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Executive Summary

Climate change represents a cross-cutting challenge for radioactive waste management (RWM) across Europe. Its effects are relevant for all disposal concepts, including surface, near-surface and deep geological repositories, and across all stages of the facility lifecycle, from construction and operation to post-closure. Within EURAD-2, WP11 CLIMATE was established as a strategic study to identify knowledge gaps, synthesise current approaches and practices, review regulatory and institutional frameworks, support knowledge transfer, and foster dialogue with stakeholders and civil society on climate-related challenges. The results of the study are relevant both for existing facilities and for those countries that are currently facing the design phase.

This synthesis report brings together the main outcomes of the WP. It includes an overview of selected scientific literature and international initiatives relevant to climate change and RWM, covering topics such as climate forcing, scenario development, coupling of climate related processes, and repository relevant impact pathways. It then examines the current regulatory landscape at international, European and national level, showing that while climate change is increasingly recognized as a relevant factor, its explicit treatment still varies considerably across countries and facility types. In parallel, the report summarizes the work carried out on knowledge management, including the preparation of the White Paper, a training course on climate change impact on RWM, and the Domain Insight document on Climate Change within the EURAD-2 Roadmap.

For the construction and operational phases, the analysis identifies extreme precipitation, flooding, heat waves, drought, groundwater level variations and sea level rise as the most significant climate-driven hazards across the participating case groups. These hazards may affect drainage systems, cooling and ventilation equipment, engineered covers, access routes and other safety-relevant infrastructure. The report also highlights the importance of compound and cascading events, such as the interaction between heavy rainfall and groundwater rise or between heat waves and drought, as well as the need for improved site-specific climate data, better process representation, more complete monitoring records and more consistent approaches to risk quantification. Operational and geographic analogues are shown to provide useful complementary evidence, especially where direct long-term observations are limited.

For the post-closure phase, the report confirms the robustness of deep geological repositories against direct surface climate impacts, while underlining the continued relevance for all repository and waste types of long-term climate-driven processes such as hydrological change, permafrost development, erosion, shoreline displacement and sea level variations. Climate is generally treated as an overarching FEP through scenario development, although the report identifies several areas where current approaches could be further strengthened. These include the treatment of the century to millennium timeframe, the availability of downscaled meteorological variables and statistical approaches for extreme events, and the representation of long-duration warm or interglacial conditions and their associated analogues. The report therefore points to the value of continued methodological development, including more formalised approaches to uncertainty management, improved translation from climate evolution to impact assessment, tailored guidance documents and benchmarking across climate zones.

A further contribution of WP11 CLIMATE concerns interaction with civil society. Through two pluralistic workshops, the WP explored stakeholder views on climate-related socio-technical challenges, uncertainty management, transparency and long-term governance. This work showed that climate change in RWM cannot be addressed only as a technical issue. It also requires fair and continuous public participation, explicit consideration of public recommendations, clear communication of uncertainties, and reflection on the roles and resources of the different actors involved. The workshops also tested the PEP dialogue tool and highlighted its potential to support more structured discussions on long-term climate-related challenges in RWM.

Overall, WP11 CLIMATE provides a consolidated knowledge base on the impacts of climate change on radioactive waste management facilities and highlights key priorities for future work. These include improving the spatial and temporal resolution of climate data for site-specific assessments, strengthening the treatment of extreme and compound hazards, expanding the use of climate-relevant natural analogues, improving the treatment of long-term warm climate conditions, and further harmonising approaches to climate impact assessment across Europe. The WP also shows that a robust response to climate change in RWM requires not only improved technical understanding, but also knowledge transfer, transparent communication of uncertainties, and sustained dialogue with civil society and other stakeholders. In this way, the outcomes of WP11 CLIMATE support a more integrated, transparent and resilient approach to climate change in radioactive waste management.

Keywords

Climate change, Radioactive waste management, Climate change risk assessment, Hazard characterisation, Site-specific modelling, Barrier performance, Multiple climate stressors

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Glossary

AD *Anno Domini*
AP After present
BP Before present
CMIP Coupled Model Intercomparison Project
CRP Coordinated Research Project
CS Civil Society
CSO Civil Society Organisation
DI Domain Insight
EBS Engineered Barrier System
EMIC Earth System Models of Intermediate Complexity
ENSREG European Nuclear Safety Regulators Group
EURAD-2 European Partnership on Radioactive Waste Management - 2
FEP Feature, Event, and Process
GCM Global Climate (or Circulation) Model
GDR Geological Disposal Repository
DGRa Deep Geological Repository, Köppen climate group D
DGRb Deep Geological Repository, Köppen climate group C
HADES High Activity Disposal Experimental Site
HLW High Level Waste
IAEA International Atomic Energy Agency
IPCC Intergovernmental Panel on Climate Change
ky kiloyears
LILW Low- and Intermediate-level waste
LLW Low-level waste
MS Member State
NS Near-surface
NSb Near-surface facility, Köppen climate group Cfb
NSc Near-surface facility, Köppen climate group Cs
NEA Nuclear Energy Agency
PEP Pathway Evaluation Process
RCM Regional Climate Model
RCP Representative Concentration Pathway
RE Research Entity
RW Radioactive Waste
RWM Radioactive Waste Management
Sa Surface facility, Köppen climate group D
Sb Surface facility, Köppen climate group Cf
Sc Surface facility, Köppen climate group Cs
Sd Surface facility, Köppen climate group D (Bulgaria)
SNF Spent Nuclear Fuel
SSP Shared Socioeconomic Pathway
SITEX Sustainable network for Independent Technical EXpertise on radioactive waste management
TSO Technical Safety Organisation
WENRA Western European Nuclear Regulators Association
WMO Waste Management Organisation
WP Work Package

1. Introduction

1.1 EURAD-2 framework

The European Partnership on Radioactive Waste Management (EURAD-2) is a five-year project (2024–2029) funded by the European Commission to coordinate research, development and knowledge management on the safe long-term management of radioactive waste. It continues the work of the first EURAD programme and PREDIS and aims to strengthen cooperation among European countries at different stages of implementing their waste management strategies.

The partnership brings together Waste Management Organisations (WMO), Technical Support Organisations (TSO), Research Entities (RE), and other affiliated institutions from EU Member States, as well as associated countries. By pooling expertise and resources, EURAD-2 supports the development of scientific and technical knowledge needed for all phases of radioactive waste management, from predisposal activities to final disposal in surface, near-surface and deep geological repositories.

Its main goal is to ensure cutting-edge knowledge creation and preservation to support safe, responsible and publicly acceptable solutions for the management of radioactive waste throughout all programme phases (from “cradle to grave”) across Europe now and in the future. Through this collaboration, EURAD-2 fosters efficiency, trust, and shared understanding in achieving safe and sustainable radioactive waste management across Europe.

1.2 WP11 CLIMATE

The EURAD-2 Work Package (WP) 11 CLIMATE is a strategic study that analyses the impact of climate change on radioactive waste management (RWM), aiming at identifying knowledge gaps and providing recommendations for future research. The study considers climate change impacts on radioactive waste management facilities (surface, near-surface and deep geological disposal, including related surface facilities), all types of waste (low-level waste (LLW); low and intermediate level waste (LILW); and high-level waste (HLW)) across a large variety of sites/disposal facilities in Europe during construction, operation and post-closure phases. This WP combines the views and experiences of RWM actors across a large range of European climate types, RWM programme status and EURAD-2 college affiliations.

The CLIMATE partnership is composed of 21 institutions and 2 associated partners, divided as follows:

- 12 research entities
- 6 waste management organisations
- 5 technical support organisations

The full list of CLIMATE participants is shown in Table 1.1.

Table 1.1 List of the participants of the EURAD-2 CLIMATE Work Package.

Partner	Country	Type of institution
Amphos 21	Spain	Research Entity
ANDRA	France	Waste Management Organisation
BGE	Germany	Waste Management Organisation
BRGM	France	Research Entity
EIMV	Slovenia	Technical Support Organisation

ENEA	Italy	Research Entity
FTMC	Lithuania	Research Entity
GI-BAS	Bulgaria	Research Entity
GRS	Germany	Technical Support Organisation
GTK	Finland	Research Entity
ASRN	France	Technical Support Organisation
Mines Paris	France	Research Entity
MITTA	Finland	Research Entity
NAGRA	Switzerland	Waste Management Organisation
Nuclear Transparency Watch	France	Technical Support Organisation
Nuclear Waste Service	United Kingdom	Waste Management Organisation
SCK CEN	Belgium	Research Entity
SSTC NRS	Ukraine	Technical Support Organisation
SÚRAO	Czech Republic	Waste Management Organisation
Technical University of Liberec	Czech Republic	Research Entity
Technical University of Sofia	Bulgaria	Research Entity
University of Turku	Finland	Research Entity
VTT	Finland	Technical Support Organisation

1.3 Goals

The main goal of the CLIMATE Work Package is to identify knowledge gaps and propose recommendations for future research related to climate-driven risks during all phases of radioactive waste management facility life cycles, including construction, operation, and post-closure. This includes surface and near-surface disposal sites, and deep geological repositories for low, intermediate-, and high-level waste.

In addition, the WP aims to synthesise existing approaches and practices for climate risk assessment in RWM, identify methodological gaps and good practices, review regulatory and institutional frameworks, support knowledge capture and transfer (through the Synthesis Report, White Paper, Domain Insight and training activities), and foster dialogue with stakeholders and civil society on climate-related challenges through dedicated workshops and training. The results of the study are relevant both for existing facilities as well for the planning and design phase of new facilities, aiming at minimising potential future impacts.

2. Project structure

As a Strategic Study, CLIMATE aims to advance collective thinking on issues that are critical and shared across multiple national programs, ensuring that this work delivers clear added value directly connected to scientific and technical priorities. By addressing these challenges at a strategic level, the study helps guarantee that any related research and development activities are demonstrably driven by real needs.

2.1 Description of tasks

CLIMATE is structured around five main tasks (Figure 2.1), which combine technical research with management, quality control and stakeholder engagement. Two tasks especially focus on technical aspects: assessing climate change impacts during the construction and operational phases (Task 3) and during the post-closure phase (Task 4) of radioactive waste facilities. The other three tasks address overall coordination (Task 1), knowledge management (Task 2), and interaction with civil society (Task 5) to ensure transparency and inclusiveness.

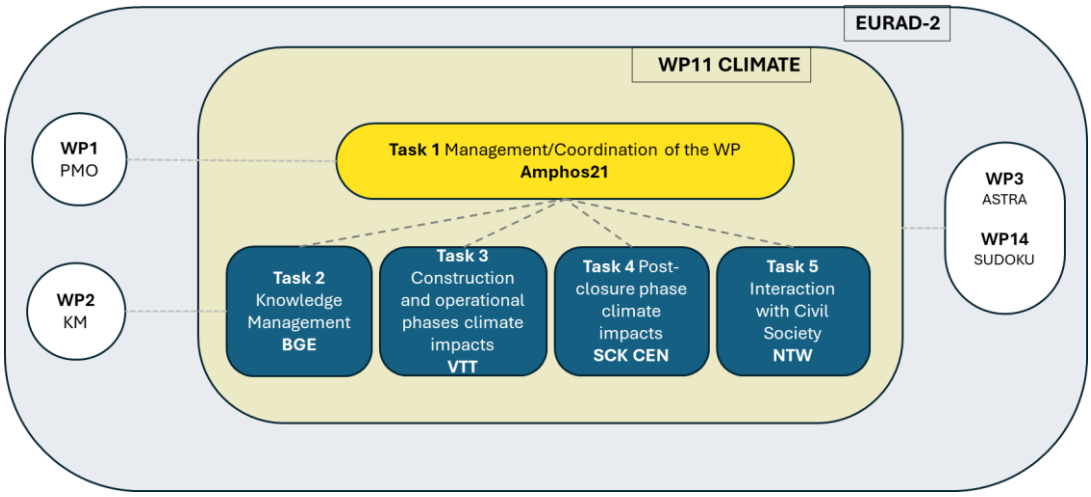


Figure 2.1 Structure of the EURAD-2 CLIMATE Work Package, indicating the Tasks and interactions with other EURAD-2 Work Packages.

- **Task 1: Management and Coordination**. Task 1 focuses on organising and steering the CLIMATE activities, including the in-person and online meetings. It also explores synergies with other EURAD-2 Work Packages (WP3 ASTRA and WP14 SUDOKU), coordinates strategy development for technical tasks, and reinforces dissemination through conference abstracts. Continuous communication with the main EURAD-2 coordination team and outreach to end-users ensured that progress remained aligned with the end-users' and stakeholders' needs.
- **Task 2: Knowledge Management.** Task 2 actively engages in EURAD-2 Knowledge Management meetings, contributed to the review of the Data Management Plan, and coordinated with WP2 to ensure consistency in knowledge capture and transfer. This task focuses on preparing the White Paper on climate change impacts, defining its structure, partner contributions, and schedule. It also organises training activities into a single comprehensive online course on climate fundamentals and risk assessment, scheduled for May 2026.
- **Task 3: Construction and Operational Phases Climate Impacts.** Task 3 identifies the climate change impacts on the construction and operation phase of the repositories, for the next few centuries. It also analyses the regulatory framework and identifies suitable natural analogues relevant for the potential and selected sites in different climate zones (similar bioclimatic geographical area, bedrock, and soil types, geo- and hydromorphological characteristics, etc.).

- **Task 4: Post-Closure Phase Climate Impacts.** Similarly to Task 3, Task 4 identified the climate change impacts on the post-closure phase of the repositories, over time periods ranging from several 100 years up to 1 million years. It also includes the identification of relevant natural analogues.
- **Task 5: Interaction with Civil Society.** This task coordinates engagement with civil society experts and organises workshops to exchange views on socio-technical challenges and uncertainties related to climate impacts on radioactive waste management. It aims to build shared positions and develop recommendations for transparent communication and collaboration between technical partners and stakeholders.

2.2 Case definition / grouping

To support its objectives, CLIMATE has developed a structured approach for assessing climate-related risks to radioactive waste facilities. This approach organises the analysis into working groups, defined by facility type (surface repository, near-surface repository and deep geological repository) and relevant climate conditions (based on the Köppen-Geiger climate classification), ensuring that the diversity of European sites and disposal concepts is properly represented.

Figure 2.2 shows the types of disposal facilities hosted in each country participating in CLIMATE, including the type of repository (surface, near-surface and deep geological repositories).

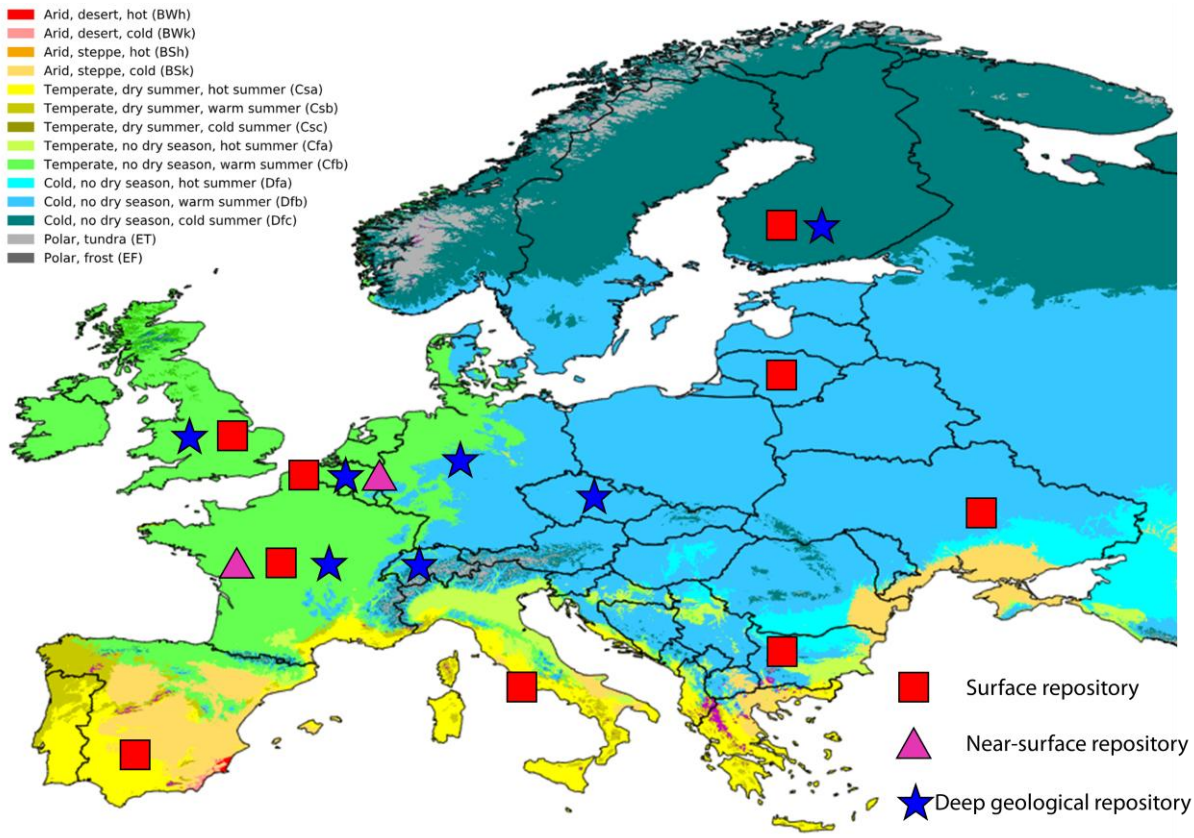


Figure 2.2 Graph indicating the type of repository hosted in each of the countries participating in CLIMATE. Note: the icon does not indicate the location of the repository, nor the phase of the RWM programme.

For the present study, the following distinction between surface, near-surface and deep geological repository has been used:

- **Surface Disposal Facilities** are repositories where waste packages are placed at or near ground surface, typically covered with engineered barriers and multi-layer covers.

These facilities exhibit high exposure to atmospheric climate hazards and direct precipitation impacts.

- **Near-Surface Disposal Facilities** emplace waste in shallow underground vaults or trenches, typically at depths of 10-30 meters. These facilities experience intermediate exposure to climate hazards, with particular sensitivity to groundwater table fluctuations and infiltration.
- **Deep Geological Repositories** place waste at depths of approximately 200-1000 meters in stable geological formations. Surface facilities for waste handling and operations remain exposed to climate hazards, while underground disposal areas experience indirect and direct effects primarily through mechanical, geomorphological, hydrogeological and hydrochemical changes. Interim Storage Facilities (ISF) included within Group 3DGRb provide temporary above-ground storage for spent nuclear fuel and high-level waste pending final disposal. These facilities exhibit maximum exposure to atmospheric climate hazards due to surface location and operational handling requirements.

Task 3 participants, who focus on analysing the impacts of climate change on the construction and operation phase of waste management facilities, were divided as indicated in Table 2.1. Task 4 participants, who focus on analysing the impacts of climate change on the post-closure phase of waste management facilities, were divided as indicated in

Table 2.2.

By grouping facilities in this way, WP11 can systematically evaluate potential hazards, compare scenarios across regions, and identify gaps in methodologies and data needed for robust risk assessments.

Table 2.1 CLIMATE Task 3 group classification.

Group	Disposal type	Climate group	Countries	Contributors
3Sa	Surface	D	Finland	Mitta, VTT
			Ukraine	SSTC NRS
3Sb	Surface	Cf	Belgium	SCK CEN
			UK	NWS
			France	Andra, ASNR, BRGM
3Sc	Surface	Cs	Spain	Amphos 21
			Italy	ENEA
3Sd	Surface	D	Bulgaria	GI-BAS, TUS
3NSb	Near-surface	Cfb	Belgium	SCK CEN
			France	Andra, ASNR, BRGM
3NSc	Near-surface	Cs	France	Andra, ASNR, BRGM
3DGRa	Deep Geological	D	Finland	Mitta, VTT
			Germany	BGE, GRS
			Czechia	SÚRAO, TUL
			Switzerland	Nagra
3DGRb	Deep Geological	C	Germany	BGE, GRS
			UK	NWS
			Belgium	SCK CEN
			France	Andra, ASNR, BRGM

Table 2.2 CLIMATE Task 4 group classification.

