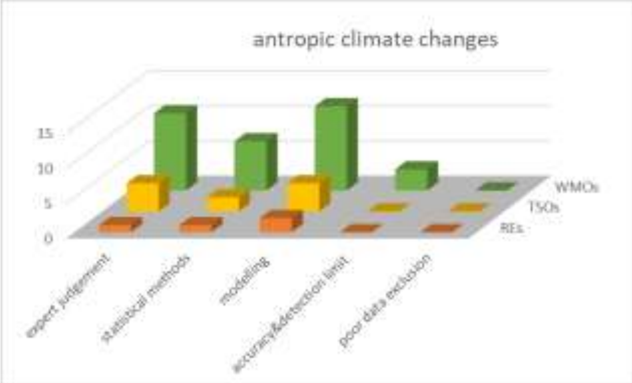


Figure 99. Actors' preferences in the characterisation of uncertainties on anthropic climate changes

5.2 Uncertainties associated to glaciations (N)

Over the last million years, the Earth's history has been marked by nine glacial cycles [10, 11]. Ice coverage was subject of many cycles of glacial ice sheet advance and retreat, separated by ice-free periods of warmer climate (interglacials), lasting from thousands to hundreds of thousands of years. During the last glaciation, starting approximately 120,000 years ago, over 97% of Canada was covered by ice, reaching in the northern part up to 4 km. The final retreat of the ice sheet occurred between 9000 and 6500 years ago [12].

The main factors that initiated these cycles (i.e., solar insolation variation due to Earth orbital dynamics and the location and size of the continents) still exist. Therefore, conditions suitable for the reglaciation of the northern zones of the Earth will likely occur in ~60,000 years from present, and again in ~125,000 years from present [13]. However, due to the current levels of greenhouse gases in the atmosphere the beginning of the next glaciation may delay.

The characteristics of the glaciation process relevant for the understanding of disposal performance and its safety include:

- Groundwater system stability, including deep groundwater chemical conditions, which has the potential to impact rates of mass transport at repository depth;
- Geo-mechanical stability of the repository system and geosphere, as impacted by the increased ground stresses due to the ice-thickness;
- Erosion, related to the movement of the ice sheet and meltwater across the land surface; and
- Permafrost formation, which will affect groundwater movement, and potentially the repository if it extends to that depth.

In assessing the long-term stability and evolution of groundwater systems at depth in the host rock, the loading and unloading of the geosphere by a glacier is believed to represent one of the most significant perturbations compared to the present-day conditions.

The ice sheet will induce new stress in the field and changes in the hydraulic parameters of the site (permeability, hydraulic gradients) with impact on the flow field. Ice melting could modify the ground water chemistry, with impact on the radionuclide behaviour in the host rock.

Future glacial conditions will be accompanied by an extended period with widespread formation of permafrost. The permafrost thickness could range from tens of meters to few hundred meters, depending on the geographic latitude of the disposal site. A repository sited 500 m depth should be below the depth of permafrost, so not directly affected. However, the presence of permafrost in the geosphere will act to reduce the hydraulic conductivity, thereby limiting recharge from the surface during glaciation. The formation of taliks (regions of perennially unfrozen ground that exist within the permafrost environments) could represent potential radionuclide accumulation zones in the upper part of the site, with impact on the dose assessment, if a well drilled by the reference group/persons would intersect it.

Successive cycles of glaciations can generate large erosion and sedimentation processes, with uncertainties on their rates.

Figure 100. Relevance of uncertainties on glaciation parameters and processes for disposal safety

A global assessment of all the answers received from all actors and for all repository types on the significance of the uncertainties associated with the glaciation processes and parameters addressed by the questionnaire (**Erreur ! Source du renvoi introuvable.**) shown that a large majority consider them as having a low impact on the disposal safety, and only 20 to 30% indicated a medium or high relevance (*Figure 100*).

With all these potential changes induced in the disposal site, glaciations could have significant impacts on the assessment of the radiological dose or risk associated to the repository, especially in the case of waste disposal in sub-surface and/or geological facilities, and less for the LIL-SL disposal in near surface facilities, for which the time until its radioactivity reach the natural level is much shorter than to the time when the next glaciation will reinstall.

The picture of the significance for safety changes when answers are differentiated with respect to the repository type. While the impact of these uncertainties is estimated to be low or not addressed by almost in majority of the near surface disposal safety cases, all actors give a higher importance to these uncertainties in the case of the geological repositories (*Figure 101* and *Figure 102*).

5.2.1 Significance for safety

Geological disposal

Glaciations will bring a series of important changes in the conditions in which a deep geologic disposal system will evolve. All the processes and their characteristic parameters have to be considered for the long-term safety of the geological repository. Their estimation is based on indirect information derived from evidences of the past glaciation events and numerical predictions of the impacts on the site.

Significance for safety of the nine uncertainties addressed by the questionnaire correlates with the impact they could have both on post-closure safety evaluations and the safety functions of the engineered and natural barriers of the disposal system.

Table 27. Synopsis of the actors' views on uncertainties related to glaciations for geological disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Starting time and duration of the next glacial period	0.53	1h; 1m; 3l; 3n	0.44	1m;2l	0.73	2h; 2m; 1l 2n		xxx	xxx
Extent and location of the ice sheet	0.60	2h 3l; 3n;	0.56	1h; 2l;	0.72	3h; 1m; 2l; 1n		xxxx	xxxx
Inter-glacial cycle frequency and duration	0.40	1m; 4l; 3n;	0.33	2l; 1n	0.73	3h;2l; 2n		xx	xx
Permafrost depth	0.53	3m; 2l; 3n	0.56	1h; 2l	0.56	4m; 2l; 1n		xxx	xxxx
Erosion/sedimentation rates	0.33	3m; 2l; 3n	0.78	1h; 2m	0.61	2h; 1m; 3l; 1n		xxxxx	xxxx
Induced stress fields	0.33	5l; 3n	0.33	1l; 2n	0.56	1h; 2m; 3l; 1n		xx	xx
Changes in groundwater flow (porosity, permeability, hydraulic gradients, flow directions,…)	0.42	1m; 3l; 4n	0.67	1h; 1m;1l	0.67	2h; 2m;2l; 1n		xxxxx	xxxx
Impact on groundwater chemistry (dilution due to plug flow, increased desorption	0.50	2n; 3l	0.50	1m; 1n; 1l	0.53	2n; 1m; 1h; 3l		xxxx	xx
Changes in the transfer pathways in the biosphere and to humans	0.42	2n; 1m; 2l	1.00	1n; 2h	0.39	5l; 1m; 1n		xxx	x

As a general remark, all uncertainties associated with glaciations are considered relevant for the safety of the geological disposal by all three actors, but in a different way. Therefore, REs seems to estimate a lower impact on safety compared to WMOs and TSOs. While TSOs consider that the uncertainties on changes in the radionuclide transport pathways and erosion/deposition rate could have the highest impact on the post-closure risk assessment and safety functions of the disposal system, the WMOs appraise that beginning of the glaciation and duration, icesheet extent and location, and the frequency of interglacial cycles are the most significant (**Erreur ! Source du renvoi introuvable.**).

The major uncertainty related to the *beginning and duration of the next glaciation cycle* is associated with the difficulties in prediction the evolution of the CO2 amount in the atmosphere. The dose estimation depends on the inventory existing at the moment when glaciations begin, which justify a medium to high significance for safety of this uncertainty in the TSOs and WMOs view.

In the REs views, glaciations control the hydrologic cycle and groundwater velocities even in the area without ice (such as the Central Europe region). The significance for safety of these uncertainties depends on the disposal concept. It ranges from high impact associated to some disposal concepts in which glaciations could affect the barrier system, to low impact when it is assumed that glaciation may affect only surface geology and not the deep disposal horizons.

Figure 101. Significance for safety of uncertainties related to glaciations (DGD)

TSOs appreciate that the impact on the dose will depend on the remaining radioactivity (i.e. decay) at the time of the next glaciation and the impact on safety functions will depend on the expected effectiveness of the functions at that time.

WMOs raised concerns regarding potential glacial excavation with influences on the total bedrock surface denudation. Long periods of temperate conditions may also lead to diluted groundwater. Safety functions such as long-term stability of external long-term evolution, and immobilisation, retention and slow release of radionuclides (geosphere, biosphere) could also be impacted by the glaciation.

The *location and extent of the ice sheet* is more relevant for repositories in the Northern part of Europe where, according to some natural evidences, it reached up to 3 Km, and less significant in the central and southern European region, where the impact of the glaciation decreases. The medium and high significance for safety is due to the supplementary load on the geological layers determining modification of the stress field in the rock and adjacent layers, reduction of the pore size and permeability and consequently, changes in the flow field. The ice sheet weight will also impact the total load on the canisters, increasing the risk of failure. As noted by TSOs, even in the regions not significantly affected by glaciations, the underground water flow patterns will change as result of the thick ice sheet presence in the northern part.

For REs, the uncertainties on the extent and location of the ice sheet are associated with high uncertainty and a high impact on the safety due to the increased risk of glacial erosion and changes in hydrogeological system for the northern countries in Europe, while from the point of view of central Europe it can be excluded based on history.

TSOs pointed out that the occurrence of an ice sheet will create substantial changes of the hydrogeological conditions and of the biosphere, and will have the potential to affect the disposal safety functions through, for example freezing (a part) of the host rock (permafrost), erosion of geological layers belonging to the disposal system and pressure changes.

For WMOs, melting of the ice sheet could affect the groundwater flow and chemistry, as well as the total isostatic pressure on canisters, affecting the integrity of the disposal barrier system and the radionuclide retention and retardation in the geological layers.

Inter-glacial cycle frequency and duration affects the number of periods with substantially increased groundwater flow during ice margin passages, and can have an impact on the repositories placed in these regions. Interglacial cycles will play an important role in defining the hydrologic cycle (REs) and could affect the long-term stability of external long-term evolution, as well as geosphere safety functions related to the immobilisation, retention and slow release of radionuclides (geosphere, biosphere).