Group	Disposal type	Climate group	Countries	Contributors
4Sa	Surface	D	Finland	GTK, Mitta, TY, VTT
			Ukraine	SSTC NRS
			Lithuania	FTMC
4Sb	Surface	Cf	Belgium	SCK CEN
			UK	NWS
			France	Andra, ASNR, BRGM, Mines Paris
4Sc	Surface	Cs	Spain	Amphos 21
			Italy	ENEA
4Sd	Surface	D	Bulgaria	GI-BAS, TUS
4NSb	Near-surface	Cf	Belgium	SCK CEN
			France	Andra, ASNR, BRGM, Mines Paris
4NSc	Near-surface	Cs	France	Andra, ASNR, BRGM, Mines Paris
4DGRa	Deep Geological	D (> 50 ºN)	Finland	GTK, Mitta, TY, VTT
			Germany	BGE, GRS
4DGRb	Deep Geological	C and D (< 50 ºN)	Czechia	SÚRAO, TUL
			Germany	BGE, GRS
			Switzerland	Nagra
4DGRc	Deep Geological	Cf	Germany	BGE, GRS
			UK	NWS
			Belgium	SCK CEN
			France	Andra, ASNR, BRGM, Mines Paris

2.3 Report structure

The present report is structured as follows: in Chapter 3, a State-of-the-Art on climate change and radioactive waste management is presented, while Chapter 4 summarises the international, European and national regulatory framework. Chapters 5 and 6, respectively, describe the impacts of climate change on the construction and operation, and post-closure phases of repositories. In Chapter 7, a description of the knowledge management activities is provided, while Chapter 8 provides insights into the interactions with the civil society. Finally, some conclusions and recommendations are presented in Chapter 9. Moreover, a set of appendices is added: Appendix A contains a summary of the regulatory framework, Appendix B contains the list of climate risk screening indicators, Appendix C and Appendix D contain the group documents for construction and operation, and post-closure phase, respectively, and Appendix E contains the keynote papers prepared prior the Civil Society Workshop 1.

3. State of the art

Since the 1990s, a series of coordinated international initiatives have progressively developed the conceptual and methodological basis for representing long-term climate and environmental change in safety assessments of radioactive waste disposal. Each stage was built on previous projects, gradually moving from climate modelling and narrative development toward fully integrated biosphere and safety-case methodologies.

In the following sections, a short description of the most relevant projects and scientific work within this field is proposed.

3.1 International projects

3.1.1 BIOMOVS II (1991-1996)

Between 1991 and 1996, the international project BIOMOVS II (Biosphere Modelling and Validation Study) marked the first coordinated effort to establish global guidance on biosphere modelling for radiological assessments. One of its working groups examined whether a set of standardised “reference biosphere” models could be developed for use in long-term safety assessments of radioactive waste disposal. The group found, however, that such universal models would not be practical because biosphere characteristics and exposure scenarios depend strongly on local environmental and societal conditions.

As a result, the project shifted its focus toward promoting harmonisation and transparency in biosphere modelling by defining a common methodological framework and compiling a list of generic biosphere Features, Events and Processes (FEPs). BIOMOVS II concluded that additional work would be required to refine and expand this methodological foundation (Swedish Radiation Protection Inst., 1996).

3.1.2 BIOMASS (1996-2001)

Between 1996 and 2001, Theme 1 of the IAEA BIOMASS (BIOsphere and Modelling Assessment) project refined and formalised the reference biosphere approach into a practical methodology for long-term safety assessments (IAEA, 2003). The BIOMASS methodology set out a clear, stepwise process for defining the assessment context, characterising the biosphere, and identifying key Features, Events and Processes (FEPs). To illustrate its use, several Example Reference Biospheres (ERB) were developed, showing how model complexity, radionuclide transport and exposure pathways influence results. The third example (ERB 3) introduced climate and environmental change, highlighting the need for further work on representing long-term environmental evolution within safety assessments.

3.1.3 BIOCLIM (2000-2003)

The European Commission’s BIOCLIM project expanded on the BIOMASS work by developing a practical framework for assessing long-term climate and environmental changes. It produced projections of global climate evolution and methods to downscale them to regional and site levels. Building on the BIOMASS approach, BIOCLIM introduced the concept of environmental change narratives, describing future evolution through sequences of biosphere states and transitions, supported by tools such as interaction matrices and state transition diagrams (Texier et al., 2003).

3.1.4 EMRAS II (2009-2011)

Between 2009 and 2011, Working Group 3 of the IAEA Environmental Modelling for Radiation Safety II (EMRAS-II) programme focused on developing reference models for radioactive waste disposal. The group examined how environmental change (climate, land use, geosphere–biosphere interactions) had been handled internationally. The group recommended development of a common framework for post-closure biosphere assessment that explicitly integrates

environmental evolution, providing a bridge between the older BIOMASS methodology and the forthcoming MODARIA work (IAEA, 2014).

3.1.5 MODARIA WP6 (2012-2015)

From 2012 to 2015, Working Group 6 of the IAEA MODARIA project (which followed EMRAS-II) advanced the treatment of climate change in safety assessments by updating the BIOCLIM recommendations and developing a common international framework for addressing long-term environmental evolution (IAEA, 2020). Through extensive climate-system modelling at global to site scales, MODARIA WG6 produced narratives of future climate and landscape change to support both performance assessments and broader safety cases, recognising that such changes can influence the entire disposal system, not only the biosphere.

3.1.6 BIOPROTA

BIOPROTA[1] is an international collaborative forum established to improve how environmental and radiological impacts are assessed for radioactive waste management. It brings together waste management organisations, regulators, and research institutes to address key uncertainties shared across national programmes—particularly those related to radionuclide behaviour in the biosphere over long timescales.

The forum's projects focus on developing and testing practical assessment methods, sharing data, and improving conceptual understanding. Notable studies include work on the geosphere–biosphere interface (clarifying radionuclide transfer between groundwater and surface systems) and contributions to updating the IAEA BIOMASS methodology in collaboration with the MODARIA II Working Group 6 (BIOPROTA, 2014 and 2024). BIOPROTA has therefore played a bridging role between scientific research and regulatory practice, providing technical input that has shaped the modern international framework for biosphere and climate-related safety assessments.

3.2 Selected scientific literature

In this section, a short state of the art on the advancement of scientific literature on the climate change impacts on radioactive waste repositories, both in the short- and long-term, is provided.

3.2.1 Short-term climate impacts

A key pathway by which climate change affects repository performance is through altered hydrology and hydroclimate extremes that challenge engineered and natural barriers. For legacy and near-surface disposal systems, (Wainwright, 2023) highlights that increasing incidence of extreme events (flooding, drought, intense precipitation/windstorms, storm surge, wildfire, erosion) can damage engineered disposal cells and supporting infrastructure (roads, buildings) and can also modify remedial strategies such as natural flushing and groundwater attenuation. They also document that engineered cover systems have already required major maintenance in some cases, with intense precipitation and erosion identified as contributing factors and as mechanisms that can exceed original design assumptions over multi-decadal stewardship periods.

On the other hand, (Nuclear Waste Services, 2024a) defines the climate parameters to be used in the 2026 Environmental Safety Case for the UK Low Level Waste Repository. It provides site-specific projections of temperature, precipitation, potential evapotranspiration and relative sea-level change from the present to 10,000 years after present, using downscaled IPCC-aligned scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5). Median values of probabilistic projections are

[1] https://www.bioprota.org/

adopted to ensure consistency across safety assessment models. The results indicate progressive warming under all scenarios, increased potential evapotranspiration, and greater seasonal contrast with drier summers and wetter winters. Relative sea-level rise is assessed by combining global sea-level change with local isostatic effects. The report emphasises that these projections represent plausible future conditions for testing repository performance rather than predictions of future climate.

As for the concerning topic of sea level rise at the UK repository, (Nuclear Waste Services, 2024b) concludes that disruption is most likely to occur through cliff recession and undercutting rather than gradual inundation, with initial erosion potentially occurring within several hundred to a few thousand years, depending on the emissions scenario. The report provides timing estimates and mechanisms of erosion to support long-term safety and impact assessments under changing coastal and flooding conditions.

3.2.2 Climate forcing

Within the scientific community, climate evolution is recognised as a major factor in developing the scenarios necessary for long-term safety studies of all RWM disposal systems.

The Earth's climate has changed throughout history, alternating between glacial (cold) and interglacial (warm) periods, a cycle that will continue in the future. Over geological timescales, these natural climate cycles are primarily driven by Milankovitch cycles, which are variations in Earth's orbit influencing insolation (Osidele, 2012). However, scenarios for future climate evolution must also account for anthropogenic forcing caused by emissions of carbon dioxide and other greenhouse gases from human activities. This anthropogenic influence is expected to persist for many centuries and millennia (Van Geet et al., 2012).

The current scientific knowledge, thanks to climate modelling, is now able to suggest that current CO_2 emissions, due to industrial emissions, will significantly delay the onset of the next glaciation. For instance, depending on the emissions scenario used, models project that the first major glacial period may be delayed to around 178 ky AP, likely resulting in smaller ice caps than in previous natural cycles. The long-term influence of fossil fuel contributions is expected to decrease after approximately 400 ky AP, allowing natural orbital variations to eventually dominate global climate cycles again (Van Geet et al., 2012).

3.2.3 Scenario construction and coupling of climate-related processes

Since precise prediction of climate evolution over timescales up to 1 Ma is virtually impossible, safety assessments use a range of illustrative scenarios to explore the full spectrum of plausible environmental conditions (Näslund, 2013 and NEA, 2021). Moreover, (IAEA, 2020) highlights the importance of linking climate change to biosphere characteristics, exposure pathways and human habits, ensuring that assessments remain robust and transparent over very long timescales. Future climate evolution cannot be predicted deterministically and should instead be addressed through stylised, internally consistent scenarios that capture key drivers such as temperature, precipitation, sea-level change, glaciation, permafrost and landscape evolution.

It should be highlighted that these scenarios are explicitly not predictions but tools to ensure comprehensive coverage of climate possibilities relevant to safety. They define the initial and boundary conditions used in subsequent quantitative calculations and serve as a crucial tool for structuring and accounting for large uncertainties inherent in long time frames. To manage this uncertainty, safety assessments typically define a limited set of climate-driven process domains that represent characteristic environmental conditions relevant to repository safety. For example, (Näslund, 2013) establishes the following climate domains, relevant for Northern Hemisphere high-latitude regions:

- Temperate Climate Domain, regions without ice sheets or permafrost, including warm periods dominated by anthropogenic global warming

- Periglacial Climate Domain, defined strictly by the presence of permafrost but without ice sheets
- Glacial Climate Domain, regions covered by glaciers or ice sheets

Because repository impacts are site-specific, downscaling becomes critical. For instance, (Thorne, 2016) notes that safety assessments span a few hundred years to about one million years and can include climates from glacial to significantly warmer than present interglacial conditions; it focuses on warmer conditions potentially persisting for 150 ky or more unless CO2 is actively reduced. It then motivates downscaling from ~100–200 km regional climate model output to ~5–10 km scales to capture local controls such as altitude, aspect, and distance to the ocean, advocating physical-statistical approaches that preserve physically meaningful gradients when translating regional signals to site-scale boundary conditions.

3.2.4 Key climate-driven processes and repository-relevant impact pathways

For Near-Surface and Surface Disposal, the primary expected impact is the potential for changing water infiltration through the engineered cover system due to variations in precipitation and temperature and/or erosion. For the extended timeframe (up to 200 ky), the critical concern is the development and timing of permafrost conditions. If freezing occurs while the short-lived radionuclide concentration is still high, the resulting degradation of shallow concrete barriers due to freezing could jeopardise containment (Näslund, 2012). Additionally, rising global temperatures are linked to continued sea-level rise, posing a risk of marine inundation for coastal sites (Osidele, 2012).

For Deep Geological Disposal, climate change drives alterations in the geosphere over 1 Ma timescales. Glacial-interglacial cycles cause eustatic sea-level changes and landscape erosion. Colder, wetter phases can increase infiltration and aquifer recharge, potentially raising the groundwater table and increasing advective water flow toward the repository, which could accelerate radionuclide release rates and alter water chemistry (Van Geet et al., 2012 and Osidele, 2012).

More profoundly, the pressure from advancing ice sheets during glacial periods can induce glaciotectonic deformation in the foreland (the area in front of the ice sheet). This deformation includes the formation of ice-pushed ridges, glacial basins, and tunnel valleys. Tunnel valleys are subglacial depressions that can be cut to great depths, reaching up to 350m. The presence of ductile geological layers, such as thick clay formations (e.g., Boom Clay), facilitates this large-scale foreland deformation and determines the distribution of these erosional features. While ice sheet advance may be unlikely to reach certain southern regions (e.g., Belgium) within the next 1 million years based on some models, the uncertainty in long-term modelling dictates that the potential for such high-impact events cannot be excluded (Beerten, 2014).

Over glacial cycles, sea level changes are large and interact with isostatic rebound, shifting coastlines and reorganising hydrological and ecological receptors. (Lindborg, 2017) emphasises that Quaternary glacial cycles have repeatedly reorganised northern landscapes and that global sea level has fluctuated by over 120 m in response to ice-sheet growth and melting, making shoreline movement a primary driver of long-term landscape evolution at coastal sites. He used climate model outputs to define temperature-dependent climate domains and to build shoreline displacement curves that determine when the repository site is above/below sea level across a glacial cycle.

As an example of maturing knowledge on climate and climate-related issues for deep geological repositories, we refer to Forsmark, the site of the existing repository for short-lived radioactive waste (SFR) and the repository for spent nuclear fuel in Sweden (Liakka, 2025).

4. Regulatory framework

The regulatory and institutional framework for addressing climate change impacts on radioactive waste management facilities during construction, operation, and post-closure phases encompasses international, European, and national levels. Current frameworks emphasise the necessity of considering climate-related risks throughout the lifecycle of radioactive waste facilities, though specific requirements vary significantly across jurisdictions. (See Appendix A)

4.1 International regulatory framework

4.1.1 International Atomic Energy Agency (IAEA)

IAEA safety standards provide specific safety requirements regarding site evaluation of external events for nuclear installations (SSR-1). Depending on the facility under consideration, a graded approach is recommended for evaluating external hazards. Further guidance is given in SSG-18, providing recommendations on how the requirements in SSR-1 can be met. This includes:

- general recommendations for data collection,
- assessment of meteorological hazards,
- assessment of hydrological hazards,
- determination of design basis parameters,
- measures for site protection,
- changes in hazards with time,
- monitoring systems and warning systems for the protection of installations

More details can be found, for instance, in IAEA's TECDOC series giving technical details, analytical methods and good practices.

Facilities for the disposal of radioactive waste differ from other nuclear facilities since they must be safe over very long time horizons, from hundreds of years for low- and intermediate-level waste up to hundreds of thousands of years for spent nuclear fuel and high-level waste. Time scales that involve large climatic shifts. To address the specific challenges associated with disposal facilities, the IAEA have developed specific safety standards and TECDOC's addressing disposal of nuclear waste. IAEA specific safety requirements for disposal of radioactive waste require that due consideration must be given to the expected natural evolution of the site, including the impacts of climate change and erosion (IAEA SSR-5, section 4.29). Further guidance for geological disposal facilities and near-surface disposal facilities for radioactive waste is given in SSG-14 and SSG-29. Safety assessments for long-lived waste should take into account how the landscape and hydrological regime change over time as a result of climate change. To evaluate the long-term evolution of the final repository, appropriate timeframes should be established and one or several climate scenarios should be assessed, including future glacial cycles (IAEA SSG-23 section 6.44).

IAEA Safety Guide Environmental and Source Monitoring for Purposes of Radiation Protection (IAEA RS-G-1.8) states that climatological conditions should be monitored, both in the pre-operational studies and during operation of the facility (section 5.134).

IAEA TECDOC 1904, which summaries the work of Working Group 6 within the IAEA's MODARIA programme, highlights that near-surface and surface disposal facilities are more directly impacted by climate and landscape development, requiring systematic approaches to climate projections based on the latest scientific understanding. The programme emphasises the development of robust climate and landscape models for application within assessment frameworks.

The Coordinated Research Project (CRP) (IAEA, 2023) addresses explicitly "Climate Change Challenges to the Safety of Nuclear Installations," recognising climate change as a critical factor requiring systematic assessment.

4.1.2 OECD Nuclear Energy Agency (NEA)

Features, events, and processes (FEPs) are a central part of the safety assessment and forms the foundation for the scenario development. The U.S. Nuclear Regulatory Commission (NRC, 2003) define them as:

- Feature –an object, structure, or condition that has the potential to affect disposal system performance.
- Event –a natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared with the period of performance.
- Process –a natural or human-caused phenomenon that has the potential to affect disposal system performance and that operates during all or a significant part of the period of performance.

Whereas the IAEA have examined FEPs for near-surface disposal facilities (IAEA, 2004), OECD/NEA have focused on deep geological repositories. The latest version 3.1 of the International FEP List was made available in 2023 and published in 2024 (NEA, 2024). The list contains a comprehensive compilation of future possible climate states such as temperate, periglacial and glacial conditions, as well as warm climate (tropical and desert) and submerged conditions. These climate conditions govern a range of climate-driven factors that can have an impact on the deep geological repository's ability to uphold its safety functions during the assessment period. Factor as hydrological/hydrogeological responses, denudation, permafrost extent, depth and extent in time, groundwater chemistry and infiltration depth, as well as glacial isostatic responses and crustal stress evolution influencing the potential for large earthquakes to occur (NEA 2024, pp. 34–41). This list supports national programs in their development of safety cases by providing FEPs that may be needed to consider, depending on the repository concept, which in turn is a reflection of the site- and inventory characteristics. For mature programs, the list can be used as a quality check of the completeness of FEPs and resulting scenarios and conceptual models safety assessment tools (NEA 2024, p. 14).

The OECD/NEA Integration Group for the Safety Case (IGSC) has held workshops and formed ad hoc groups addressing the uncertainties associated with the extended timescales for assessments related to the geological disposal of radioactive waste (for example NEA, 2005; NEA, 2009). Future climate is one of these uncertainties that IGSC has addressed.

4.2 European regulatory framework

4.2.1 WENRA (Western European Nuclear Regulators Association)

WENRA (WENRA, 2014) establish performance-based requirements that do not explicitly name climate change but implicitly require its consideration across all lifecycle phases:

- Construction: Proven techniques must preserve host environment safety functions; monitoring must capture baseline environmental properties — necessitating climatic and hydrological baseline data.
- Operation: Arrangements for anticipated occurrences, operational limits, and emergency preparedness must be maintained — encompassing climate-driven disruptions and extreme weather events.
- Post-closure: Passive-only safety demands inherent robustness to long-term climate-related variability; surveillance enables detection of climate-related deviations.
- Safety case: Robustness demonstration, multi-line confidence evaluation, justified timescales, and scenario analysis of disturbing FEPs collectively require that climate-related evolution be systematically addressed.

4.2.2 ENSREG (European Nuclear Safety Regulators Group)

ENSREG (ENSREG, 2023) recognise that climate change affects various aspects of nuclear safety and radioactive waste management. While ENSREG itself focuses primarily on institutional

activities, the ENSREG framework, through the Nuclear Safety Directive and the Waste Directive, establishes principles that apply to climate-related challenges:

- Safety of facilities: The regulatory framework requires that nuclear installations be designed, sited, constructed, commissioned, operated and decommissioned to prevent accidents and mitigate their consequences, implicitly encompassing climate-driven hazards.
- Adaptation measures: National regulators are expected to ensure that periodic safety reviews incorporate the latest understanding of climate-related risks, with sufficient safety margins built in for more distant time horizons.
- Regulatory oversight: ENSREG emphasises continuous improvement in nuclear safety and radioactive waste management, including through the EU topical peer review mechanism.

4.2.3 European Commission Directives

Council Directive 2011/70/EURATOM establishes a community framework for responsible and safe management of spent fuel and radioactive waste, focusing on high safety standards, responsible management, and transparency, though it does not explicitly address climate change impacts.

Directive 2006/117/EURATOM focuses on the supervision and control of radioactive waste shipments but does not explicitly address climate change impacts.

4.3 Summary of national regulatory frameworks

4.3.1 Belgium

The Royal Decree of May 7, 2024 (BELGISCH STAATSBLAD, 2024), updating the Royal Decree of November 30, 2011, regarding safety requirements for radioactive waste disposal systems does not explicitly address climate change impact. However, it should be demonstrated that the performance of the disposal system and its components will remain adequate to protect man and the environment, even in the face of reasonably foreseeable perturbations.

The design basis should be developed through a site characterisation program that defines the reference situation, and that underpins a thorough understanding of the expected evolution and the identification of events and processes that may alter the expected evolution.

For surface disposal specifically, meteorological phenomena must be considered as external natural events in the design basis definition (FANC NOTA, 2010). In the evaluation of long-term safety, climate change impact is analysed through FEP analysis, which leads to conservative assumptions in the reference scenario or an alternative evolution scenario.

4.3.2 Bulgaria

The whole RWM regulatory and institutional framework, including the aspects mentioned for climate change influence on RWM, is based on the national fundamental documents and the following regulations:

- Act on the Safe Use of Nuclear Energy (ASUNE, 2018) transposes Council Directive 2011/70/Euratom, regulating safe radioactive waste management under normal and extraordinary operational, meteorological, climatic conditions.
- Strategy for Management of SNF and RAW (Strategy, 2017) formulates policy and principles for safe management, including tasks relevant to climate change impact consideration such as assessments of geological and geomorphological conditions and achieving sustainability in radioactive waste management.

- Climate Change Mitigation Act (Act, 2014) implements government policy on climate change mitigation and long-term planning of adaptation measures, including rolling cycle of statutory national risk assessments and resulting Adaptation Programme.
- Third National Action Plan on Climate Change (2013-2020) (NAP, 2012) provides specific measures for reduction of greenhouse gas emissions and presents global trends and scenarios on climate change relating to Bulgaria.

4.3.3 Czech Republic

The Czech regulatory framework addresses climate change through nuclear safety legislation and environmental protection requirements. While the Atomic Act does not explicitly name climate change, it requires consideration of external natural hazards in siting, construction, and operation of nuclear facilities. The most explicit climate change provisions appear in Decree on the Siting of a Nuclear Installation (DECREE378, 2016), which requires DGR site assessments to evaluate: (i) palaeohydrogeological processes, climate history and anticipated long-term climate development at regional and global scales; and (ii) vulnerability of the rock environment and groundwater to long-term climate changes and associated phenomena, specifically potential coverage by ice, permafrost, or water. Preliminary safety reports must also include independent assessment of climatic and meteorological phenomena as part of site characterisation.

4.3.4 France

France's regulatory approach differentiates between existing and new facilities.

- For existing facilities, the analysis of external hazards, including natural hazards, is reviewed every 10 years during safety assessments, considering new knowledge, feedback from the Fukushima accident, and climate change forecasts. However, there is no specific guideline for radioactive waste disposal facilities.
- For new facilities, climate change must be integrated into the design when selecting sites, designing operational systems, and anticipating hazard levels throughout the entire facility lifespan. The design must be capable of adapting to changes in hazards such as flooding, heat waves, tornadoes, and snow on-site. For deep geological disposal (ASN Guide No. 1, 2008), the reference situation following closure requires calculated individual effective doses not to exceed 0.25 mSv/year for prolonged exposure. Events to consider include a range of probable natural events, including climatic cycles.

4.3.5 Finland

STUK (Finnish Radiation and Nuclear Safety Authority) has approved the Onkalo® repository, emphasising its resilience to future climate changes, including glacial periods and rising groundwater levels.

The Finnish Law on Environmental Impact Assessment (LAW, 252/2017) applies to radioactive waste management and disposal facilities, requiring assessment of major accident and disaster risks relevant to the project, including risks caused by climate change, based on scientific knowledge.

Moreover, the STUK Regulation Y/4/2018 (STUK, 2018) states that long-term safety of disposal facilities must be based on mutually complementary barriers so that degradation of one or more long-term safety functions or foreseeable change in bedrock or climate will not jeopardise long-term safety.

Finally, the YVL Guide D.5/2018 (YVL, 2018) specifies that scenarios used in assessing alternative evolutions of the disposal system shall cover events and factors arising from external factors, such as climate changes, geological events, and that rare events impairing long-term safety may be caused by climatic phenomena.

4.3.6 Germany

Germany's regulatory framework for high-level waste (HLW) and low-intermediate level waste (LILW) differs significantly, as explained below.

On one side, for High-Level Waste, the Atomic Energy Act (AtG, 2022) establishes the National Waste Management Programme, updated every ten years based on progress in science and technology. Also, the Repository Site Selection Act (StandAG, 2023) aims to identify a repository site that ensures optimal safety for one million years, considering climate factors indirectly through exclusion criteria such as "Large-scale vertical movements" caused by isostatic adjustments from ice sheet formation and melting, which are directly influenced by climatic conditions, and minimum depth requirements requiring the top of the containment-providing rock zone to be at least 300 meters below ground, with deeper placement mandated in areas susceptible to exogenous processes like intensive erosion during future ice ages. , The Disposal Safety Requirements Ordinance (EndlSiAnfV, 2020) requires systematic determination and classification of expected and deviating evolutions of the disposal system and geological situation for a one-million-year assessment period, with evolutions classified regarding geological and climatic situation. Calculation Basis for Dose Estimation assumes a cool-temperate climate as default, but requires consideration of other possible climates and transitions between climate states during the assessment period.

On the other side, for Low and Intermediate-Level Waste (Konrad Repository), Plan Approval Decision (PFB, 2002) describes potential changes during future ice ages and warmer climate conditions, neither of which is deemed to pose a risk to safe containment. The Guidelines (Guideline, 2023) specify safety-technical design requirements. This Guideline for Safe Operation requires surface facilities to comply with design standards for flood protection. The Guideline for Safeguarding Against Flooding (Guideline, 2018) describes potential consequences, causative factors, evaluation methods, and protective measures related to flooding. It also emphasises the influence of climate change and extreme weather events on site-specific repository determination.

4.3.7 Italy

In Italian legislation on radioactive waste management, there is no specific mention of managing the impacts of climate change on nuclear sites. However, future scenario assessments in radioactive waste management and the risks caused by climate change will naturally follow from safety analyses and will be considered indirectly.

- Legislative Decree 101/2020 (Decreto, 2020) requires authorisations for nuclear plant (i.e. final repositories) operations to verify site suitability from a radiation protection perspective, considering current meteorological and climatological conditions. Since this ensures long-term nuclear safety, safety assessments for new nuclear plants must evaluate the future impacts of climate change on the facilities.
- ISIN (Italian Safety Authority) Technical Guide 29 (ISIN, 2014) uses area Exclusion Criteria to limit potential impacts of natural events, thereby indirectly reducing the effects of climate change on the surface repository.
- ISIN Technical Guide 32 (ISIN, 2022) states that, for safety analysis in the post-closure phase, climate changes must be considered, taking into account the environment's evolution over the long-term perspective.

4.3.8 Spain

Spain currently has no specific regulations on how nuclear waste facilities should address climate change. However, several laws and regulations indirectly include climate change:

- Law 25 (Law, 1964) on Nuclear Energy regulates nuclear energy use but does not include climate change provisions.

- Royal Decree 102 (Royal Decree, 2014) regulates the responsible and safe management of spent nuclear fuel and radioactive waste but does not include provisions regarding climate change.
- Law 7 (Law, 2021) on Climate Change and Energy Transition mandates that critical infrastructure include measures in planning, design, and management to adapt to and be resilient against climate change challenges.
- The 7th Radioactive Waste Management Plan (PGRR, 2023) states that post-closure actions include radiological and environmental monitoring, control of meteorological and hydrogeological data, and physical security measures.
- Law 21 (Law, 2013) on Environmental Assessment subjects' facilities exclusively for radioactive waste disposal to mandatory ordinary Environmental Impact Assessment.
- The Strategic Environmental Assessment of Chapter 5.8 (SIA, 2022), "Potential evolution of most significant environmental elements during plan implementation, taking climate change into account," addresses climate change and nuclear repositories.

4.3.9 Switzerland

The ENSI (Swiss Federal Nuclear Safety Inspectorate) Guidelines (ENSI, 2024) specify that detailed probabilistic safety analyses (PSA) are mandatory during both construction and operation phases. This guideline covers various extreme weather conditions, including droughts, harsh winter or summer periods, and variations in river water levels. Regarding long-term safety after site sealing, the guidelines acknowledge the impact of climate change, but do not define explicit thresholds for climate-related parameters. Instead, they require that the site be characterised sufficiently to understand the probable future natural evolution over the period of interest with respect to safety.

Nagra needed to show that climate-driven processes (such as during future glaciations) do not cause a reduction in the barrier effect of host rock or the effectiveness of the containment rock zone, nor lead to the exposure of the repository within the considered period (100,000 years for LLW/ILW or 1 million years for HLW).

4.3.10 Sweden

Please note that translated versions of the Authority's regulations lack legal force and are for information purposes only.

SSMFS 2008:21

The safety of a repository after closure is analysed quantitatively primarily by calculating the potential dispersion of radioactive substances and how they are distributed over time for a relevant selection of future possible sequences of events (scenarios). The purpose of the safety analysis is, among other things, to demonstrate that the risks from these scenarios are acceptable in relation to the requirements for the protection of human health and the environment issued by the Swedish Radiation Safety Authority (SSMFS 2008:37). The safety analysis should also aim to provide a fundamental understanding of the repository's function over different time frames and to identify requirements on the function and design of the repository's various components.

A scenario in the safety analysis comprises a description of how a given combination of external and internal conditions affects the function of the repository. Two groups of such conditions are:

- external conditions in the form of features, events, and processes acting outside the repository's barriers; these include climate change and its consequences on the repository's surroundings, such as permafrost, glaciation, land subsidence, and post-glacial rebound, as well as the effects of human activities,
- internal conditions in the form of features, events, and processes acting within the repository; these include properties, including defects, of nuclear material, nuclear

waste, and engineered barriers together with associated processes, as well as properties of the surrounding host rock together with associated processes.

Based on an analysis of the probability of different types of scenarios occurring in various time frames, scenarios with a significant impact on the repository's function should be divided into different categories:

- main scenario,
- less likely scenarios,
- residual scenarios (or other scenarios).

SSMFS 2008:37

Dealing with climate evolution

Taking into consideration the great uncertainties associated with the assumptions concerning climate evolution in a remote future and to facilitate interpretation of the risk to be calculated, the risk analysis should be simplified to include a few possible climate evolutions. A realistic set of biosphere conditions should be associated with each climate evolution. The different climate evolutions should be selected so that they together illustrate the most important and reasonably foreseeable sequences of future climate states and their impact on the protective capability of the repository and their environmental consequences. The choice of the climate evolutions that serve as the basis for the analysis should be based on a combination of sensitivity analyses and expert judgements.

The risk posed by the repository should be calculated for each assumed climate evolution by summing the risk contributions from a number of scenarios that together illustrate how the more or less probable courses of development in the repository and the surrounding rock affect the repository's protective capability and environmental consequences. The calculated risk should be reported and evaluated separately for each climate evolution in relation to the criterion of the regulations for individual risk. Hence, it should be shown that the repository complies with the risk criterion for each of the alternative climate evolutions. If a lower probability than one (1) is stated for a particular climate evolution, this should be justified, for instance by expert judgements.

Limitation of the risk analysis in time

The following principles should provide guidance for the limitation of the risk analysis in time:

1. For a repository for spent nuclear fuel or other long-lived nuclear waste, the risk analysis should at least cover approximately one hundred thousand years or the period for a glaciation cycle to illustrate reasonably predictable external strains on the repository. The risk analysis should thereafter be extended in time for as long as it provides important information about the possibility of improving the protective capability of the repository, although for a maximum time period of up to one million years.
2. For repositories for nuclear waste other than those referred to in item 1, the risk analysis should at least cover the period of time until the expected maximum consequences in terms of risk and environmental impact have taken place, although for a maximum time period of up to one hundred thousand years. The arguments for the selected limitations of the risk analysis should be presented.

Reporting on the first thousand years after closure

The period of time of one thousand years should be regarded as the approximate time period for which a risk analysis can be carried out with a high level of credibility with regard to many factors, such as climate and biosphere conditions. For this time period, available measurement data and other knowledge about the initial conditions should be used for a detailed analysis and description

of the protective capability of the repository and the evolution of its surroundings. The conditions and processes during the early evolution of the repository which can affect its long-term protective capability should be described in as much detail as possible. Examples of such conditions and processes include the resaturation of the repository, stabilisation of hydrogeological and geochemical conditions, thermal evolution and other transient events. Biosphere conditions and known trends in the surroundings of the repository should also be described in detail, partly to be able to characterise “today’s biosphere” and partly to be able to characterise the possible conditions applicable to a conceivable early release from the repository. Known trends here for instance, refer to land uplift (or subsidence), any trends in climate evolution and appurtenant changes in use of land and water.

Reporting on very long time periods

Up to one hundred thousand years

Reporting should be based on a quantitative risk analysis. Supplementary indicators of the repository’s protective capability, such as barrier functions, radionuclide fluxes and concentrations in the environment, should be used to strengthen the confidence in the calculated risks. The given period of time of one hundred thousand years is approximate and should be selected in such a way that the effect of expected large climate changes, for instance a glaciation cycle, on the protective capability of the repository, and the consequences for the surroundings can be illustrated.

Beyond one hundred thousand years

The risk analysis should illustrate the long-term evolution of the repository’s barrier functions and the impact of major external disturbances on the repository, such as earthquakes and glaciations. Taking into consideration the increasing uncertainties over time, the calculation of doses to people and the environment should be made in a simplified way with respect to climate development, biosphere conditions and exposure pathways. The climate evolution may be described as an idealised repetition of identical glaciation cycles. A strict quantitative comparison of calculated risk with the criterion for individual risk contained in the regulations is not meaningful. The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with several supplementary indicators of the protective capability of the repository, such as barrier functions, radionuclide fluxes and concentrations in the environment. If the calculated risk exceeds the criterion of the regulations for individual risk or if there are other indications of substantial disruptions to the protective capability of the repository, the underlying causes of this should be reported on, as well as possible measures to improve the protective capability of the repository.

4.3.11 Ukraine

Ukraine's framework recognises climate change as a crucial factor requiring systematic assessment throughout the facility lifecycle. The Legislative Framework includes the following laws:

- Law "On Radioactive Waste Management" (UkrLaw, 1995) establishes requirements for long-term safety, incorporating natural factors, including climate change, throughout all facility phases, emphasising complete isolation of radioactive waste from biosphere and defence-in-depth protection principles.
- Law "On Environmental Impact Assessment (EIA)" (UkrLaw, 2017) establishes mandatory environmental impact assessment procedures for radioactive waste management activities, requiring analysis of climate impacts, including greenhouse gas emissions and operational sensitivity to climate change.

On the other side, the technical Regulatory Framework includes the following:

- NP 306.4.219-2018 (NP, 2018) defines requirements for assessing extreme natural events and climate change forecasts with occurrence probabilities of at least 10E-6 per year that could affect repositories over extended timeframes.
- NP 306.4.213-2017 (NP, 2017) regulates consideration of extreme weather conditions during RW disposal design processes or provides a justification for their non-consideration.
- NP 306.4.142-2008 (NP, 2008a) specifies requirements for describing regional climate, characterising extreme weather, documenting atmospheric parameters, and incorporating these factors into design and emergency planning.
- NP 306.4.223-2020 (NP, 2020) defines requirements for mandatory detailed meteorological justification of site suitability, comprehensive consideration of climate changes, and long-term safety modelling incorporating projected climate scenarios.
- NP 306.4.149-2008 (NP, 2008b) specifies that radioactive waste repository sites must be located in areas with minimal climatic risks, ensure barrier isolation from extreme events, and remain suitable for safe operation while preserving barrier integrity for minimum of 300 years.

As for Construction and Climatological Standards, the following should be highlighted:

- DBN A.2.2-1:2021 (DBN, 2021) establishes requirements for EIA section composition and content, mandating inclusion of "Climate and Microclimate" section documenting principal climatic characteristics and current/projected climate changes.
- DBN A.2.1-1-2008 (DBN, 2008) and DBN A.2.1-1-2014 (DBN, 2014) regulate engineering-meteorological survey implementation, including studies of extreme weather phenomena, analysis of potential climate risks, and forecasting their impacts on facility safety.
- DSTU-N B V.1.1-27:2010 (DSTU, 2010) establishes required climatic parameters for building and structure design under climate change conditions, essential for radioactive waste management facilities.

Finally, as for practical climate change considerations, it can be remarked that the Ukrainian regulations require radioactive waste management facility designers and operators to account for:

- Temperature increases potentially leading to material degradation
- Increased frequency and intensity of extreme weather events
- Groundwater level changes potentially affecting disposal and storage facility sealing integrity
- Elevated humidity and associated corrosion hazards compromise isolation systems
- Accelerated erosion processes and long-term degradation scenarios

4.3.12 United Kingdom

The UK's regulatory framework for radioactive waste disposal involves the Office for Nuclear Regulation (ONR), which oversees nuclear safety and security, the Environment Agency (EA), which ensures environmental protection and compliance with standards, and the Department for Energy Security and Net Zero, responsible for radioactive substances and decommissioning policies

4.4 Key gaps and recommendations

To sum up, the identified gaps in the regulatory framework are the following:

- **Explicit climate change requirements**: Many national frameworks lack specific, explicit requirements for climate change consideration in radioactive waste facility design, construction, and operation.

- **Standardisation**: There is significant variation in approaches, methodologies, and requirements across different countries, which limits the ability to share best practices and lessons learned.
- **Temporal scales**: Challenges exist in aligning short-term regulatory requirements with long-term climate projections and facility operational periods.
- **Monitoring and adaptation**: Guidance on continuous monitoring and adaptive management strategies for changing climate conditions is limited.
- **Compound and cascading risks**: There is insufficient consideration of interactions between multiple climate hazards and their potential cascading effects.

Therefore, the following recommendations are suggested:

- **Harmonisation efforts**: It is advised to create more unified European guidance on climate risk assessment methods specifically designed for radioactive waste facilities.
- **Explicit requirements**: National regulatory frameworks should explicitly incorporate climate change considerations where these are currently absent, ensuring comprehensive risk management.
- **Adaptive frameworks**: It is advisable to develop regulatory frameworks that adopt adaptive management approaches, allowing updates based on the latest climate science and monitoring data.
- **Stakeholder engagement**: Mechanisms for engaging stakeholders and civil society in climate risk assessment processes should be strengthened to promote transparency and inclusivity.
- **Research and development**: Continued support for research into the impacts of climate change on radioactive waste management and the development of effective adaptation strategies is essential.

4.5 Conclusions

The regulatory and institutional framework for addressing climate change impacts on radioactive waste disposal facilities during construction, operational and post-closure phases is evolving at international, European, and national levels. While international organisations (IAEA, NEA) and European regulatory bodies (WENRA, ENSREG) provide comprehensive guidance, implementation at the national level varies considerably.

Some countries, such as Finland, Germany, Ukraine, UK, have developed detailed frameworks explicitly addressing climate change, while others rely on more general safety requirements that can be interpreted to include climate considerations.

The framework generally recognises that climate change affects radioactive waste facilities through increased frequency and intensity of extreme weather events, changes in temperature and precipitation patterns, sea level rise, and long-term geological and hydrological changes. However, significant work remains to harmonise approaches, develop standardised methodologies, and ensure regulatory frameworks adequately address long-term climate uncertainties and compound risks.

Future developments should focus on enhancing harmonisation across jurisdictions, explicitly incorporating climate change requirements where absent, developing adaptive regulatory frameworks, improving stakeholder engagement, and supporting continued research and development in this critical area of nuclear safety.

5. Climate risk assessment during construction and operation

5.1 Introduction

Task 3 of the EURAD-2 WP11 CLIMATE project includes a comprehensive analysis to identify knowledge gaps and provide recommendations for future research on the impacts of climate risk for radioactive waste disposal facilities during construction and operational phases across eight climate groups representing diverse geological, climatic, and operational contexts throughout Europe (see Section 2.2 for the description of the grouping).

5.1.1 Clarification of terms

In the present study, risk is defined as a combination of hazard, exposure and vulnerability (IPCC, 2022), where:

- **Hazard** refers to the physical manifestations of climate change, including extreme rainfall, flooding, drought, temperature shifts, and sea level rise. A single climate hazard can cascade into multiple impacts depending on what is exposed and how vulnerable it is.
- **Exposure** relates to the presence of assets or operational systems in areas affected by these hazards, such as surface infrastructure, drainage systems, and engineered barriers.
- **Vulnerability** reflects the sensitivity of these systems to climate impacts and their capacity to adapt or resist those impacts.

Moreover, **climate impacts** represent the actual effects of hazards on specific receptors, including the facility structure, workers, operational activities, and the surrounding environment.

5.1.2 Methodology

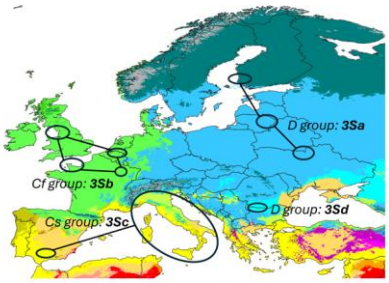
To analyse the risk to radioactive waste facilities, a two-step methodology was followed. This approach is recommended by international frameworks such as IPCC AR6 (IPCC, 2022) and European projects (CLIMAAX, 2021), as it supports evidence-based prioritisation, efficient use of resources, and clear communication of preliminary results to stakeholders and regulators. It is especially useful when early outputs are needed to validate the direction of work with stakeholders, or in regulated contexts where justification for focusing on certain sites or risks is required.

The first step of the evaluation consisted of a questionnaire, which was circulated among the WP11 CLIMATE participants, to establish a structured and systematic framework for assessing climate-related risks. They guided the evaluation process from the initial identification of potential climate hazards, through the assessment of data sources, indicators, and methodological limitations, toward prioritising the most critical risks and developing detailed adaptation strategies. The list of questions is included in Table 5.1.

The climate risk assessment was conducted in two sequential phases:

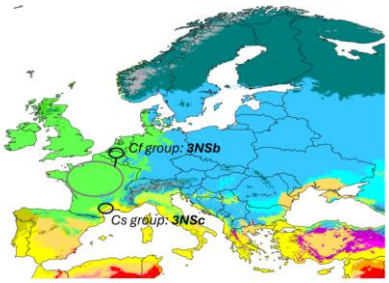
- **Phase 1**: Screening Assessment involved initial hazard identification, preliminary risk scoring using semi-quantitative methods, and prioritisation of hazards requiring a further detailed analysis. This phase is based on coarse-resolution climate data, historical evidence, and expert judgment to identify potentially significant risks.
- **Phase 2**: Detailed Assessment focused on priority hazards identified during screening, employing high-resolution modelling, quantitative risk analysis, and development of specific adaptation measures. This phase required detailed facility-specific data, advanced computational models, and comprehensive uncertainty analysis.