The uncertainties related to the *permafrost* have been scored as having a medium significance by all three actors (*Figure 101*). All actors recognized the positive impact of the permafrost, which could disconnect the surface water from deeper groundwater, reducing therefore the flow rate and the radionuclide release into the biosphere. The TSOs highlighted the influence of the permafrost depth on the hydrogeological conditions of the site, with consequences on the radionuclide dilution in the aquifers, while WMOs mentioned the potential freezing of buffer and backfill material and the changes in the groundwater flow due to the bedrock freezing.

With regard to the safety functions, all actors agree that safety functions fulfilled by the host rock could be impacted if permafrost reaches the repository depth.

Erosion processes activated by the glaciers melting could remove large amounts of soil from above the repository, reducing the total depth to the repository, or could bring sediments on the site, changing the landscape and the surface hydrology. Uncertainties on the erosion/deposition rate is directly linked to the radionuclide transport length, on which the dose value depends. Furthermore, the high significance for safety associated to this uncertainty by WMOs is linked to potential freezing depths affected by the erosion/deposition processes at the disposal site.

The safety function "protection against human intrusion" fulfilled by geological layers located above the waste would be impacted. Depending on the depth of erosion and of the host rock, the safety functions “long-term stability of external long-term evolution”, "limitation of the water flow" and "chemical retention" could also be impacted.

Stress fields induced by the ice sheet is perceived to have a lower impact on the safety assessment, being associated by TSOs with potential glacially induced faulting, and with the radionuclide transport rate in the geosphere.

Changes in groundwater flow will probably occur due to the modifications of physical and hydraulic properties of the rock under the ice sheet isostatic pressure variations (porosity, permeability, hydraulic gradients, flow directions,…). All these parameters govern the dynamic of the radionuclide transport into the geosphere and the radionuclide release flux into the biosphere, and therefore significance for safety of their related uncertainties is important for the assessment of the radiological dose or risk after closure, especially from the WMOs and TSOs points of view.

Changes in hydraulic gradients caused by glaciations could impact the safety functions "limitation of the water flow", “long-term stability” and slow radionuclide release which had to be fulfilled by the host rock and the adjacent layers.

According to REs, the effects of the groundwater flow modification on the post-closure safety assessment depend on the extent and location of the ice sheet and/or permafrost.

Impact of glaciations on the *groundwater chemistry* due to infiltration of the ice-sheet melted water into the site could dilute the existing groundwater and therefore, increase the radionuclide desorption. This would increase the contaminant release into the biosphere, with impact on the post-closure dose and risk assessment. On the other side, as noticed by REs, during permafrost conditions, out-freezing of salts in aquifer systems may occur, leading to local salinization.

The significance for safety of the uncertainties associated to changes in the water chemistry is however considered low to medium by almost all actors.

Glaciation will bring as well *changes in the transfer pathways in the biosphere and to humans* which should be considered in the safety case and assessment. For REs, uncertainties on these changes could have a strong impact, but the efforts to predict it is questionable.

For TSOs these uncertainties have a high significance, since the occurrence of a glaciation create substantial changes to hydrogeological conditions and to the biosphere, which has to be considered for the post closure dose calculations. WMOs noticed the changes occurring in the biosphere properties, and the influence they could play on the release points to the biosphere.

Near surface disposal

In the case of near surface disposal, in which the period of interest for safety is considerably shorter, the effects of a future glaciations are considered practically irrelevant (*Figure 102*).

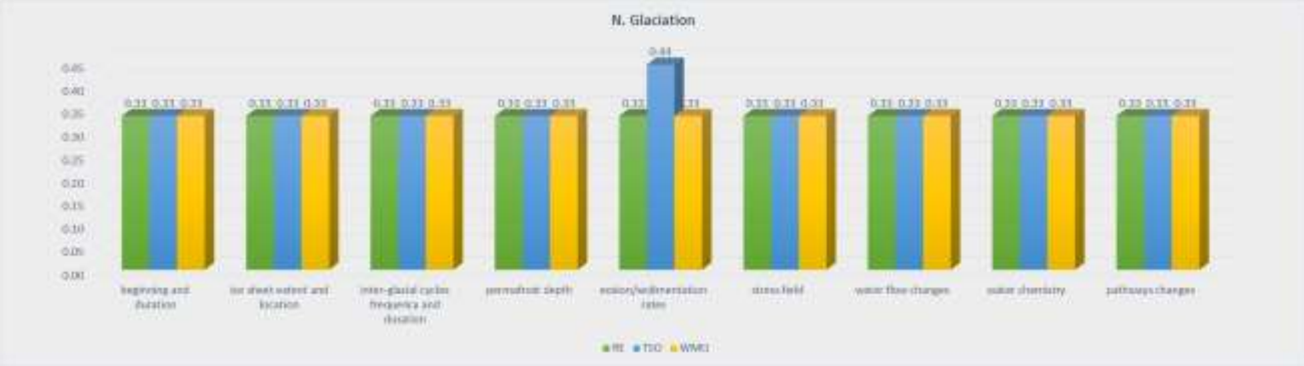


Figure 102. Significance for safety of uncertainties related to glaciations (NSD)

Table 28. *Synopsis of the actors' views on uncertainties related to glaciations for near surface disposal*

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Starting time and duration of the next glacial period	0.33	2n; 3l	0.33	3l	0.33	1l	-	-	-
Extent and location of the ice sheet	0.33	2n; 3l	0.33	3l	0.33	1l	-	-	-
Inter-glacial cycle frequency and duration	0.33	2n; 3l	0.33	3l	0.33	1l	-	-	-
Permafrost depth	0.33	2n; 3l	0.33	3l	0.33	1l	-	-	-
Erosion/sedimentation rates	0.33	2n; 3l	0.44	1m; 2l	0.33	1l		x	x
Induced stress fields	0.33	2n; 3l	0.33	1n; 2l	0.33	1l			
Changes in groundwater flow (porosity, permeability, hydraulic gradients, flow directions,…)	0.33	2n; 3l	0.33	3l	0.33	1l			
Impact on groundwater chemistry (dilution due to plug flow, increased desorption	0.33	2n; 3l	0.33	3l	0.33	1l			
Changes in the transfer pathways in the biosphere and to humans	0.33	2n; 3l	0.33	1n; 2l	0.33	1l			

Most likely these processes and their effects were excluded from the list of FEPs, or if included, they have been scored with low significance (Table 28).

5.2.2 Uncertainties characterisation

Methods used or recommended for the characterisation of the uncertainties associated with glaciations are (*Figure 103*):

- quantification by expert judgement *(preferred or mostly applied by RE, Figure 104)*
- modelling, for example for prediction of the ice sheet advance, permafrost thickness, changes in the groundwater flow and chemistry (*preferred/mostly used by WMOs and TSOs, Figure 104*.

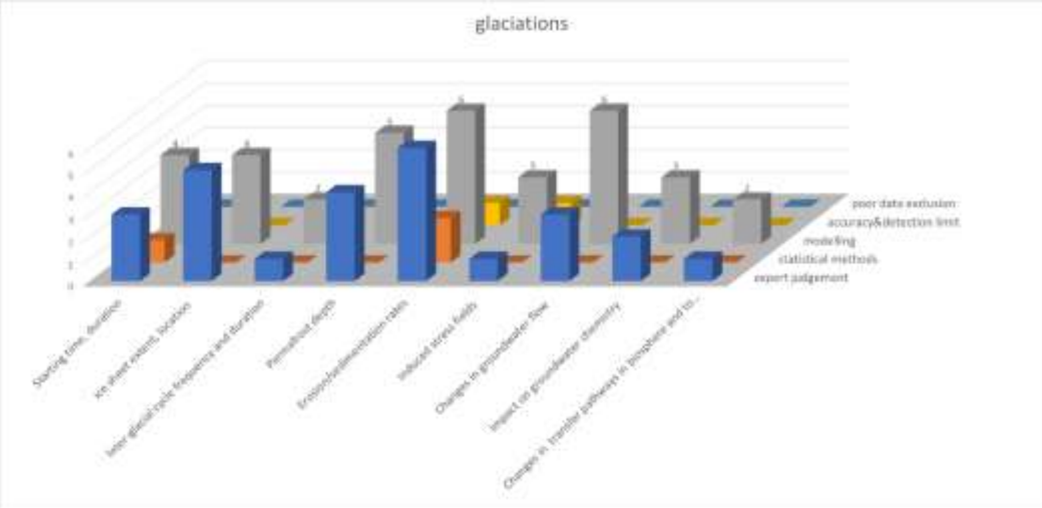


Figure 103. Frequency of the methods used in characterisation of uncertainties related to glaciations

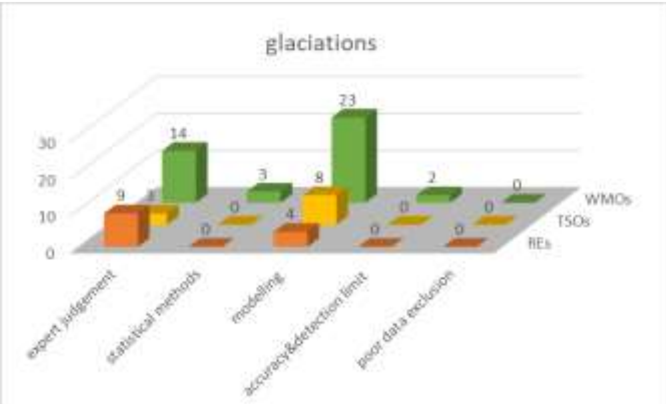


Figure 104. Actors' preferences in the characterisation of uncertainties on glaciations

In the estimation of the maximum depth to which the permafrost could extend, as well as in the associated uncertainty characterisation, all actors use more frequently, modelling but also the quantification based on expert judgement (*Figure 105*).