As also indicated in Section 2.2, the construction and operation phase climate risk analysis encompassed 8 climate groups representing 24 radioactive waste management facilities across 14 European countries. Figure 5.1 indicates the division into groups for Task 3.



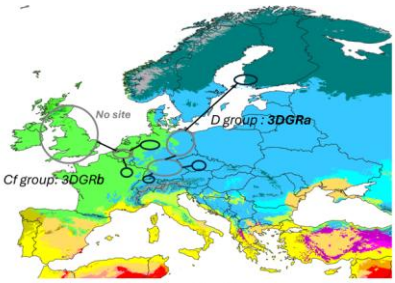
Surface disposal facilities

3Sa	Surface	D	Finland, Ukraine, (Lithuania)
3Sb	Surface	Cf	Belgium, UK, France
3Sc	Surface	Cs	Spain, Italy
3Sd	Surface	D	Bulgaria



Near-surface disposal facilities

3NSb	Near-surface	Cfb	Belgium, France
3NSc	Near-surface	Cs	France



DGR facilities

3DGRa	Deep Geological	D	Finland, Germany, Czechia, Switzerland
3DGRb	Deep Geological	C	Germany, UK, Belgium, France

Figure 5.1 Climate groups in Task 3

Table 5.1 Questionnaire directed to climate groups for the evaluation of the construction and operation phase climate risk assessment.

No	Question
1	Which climate hazards would you consider during the screening phase? Please include interdependencies, cascading and combined hazards.
2	Please indicate the data source for climatic and sea level information, time horizons for different periods to be analysed (historical, short, medium, long-term), emission scenario (RCP), and type of climate models you would use for the screening phase.
3	For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use? Which hazard indicator would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)? Which exposure indicator would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones? Which vulnerability indicator would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks? Finally, for each hazard, indicate the expected impact(s) on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.
4	Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.
5	How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability. In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.
6	Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?
7	Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate

	these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?
8	Based on your knowledge and understanding, which are the most critical risks requiring deeper analysis in the detailed assessment?
9	Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?
10	Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?
11	Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?
12	Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

5.1.3 Data sources, scenarios and geographical coverage

Most climate groups analyse multiple Representative Concentration Pathway (RCP) scenarios to span a plausible range of future climate conditions, typically focusing on RCP 4.5 and RCP 8.5 to represent moderate and high-warming scenarios. Climate groups employ diverse data sources reflecting facility locations, available national databases, and assessment requirements. A list of these sources can be found in Table 5.2.

Table 5.2 Summary of climate hazard data source.

Climate Group	Data Source	Emission scenario	Geographic coverage
3Sa	Baltic Sea SLR Projections	RCP8.5	Gulf of Finland/ENSDF L3
3Sa	EURO-CORDEX Regional Models	RCP2.6, 4.5, 8.5	Baltic Sea Region
3Sb	CCI-HYDR	SRES	Belgium
3Sb	Cordex.be	RCP2.6, 4.5, 8.5	Belgium
3Sb	UK Climate Projections	RCP2.6, 4.5, 8.5	UK
3Sc	AdapteCCa	RCP2.6, 8.5	Spain
3Sc	Med-CORDEX	RCP4.5, 8.5	Italy
3Sd	NIMH (ISIMIP Fast Track)	RCP4.5, 8.5	Bulgaria
3Sd	World Bank	RCP4.5, 8.5	Bulgaria
3NSb	EURO-CORDEX (CMIP6/CMIP5) RCMs	RCP2.6, 4.5, 7.0, 8.5	Western Europe; Belgium/France domains
3NSc	Explore 2	RCP8.5	European France
3DGRa	EURO-CORDEX RCMs	RCP2.6, 4.5, 8.5	Europe
3DGRa	CMIP6 (Coupled Model Intercomparison Project Phase	RCP2.6, 4.5, 8.5	Global

	6) GCMs(General Circulation Models)		
3DGRa	Copernicus C3S	Multiple SSPs	Europe
3DGRa	ALADIN-climate	RCP 4.5, 8.5	Central Europe
3DGRb	National Meteorological Services	RCP4.5, 8.5	National
3DGRb	CLIMAAX Toolbox Data	RCP2.6, 4.5, 8.5	Europe
3DGRb	CCI-HYDR	SRES	Belgium
3DGRb	Cordex.be	RCP2.6, 4.5, 8.5	Belgium

5.2 Screening phase

5.2.1 Identification of risks

The screening phase across all climate groups identifies 15 primary climate hazards relevant to radioactive waste facilities during construction and operational phases. They are indicated in Table 5.3. A detailed description of the indicators employed in this phase can be found in Appendix B.

Table 5.3 Summary of climate hazard identification for screening phase.

Hazard	3Sa	3Sb	3Sc	3Sd	3NSb	3NSc	3DGRa	3DGRb
Heavy Rainfall	○	○	○	○	○	○	○	○
Flash Flooding	○	○			○	○	○	○
River Flooding	○	○	○		○		○	○
Coastal Flooding	○	○				○	○	○
Sea Level Rise	○	○			○	○	○	
Heat Waves	○	○	○	○	○		○	○
Cold Spells	○	○					○	○
Droughts	○	○	○	○	○	○	○	○
Windstorms	○	○	○	○	○		○	○
Soil Erosion	○	○	○	○	○	○		
Water Table Variations	○	○	○		○	○	○	○
Desertification			○					
Wildfires		○	○			○	○	
Permafrost Thaw								
Landslides	○						○	○

In detail, the main identified risks are the following:

- Heavy Rainfall and Flash Floods emerge as the most universally identified hazard, relevant to all eight climate groups. Extreme precipitation events pose risks through surface water accumulation, drainage system overwhelming, erosion of protective covers, and infiltration into facility structures. Climate projections indicate increasing intensity and frequency of extreme precipitation events across Europe, with particular concern for short-duration, high-intensity rainfall exceeding existing infrastructure design capacities.
- River Flooding affects facilities located in floodplains or near major water bodies. Changes in precipitation patterns, snowmelt timing, and land use modifications alter river discharge regimes and flood frequencies. Facilities constructed based on historical flood statistics may face exceedance of design basis flood levels under future climate scenarios.
- Coastal Flooding and Sea Level Rise represent critical hazards for coastal facilities. Projected sea level rise of 0.3-1.1 meters by 2100 under RCP scenarios, combined with storm surge and coastal erosion, threatens facility integrity through inundation, saltwater intrusion, and foundation destabilisation. Coastal facilities require consideration of compound events combining high tides, storm surge, and extreme precipitation.
- Heat Waves and Extreme Heat affect seven climate groups, with particularly severe implications for operational safety and system reliability. Increasing frequency, duration, and intensity of heat waves pose risks to cooling systems, ventilation and air conditioning (HVAC) infrastructure, worker safety, electronic control systems, and structural materials through thermal stress. Projections indicate 2-5°C temperature increases across Europe by 2100, with summer maximum temperatures potentially exceeding 40°C in currently temperate regions.
- Cold Spells and Winter Extremes remain relevant for northern facilities, despite general warming trends. Polar vortex disruptions and reduced Arctic ice extent can paradoxically increase the frequency of cold air outbreaks in mid-latitudes. Extreme cold events risk infrastructure damage through freeze-thaw cycling, ice accumulation, and heating system failures.
- Drought affects repositories through multiple pathways. Extended dry periods compromise water availability for cooling systems, concrete curing, dust suppression, and worker facilities. Drought-induced soil moisture deficits alter groundwater recharge, affect engineered barrier performance, and modify surface vegetation effectiveness for erosion control.
- Windstorms and Extreme Wind Events impact facilities through direct structural loading, debris impact, and power infrastructure damage. While climate model projections for wind extremes show greater uncertainty than temperature-related hazards, some regions may experience increased storm frequency or intensity, particularly in transitional seasons.
- Soil Erosion represents a critical hazard for surface and near-surface disposal facilities. Enhanced by increased precipitation intensity, drought-weakened vegetation, and windstorm frequency, erosion progressively degrades protective cover systems, potentially exposing waste packages or reducing barrier thickness below design specifications. Erosion assessment requires consideration of long-term cumulative effects over decades to centuries.
- Water Table Variations affect repositories through altered precipitation-evapotranspiration balance and modified groundwater recharge. Rising water tables increase hydrostatic pressure on underground structures and enhance contaminant transport potential, while falling water tables may cause settlement and structural stress. Seasonal and inter-annual water table fluctuations challenge long-term barrier performance, particularly for clay-based systems sensitive to saturation cycling.

- Desertification emerges as a region-specific hazard for Mediterranean facilities, where progressively drier conditions, soil degradation, and vegetation loss create hostile conditions for facility operations and long-term cover system stability.
- Wildfires threaten facilities through direct fire contact, smoke and ash deposition, firefighting water impacts, and post-fire erosion. Climate-driven increases in fire weather conditions expand wildfire risk beyond historically fire-prone areas.
- Landslides affect facilities in topographically complex terrain, triggered or exacerbated by extreme precipitation, rapid snowmelt, permafrost degradation, and seismic activity potentially intensified by climate change.

5.2.2 Historical evidence

Climate groups analyse historical climate events affecting facilities or natural analogous sites to validate hazard identification and calibrate vulnerability assessments:

- Documented Flood Events included 2002 Elbe River floods affecting German facilities, 2021 extreme flooding in Belgium and Germany causing infrastructure damage and operational disruptions, coastal storm surges affecting UK and Baltic Sea facilities, and flash flood events overwhelming urban drainage systems.
- Heat Wave Events, particularly the 2003 European heat wave, causing widespread HVAC failures and cooling water shortages, the 2010 Russian heat wave demonstrating compound drought-heat impacts, and the 2018 Northern European heat wave affecting Nordic facilities.
- Drought Periods, including 2018-2019 European drought, causing widespread water supply issues, Mediterranean multi-year droughts affecting Spanish and Italian facilities, and Baltic Sea region droughts affecting Finnish facilities.
- Storm Events such as winter storm Xaver (2013), causing North Sea storm surge, various named Atlantic storms affecting UK and French facilities, and severe thunderstorms causing local flash flooding and infrastructure damage.

Historical evidence shows that several facilities had already experienced climate-related impacts near or surpassing their original design assumptions, emphasising the need for improved climate resilience in future planning.

5.2.3 Interdependencies and Cascading Risks

Generally, climate hazards do not occur in isolation but interact through complex interdependencies, creating cascading and amplified risks. The most relevant interdependencies identified during the construction and operation phase climate risk assessment are:

- **Sequential Cascades** involve primary hazards triggering secondary and tertiary effects through cause-and-effect chains. Heavy rainfall initiating flash floods leads to soil erosion, which degrades protective covers, increasing infiltration potential and groundwater table rise, ultimately affecting engineered barrier integrity. This cascade develops over timescales ranging from hours (flooding) to decades (barrier degradation).
- **Compound Events** occur when multiple hazards coincide temporally, producing impacts exceeding the sum of individual hazards. Coastal storm surge coinciding with extreme precipitation and high tide creates compound flooding with dramatically higher inundation than any single event. Drought combined with heat waves overwhelms cooling systems while simultaneously reducing water availability for emergency response. Winter storms, combining extreme wind, heavy snow, and freezing temperatures, stress multiple facility systems concurrently.
- **Infrastructure Cascades** propagate through interconnected facility systems. Windstorm damage to power distribution causes HVAC failure during heat wave conditions, resulting in worker safety risks and operational shutdown. Flooding of drainage systems leads to

surface water intrusion, causing humidity control loss, accelerating corrosion of containment systems. These cascades demonstrate the vulnerability of complex technical systems to climate-driven perturbations.

- **Temporal Accumulation** involves repeated modest-intensity events causing cumulative degradation exceeding the effects of a single extreme event. Seasonal freeze-thaw cycling progressively fractures concrete structures, creating infiltration pathways. Repeated drought-rewetting cycles degrade clay barrier plasticity and swelling capacity. This temporal accumulation challenges traditional design approaches based on single extreme event scenarios.
- **Spatial Propagation** transmits climate impacts through environmental pathways beyond the immediate facility footprint. Upstream watershed changes alter downstream flood characteristics at the facility location. Regional groundwater depletion modifies local hydrogeological conditions. Spatial propagation requires assessment beyond facility boundaries to watershed and regional scales.

5.2.3.1 Drought-Heat Wave Compounds

The simultaneous occurrence of prolonged drought periods with extreme heat waves creates severe operational challenges through multiple pathways. Limited water availability reduces cooling system capacity precisely when cooling demands are at their peak. Drought-stressed vegetation fails to provide evapotranspiration cooling, worsening heat island effects at disposal facility sites. Soil moisture deficits increase dust generation, impacting air quality and equipment, while also allowing deeper heat penetration that affects underground structures. This combination particularly impacts facilities with substantial cooling needs.

The historical analogue of the 2003 European heatwave, combined with severe drought, demonstrates cascading failures in facility cooling systems, agricultural water supply, and ecosystem services. Projections indicate increasing co-occurrence probability of drought and heat under climate change, requiring integrated assessment and adaptation strategies.

5.2.3.2 Coastal Storm Surge with Extreme Precipitation and High Tide

Compound coastal flooding combines multiple drivers: astronomical high tide provides an elevated baseline water level, storm surge from low-pressure systems and wind stress raises water levels further, extreme precipitation overwhelms inland drainage systems, preventing discharge, and wave action adds dynamic overtopping and impacts. The timing coincidence of these factors creates a flood severity that dramatically exceeds any individual component. This compound critically affects coastal facilities.

Climate change increases compound coastal flooding risk through multiple mechanisms: sea level rise elevates the baseline for all components, a potential increase in storm intensity enhances surge, intensified precipitation increases inland runoff contribution, and modified storm tracks may alter timing relationships.

5.2.3.3 Heavy Precipitation on Frozen or Saturated Ground

Heavy rainfall occurring on frozen ground during the winter-spring transition, or on already saturated soils following antecedent precipitation, produces rapid runoff with minimal infiltration. Frozen or saturated soils prevent precipitation storage, concentrating the entire rainfall into immediate surface flow. This compound creates flash flooding, exceeding expectations based on precipitation intensity alone. Particular concern exists for facilities experiencing freeze-thaw transitions.

Climate change modifies this compound through altered freeze-thaw timing, increased likelihood of rain-on-snow events as more winter precipitation falls as rain rather than snow, and potential for higher-intensity precipitation events during transitional seasons.

5.2.3.4 Windstorm with Power Outage During Heat Wave

Severe windstorms damaging electrical distribution infrastructure cause extended power outages coinciding with heat wave conditions, creating compounding risks to facility operations and worker safety. Loss of powered cooling and ventilation during extreme heat leads to rapid internal temperature rise, potential equipment failure, and hazardous working conditions. Emergency power systems face maximum stress precisely when most critical. This compound affects all climate groups but particularly those with substantial heat loads.

Adaptation measures for this compound require redundant cooling systems, enhanced emergency power capacity and fuel reserves, passive cooling design elements reducing powered cooling dependency, and operational procedures for safe facility evacuation or minimal staffing during compound events.

5.2.3.5 Pluvial-Fluvial Compound Flooding

Compound flooding occurs when intense local precipitation (pluvial flooding) coincides with high river water levels (fluvial flooding), creating backwater effects preventing drainage system discharge. Urban and developed areas experience particularly severe impacts as storm drainage systems become surcharged and reverse-flow, causing widespread surface flooding. Facilities in river valleys face this compound risk.

Climate change amplifies the combined impact of rain and river floods by increasing extreme rainfall, which leads to higher runoff, altering river discharge patterns with rising peak flows, and possibly expanding the area affected by storms, raising the chances of precipitation events coinciding at local and watershed levels.

5.2.3.6 Fire-Drought-Heat Compound

Mediterranean and continental climate facilities face compound wildfire risks where prolonged drought dehydrates vegetation, extreme heat lowers ignition thresholds and speeds up fire spread, and windstorms facilitate fire dissemination. Post-fire conditions create secondary hazards such as loss of erosion control, hydrophobic soils that change infiltration and runoff, and increased debris flow risk. This compound exhibits strong positive feedback: drought-stressed vegetation becomes more flammable, heat accelerates vegetation water stress, fire removes vegetation, increasing drought sensitivity of residual plants, and bare soil experiences enhanced heating.

5.2.3.7 Winter Storm with Ice Accretion and Power Loss

Compound winter storms combining freezing rain, causing ice accumulation on infrastructure, strong winds stressing ice-laden structures, and power outages from transmission line failures create severe operational challenges for northern facilities. Ice loading exceeding structural design limits risks collapse of overhead structures, loss of power prevents active heating, causing facility freeze-up, and emergency response access becomes severely limited.

Climate change effects on this compound show greater uncertainty, with some projections suggesting decreased ice storm frequency in warming climates, while others indicate potential increases in transitional seasons when temperatures fluctuate around freezing.

5.3 Detailed assessment

5.3.1 Identification of risks

After analysing the results of the first phase, a set of the most critical risks is identified for each group. The results are indicated in Table 5.4 and discussed below.

Table 5.4 Summary of the most critical risk for detailed assessment.

Hazard	3Sa	3Sb	3Sc	3Sd	3NSb	3NSc	3DGRa	3DGRb
Heavy Rainfall	○	○	○	○	○	○	○	○
Flash Flooding	○		○		○	○		
River Flooding	○	○			○	○		
Coastal Flooding	○	○					○	
Sea Level Rise	○	○					○	
Heat Waves	○	○	○	○	○		○	○
Cold Spells								
Droughts							○	○
Windstorms	○	○		○				
Soil Erosion	○		○	○		○		
Water Table Variations	○	○	○		○			○
Desertification								
Wildfires		○	○					
Permafrost Thaw							○	
Landslides								

5.3.1.1 Heavy Rainfall and Drainage Performance

Heavy rainfall and related drainage challenges have been identified as the highest-priority risks across most climate groups. These groups typically select heavy rainfall for detailed evaluation, employing high-resolution hydrological modelling, hydraulic analysis of drainage systems, and assessments of infrastructure vulnerability.

Climate projections consistently forecast increasing intensity of extreme precipitation events. Facilities designed according to historical data are expected to face exceedance probability increases ranging from 50% to 200% by the end of the century under high-emission scenarios. Drainage infrastructure generally does not incorporate design margins sufficient to address these predicted increases.

Key concerns include surface water ponding at facilities beyond their design capacity, infiltration through covers into disposal cells which may mobilize contaminants, and erosion affecting earthen structures and protective barriers. Flash flooding can trigger cascading failures, potentially overwhelming multiple facility systems simultaneously.

5.3.1.2 Heat Waves and HVAC Reliability

Most climate groups identified heat waves as requiring detailed assessment, focusing on thermal modelling of buildings and systems, HVAC performance simulation, and development of operational heat stress protocols.

Rising heat wave frequency, intensity, and duration pose serious risks to facility operations, worker safety, and infrastructure reliability across all groups. Projections suggest European summer heat extremes could reach 40-45°C in regions where maximum temperatures currently range from 30-35°C.

Performance degradation of the HVAC system, precisely when cooling demands reach their peak, can cause potential operational failures. Electronic control systems and instrumentation face temperature-induced failures. Worker productivity and safety decline under extreme heat, potentially necessitating operational restrictions during periods of peak demand. Construction activities face constraints from concrete temperature specifications and worker safety limits.

5.3.1.3 Drought Impacts on Water Supply and Cooling

Groups of DGR identified drought as requiring detailed assessment, particularly facilities in water-stressed regions or those with substantial cooling requirements.

Extended drought periods threaten facility water supply for cooling systems, concrete curing, dust suppression, and worker facilities. Drought simultaneously reduces water availability while increasing cooling demands during associated heat waves, creating compound stress on operations.

Drought-induced vegetation stress affects erosion control effectiveness of vegetated covers, potentially triggering accelerated degradation. Soil moisture deficits modify infiltration patterns and groundwater recharge, with long-term implications for barrier performance.

5.3.1.4 River and Coastal Flooding

River flooding affects groups 3Sa, 3Sb, 3NSb, and 3NSc, with particular concern where facilities were sited based on historical flood frequencies potentially underestimating future risk. Coastal flooding critically affects groups 3Sa, 3Sb, and 3DGRa, especially where sea level rise occurs along with storm surge and extreme precipitation.

Facilities in floodplains or coastal locations face critical flooding risks amplified by climate change through multiple mechanisms: increased precipitation intensity raises watershed runoff, modified seasonal patterns shift flood timing, and sea level rise elevates coastal flood baselines.

Detailed assessment of river and coastal flooding requires hydrodynamic modelling coupling watershed hydrology, river hydraulics, and facility-scale inundation mapping, integrated with climate projections spanning range of plausible futures.