However, according to the existing literature, models for predicting the ice sheet advance and permafrost thickness are uncertain. Useful references documenting the modeling associated to glaciation, retrieved from http://publications.sckcen.be/dspace/bitstream/10038/7377/1/er_148.pdf are:

- *Beerten, K. (2011). Permafrost in northwestern Europe during the Last Glacial;*
- *Busby, J. P., Kender, S., Williamson, J. P., & Lee, J. R. (2014). Regional modelling of the potential for permafrost development in Great Britain. British Geological Survey Commissioned Report, CR/14/023, 73.;*
- *Govaerts, J., Beerten, K., Jacops, E., & De Craen, M. (2015a). Numerical simulation of Permafrost Depth in the Netherlands, 25.*

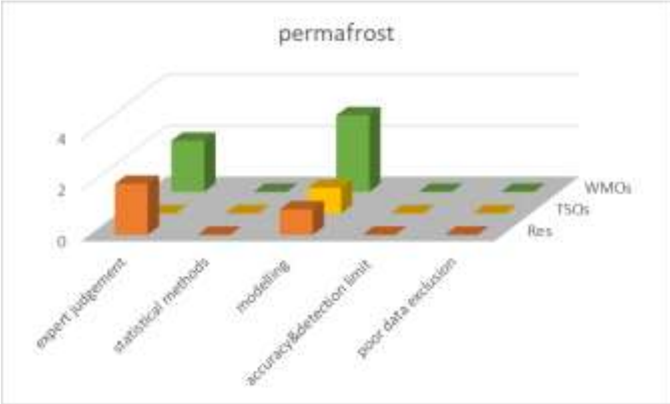


Figure 105. Actors' preferences in the characterisation of uncertainties on permafrost

For the actors in countries in the early stage of the disposal programme, uncertainties are just beginning to become relevant in the site selection procedure and strategies for characterisation have yet to be developed, while their characterisation is quite advanced in the more advanced programme [14].

5.2.3 Uncertainty evolution in time

Uncertainties associated to glacial modelling are perceived to be high, with relatively small potential for reduction. Depending on the safety assessment methodology and regulatory requirements, these uncertainties are usually dealt with through stylized approaches. So, in the REs view, the uncertainties on glaciations will remain unchanged along the implementation programme.

TSOs and WMOs are more optimistic. They believe that uncertainties might reduce as new knowledge on climate changes and better system understanding will be acquired and models will be validated with real data.

For geological disposal, uncertainties will be significant anyway until the construction phase (*Figure 106*).

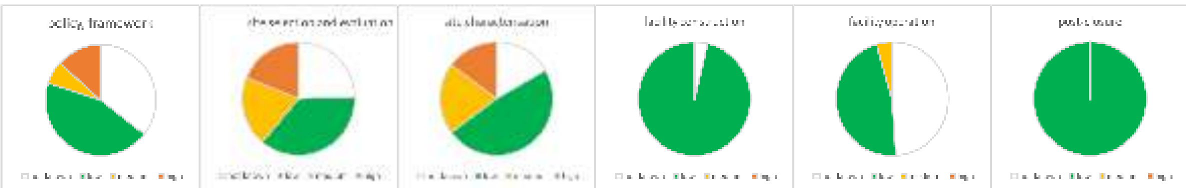


Figure 106. Evolution of global significance for safety of glaciations-related uncertainties (all actors, all disposal concepts)

5.3 Uncertainties associated to marine transgression and regressions (O)

5.3.1 Significance for safety

Changes in sea level occur as a result of the relaxation of the layers of the earth's crust after the last glacial period, which can lead to significant changes in the landscape, especially in coastal areas. Regions covered today by seawater can become exposed to the surface, radically changing the flow of groundwater, radionuclide transport routes, flora and fauna, habits and diet of the critical group. In very long term, due to glaciations, this process will reverse.

These processes are highly relevant for those geological and sub-surface repositories sited in the proximity of coastal areas, as for example in Belgium, Sweden or Germany. That is why the TSOs and WMOs from these countries appreciated that uncertainty associated the marine transgression/regression process has a medium to high significance for disposal safety, the highest relevance being associated with the uncertainty on the transport pathways of radionuclide in the new landscape, which is essential in the conceptual model elaboration for dose or risk assessment.

In contrast, this process is of very low relevance for the repositories sited in land, far from the coastal areas (*Figure 107* and *Table 29*).

In the case of near surface disposal, these uncertainties were either not addressed in the safety case or are considered to have a very low impact (*Figure 108* and

Table 30).