5.3.1.5 Water Table Variations and Barrier Performance

Climate groups 3Sa, 3Sb, 3Sc, 3NSb, and 3DGRb prioritized water table variation impacts for detailed assessment, requiring coupled climate-hydrogeological modelling, geotechnical testing of barrier materials under cyclic saturation conditions, and long-term performance simulation.

Groundwater table fluctuations from modified precipitation-evapotranspiration balance critically affect engineered barrier systems, particularly clay-based barriers sensitive to saturation state. Rising water tables increase hydrostatic pressure on structures and enhance contaminant transport potential, while falling water tables cause settlement and structural stress.

Seasonal and inter-annual water table variations induce wet-dry cycling in clay barriers, progressively degrading plasticity, swelling capacity, and hydraulic performance.

5.3.1.6 Soil Erosion and Cover Degradation

Climate groups 3Sa, 3Sc, 3Sd and, 3NSc prioritized erosion for detailed assessment, requiring long-term landscape evolution modelling, vegetation dynamics simulation under changing climate, and engineering analysis of cover system resilience.

Progressive erosion of engineered cover systems presents critical risk to surface and near-surface facilities. Climate change amplifies erosion through increased precipitation intensity, drought-weakened vegetation, and potentially enhanced wind erosion in drying regions.

Erosion processes operate cumulatively over decades to centuries, potentially reducing cover thickness below design specifications or creating preferential flow paths compromising barrier function.

5.3.1.7 Coastal Sea Level Rise and Storm Surge

Climate groups 3Sa, 3Sb, and 3DGRa facilities with coastal locations prioritized this risk for detailed assessment requiring integrated coastal modelling spanning ocean dynamics, groundwater, and facility response.

Coastal facilities face existential threat from projected sea level rise combined with storm surge intensification. Mean sea level rise of 0.5-1.0 meters or more by 2100 fundamentally alters facility relationship to marine environment, with storm surges propagating further inland and reaching higher elevations.

Saltwater intrusion into groundwater systems threatens facility operations and potentially accelerates corrosion. Coastal erosion progressively reduces buffer distance between facility and shoreline. Loss of coastal wetlands and natural protection ecosystems amplifies wave impacts.

5.4 Data gaps and limitations

Data gaps and methodological limitations affect both screening and detailed climate risk assessments across all climate groups, constraining confidence in impact projections and adaptation recommendations. These limitations arise from climate data availability, model resolution, process representation, facility-specific information, and the inherent uncertainty associated with long-term projections.

5.4.1 Climate data limitations

Most regional climate models provide daily outputs at spatial resolutions of 12.5–50 km, which are insufficient to represent local-scale processes relevant for facility impacts. Sub-daily precipitation data critical for flash flooding and drainage performance are largely unavailable, requiring statistical disaggregation that introduces additional uncertainty. Long-term data records required for extreme value and compound event analysis are often lacking, especially for multivariate assessments. Downscaling and bias correction methods further rely on assumptions about scale relationships and stationarity.

5.4.2 Spatial resolution

Spatial resolution mismatches limit the representation of topography, coastal processes, snow dynamics, and facility-scale microclimates. Local phenomena such as convective precipitation enhancement, frost hollows, and valley winds occur at scales far below climate model grid sizes, necessitating downscaling approaches. Coastal hazards, including storm surge, waves, erosion, and dynamic ice-sheet contributions to sea level rise, require specialised models that are often loosely coupled to climate projections.

5.4.3 Process representation gaps

Climate models have limited capability to represent compound and cascading events, such as coincident wind and precipitation extremes or persistent heat–drought sequences. Snow and ice processes relevant for northern facilities show high inter-model variability, particularly for snow accumulation, melt timing, and soil freezing. Dependence structures between climate variables under future warming remain poorly constrained.

5.4.4 Facility-specific data limitations

As-built infrastructure characteristics, drainage capacities, material specifications, and emergency systems are often incompletely documented, particularly for older facilities. Site-specific measurements of soil, groundwater, and local climate conditions are frequently sparse or of insufficient duration for robust model calibration and validation. Material performance data under climate stress, including ageing of barriers, concrete degradation, and clay behaviour under repeated wet–dry or freeze–thaw cycles, rely heavily on extrapolation beyond experimental timeframes.

5.4.5 Monitoring and validation data

Few facilities have comprehensive datasets capturing system performance during extreme climate events, reducing opportunities for empirical model testing. Regional monitoring networks are often too coarse to support facility-scale assessments, and extrapolation introduces further uncertainty.

5.4.6 Methodology limitations

Screening methodologies exhibit inherent constraints. Semi-quantitative scoring relies on expert judgement, introducing subjectivity and variability. Risk aggregation methods lack strong theoretical foundations and poorly capture nonlinearities, thresholds, temporal evolution, and cascading risks. Static screening approaches do not adequately represent infrastructure ageing, adaptation measures, or changing vulnerability over time.

5.4.7 Intrinsic uncertainty

Climate projections introduce deep uncertainty, as facility lifetimes often exceed the reliable horizon of climate models. Beyond-century projections are affected by uncertain emission pathways, Earth system feedback, landscape evolution, and socioeconomic change. Regulatory requirements for quantitative safety demonstration may be challenged by these uncertainties, complicating compliance, stakeholder communication, and decision-making.

5.5 Risk quantification methodology

Priority risks identified during screening undergo quantitative probabilistic assessment integrating climate model ensembles, impact models, and statistical extreme value analysis:

- Climate Hazard Probability derived from ensemble climate projections, typically analysing multiple models and emission scenarios to quantify uncertainty. Extreme value distributions (Generalized Extreme Value, Generalized Pareto) fitted to modelled climate variables provided return period estimates for extreme events. For example, 100-year return period precipitation intensities for 2071-2100 were estimated from ensemble of regional climate models, with uncertainty bounds reflecting inter-model spread.
- Exposure Quantification mapped facility elements vulnerable to specific hazards using Geographic Information Systems, engineering drawings, and operational databases. Exposure-elevation relationships, inundation mapping, and infrastructure network analysis identified pathways for hazard propagation. Probabilistic exposure assessment accounted for temporal evolution of facility configuration through operational lifetime.
- Vulnerability Assessment quantified system response to hazard exposure using damage functions, fragility curves, or process-based models. For example, structural vulnerability to flooding employed depth-damage functions derived from engineering analysis or historical damage data. HVAC vulnerability to heat used thermodynamic performance models showing efficiency degradation with temperature. Barrier vulnerability to erosion employed physical process models (RUSLE, WEPP) simulating long-term degradation.

- Integrated Risk Calculation combined hazard probability, exposure, and vulnerability through convolution integrals, Monte Carlo simulation, or Bayesian networks. Risk metrics included expected annual damage, probability of exceeding damage thresholds, and time to failure under various climate scenarios.

For example, group 3Sb flood risk assessment combined extreme value analysis of river discharge from hydrological model ensemble (hazard), inundation modelling defining flooded areas at various discharge levels (exposure), and structural damage functions for buildings and equipment (vulnerability), yielding probability distributions of annual flood damage for current and future climate.

5.5.1 Sensitivity and uncertainty analysis

Comprehensive uncertainty quantification addresses multiple sources of assessment uncertainty:

- Climate Model Uncertainty quantified through multi-model ensembles analysing spread in projections across global climate models, regional climate models, and emission scenarios. Variance decomposition attributed uncertainty to model structure versus scenario choice, typically finding model uncertainty dominates for near-term (2050) while scenario uncertainty increases for long-term (2100).
- Impact Model Uncertainty assessed through parameter sensitivity analysis, model structure comparison, and calibration uncertainty propagation. Key sources included hydrological model parameters, material property uncertainty for geotechnical models, and damage function specification.
- Natural Variability distinguished from climate change signal through ensemble initial condition perturbations or statistical decomposition. Natural variability remains substantial contributor to uncertainty for rare extreme events even under strong climate change.

Uncertainty communication employed multiple approaches: probability distributions and confidence intervals for quantitative metrics, qualitative confidence levels based on evidence quality and agreement, and scenario framing acknowledging deep uncertainties precluding probabilistic characterization.

5.6 Climate-related natural analogues

Natural analogues provide valuable empirical evidence on long-term system behaviour under climate conditions beyond available instrumental records or experimental capabilities. In the following section, a description of the most suitable climate analogues for the analysed facilities is provided.

5.6.1 Operational facility analogues

- The Swedish Waste Repositories (SFR-Forsmark, SFR-Ringhals), operating since 1988, provide multi-decade experience with Nordic climate conditions, including severe cold, ice loading, snowmelt-driven flooding, and seasonal temperature extremes. Performance data on concrete vault systems, drainage infrastructure, and operational procedures inform Finnish facilities in Group 3Sa. Applicable period covers 35+ years of operational experience.
- The French Surface Disposal Centre (Aube facility) provides analogues for Groups 3Sb and 3NSb regarding concrete vault performance, engineered cover evolution, and operational experience with an Atlantic maritime climate, including precipitation extremes and moisture cycling.

- The UK Low-Level Waste Repository (LLWR) offers coastal facility experience relevant to Groups 3Sb and 3DGRb, including impacts of coastal storms, precipitation extremes, and infrastructure ageing under maritime conditions.
- The Spanish El Cabril facility, in operation since 1992, provides an analogue for Groups 3Sc and 3NSc, and more broadly for Mediterranean and seasonally dry contexts. Its experience is relevant for assessing the performance of engineered covers, drainage systems, infiltration control and operational adaptation under prolonged summer drought, high temperatures, wildfire risk and episodic intense rainfall.

Evidence from operational analogues includes actual performance data on drainage system adequacy during extreme precipitation events, structural integrity under weather loading, material ageing and degradation rates, effectiveness of operational procedures during adverse weather, and ecosystem establishment on engineered covers. Limitations include relatively short operational periods compared to facility design lifetimes, historical climate conditions potentially not representative of future climate, and site-specific differences in geology, design, and operations limiting direct transferability.

5.6.2 Historical climate analogues

- The Medieval Climate Anomaly (MCA, ~950-1250 CE) provides an analogue for warmer, drier conditions, potentially comparable to moderate warming scenarios. Paleoclimate records from this period inform hydrogeological responses, vegetation distributions, and erosion patterns under warmer temperatures. It might apply to understanding 21st-22nd century conditions under moderate mitigation.
- The Little Ice Age (LIA, ~1450-1850 CE) represents cooler, wetter conditions relevant for understanding climate variability and impacts of cold extremes. LIA glacier advances and permafrost extent inform the sensitivity of Nordic facilities to cold-period conditions during potential future climate oscillations.

Evidence includes geological and biological records preserving information on past climate conditions, sea levels, vegetation, hydrological regimes, and landscape evolution. Limitations involve imperfect knowledge of past climate characteristics, differences in atmospheric composition and solar forcing between past and future warmth, and challenges in quantitatively translating paleoclimate evidence to engineering-relevant parameters.

5.6.3 Geographic analogues

- Mediterranean Region Facilities provide analogues for Groups 3Sa, 3Sb, 3Sc, and 3NSb regarding potential future conditions under progressive warming and drying. Spanish El Cabril demonstrate design and operational approaches for hot, dry conditions with wildfire risk and droughts.
- Facilities in Water-Stressed Regions inform drought adaptation strategies for groups facing increasing aridity. Experience with water conservation, recycling systems, and drought-resistant designs applicable across multiple facilities.
- Coastal Facilities in Regions with Active Coastal Management provide insights into coastal adaptation strategies, including structural protection, accommodation through elevating infrastructure, and retreat where adaptation becomes infeasible.

Evidence includes engineering solutions demonstrated to be effective in analogous climates, operational experiences managing climate-related challenges, and ecosystem approaches (vegetation selection, erosion control) proven successful. Limitations include potentially slow transferability of lessons requiring local validation, regulatory and institutional differences affecting applicability, and site-specific conditions modifying the effectiveness of measures.

5.7 Synthesis and findings

5.7.1 Commonalities across climate groups

Despite diversity in facility types, locations, and climatic contexts, the construction and operational phase climate change risk assessment reveals striking commonalities across climate groups:

- Universal Hazards: Heavy rainfall/flooding and heat waves are identified as high-priority risks across all eight groups, transcending geographical and facility-type differences. This universality reflects Europe-wide projections of increasing precipitation extremes and rising temperatures.
- Infrastructure Vulnerability: Drainage systems emerge as critically vulnerable for nearly all facilities, typically designed with limited margins relative to projected future precipitation extremes. HVAC and cooling systems are similarly vulnerable across diverse facility types.
- Data and Methodology Limitations: All groups encounter similar constraints, including inadequate spatial and temporal resolution of climate data, limited facility-specific characterisation data, and challenges in modelling compound events and cascades.
- Adaptation Themes: Enhanced drainage capacity, HVAC upgrades, improved monitoring, and adaptive management frameworks identified as priority adaptation measures across multiple groups.

5.7.2 Facility-typesSpecific insights

Surface Disposal Facilities exhibit maximum exposure to atmospheric climate hazards with direct impacts on waste emplacement zones. Erosion and cover system degradation represent unique long-term concerns. These facilities benefit most from robust engineered covers, enhanced drainage, and vegetation management.

Near-Surface Disposal Facilities show intermediate exposure with particular sensitivity to groundwater table fluctuations and infiltration. Vault and barrier performance under moisture cycling represents a critical concern. These facilities require emphasis on hydrogeological monitoring and barrier material selection tolerant to saturation variations.

Deep Geological Repositories feature surface facilities exposed to climate hazards, while underground disposal areas remain buffered. Operational phase climate risks concentrate on surface infrastructure performance. Long-term post-closure safety depends primarily on hydrogeological changes rather than direct atmospheric impacts. Interim Storage Facilities represent the highest-intensity operations with maximum cooling and infrastructure requirements, creating elevated vulnerability to heat waves, power outages, and operational disruptions from extreme weather.

5.7.3 Regional climate patterns

The Nordic Climate Zone (Dfc/Dfb) facilities in Groups 3Sa and 3DGRa face cold-region challenges, including freeze-thaw cycling, snowmelt flooding, permafrost considerations, and transitional-season compound events. Climate change brings moderate warming with increasing winter precipitation and earlier spring snowmelt.

The Maritime Temperate Zone (Cfb) facilities in Groups 3Sb, 3NSb, 3DGRa, and 3DGRb experience moderate temperatures with year-round precipitation. Climate change projections indicate increasing winter precipitation, more intense summer extremes, and elevated coastal flooding risk from sea level rise.

The Mediterranean Zone (Csa) facilities in Groups 3Sc and 3NSc face distinct seasonal patterns with hot dry summers and mild wet winters. Climate change exacerbates summer heat and

drought while potentially intensifying winter precipitation extremes, creating amplified seasonal contrasts. Wildfire risk and water scarcity represent unique regional challenges.

The Continental Zone (Dc) facility in Group 3Sd experiences large seasonal temperature ranges and continental precipitation patterns. Climate change brings general warming with potential increases in both summer heat extremes and winter precipitation.

5.8 Conclusions

Climate risk assessment for radioactive waste disposal facilities during construction and operational phases encompasses complex interactions between physical climate hazards, facility exposure, and system vulnerability across diverse European contexts.

This systematic assessment across eight climate-facility type groups representing 24 facilities demonstrates that:

- Climate change poses material risks to facility safety and operations through increasing extreme precipitation overwhelming drainage systems, heat waves stressing cooling infrastructure and worker safety, sea level rise and coastal flooding threatening coastal facilities, and long-term hydrogeological changes affecting engineered barriers.
- Comprehensive assessment requires integrated multi-model approaches combining climate projections, impact modelling, and uncertainty quantification spanning multiple spatial and temporal scales. Two-phase screening and detailed assessment methodology provide a structured framework for prioritising risks and allocating resources.
- Substantial data and methodological limitations constrain assessment confidence, particularly for high-resolution climate variables, compound events, long-term projections, and facility-specific vulnerability parameters. Ongoing research and monitoring programs are essential for reducing uncertainties.
- Adaptation measures are available and technically feasible for identified priority risks, though requiring proactive implementation, accounting for long lead times in facility planning, design, and construction. Enhanced drainage, HVAC upgrades, improved monitoring, and adaptive management frameworks provide pathways to enhanced climate resilience.
- Regulatory frameworks and safety cases may evolve to explicitly address climate risks with transparent communication of uncertainties and demonstration of adequate safety margins accounting for a range of plausible climate futures.

Future work should emphasise enhanced monitoring networks providing empirical data on facility performance under extreme conditions, development of high-resolution climate projections tailored to waste facility needs, integrated modelling frameworks coupling multiple physical processes and cascade pathways, and adaptive management approaches enabling course correction as climate conditions and understanding evolve.

6. Climate risk assessment during post-closure

6.1 Introduction

Because radioactive waste remains hazardous far beyond conventional planning horizons, climate change is treated as a fundamental external driver in post-closure safety assessments. Over long timescales (millennia), climate evolution can significantly modify geological, hydrogeological, geochemical, mechanical and biospheric processes that are critical for the long-term containment and isolation of radioactive waste.

This chapter synthesises the results of Task 4 of WP11 CLIMATE, focusing on climate change impacts during the post-closure phase for different disposal concepts across Europe. The assessment covers deep geological repositories, near-surface disposal facilities, and surface disposal systems, considering timescales ranging from centuries to up to one million years. Particular attention is given to how long-term climate evolution influences safety-relevant boundary conditions rather than short-term operational disruptions.

6.2 Deep geological repositories (DGR)

6.2.1 Climate change scenarios

Over the next one million years, Earth's climate is expected to undergo repeated glacial cycles, alternating between warm interglacial periods and cold glacial stages with the development of permafrost, ice sheets, and fluctuating sea levels. These long-term changes are primarily driven by variations in Earth's orbital parameters (insolation) and atmospheric CO_2 concentrations. Future projections are often, but not always, based on established climate scenarios (RCPs) from the IPCC and a combination of advanced Earth system models and statistical emulators that simulate climate, carbon cycle, and sea-level evolution over geological timescales.

In Climate Group 4DGRa, which represents northern or high-latitude regions such as Fennoscandia, state-of-the-art models (CLIMBER–SICOPOLIS EMIC, CLIMBER-2, and CGSLM) have been used to simulate long-term climate behaviour. These models reproduce past glacial–interglacial patterns reliably, providing confidence in their future projections. Under a moderate warming scenario (extended RCP4.5), the current interglacial is expected to continue for about 50,000 years After Present (AP), followed by the return of permafrost and glacial conditions. Under a high-emission scenario (RCP8.5), this interglacial may last up to 200,000 years AP before glaciation resumes. Over the full million-year timescale, several glacial cycles are expected to occur, bringing recurring cold conditions, permafrost development, and, depending on location and altitude, glacier and ice-sheet formation.

For Climate Group 4DGRb, covering Central Europe (Switzerland, Czechia and southern Germany), the currently available information is based on reduced-complexity models and conceptual climate scenarios based on the geological past. Rather than producing a deterministic climate sequence, studies (e.g., NAGRA) focus on extreme climatic states and their potential impacts. The most extreme scenario involves the advance of glaciers or an ice sheet, which is not expected before about 100,000 years AP, depending on future greenhouse gas concentrations. In Czechia, full glacial conditions are unlikely, but the development of permafrost during cold phases is expected.

Scenarios for Climate Group 4DGRc, represented by France, Belgium and the UK, seem all to be based on the BIOCLIM project (2001), which modelled future climate evolution under two groups of greenhouse gas emission scenarios: A (no emissions) and B (with emissions). According to these models, the period up to about 50,000 years AP will likely remain relatively warm, with conditions similar to or warmer than the present and possible marine inundation of low-lying coastal areas. Between 50,000 and 170,000 years AP, warm interglacial conditions are expected to continue, although short cold intervals cannot be excluded. The reappearance of cold

climates is projected between 170,000 and 400,000 years AP, with permafrost development during glacial maxima but no formation of large ice sheets over Belgium or France. Beyond 400,000 years AP, alternating warm and cold phases will continue, with permafrost recurring during glacial maxima. Ice sheets may extend over northern Germany or the UK but are unlikely in Belgium or France. Sea levels are projected to fluctuate between about +40 meters during warm periods and –120 to –130 meters during glacial maxima. These estimates are based on data from the geological past (Pliocene and Miocene sea level estimates) and EMIC output.

In summary, all three climate groups indicate that multiple glacial–interglacial cycles will occur within the next million years. The duration of the present interglacial is expected to be significantly prolonged by elevated CO_2 concentrations, possibly lasting tens to hundreds of thousands of years, far longer than typical interglacials in the past 800,000 years. Eventually, however, glacial conditions, permafrost, and fluctuating sea levels will return. The likelihood and intensity of ice-sheet development vary by region—being greatest in northern Europe (4DGRa), likely in Alpine regions (4DGRb), and unexpected in most parts of western Europe (4DGRc). Across all regions, permafrost is anticipated to be a recurring feature of future glacial periods.

6.2.2 Gaps and constraints

Climate projections for Fennoscandian and adjacent areas depend heavily on simplifying assumptions about future human influence and the natural evolution of the climate system. Models assume that after about 500 years AP, humans will make no further significant changes to natural atmospheric CO_2 levels or other radiative forcing agents. This introduces major uncertainty, as long-term socioeconomic and technological developments are unpredictable. The models assume that future glaciations will follow the same patterns as the last Weichselian, even though future orbital and CO_2 conditions may lead to different ice-sheet geometries or dynamics. This reliance on historical analogues is a key constraint in long-term glacial modelling.

In some cases (Switzerland, Czechia), there are no detailed or deterministic climatic sequences, reflecting the high uncertainty of future regional climate evolution. Instead, only extreme and conservative scenarios—such as extended permafrost or glacial advances—are considered. While this approach ensures safety under worst-case conditions, it provides limited temporal or climatic resolution, leaving uncertainty about the timing, duration, and variability of future climate states. The lack of detailed modelling also means that transient climate behaviour between extremes is not well understood.

In Western Europe (Belgium, France), large uncertainties stem from the unknown future of CO_2 emissions and the coarse nature of BIOCLIM model outputs. For example, under the high-emission B4 scenario, warm conditions persist for almost 500,000 years, demonstrating how sensitive long-term results are to greenhouse gas assumptions. To manage uncertainty, Belgium and France use representative or envelope climate states rather than continuous deterministic time series. Several scientific and methodological gaps constrain climate modelling. Downscaling techniques, needed to convert coarse model output to local meteorological data, often produce non-meaningful or inconsistent results and remain an unresolved methodological issue. Finally, there are gaps in process-based modelling, computational techniques, and integration of local-scale processes into long-term simulations.

The main constraints across all climate groups lie in the limited predictability of human influence, the simplifying assumptions about ice-sheet and climate behaviour, and the technical challenges in regional downscaling and model interpretation. While existing models provide valuable insights into long-term trends, their results should be viewed as broad envelopes of possible futures rather than precise forecasts. Continued methodological refinement, inclusion of updated emission pathways, and better integration of local processes are essential to reduce these uncertainties in future climate scenario development.

6.2.3 Natural analogues

Natural analogues are a key tool in assessing how climate change over geological timescales may affect the long-term safety of DGRs for radioactive waste. Because these facilities must remain stable for hundreds of thousands of years, and direct experimentation is impossible over such timescales, analogues drawn from natural systems provide essential evidence for validating models and evaluating long-term processes under different climate conditions.

In Climate Group 4DGRa (Fennoscandia), analogue studies have focused on glacial and permafrost processes, as these regions are strongly influenced by repeated glaciations. Research on glacially induced seismicity and post-glacial faulting has improved understanding of crustal stability, while sedimentological and cosmogenic nuclide data provide erosion rate estimates. Analogues from Greenland have clarified permafrost–groundwater interactions, and natural bentonite deposits in permafrost regions confirm the long-term stability of engineered buffer materials under cold conditions. However, analogues for extended global warming scenarios are missing.

In Climate Group 4DGRb (Central Europe, including Switzerland, Czechia and southern Germany), analogues emphasise geochemical stability of host rocks and groundwater systems under varying climates. The Rožná uranium deposit demonstrates long-term radionuclide retention in granite over 250 million years, supporting repository safety arguments. Other analogues that have already been explored include natural clay deposits, ancient groundwater systems, and geomorphological archives.

In Climate Group 4DGRc (Western Europe, including Belgium, France and the UK), a wide range of geographical, past climatic, and geological analogues is proposed to assess processes like erosion, vegetation change, sea-level variation, diffusion, and permafrost formation. Modern Mediterranean and subtropical sites provide analogues for future warm conditions, while past glaciations (e.g., Weichselian, Saalian) inform understanding of cold-climate erosion, river incision, and permafrost. Long-term geomorphological records can be used to estimate future erosion and sea-level changes, and projects such as CLAYTRAC demonstrate that in many clay-rich host rocks, solute transport is predominantly diffusive over geological time. Yet, analogues here face issues of non-equivalence: modern and past analogue sites often differ in topography, hydrology, and sediment supply, making direct transfer of quantitative results uncertain.

6.2.4 Evolution of climate change risks

Over the next million years, DGRs for radioactive waste will be exposed to the full range of natural climate variability, from extended interglacials and global warming to renewed permafrost and glaciations. The magnitude and timing of these climate-driven changes differ across Europe's major climate regions, defined as Climate Groups 4DGRa (Fennoscandia), 4DGRb (central Europe), and 4DGRc (western Europe). Each group faces distinct, though interrelated, risks related to groundwater evolution, permafrost, erosion, sea-level change, and mechanical loading, all of which can influence repository safety over long timescales.

In Climate Group 4DGRa, represented by Finland and other Fennoscandian regions, glacial and periglacial processes dominate long-term risks. The design of Finland's repository at Olkiluoto already accounts for the potential penetration of permafrost by locating disposal tunnels at depths between 400 and 500 meters, below the estimated reach of future frozen ground. Over glacial cycles, the key risks arise from infiltration of glacial meltwater and mechanical stresses from ice-sheet loading and unloading. Meltwater infiltration through fracture zones during ice retreat could alter groundwater chemistry, dilute saline water, and degrade bentonite barriers. Warm-based ice sheets, especially during retreat phases, may generate hydraulic gradients that drive deep infiltration of meltwater and seawater, potentially changing groundwater flow paths and compositions. During cold-based ice sheets and permafrost-dominated conditions, however, infiltration becomes negligible, limiting geochemical disturbances from the surface. Furthermore,

erosion rates are minimal (around 10 meters per glacial cycle), ensuring repository burial for at least hundreds of thousands of years. The low topography and coastal position of Olkiluoto create a moderate risk of seawater infiltration during periods of high sea level, but laboratory experiments confirm that saline water would have negligible effects on bentonite stability.

In Climate Group 4DGRb, covering Central Europe, the following risks are reported. Under global warming or during prolonged interglacials, the main challenges relate to reduced groundwater recharge and enhanced rock weathering. Lower recharge rates would slow down groundwater circulation, increase water residence times, and potentially affect geochemical equilibrium in the host rock, while increased weathering could modify near-surface geochemistry. Conversely, under global cooling, the development of permafrost would reduce groundwater recharge and hydraulic conductivity, altering subsurface flow and potentially leading to stagnant groundwater conditions. During extreme cooling and glaciation, risks become mechanical: erosion rates increase, and ice loading and unloading can deform the bedrock, modify fracture permeability, and affect hydrogeological conditions. Post-glacial rebound may induce renewed rock fracturing and surface erosion, temporarily increasing groundwater flow.

In Climate Group 4DGRc, the risks that are reported are associated with surface processes, particularly erosion, river incision, and sea-level change, that evolve gradually over hundreds of thousands of years. Future warming and increased precipitation may intensify river incision and landscape erosion, potentially altering hydraulic gradients and leading to upward flow from deeper aquifers that could reduce radionuclide travel times. For instance, Quaternary analogues from the Paris Basin show that climatic cycles have caused repeated episodes of river deepening and topographic reorganisation, including river captures that changed drainage networks. Such processes could, over very long periods, modify groundwater flow paths and outcropping layers relevant to repository sites. Under cold climates, permafrost may influence the upper hundreds of meters of rock, but is unlikely to reach repository depth if located at sufficient depth. Nonetheless, erosion and denudation rates tend to increase during permafrost periods and especially during climatic transitions (warm–cold or cold–warm). Ice-sheet development is considered unlikely south of northern Germany and the northern UK, but cannot be ruled out entirely over the next million years. In the unlikely event of an ice sheet reaching western Europe, glacial erosion and tunnel valley formation may pose a significant risk, reaching erosion depths of several hundred meters. Sea-level fluctuations further shape the hydrogeological boundary conditions: high sea levels could cause partial marine inundation of low-lying sites and induce subsidence or coastal erosion, while low sea levels may enhance river incision and modify hydraulic gradients within aquifers. Although most analyses remain qualitative, numerical simulations in France (e.g., for the Cigéo facility) suggest that future landscape evolution and sea-level changes could increase vertical groundwater gradients and promote upward flow through the Callovo–Oxfordian clay formation that hosts the repository.

In summary, while each climatic region experiences distinct dominant risks, ranging from ice-sheet loading in Fennoscandia to fluvial incision in Western Europe, all share the challenge of evolving hydrological and geochemical boundary conditions over glacial–interglacial cycles. The cumulative evidence indicates that these risks are manageable and well-understood, though continued refinement of models and analogues is essential, particularly for long-duration global warming scenarios and climate transitions, where the greatest uncertainties remain.

6.2.5 Risk methodology

Across all climate groups (4DGRa–4DGRc), climate evolution is recognised as a fundamental driver in the long-term safety assessment of deep geological repositories for radioactive waste. The methodological approaches vary in detail and maturity, but they share a common structure: climate is treated as a major external FEP (Feature, Event, and Process) that influences other FEPs, including hydrological, geochemical, and mechanical processes within both the natural (geosphere–biosphere) and engineered barrier systems (EBS). The overarching objective of the

methodology is to define and test how future climate evolution may alter repository performance over time, using conceptual models, climate scenarios, natural analogues and quantitative simulations where possible.

In Finland, the methodological framework for risk assessment is the most comprehensive and integrated. Climate is explicitly treated as an overarching FEP that drives many secondary processes relevant to long-term safety. The methodology begins with a reconstruction of past climate dynamics, using paleoclimate evidence to understand the timing and mechanisms of glacial–interglacial cycles. These reconstructions are then used to project future climate sequences over hundreds of thousands of years, accounting for the dominant long-term forcing mechanisms: solar insolation (orbital variations) and atmospheric CO_2 concentrations (including anthropogenic forcing scenarios).

The projected climate sequence defines the boundary conditions for surface and subsurface processes, such as precipitation, permafrost, and ice-sheet development, which in turn determine groundwater recharge, salinity, and flow patterns. The methodology directly links these processes to the safety functions of the engineered and geological barriers. For example, models assess how climate-induced changes in groundwater chemistry could affect bentonite buffer stability, or how glacial loading and unloading could influence fracture reactivation and rock permeability.

Other approaches are used in Climate group 4DGRb. In Czechia, hypothetical climate scenarios are based on extreme Quaternary climatic conditions, reflecting glacial-interglacial cyclicity, without smooth transitions for simplicity. These boundary conditions were then applied to a groundwater and geochemical model, taking into account long-term erosion. The focus is primarily on identifying potential long-term trends and boundary conditions rather than producing probabilistic risk estimates. This approach represents an early-stage screening methodology, where conceptual understanding and conservative assumptions are used to identify potentially sensitive processes, but comprehensive propagation of climate scenarios into quantitative risk models is not yet achieved.

For 4DGRc, the risk assessment methodology for climate impacts is based on the BIOCLIM framework. This model suite provides a set of long-term climate scenarios driven by orbital parameters and greenhouse gas concentrations, which serve as the foundation for defining future boundary conditions. In France (Cigéo), two extreme climate scenarios – a warm (B4) and a cold (A4) end-member – were selected to define an envelope of possible future conditions. This approach enables bounding analyses of repository performance under the most divergent climates expected over the next million years. In Belgium, a synthesis of six BIOCLIM scenarios was used to define a set of representative climate states corresponding to specific time horizons. These representative states form a conceptual framework for assessing how long-term processes such as erosion, infiltration, or groundwater flow might evolve. Although these scenarios provide a structured way to screen climate-related risks, in many cases, the results have not yet been propagated into fully quantitative risk models. The methodology remains primarily conceptual, aimed at ensuring that the full spectrum of potential climate conditions is represented in the safety case.

6.2.6 Recommendations

Across all climate groups, there is consensus that future climate evolution introduces significant uncertainties for the long-term safety of geological repositories, and that existing methodologies, while adequate for screening major risks, require further refinement to capture complex climate–geosphere–hydrosphere–biosphere interactions.

Current climate projections assume that, beyond approximately 2300-2500 AD, human influence on climate will cease to increase significantly; however, this assumption is recognised as a major source of uncertainty. Therefore, a range of IPCC emission scenarios should continue to be included to account for different possible societal and technological pathways.

The adoption of high-resolution and computationally efficient climate models (both global and regional, GCMs and RCMs) and improved downscaling techniques is seen as essential to reduce uncertainty and avoid overly conservative assumptions in safety cases.

A key gap identified is the lack of natural analogues for future interglacial and global warming conditions. Most existing analogues and models emphasise cold or glacial climates, leaving high-temperature and high-precipitation (high mean precipitation and more extreme precipitation) scenarios underrepresented. Expanding analogue research to include warm-climate analogues would improve the completeness of long-term safety assessments.

6.3 Near-surface (shallow depth) disposal

6.3.1 Climate change scenarios

For climate group 4NSb, scenarios are available from downscaled EMIC simulations developed for the CSA and Cigéo sites in France, and sea-level rise projections from the SEA report for Olen (Belgium). In the short term (0–1000 years AP), two variants roughly following RCP8.5 were used: a standard scenario and a 2aT scenario with doubled temperature increase. In the long term (up to 50,000 years AP), a natural scenario (BIOCLIM A4) without greenhouse gas emissions and a perturbed scenario (BIOCLIM B4) continuing RCP8.5 forcing were considered. The climate is expected to shift from an oceanic (Do; Köppen-Trewartha) to a Mediterranean/subtropical (Cs/Cr) regime within 100–200 years, with temporary steppe (BS) phases after 200 years. Over tens of millennia, the natural scenario suggests a return to Do conditions, while the perturbed one maintains a warmer Cs climate. Sea-level projections based on EMIC and ECP scenarios indicate a rise of 9–37 m within 10,000 years, with possible complete Antarctic melting under extreme forcing.

For climate group 4NSc, no site-specific modelling has yet been done; based on generic data, this climate group is expected to evolve toward a semi-arid climate in the future. Marine flooding is estimated to be around +1.25 m by 2100 and +16 m by 2300 under extreme ice-cap instability scenarios.

6.3.2 Gaps and constraints

A key limitation is the transferability of downscaled EMIC data to nearby sites. Even within the same region, the representativeness of the downscaling area should be verified before applying results elsewhere. When using climate data for hydrological or erosion modelling, describing only the average climate state, using monthly temperature and precipitation data is inadequate. Perturbation tools are needed to create realistic meteorological time series suitable for process-based simulations. In addition, sea-level rise projections remain highly uncertain and strongly dependent on cumulative greenhouse gas emissions assumed in the scenarios.

6.3.3 Natural analogues

For climate group 4NSb, natural analogues are used to estimate terrestrial processes such as erosion rates and magnitudes under future climates. For Cs (Mediterranean) conditions, the analogue is the Guadalquivir Basin in Spain, and for Cr (humid subtropical) conditions, the analogue is the state of Georgia (USA). These examples are site-specific to the FAVL project and should not be transferred to other locations, even within the same climate class, without careful validation. In areas potentially affected by future sea-level rise, estuarine and marine erosion processes can be studied through analogues in the geological record and in present-day estuaries with comparable morphodynamics.

For climate group 4NSc, appropriate natural analogues in clay or marl formations should be identified once the future climate conditions for the site are defined.

6.3.4 Evolution of climate change risks

The main long-term risks for the near-field concern erosion (affecting waste isolation) and barrier degradation (affecting containment). These processes cannot be excluded over the assessment period, up to 20,000 years for Belgium and 50,000 years for France. While fluvial incision is unlikely under the expected subtropical climate in the future, sheet erosion may intensify due to fewer but more extreme rainfall events, leading to a gradual smoothing of the topography through denudation and valley infilling. In low-lying coastal zones, sea-level rise introduces risks of estuarine erosion and marine water intrusion into disposal cells. Submergence could reduce hydraulic gradients but accelerate corrosion of engineered barriers. Alternating saline intrusion and freshwater flushing could compound risks. Mitigation is possible by increasing disposal depth and selecting a resistant host rock, though complete prevention of seawater ingress is unlikely. Even under continued terrestrial conditions, groundwater flow regimes may increase drastically and remain to be assessed for several case studies.

6.3.5 Risk methodology

Climate risk methodology emphasises evaluating marine erosion processes under future sea-level rise scenarios and terrestrial erosion. Sites potentially affected by sea-level variation should assess risks of marine erosion and saltwater intrusion, though these effects have not yet been modelled through erosion, hydrogeological, or corrosion simulations in all case studies. Given the strong dependence of sea-level projections on greenhouse gas emission scenarios, substantial uncertainty remains. The approach would also include screening terrestrial erosion magnitudes across successive climatic states to confirm or adjust the disposal depth for near-surface or shallow geological repositories. Such erosion modelling has already been applied at the FAVL site.

6.3.6 Recommendations

For climate group 4NSb, recommendations focus on accounting for the rapid transition from temperate to subtropical conditions and its implications for long-term erosion and waste isolation. Since disposal depths are only a few tens of meters, the effects of sustained or alternating climates on overburden stability should be evaluated. This can be done through numerical erosion modelling or by using well-characterised natural analogues with comparable climate, vegetation, hydrogeology, and substrate conditions. For low-lying sites (<30 m a.s.l.), a complete marine inundation over several tens of thousands of years cannot be excluded. Therefore, potential impacts of marine and estuarine erosion and saline water intrusion into disposal cells should be explicitly assessed, including the use of natural analogues.

6.4 Surface disposal

6.4.1 Climate change scenarios

Projections are based on a wide variety of scenarios, from older scenarios for advanced programs (e.g., SRES A1B, A2 and B2 for the Dessel site) up to the most recent scenarios such as SSP5-8.5. In the majority of case studies, climate scenarios corresponding to RCP4.5 (moderate emissions) and RCP8.5 (high emissions) are used. For northern regions (Climate Group 4Sa), they predict a shift towards Dfa and/or Cfb climates, with pronounced warming and increased rainfall seasonality. For Climate Group 4Sb, a shift towards a Csa climate (Cs in Köppen-Trewartha) is expected within the next century, which could dominate most of the next millennium. In the UK, a humid subtropical climate may develop within 3,000 years. For southern regions (Climate Groups 4Sc), a transition towards an arid B-climate is expected for many areas (but not all), with a sharp increase in heatwave frequency and intensity, and more irregular, intense storms. Finally, the Cfa climate of Climate Group 4Sd is expected to continue over the next millennia, albeit with gradual warming and increased rainfall seasonality.

6.4.2 Gaps and constraints

A common limitation lies in the lack of high-resolution, locally calibrated climate models and the uncertainty of long-term projections, particularly beyond the year 2100. Another reported gap is the limited availability of paleoclimate analogues for multi-century or millennial timescales, and reliance on extrapolated or generalised projections. As a result, projections beyond 2100 have low confidence, especially for long-term hydrological and geomorphological impacts (see further below). In some case studies, more in particular those that are in an advanced state, impact assessments are based on outdated scenarios (e.g., older SRES pathways). Downscaling remains an active research challenge, with statistical and geometrical methods sometimes yielding non-meaningful or inconsistent results. The classification-based description of climate states (e.g., Köppen types) is also a limitation, as changes in precipitation or temperature do not always correspond to meaningful class transitions. These constraints hinder the assessment of site-specific risks such as erosion or infiltration.

6.4.3 Natural analogues

In Lithuania, analogues for the present Dfb climate include mid-latitude Atlantic–continental regions such as the southern Baltic and western Europe (e.g., Forsmark, Sweden), though the geological settings differ. Potential analogues for future warmer climates include northern Ukraine, central Poland, and southern Belarus (for a Dfb→Dfa transition) and northern Germany, Denmark, and the Netherlands (for a Dfb→Cfb shift). In Ukraine, analogues for early warming exist in northeastern North America (Dfa) and northwest Iberia (Csa) to study temperature rise, drought, and seasonal precipitation changes.

For Climate Group 4Sb (Belgium, France, UK), natural analogues are already in use. The Guadalquivir Basin (Spain) and Georgia (USA) serve as dry and wet subtropical analogues, respectively, for soil erosion and vegetation studies in the Paris Basin (parameter estimation). Weather station data from Ourense (NW Spain) were initially used (Tier 1 approach) for infiltration calculations through the multi-layer cover at Dessel (Belgium) as an analogue for a future Cs (Köppen-Trewartha) climate. Other examples that are proposed include Holocene palaeosol sequences as an analogue for multi-layer covers, under different climates. Anthropogenic analogues are also proposed from the Neolithic to modern times for studying infiltration, slope stability, and material degradation, and paleoclimate sea-level analogues over the past million years. However, analogues must be carefully adjusted for differences in relief, geology, and climate drivers, since perfect equivalence does not exist.

For Climate Group 4Sc (Italy and Spain), analogues are proposed from semi-arid Mediterranean–steppe regions in southern Spain and North Africa, which reflect projected BSh-type climates and are used to assess erosion, infiltration, and cover durability for the El Cabril site. Over longer timescales, cold-steppe and desert regions from the Black Sea to Central Asia are proposed as analogues for future glacial–interglacial cycles, especially for deep geological repositories. Still, differences in lithology and the absence of natural counterparts for engineered barriers limit direct transferability.

For Climate Group 4Sd, loess archives covering the last 800,000 years are used as paleoclimate analogues to reconstruct past geohazards and provide baselines for long-term risk assessment.