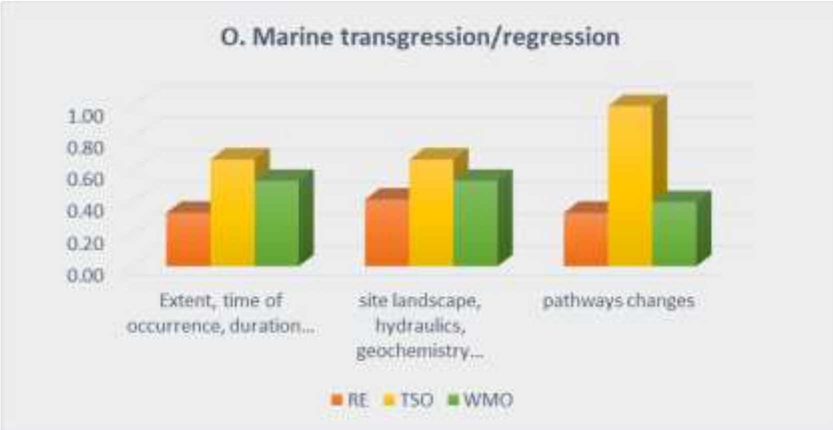


Figure 107. Significance for safety of uncertainties related to marine transgression/regression (DGD)

Table 29. Synopsis of the actors' views on uncertainties related to marine transgression/regression for geological disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Extent, time of occurrence, duration…	0.33	2n; 3l	0.67	1n; 1h; 1l	0.53	2l; 1m	x	xx	xx
site landscape, hydraulics, geochemistry…	0.42	1n; 2l; 1m	0.67	1n; 1h; 1l	0.53	3l; 1h	x	xx	xx
pathways changes	0.33	2n; 2l	1.00	1n; 1h; 1l	0.40	2l; 1m	x	xx	x

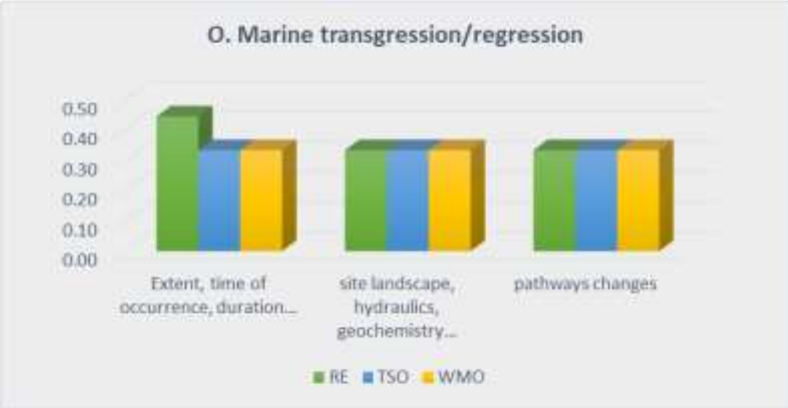


Figure 108. Significance for safety of uncertainties related to marine transgression/regression (NSD)

Table 30. Synopsis of the actors' views on uncertainties related to marine transgression/regression for near surface disposal

Uncertainty	Score of uncertainty relevance for safety						Impact on:		
	REs		TSOs		WMOs		Operational dose/risk	Post-closure dose/risk	Safety functions
Extent, time of occurrence, duration…	0.44	2n; 2l; 1m	0.33	1n; 2l		0.33			
site landscape, hydraulics, geochemistry…	0.33	3n; 2l	0.33	1n; 2l		0.33			
pathways changes	0.33	3n; 2l	0.33	1n; 2l		0.33			

5.3.2 Uncertainties characterisation

Modelling and quantification by expert judgement are the most appropriate methods, most frequently used by the actors in the characterisation of uncertainties related to marine transgression and regression. In addition, statistical methods applied to the existing data have been used in the uncertainties on the extend of this process and time of its occurrence, by WMOs.

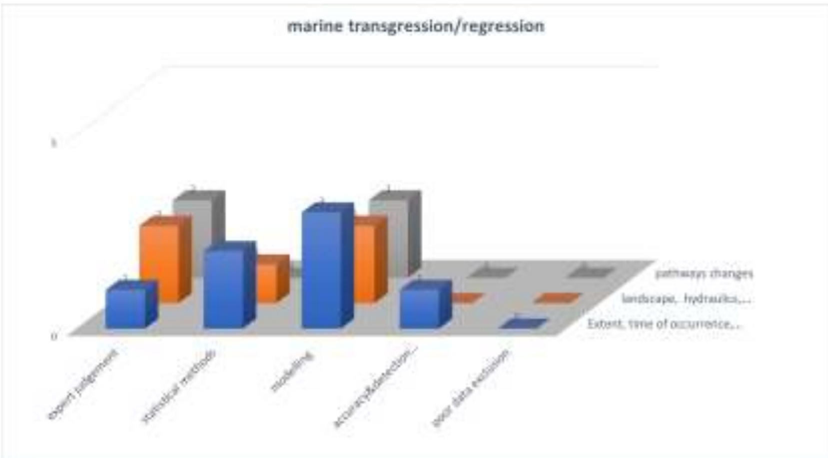


Figure 109. Frequency of the methods used in characterisation of uncertainties related to marine transgression/regression

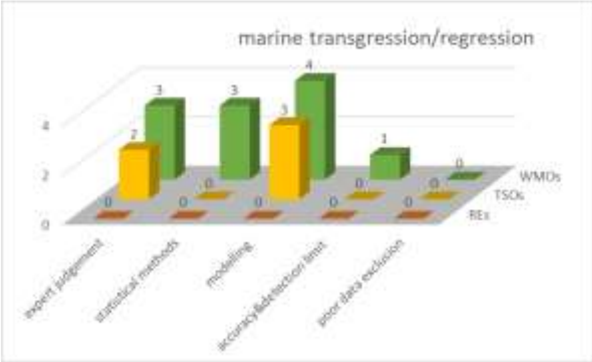


Figure 110. Actors' preferences in the characterisation of uncertainties on marine transgression/regression

6. Recommendations for future EURAD activities

As shown in the uncertainty management approach, jointly developed under the WP UMAN by all involved actors [15], there are different types of actions which can be applied to reduce uncertainties, or to avoid or mitigate their impact on disposal safety.