6.4.4 Evolution of climate change risks

For Climate Group 4Sa (Finland, Ukraine, Lithuania), climate risks are reported for the near-field, including increased infiltration due to extreme precipitation, soil desiccation and cracking during droughts, and erosion of engineered covers from heavy rainfall, vegetation loss, and freeze–thaw cycles. Warmer and wetter conditions could enhance radionuclide transport and alter runoff pathways, while long-term land use changes may raise intrusion risks. Sites that are located in floodplains may face flooding and radionuclide transport along river pathways if drainage systems

become overwhelmed. Floodplain levels may rise with rising sea-level and future marine transgression (after ~300 years in Finland) could alter groundwater salinity if sea-level rise submerges the area.

For Climate Group 4Sb (Belgium, France, UK), the main risks involve seasonal contrasts (hotter, drier summers; wetter winters), intensified rainfall, and sea-level rise. These processes may degrade engineered barriers through vegetation loss, soil cracking, clay desiccation, and erosion of top layers. Modelling studies (RUSLE-type) show erosion rates could increase by an order of magnitude under a future Mediterranean-type climate (Cs/Csa) if vegetation cover declines. Vegetation thus remains a key protective factor, reducing erosion by up to two orders of magnitude. For Dessel (Belgium) and CSM (France), barrier degradation is expected to be gradual and localised, but extreme erosion or persistent drought could accelerate infiltration after 350–650 years. Additional risks include saline intrusion and corrosion from possible long-term sea-level rise (up to +14 m in 1000 years). Adaptation measures under study include reducing cover slopes, using gravel or protective top layers, enhancing vegetation stability, and testing full-scale covers (e.g., Dessel's 1:1 test model).

For Climate Group 4Sc (Italy and Spain), increasing temperatures, reduced mean rainfall, and greater variability between dry and wet periods will intensify erosion, runoff, and drought stress. In southern Italy and Spain, warmer and drier conditions (Csa to BSh) will drive soil desiccation, cover cracking, and vegetation loss, while in northern Italy, increased precipitation could raise groundwater recharge and radionuclide migration potential. At El Cabril, soil cover stability and concrete vault durability are the key concerns: repeated dry–wet and hot–cold cycles may weaken materials through microcracking and evaporation–condensation processes. However, the multi-barrier system is expected to maintain its performance. Recommended adaptations include maintaining dense vegetation, optimising cover slope and materials for erosion resistance, and installing drainage and edge-protection systems. Instrumented test covers and ongoing monitoring programs are advised to calibrate infiltration and erosion models and ensure resilience under future climatic stress.

For Climate Group 4Sd (humid subtropical regions), the expected rise in extreme weather events, notably storms, heatwaves, droughts, and intense rainfall, will increase erosion and flood hazards. These could undermine surface covers, increase infiltration, and threaten site accessibility. Potential adaptation measures include enhanced surface water management, fire-resistant vegetation, and storm drainage upgrades.

6.4.5 Risk methodology

For Lithuania in particular (Climate Group 4Sa), future climate states were not formally integrated into the safety assessment, and no defined sequence of climate evolutions was applied. Instead, the approach relied on "what-if" sensitivity analyses, examining how extreme boundary values for temperature, precipitation, and infiltration could affect system components such as engineered barriers, vaults, and radionuclide migration. This method demonstrated repository robustness under simplified perturbations but lacked the formal rigour of systematic scenario development aligned with recognised frameworks (e.g., RCP-based trajectories). As a result, while key processes were qualitatively addressed, the methodology provided only partial coverage of potential long-term impacts. The introduction of explicit, scenario-based climate evolution sequences would substantially enhance completeness and traceability of the analysis.

For Climate Group 4Sb (Belgium, France, UK), the methodology was primarily classification-based, using averaged climatic parameters (annual or monthly means of temperature, precipitation, evapotranspiration) and Köppen–Geiger (KG) or Köppen–Trewartha (KT) climate typologies. This allowed the identification of general risks such as erosion and infiltration processes through the multi-layer cover. However, the method is highly sensitive to small variations in temperature or rainfall and cannot capture extreme events, short-term variability, or

local-scale phenomena such as gully erosion or flash flooding. It also remains too coarse to account for differences in vegetation cover, soil response, or site-specific hydrology. The approach is useful for screening obvious risks but insufficient for quantifying or ranking them.

For El Cabril (Climate Group 4Sc, Spain), two specific scenarios (EC1 and EC2) were developed to test system robustness under climatic perturbations: EC1, addressing changes in average annual precipitation and infiltration, and EC2, simulating variations in groundwater table elevation leading to potential contact between groundwater and waste. These scenarios were used to estimate how climate-driven hydrological shifts could alter contaminant transport, radionuclide release, and exposure timing. For longer periods, oscillatory climate sequences reflecting glacial–interglacial alternations were conceptually included to evaluate system performance under extreme wet and arid phases. This approach combines quantitative modelling for short to medium timescales with qualitative screening for multi-millennial horizons, aligning with European regulatory standards that require explicit climate consideration in safety cases.

6.4.6 Recommendations

For Climate Group 4Sa (Lithuania, Ukraine, Finland), climate factors are only treated qualitatively or as boundary “what-if” cases, without systematic linkage to Features, Events, and Processes (FEPs) or safety function analyses. It is therefore recommended to develop methodologies that explicitly couple climate-driven parameters—such as temperature, precipitation, sea-level rise, and potential glaciation—to safety-relevant processes like barrier degradation, infiltration, and radionuclide transport.

Another major priority is capacity building and methodological harmonization among European states to strengthen expertise in climate scenario development and ensure alignment with advanced EU practices. The creation of site-specific climate evolution scenarios over repository-relevant timescales (10–1,000+ years) is advised, incorporating both statistical and dynamical downscaling techniques to achieve finer spatial and temporal resolution. These scenarios should reflect local climatic dynamics rather than global averages.

Given the wide variability in future projections for the Baltic region (e.g., Dfb→Dfa or Cfb, and even Cfa beyond 2200), it is recommended to introduce probabilistic or ensemble approaches to capture scenario uncertainty. This would enable quantitative treatment of uncertainty and support transparent safety margins in performance assessments.

For Climate Group 4Sb (Belgium, France, UK), recommendations focus on improving the resolution, completeness, and comparability of climate scenarios used in safety evaluations. Although broad climate trends (toward Csa/Cs or Cfa/Cr regimes) are well established, these alone are insufficient for assessing erosion, infiltration, and extreme events. Future work should therefore include alternative climate variants (e.g., steppe-type BSh climates) to represent the full range of plausible site conditions.

The current erosion studies in Dessel and CSM highlight the need to better quantify extreme event impacts and to explicitly test the resilience of critical layers such as the bio-intrusion barrier. It is recommended to perform sensitivity analyses, linking climate uncertainties directly to model outputs for infiltration and erosion, and to investigate extreme rainfall events through combined modelling, field experiments, and natural analogue studies.

For Climate Group 4Sc (Italy and Spain), recommendations focus on developing quantitative, coupled climate–hydrogeological frameworks for post-closure assessments. It is recommended to establish formalised frameworks for managing uncertainty, using probabilistic approaches such as Monte Carlo simulations to quantify risk margins.

Further general recommendations include improving future climate scenarios to represent hydroclimatic variability more accurately; running coupled climate–hydrogeological models to simulate recharge, groundwater heads, and flow regimes; and formalising a natural analogue

research programme to benchmark processes such as erosion, infiltration, and weathering under analogue climatic conditions. Tailored guidance documents should distinguish between surface and deep facilities, defining timeframes, data requirements, and acceptable uncertainty thresholds.

6.5 General conclusion

Climate as an overarching FEP is treated using scenario development. The methodology to develop scenarios ranges from deterministic climate sequences based on model output (GCM, EMIC, reduced-complexity) using various combinations of forcings (e.g., high-low), to the use of stylized climatic sequences using conservative and simple assumptions on climate evolution (what-if). In that sense, it can be advocated that a large amount of climate model output is available for the radwaste community, except for the timeframe covering the century-millennium window, and except downscaled meteorological parameters and statistical approaches to develop e.g. intensity-duration-frequency plots of extreme events.

The continuous refinement of models and analogues are essential as they lead to progressive insight. However, the timing and magnitude of events remain uncertain and there is a need for better translation of climate phenomenology to impact assessment.

Long-duration/extended interglacial conditions are mostly overlooked in impact studies, such as sea-level rise, marine inundation and erosion, and saltwater intrusion. The same applies to natural analogues, most analogues (especially for DGR) deal with cold climate conditions and glacial-interglacial cyclicity.

Overall, a methodological harmonization of climate impact assessment is recommended, with the development of formalized frameworks to manage uncertainties, the drafting of tailored guidance documents and benchmarking processes such as erosion and infiltration using cross-climate zone experiences and knowledge transfer.

7. Knowledge Management

Knowledge Management (KM) activities of WP 11 Climate were developed and undertaken under the framework and guidance of the EURAD-2 Work Package 02 KM. These activities included three specific actions in relation to climate change impact on radioactive waste management, namely 1) the development of a White Paper (deliverable D11.1); 2) a training course; and 3) the development of a Domain Insight (DI) document for Domain "4.3.2 Climate Change" of the EURAD-2 Goal Breakdown Structure (GBS) / Roadmap.

7.1 Development of White Paper on climate change impact on radioactive waste management

In accordance with, and guided by, WP 02 KM, the strategic study WP 11 Climate produces a White Paper, which describes identified gaps, outlines proposed actions to address these gaps and gives recommendations for potential research to be prioritised to address those gaps. This document relies on the results of Tasks 3, 4, and 5 of WP 11 (see chapters 4, 5, 6, and 8).

The completion of the White Paper (D11.1) is foreseen around the same time as this synthesis report (Q1 of 2026).

7.2 Training course on climate change impact on radioactive waste management

This training course is foreseen to be held in May 2026 after the conclusion of the majority of the work of the WP, to maximise the incorporation of the WP's outcomes into the training course. The training course will span a wide range of topics, from fundamentals of climate change and its impacts to more advanced aspects and discussion of open questions and potential research needs.

The training is intended to support knowledge transfer within the EURAD-2 community, and to provide participants with a structured overview of the main concepts, challenges and methodological issues addressed in the WP.

7.3 Development of Domain Insight "4.3.2 Climate Change"

WP11 CLIMATE also contributed to the development of the Domain Insight document for Domain 4.3.2 Climate Change (Marcos & Liakka, 2026), following EURAD-1's initiative to produce KM documents to substantiate the goal breakdown structure (GBS) with documents on different levels of detail. The document was prepared by two authors from the WP, one partner and one end-user, guided by the Task 2 and Subtask 2.2 leaders. A further end-user from the WP agreed to review the DI document.

The Domain Insight 4.3.2 Climate Change is intended as a concise knowledge transfer output for the wider EURAD-2 community, in particular for early career professionals and new starters looking for an accessible overview of the topic. It presents climate as an integral part of the safety case for surface, near-surface and deep geological disposal, and explains its relevance across the EURAD Roadmap themes, from site selection and design to licensing and safety assessment. It summarises the typical goals and activities in the domain, outlines the role of climate change in safety functions and long-term repository performance, discusses the maturity of knowledge and the main uncertainties, and provides references, training resources and external links for further use. In this way, it complements the more detailed outputs of WP11 by distilling the main concepts and knowledge sources into a short, practical reference document.

8. Insights from Civil Society

The main goal of Task 5 was to coordinate the interaction between CLIMATE actors with Civil Society (CS) representatives (also possibly outside the radioactive waste management field) on socio-technical challenges and associated uncertainties:

- Identify stakeholder views related to impacts of climate change on RWM,
- Foster an efficient collaboration between WP partners, and develop recommendations for transparent information exchange and dialogue with civil society.
- To achieve these goals, Task 5 implemented an interaction process based on two pluralistic workshops (with EURAD partners, end-users, civil society experts, and other stakeholders) by using
    - Innovative participation methodologies and discussing socio-technical challenges,
    - Sharing knowledge on climate changes impacts and exploring the needs for future research on transparency and public participation and
    - The means for publics and CS representatives to be part of future research activities related to climate.

More precisely, the objectives of the workshops were to bring a landscape of viewpoints by confronting views based on keynotes paper prepared by different types of actors. Then, Task 5 tried to establish a shared vision about climate change impact on RWM, establishing priorities on key topics, and build as much as possible a mutual understanding on roles for all actors and views on climate change relationship with RWM. Task 5 also developed a tool of dialogue enabling to pluralistically discuss the identified key topics. This tool was tested during the second workshop. Finally, all along the process, Task 5 collected insights from civil society to develop recommendations on how to tackle challenges on these key topics in the future research and how to ensure transparency and public participation in RWM related to climate change.

8.1 Workshop 1

The EURAD-2 Fontainebleau Workshop, held on 26–27 March 2025, was organized as part of Work Package CLIMATE to advance discussions with a plurality of partners about how climate change affects RWM over various timescales. It was hosted by the Ecole des Mines de Paris. The event brought together around 40 participants from multiple stakeholder groups, including Waste Management Organisations (WMOs), Technical Safety Organisations (TSOs), research entities (RE), and representatives from Civil Society. The central aim was to explore the interface between evolving climate conditions and the safety, design, regulation, and long-term governance of radioactive waste facilities, including surface, near-surface, and geological repositories.

The workshop built on previous efforts of methodology under EURAD-1 while taking a broader and more inclusive approach in EURAD-2. In this phase civil society actors and research actors contributed altogether throughout the workshop to pluralistic reflections on climate-driven risks and adaptation strategies. In this sense, the event acted both as a technical exchange and as a participatory forum where scientific, regulatory, and societal perspectives could interact.

The main preparation step needed for this workshop was the elaboration of 4 documents “Keynote Papers” from 4 kinds of partners: WMOs, TSOs, REs and Civil Society, in accordance with the 3+1 methodology[2] elaborated for interactions with Civil Society. The keynote papers were

[2] The 3+1 methodology is a pluralistic dialogue process between the three types of actors involved in EURAD (WMO, TSO, RE) and actors from civil society. The process lies on two-steps: it starts with setting the landscape of viewpoints on a dedicated topic (each type of actors works on a keynote detailing its views). During a first workshop, the keynotes are presented and discussed. It helps building first elements on a common understanding of the topic. Then, a second workshop enables continues the discussion based on concrete cases (with the support of PEP methodology) to precise the common understanding and establish recommendations.

prepared in the 3 months before the workshop, with 6 shared questions being addressed to the 4 types of partners. The 4 finalized keynote papers can be found in the Appendix E of this document.

The format of the workshop included one technical visit, a general introduction, the presentation of the four keynote papers via plenary presentations, and working group discussions structured around six guiding questions, followed by conclusive plenary exchanges. The technical visit was organized at of the CEREEP laboratory (CNRS-ENS). During the following exchanges, the themes addressed included the reliability of climate models, the application of time-series versus scenario-based approaches, cross-border issues in climate projections, the role of hydrogeology and biosphere in modelling, and the need to integrate cumulative and cascading effects of climate phenomena.

Central to the discussions was the articulation of timeframes. Participants repeatedly emphasized that the short-, mid-, and long-term temporal scales, ranging from generational horizons (e.g., 25 years) to projections over 300 years and beyond, need to be clearly defined and differentiated when assessing climate impacts. Specific emphasis was placed on near-term effects on surface and near-surface facilities, and on longer-term risks such as glaciation, permafrost, sea-level rise, and extreme precipitation. The question of whether current repository design assumptions fully integrate future climate scenarios was raised, along with the implications for safety cases, regulatory thresholds, and public communication.

Another key dimension of the event was the interdisciplinary examination of uncertainty. While climate modelling continues to improve, participants acknowledged the difficulty in deriving precise, long-term forecasts for use in site-specific safety assessments. Instead, the workshop emphasized the value of combining "what-if" scenarios with established time-series methods, highlighting the importance of transparency in uncertainty communication.

The scope of the discussions also touched on institutional and strategic questions, such as the articulation of research partners and regulators with climate science, the limits of existing regulatory frameworks, and the potential for developing shared European standards on climate adaptation in RWM. Moreover, the societal dimension was repeatedly invoked, including the need to define clear roles for civil society in scenario development and risk governance.

The workshop outcomes supported the development of Tasks 3 and 4 works and shaped the agenda for the second CLIMATE workshop. It also identified priorities including the refining of methodological pathways for scenario development (including PEP methodology development), expanding climate model applications to site-specific contexts, and fostering clearer articulation between regulatory bodies, scientific communities, and societal stakeholders.

8.2 Workshop 2

The EURAD-2 second Climate Workshop, held on 28–29 January 2026, was organized at the University of Liège in Belgium to advance discussions on how climate change affects RWM over various timescales. The event brought together around 32 participants from multiple stakeholder groups, including WMOs, TSOs, REs, and representatives from Civil Society. The central aim was to continue the pluralistic discussions started during the first workshop trying to establish a shared vision on climate change impacts in RWM. Participants continued to explore the interface between evolving climate conditions and the safety, design, regulation, and long-term governance

This methodology was established and tested in EURAD-1 in the MODATS WP. It is more detailed in the report EURAD - D17.5 Enhanced system understanding, multi-party dialoguehttps://www.ejp-eurad.eu/publications/eurad-d175-enhanced-system-understanding-multi-party-dialogue

of radioactive waste facilities, including surface, near-surface, and geological repositories. The workshop built on the results of the CLIMATE WP Task 5 first pluralistic workshop to enable civil society actors and research actors to continue to contribute altogether throughout the workshop to pluralistic reflections on climate-driven risks and adaptation strategies. In this sense, the event acted both as a technical exchange and as a participatory forum where scientific, regulatory, and societal perspectives could interact.

The format of the workshop included a technical visit of HADES underground laboratory, at the SCK- CEN site in Mol (Belgium). After the visit, the workshop started with an interactive session: the participants tested the PEP (Pathway Evaluation Process) tool of dialogue dedicated to climate change impacts on radioactive waste facilities and processes. This tool was elaborated through the PEP tool developed by the SITEX Network[3]. It enabled participants to frame the discussions by elaborating their own scenarios based on set of events cards and evaluation cards aiming at orienting the discussion on specific questions they wanted to ask to others. The PEP on climate change impacts allowed the participants to mix issues related to RWM and climate change impacts. Together, they tried to solve complex problems linked to the scenarios. A debriefing session was then held, during which participants expressed a positive view of the PEP tool and discussed possible improvements. Furthermore, participants shared views on public participation in processes on climate change. Finally, a prospective session dedicated to gather recommendations for future research helped deepening and reflect on the interactions and results developed during the CLIMATE WP.

8.3 Recommendations

Through this two-workshop process, members of Civil Society provided some recommendations linked with the CLIMATE WP and the impacts of climate change on the nuclear industry and RWM in general.

These following recommendations were addressed in the CS keynote paper and in the two workshops.

8.3.1 Civil Society keynote paper recommendations

Several recommendations can be drawn from the CS keynote, mainly about safety culture, the interactions between stakeholders and the public participation and transparency, and the roles of different actors.

1. Establish a shared culture for safety and security:

The establishment of a shared culture for safety and security, following the recommendations from INSAG-4 on Safety Culture, can help grasp the complexity of the impacts of climate change on RWM, notably by taking into account all elements of the materiality of RWM (transportations, indirectly related infrastructures, etc.) and not only the repositories alone, and by addressing the long-term issues. Such culture has to be developed at a transnational level, since the consequences of climate change and their impacts are not confined to national boundaries, but

[3] The purpose of SITEX_Network is to enhance and foster cooperation at the international level in order to achieve a high quality Expertise Function in the field of safety of radioactive waste management, independent from organizations responsible for the implementation of waste management programs and waste producers, aiming at supporting the Nuclear Regulatory Authorities, as well as the Civil Society. The network is open to any institution or individual party having interest in independent regulatory assessment of RWM activities and willing to proactively contribute to the achievement of SITEX_Network vision and objectives. Members belong to one out of three colleges (Technical Expertise Function, Regulatory Function, Civil Society Function), https://www.sitex.network/

may also involve broader changes in population movements, territorial use, geopolitical stability and institutional contexts.

2. Enhance interactions between all stakeholders (including CS), transparency and public participation

Exchanges among stakeholders on climate change impacts on RWM should be organised according to a dynamic and pluralistic approach, enabling different framings of the issues and preventing any instrumentalization of stakeholders' arguments. Mutual trust is a necessary condition for such interactions.

Public participation must be initiated as early as possible in the RWM process (including during R&D phases, as is practised within the EURAD programmes) and maintained on a continuous basis, without being confined to the formal consultative steps required by regulation. This process must be duly taken into account, and the reasons for their integration or non-integration into the decision-making process must be explicitly stated and made publicly available.