R&D activities on the long term processes occurring in the host rocks in the presence of a radioactive waste repository or on the long-term climate evolution, site investigations, modelling and models validation are options commonly used by all three categories of actors in their efforts for uncertainty management. Of curse, uncertainties with higher significance for safety should be a priority in the uncertainty management activity.

Needs for R&D, strategic studies and knowledge management activities have been identified as part of the Workshop 1 dedicated to management options for site and geosphere uncertainties, and have been formulated as recommendations for future EURAD activities [Milestone document MS67].

6.1 Future needs on the upscaling and transposition of available data on site and geosphere characteristics

The need for future activities on the upscaling of site-related data to the actual disposal system scale was identified by all the actor groups that participated in the UMAN workshop on the management of uncertainties related to the site and geosphere [3]. The transposition of available data (e.g. from lab or areas surrounding the repository or geophysical investigations) to the actual site location and the management of associated uncertainties was also identified as a topic deserving further attention.

Upscaling and characterisation of heterogeneities (including faults) before the construction of the repository (and in absence of borehole data from the disposal area) are of particular interest. Treating these elements in the safety case and safety assessment, raises questions such as:

- what is really understood by “homogeneity”, within what degree of variation of what safety relevant property (retention, hydraulic or thermal conductivity, fracture mechanics,….) a host rock volume is considered homogeneous.
- what are the assumptions for "homogeneous medium approach" having in mind that using worse and best case parameters in PA yield very likely too conservative approximations of "heterogeneity“.

Uncertainties associated with upscaling and heterogeneity characterisation have been found relevant for the disposal safety and therefore further activities as guidance/strategic study/SoK or R&D have been considered useful on:

- upscaling and transposition of available data (e.g. from lab, areas surrounding the repository or geophysical investigations) to in situ conditions and the management of associated uncertainties (Guidance/strategic study/SoK)

Since faults are highly relevant to safety, it seems particularly important to:

- investigate the uncertainties related to the methods used to identify and characterize active faults;
- elaborate a strategy indicating how and to what extent the uncertainties associated with failures could be reduced to the lowest possible level;
- elucidate the open aspects related to the reactivation potential of dormant faults, if they cannot be avoided through siting (R&D).

6.2 Activities needed to reduce uncertainties associated with underground water flow & radionuclide transport

6.2.1 R&D activities on hydraulic conductivity

Still open aspects and uncertainties exist in regards with the hydraulic conductivity of the host rock when resaturation process following the repository closure is considered.

A key uncertainty linked to hydraulic conductivity in clay to be assessed experimentally is related to the time it takes for a void volume to become filled by porewater from the host rock after closure of emplacement locations, considering the simultaneous occurrence of the following processes:

- Diffusion/advection in host rock, plugs, seals and EDZ
- Hydrogen production by corrosion of containers or of cement enforcements, H_2 transport and build-up of counter pressure

In addition, anomalous values of the hydraulic pressure measured in the clay rocks request a deeper understanding and an evaluation of the impact on the radionuclide transport.

Therefore, further R&D activities should investigate:

- Resaturation process of the near and far field after repository closure;
- Anomalous pressure in clay rocks (origin, impact on the flow field and radionuclide transport).

6.2.2 Further investigations on sorption capacity of host rocks

Highest safety relevant uncertainties in sorption capacity in clay rock are for anions. Often zero retention is assumed while even a small retention would block these anions from moving to the biosphere.

As this concerns all repository projects in clay rock, and as large statistics is required, the following activities have been found necessary:

- large scale diffusion experiment to assess very weak but non-zero Kds, focused on I129 and Cl36 (maybe as a first step a conclusive SoK or SOTA shall be produced);
- further R&D on the identification of relevant sorption processes / mechanisms for a better consolidated bottom-up approach for Kd understanding and improved sorption models;
- R&D on upscaling from batch systems on pure phases to the real host rock in confined conditions, and corresponding availability of sorption sites;
- guidance on the justification of a Kd approach in the SA considering associated uncertainties.

6.2.3 Research activities on climate changes

Further research on the climate history and the effects of glaciations will lead to a reduction of uncertainties but some uncertainty will of course remain, especially considering the timescale of one million years.

- Validation of permafrost depth models
- Development of coupled climate-permafrost-flow models
- Influence of decompaction on host rock properties from analogues and modelling
- Development of a common approach on how to handle glaciation periods because glaciation periods are not restricted to national borders through a guidance/SoK/strategic study on the treatment of climate changes in a disposal programme
- Elaborate recommendations on how to communicate that the disposal system is safe despite the remaining uncertainty related to the climate changes.

7. Conclusions

The safety analysis of the radioactive waste disposal in geological formations is affected by inherent uncertainties related to the processes, parameters and long-term evolutions of the disposal system, of the environment in its totality and complexity and, last but not least, of the behaviour at the society level.

The uncertainties significance for safety differs depending on the type of disposal concept (near surface or geological), the role of the actors involved in implementing the program, and the phase in the programme implementation.

The investigation of the significance and impact of uncertainties associated with the site and geosphere on the safety assessment of radioactive waste disposal covered a large range of features, events and processes involved in the transport of radionuclides from repository to the biosphere and to humans. It was performed based on the answers received to the 2nd UMAN questionnaire elaborated by Task 3 from 22 organisations involved in EURAD project, representing WMOs, TSOs and REs.

Uncertainties, grouped into 15 thematic groups, were structured into three broad categories:

- uncertainties associated with the necessary parameters in the conceptualization of flow and transport models;
- uncertainties associated with long-term geodynamic processes and tectonic disturbances;
- uncertainties associated with climate change.

The uncertainties addressed by the questionnaire cover uncertainties regarding the current state of the site as well as uncertainties associated with its long-term evolution. The answers analysed in this study reflect the views on the current phase of the programmes, for each actor.

As a general observation, valid for both types of disposal concepts considered in this deliverable, there are differences between the importance given by the three categories of actors to the same group of uncertainties, with WMOs and REs generally giving more significance to uncertainties and their impact on safety than technical support organisations.

The uncertainties of greatest significance in terms of geological disposal safety, scored as medium to high by all actors, are those associated with:

- the conditions and hydraulic parameters of the host rock that determine the groundwater flow field (especially hydraulic conductivity, hydraulic heads, gradients in the host rock);
- geochemistry and transport properties, with particular emphasis on groundwater chemistry and host rock-specific sorption parameters;
- the thermal and mechanical properties of the host rock in its natural state.

REs and WMOs consider of high importance the uncertainties related to the site characteristics necessary for the creation of the conceptual model (geological structures, stratigraphic characteristics, homogeneity of geological layers).

TSOs and WMOs share the same high concern on the uncertainties associated to:

- tectonic processes ;
- hydraulic and geo-mechanical properties of the excavated disturbed area (EDS), including re-saturation of the EDZ area;
- glaciations.

Uncertainties with the lowest significance for the safety assessment, for the three categories of actors, are those associated to:

- volcanic activity;
- diapirism;
- seismic events and the pumping effect of water following an earthquake.

TSOs add to the list the uncertainties with low impact on the disposal safety those related to scaling effects, while WMOs consider uncertainties on: water flow and radionuclide transport parameters of radionuclides in adjacent aquifers (sorption, diffusion, colloidal transport) having the lowest impact on the safety case.

In the case of near surface disposal, uncertainties of highest significance for both REs and TSOs are associated with the hydraulic properties of the adjacent aquifers. While REs are highly concerned by the uncertainties related to the radionuclide transport properties, TSOs give a greater relevance to the tectonics and seismic processes.

Each category of actors uses for the uncertainties' characterisations a diversity of methods, adequate to the uncertainty type (parametric, scenario, conceptual, etc.), which complement each others, with the aim to reduce the uncertainty level. The methods mostly applied by all actors are:

- statistical methods applied on relevant (measured) data
- quantification by expert judgement
- modelling (likelihood of events, geochemical databases…)

Accuracy of measurements and detection limit of equipment and exclusion of poor quality/inappropriate data (reducing the order of magnitude of the uncertainty) are less frequently used, and especially by REs and WMOs.

Generally, all actors' opinions converge on the fact that uncertainties will decrease along the programme phases, as the knowledge of the site and scientific accumulations evolve until a certain level, which will have a reasonable low impact on the safety assessment.

Further R&D activities should be performed to improve knowledge and databases related to the radionuclide transport in different host rocks. Therefore, e*xperimental studies on hydraulic conductivity* would be useful for the investigation of clay re-saturation kinetics taking into account all processes occuring in the disposal system: diffusion/advection in host rock, plugs & seals, hydraulic conductivity of host rock and EDZ, hydrogen production and transport, and counter-pressure build-up.

Large scale and laboratory experiments on sorption of anionic species in clay rocks should be performed for low but non-zero K_d. Future R&D activities addressing the identification of relevant sorption processes/mechanism for the development of mechanistic sorption models based on a bottom-up approach for improved sorption models, and the upscaling from batch systems on pure phases to the real host rock in confined conditions could bring in-depth understanding and supplementary knowledge on the radionuclide transport mechanisms.

Further works should be done in the *development of computational tools* (such as *geochemical codes* allowing to combine uncertainty components in a non-additive model and *improved glaciations codes* coupling the climate evolution, permafrost and groundwater flow models).

A *strategic study on climate change* could provide additional insight on how to deal with glacial periods in safety case and safety assessment, while a *strategic study on site homogeneity* could clarify the conditions under which a host rock volume can be considered homogeneous.

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