3. Roles of different actors for the future

The different actors involved in the assessment and management of the climate change impacts of RWM should define more precisely their different roles. These different roles could be

- For CS, there is a need to receive and collect information related to climate change and uncertainty management, and to remain informed of ongoing R&D results. This requires the implementation of processes that enable fair public participation, with due consideration of public recommendations. The human, financial and methodological resources available to civil society to assess these impacts independently should be explicitly addressed.
- This requires the implementation of processes that enable fair and meaningful public participation, with due consideration of public recommendations. The human, financial and methodological resources available to civil society to assess these impacts independently should also be explicitly addressed.
- From actors involved in research and development, and especially Research entities, continuous R&D efforts should be maintained across the full RWM process, with a view to developing or improving technologies that enhance the safety of facilities in light of climate change impacts.
- For WMOs, to design and operate their facilities in a flexible enough manner that allows new technological results to be integrated during the operational phase. The way in which climate change is accounted for in licence applications and safety assessments must be documented and made publicly available.
- For TSOs and regulators, ensure broad public dissemination of the safety case assessment results, explicitly indicating how climate change is incorporated and what resources are mobilised for that purpose.
- For WMOs, regulators and ministries in charge of RWM, to ensure that sufficient financial resources will be available in the future to address the uncertain impacts of climate change. This implies not only sustained assessment capacity, but also provisions constituted today to cover future adaptation costs.

  For all involved actors, to consider that climate change strengthens the case for integrating, to the extent possible, the principles of process reversibility and waste retrievability into the design and governance of RWM facilities.

8.3.2 Recommendations arising from Workshops

The recommendations form the workshops were mainly based on discussions regarding the future of CLIMATE WP.

Various different topics regarding future research were thus discussed. Among them, it was stated that there was a need for clarification regarding:

- The possible civil society contribution and involvement in future research.
- Data collection and management in relation to communities' practice.

How Civil Society engagement in communication and Knowledge Management could be enhanced by PEP tool and dissemination events though monthly topics or local events or field trips. Suggestions were also made to:

- Include CS advisors/observers in EURAD Bureau and PMO.
- Reassess and explicit the reasons supporting the civil society engagement.
- Address the differences of approaches between CS members and researchers in relation to uncertainties management and the need to better articulate them
- Use innovative tools for dissemination and democratic participation (visualization tool, fact sheet for each WP or synthetical document or framework, tailored information for students or children, etc.)
- Implement an hybrid forum and organise collaboration with research centres
- Integrate further the inputs shared by the participants to improve the global alignment.
- Have the presentations more in advance to improve the interactions.

9. Conclusions and recommendations

Climate change represents a cross-cutting and long-term challenge for RWM facilities across Europe, affecting all disposal concepts and all stages of the facility lifecycle. The analysis developed in the EURAD-2 WP11 CLIMATE indicates that climate-related risks are already relevant during construction and operational phases, while remaining a critical boundary condition for post-closure safety over longer (geological) timescales.

For the construction and operation phases, extreme precipitation, flooding, heat waves, drought, groundwater level variations and sea level rise are highlighted as the most significant climate-driven hazards. They can affect the performance of safety-relevant infrastructure, including drainage systems, cooling and ventilation equipment, engineered covers and access routes. Some existing facilities have been designed based on historical climate conditions, and future climate projections may exceed original design assumptions. In addition, compound and cascading events, such as the interaction between extreme precipitation and groundwater rise or between heat waves and droughts, emerge as an important source of risk.

At the post-closure phase, the synthesis confirms the robustness of deep geological repositories against direct surface climate impacts, while highlighting the continued relevance, for all repository and waste types, of climate-driven processes such as long-term hydrological change, permafrost development, erosion and sea level variations. The influence of anthropogenic greenhouse gas emissions on the duration and characteristics of future warm periods, and on the timing of subsequent glacial cycles, reinforces the need to consider a wide envelope of climate scenarios in long-term safety assessments. Scenario-based approaches and the use of natural analogues remain essential tools for addressing uncertainties over timescales extending to hundreds of thousands or millions of years.

The review of international, European and national regulatory frameworks reveals considerable variability in the explicit treatment of climate change. While some programmes have developed advanced methodologies and regulatory expectations, others rely on implicit or generic provisions. The lack of harmonisation may make it more challenging to compare safety cases and systematically incorporate climate resilience into RWM planning.

In addition to the technical and regulatory challenges identified, the work of Task 5 has shown that climate change in RWM also requires transparent, pluralistic and continuous dialogue with civil society and other stakeholders. Public participation should start early and be maintained throughout the different phases of RWM, with clear communication on how climate-related uncertainties are addressed and how public input is considered in decision-making. The WP also highlights the value of dialogue tools such as PEP to support mutual understanding of long-term climate risks, roles and responsibilities, and future research needs.

Several priorities for future research and development can be identified. Further work is needed to improve the spatial and temporal resolution of climate data used in site-specific assessments, particularly for extreme events and compound hazards. Methodological advances are required to better represent cascading and interacting climate risks within safety and risk assessment frameworks. For long-term post-closure assessments, continued research on climate evolution under different greenhouse gas emission pathways would strengthen confidence in scenario development. In addition, expanded use of climate-relevant natural analogues could support the validation of long-term assumptions and models. Finally, research on adaptive and iterative safety assessment approaches, including the role of monitoring and periodic reassessment, would support more resilient and transparent radioactive waste management strategies under changing climate conditions.

Climate is generally treated as an overarching FEP through scenario development, but this document also highlights several areas where current approaches could be further strengthened. In particular, future work should improve the translation of climate evolution into impact

assessment, including the derivation of boundary conditions and impact-relevant parameters for safety analyses. Important gaps remain in the century-to-millennium timeframe, in the availability of downscaled meteorological variables and statistical approaches for extreme events, and in the treatment of long-duration warm or interglacial conditions such as sea-level rise, marine inundation, erosion and saltwater intrusion. The report therefore supports further methodological harmonization, including more formalized frameworks for uncertainty management, tailored guidance documents and benchmarking across climate zones.

Overall, the outcomes of WP11 CLIMATE provide a consolidated knowledge base and highlights potential directions for future work aimed at ensuring the long-term safety and robustness of RWM facilities in a changing climate. The WP has shown that this challenge requires not only improved technical understanding, but also transparent communication of uncertainties, knowledge transfer, and sustained dialogue with civil society and other stakeholders.

Appendix A. Regulatory Framework

International Regulatory Framework

WENRA

WENRA (WENRA, 2014) do not explicitly address climate change as a named hazard. However, the performance-based requirements set out in the SRLs implicitly require consideration of climate-related factors throughout the facility lifecycle, as follows:

Construction Phase

- Construction shall use proven techniques and preserve post-closure safety functions of the host environment, implying designs must account for evolving environmental conditions
- Information on the host environment's properties and response shall be gathered during construction via monitoring, which would include baseline climatic and hydrological data

Operational Phase

- Arrangements shall be in place for detecting and responding to anticipated occurrences and accidents, encompassing extreme weather events
- Operational limits and conditions shall be established and respected, which may need updating as climate conditions change
- Emergency plans shall be proportional to hazards, regularly tested, and coordinated with authorities.

Post-Closure Phase

- Post-closure safety shall be provided entirely by passive safety features-requiring robustness against long-term climate variability without active intervention
- Surveillance programmes and remedial actions shall be maintained as appropriate

Safety Case

- The safety case must address uncertainties and demonstrate robustness over required timescales, which necessarily encompasses climate evolution over post-closure periods up to 1 million years
- Scenario analysis must include disturbing events and processes, under which climate-driven events (glaciation, sea-level rise, permafrost development) should be considered

ENSREG

ENSREG (European Nuclear Safety Regulators Group) (ENSREG, 2023) recognise that climate change affects various aspects of nuclear safety and radioactive waste management. While ENSREG itself focuses primarily on institutional activities, the ENSREG framework-through the Nuclear Safety Directive and the Waste Directive, establishes principles that apply to climate-related challenges:

- Safety of facilities: The regulatory framework requires that nuclear installations be designed, sited, constructed, commissioned, operated and decommissioned to prevent accidents and mitigate their consequences, implicitly encompassing climate-driven hazards.

- Adaptation measures: National regulators are expected to ensure that periodic safety reviews incorporate the latest understanding of climate-related risks, with sufficient safety margins built in for more distant time horizons.
- Regulatory oversight: ENSREG emphasises continuous improvement in nuclear safety and radioactive waste management, including through the EU topical peer review mechanism.

IAEA

IAEA (IAEA, 2018) focuses primarily on nuclear power plants rather than radioactive waste disposal facilities specifically. Its relevance to waste management safety cases is through the analogous climate hazards affecting surface infrastructure at disposal sites. However, IAEA (IAEA, 2018) assesses the impacts of climate change on nuclear energy and identifies adaptation options for both gradual climate change and extreme weather events. (Section 5.5)

Gradual Climate Change (Section 5.5.1)

- Higher mean temperatures reduce thermal efficiency of generation and cooling efficiency, potentially leading to output reductions or shutdown
- Lower mean precipitation reduces cooling water availability and raises water temperature
- Sea level rise threatens low-lying coastal sites with flooding; raising dykes and protective embankments is identified as a key countermeasure

Extreme Weather Events (Section 5.5.2)

- More frequent and intense extreme weather events (heat waves, storms, droughts) exacerbate the impacts of gradual climate change
- Events can disrupt power supplies, damage infrastructure, and hinder facility access

Adaptation Measures for Existing Plants

- Reusing wastewater and recovering evaporated water
- Improving wet cooling systems
- Installing cooling ponds and dry cooling

Construction/New Build Considerations

- Site selection for cooler local climates where possible
- Adoption of different cooling designs to mitigate reduced cooling efficiency

MODARIA IAEA (IAEA, 2020) establishes an internationally agreed common framework for systematically integrating climate and environmental change into post-closure radiological assessments of radioactive waste disposal facilities. From a regulatory perspective, the document provides three key contributions:

- It establishes that climate evolution is not optional in safety assessments, near-surface and surface facilities are directly vulnerable to climate and landscape development, while deep geological repositories are affected indirectly through hydrogeological changes. Regulators should expect safety cases to address these impacts explicitly and proportionately to the facility type and location.

- It defines a traceable, stepwise methodology (the "road map") that regulators can use as a benchmark for evaluating the adequacy of licensees' treatment of climate change. This includes global climate modelling, downscaling to site-specific conditions, landscape evolution narratives, and dose modelling, all conducted using ensembles of models to capture uncertainties. The methodology provides regulators with a transparent basis for judging whether a safety case has adequately explored the range of plausible future environmental conditions.
- It identifies remaining knowledge gaps that regulators should be aware of: while quantitative long-term climate modelling is sufficiently mature to define the envelope of reference futures, landscape evolution modelling has not yet been fully developed for all relevant climates and landscapes, particularly periglacial and glacial environments. Regulators should therefore expect licensees to acknowledge and manage these uncertainties rather than claim precise predictions of future conditions.

European Commission Regulatory Framework

Council Directive 2011/70/EURATOM

Council Directive 2011/70/EURATOM does not explicitly address the impact of climate change on radioactive waste management facilities. The directive focuses on establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, ensuring high safety standards, responsible management, and transparency.

Directive 2006/117/EURATOM

Council Directive 2006/117/EURATOM, which focuses on the supervision and control of shipments of radioactive waste and spent fuel, does not explicitly address the impact of climate change on radioactive waste management facilities. The directive primarily establishes a system of prior authorization for shipments to ensure the health protection of workers and the general public.

OECD NEA

NEA (NEA/OECD, 2021) discusses the impact of climate change on nuclear power plants and associated infrastructure through the lens of EU environmental regulations, strategic environmental assessments, and safety regulations (Chapter 11), as well as vulnerability assessment and adaptation measures (Chapter 12).

Environmental Regulations

The document emphasizes the importance of minimizing emissions to soil and terrestrial habitats. Adaptation to climate change is expected to be a factor in future documents and may pose new challenges for nuclear installations.

Strategic Environmental Assessment (SEA)

The SEA Directive (EU, 2001) requires identification and evaluation of planned impacts on various environmental issues, including climatic factors.

- Ensuring that drainage systems can cope with changing rainfall patterns/intensity.
- Taking a precautionary approach to developing in floodplains.
- Ensuring adequate future water supply and demand management.

- Avoiding actions that limit future adaptation.

Environmental Impact Assessment (EIA)

- The EIA Directive (EU, 2014) incorporates environmental challenges such as resource efficiency, climate change (including adaptation), biodiversity, and disaster prevention.
- Detail the scope and control the quality of the information.
- Assess reasonable alternatives, justify final decisions, and monitor significant adverse effects post-EIA.
- Assess the needs to adapt to challenges like biodiversity loss, climate change, disaster risks, and availability of natural resources.

Adaptation Measures

The document outlines several adaptation measures for nuclear power plants to cope with climate change impacts, which are also applicable by analogy to surface infrastructure at radioactive waste disposal facilities:

- Cooling Systems: Implementing alternative cooling options such as dry cooling and recirculating systems Flood Protection: Constructing flood barriers, improving drainage systems, and raising the elevation of critical infrastructure
- Maintenance and Shielding: Increasing preventive maintenance and shielding critical equipment from environmental factors
- Emergency Preparedness: Developing comprehensive emergency response plans to address the impacts of extreme weather events on both operational and construction phases.

National Regulatory Frameworks

Czech Republic

In Czech Republic, the radioactive waste (RAW) is generated by nuclear installations and workplaces with ionizing radiation sources in healthcare, research and industry. Spent fuel (SF) is generated as a by-product from the operation of nuclear power and research reactors. (SÚJB, 2024)

RAW management and SF management fully comply with the Policy of Radioactive Waste Management and Spent Fuel Management. This Policy (i.e. National policy and practice according to the Joint Convention terminology, and National programme and national policy (2011) according to the Council Directive 2011/70/EURATOM terminology) is a fundamental document which defines the RAW management policy and strategy of the government and its agencies. Currently valid document was discussed and approved by the Czech government by the Resolution No. 597 of 26 June 2019. The requirements of the RAW management are defined in Part IV. of the Atomic Act (No. 263/2019 Coll. (ACT263, 2016) and in Decree No. 377/2016 Coll. (DECREE377, 2016).

The Czech Republic is a signatory to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. In agreement with the obligations resulting from its accession to the Joint Convention, the Czech Republic has compiled already the eight National Report (NRJC, 2024) for the purpose of review meetings of the Contracting Parties, which describes the spent fuel and radioactive waste management system in the scope required by the specific articles of the Joint Convention. At the same time the National

Report contains information on the implementation of Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. The National Report (NRJC, 2024) provides, at the national level, a source of up-to-date and public information on spent fuel and radioactive waste management practices across the facilities subject to the Joint Convention.

For the purpose of management of activities associated with RAW disposal, the Ministry of Industry and Trade set up in 1997 the organization of SÚRAO (Radioactive Waste Repository Authority). Costs of activities associated with RAW and SF disposal are paid from the nuclear account, a source funded by RAO and SF generators in agreement with the Atomic Act and the Government Order while the nuclear account as part of the governmental assets and liabilities is managed by the Ministry of Finance. This ensures that disposal costs for waste currently generated will not be transferred to future generations. Currently there are three radioactive waste disposal facilities (ÚRAO) at the territory of the Czech Republic in operation - ÚRAO Dukovany, ÚRAO Richard and ÚRAO Bratrství.

Another disposal facility, which is expected to be operational after 2050, will be the deep geological repository (DGR) for RAW not complying with waste acceptance criteria of ÚRAO and for SF once declared for RAW. On 21 December 2020 the Government of the Czech Republic decided that the DGR will be placed in one of the following four locations - Janoch (South Bohemian Region), Horka (Třebíč Region), Hrádek (Jihlava Region; the site is referred to as the Dunaj site in a climatic study), or Březový potok (Klatovy Region). The narrowing of the number of potential sites to four, approximately 30 years after the start of the DGR project in the Czech Republic, is the first significant milestone approaching the start of the DGR operation in 2050.

The Czech regulatory framework addresses climate change in radioactive waste management through a combination of nuclear safety, environmental protection, and climate adaptation strategies. While the Atomic Act does not explicitly name climate change, it requires consideration of external natural hazards (including extreme weather events) in siting, construction, and operation of nuclear facilities. The Environmental Impact Assessment Act explicitly requires assessment of climate change vulnerability.

Citation from the only legislative document that explicitly addresses the impact of climate change on radioactive waste disposal: Decree on the Siting of a Nuclear Installation (DECREE378, 2016).

§ 18 Special requirements for the scope and method of site assessment for the siting of a deep geological repository

(2) The site assessment for the siting of a deep geological repository must also evaluate in i) paleohydrogeological processes, climate history and the anticipated long-term climate development on a regional and global scale, and j) the vulnerability of the rock environment and groundwater in terms of long-term climate changes and their associated phenomena, in particular the potential coverage of the deep geological repository by ice, permafrost, or water.

§ 20 Requirements for the content of documentation for the siting of a nuclear installation

The preliminary safety report must include: b) an independent assessment of the site characteristics and their features for the siting of a nuclear installation, including a list of the sources and information used in the assessment and the assessment methods, covering ‘3. climatic and meteorological phenomena’.

Belgium

The Royal Decree of 7 May 2024 (BELGISCH STAATSBLAD, 2024), published in the Belgian Official Journal of 24 May 2024 as a complement to the Royal Decree of 30 November 2011 concerning safety prescriptions for nuclear waste disposal systems, does not mention climate change explicitly.

It only stipulates that it should be demonstrated that the performance of the disposal system and its components will remain sufficient in order to protect man and environment from ionizing radiation, regardless reasonably foreseeable perturbations (Art. 59). The design basis should be developed with the aid of a site characterization program that defines the reference situation of the site and its environment, and that underpins a thorough understanding of the expected evolution and the identification of events and processes that may alter the expected evolution (Art. 61). For the post-operational period, the design basis should describe the expected evolution, as well as the postulated initiating events and degradation processes that may have an impact on the performance of the disposal system. External natural events that need to be considered in the design basis include those that are typical for the site and its environment, and it is assumed that the initiating event occurs at the most unfavourable moment in the most unfavourable circumstances.

For surface disposal of short-lived low and intermediate level waste in particular, it is explicitly required that meteorological phenomena are considered as an external natural event in the definition of the design basis (FANC NOTA, 2010). External events with a probability of less than 10^{-7}/year should not be considered (operational and post-operational). However, for all other events, the probability as well as the magnitude should be assessed. In the evaluation of long-term safety, climate change impact is analyzed through FEP analysis, which leads to conservative assumptions in the reference scenario, or an alternative evolution scenario.

Specific safety requirements are not available yet for deep geological disposal and shallow-depth/near-surface disposal.

Bulgaria

In Republic of Bulgaria, the whole regulatory and institutional framework of RWM, including the aspects mentioned for climate change influence on RWM, is based on the national fundamental documents and numbers of regulations. The main of them which related with the case, are briefly presented below:

Act on the Safe Use of Nuclear Energy (ASUNE, 2018) which transposed the Council Directive 2011/70/Euratom of 19 July 2011 and regulates:

- On one hand, the social relations associated with the State regulation of the safe use of nuclear energy and ionizing radiation and with the safety of radioactive waste management and spent fuel management, as well as the rights and duties of licensees implementing these activities, to ensure nuclear safety, radiation protection, and physical protection.
- On other hand, all aspects of RWM, including the safe RWM under normal and extraordinary operational, meteorological, climatic and other conditions.
- So, this Act is a fundamental document when considering current issues of climate change in terms of their possible impact and its assessment on RWM.

Strategy for spent fuel and radioactive waste management until 2030 (Strategy, 2017), developed according to the requirements of the Council Directive 2011/70/Euratom of 19 July 2011. In 2023 there is developed an actual document - draft strategy for the management of SNF and RAW in Bulgaria, which has a role of national program, also in conformity with Directive 2011/70/Euratom. The Strategy formulate the policy and principles for safe management of all activities associated with spent nuclear fuel and radioactive waste.

The Action Plan according to the Strategy contents numbers of tasks which are relevant to subject to consideration taking into account the possible impact of climate change, as:

- Assessments of the geological and geomorphological conditions of the Danube Plain.
- Achieving and maintaining sustainability in the management of RAW.
- Safe management of SNF and RAW with high, medium and low level from Kozloduy NPP.

Regulation for safe management of radioactive waste (BNRA, 2013) sets out the necessary standards and procedures to be observed at activities and facilities dealing/producing and/or handling with radioactive waste on the territory of the country, and to be observed at RWM by normal conditions and such, influenced from climate changes.

In addition, the following documents are important regulatory documents for the practice, and a subject of consideration by normal conditions and such, influenced from climate changes.

- Ordinance on the terms and conditions for transportation of radioactive substances (Ordinance, 2005),
- Ordinance on the terms and conditions for the transfer of radioactive waste to SE RAW (Ordinance, 2015),
- Guide for safe transport of radioactive materials - management of non-compliances (BNRA, 2016).

Moreover, and in particular, when discussing the climate change potential impact on RWM in Bulgaria, are considered and the determinations, requirements and recommendations of the documents, which are entirely corresponding with the EU climate change policy, namely:

Climate Change Mitigation Act (2014) (Act, 2014)

- With importance for indirectly reducing the influence of the climate changes on the RWM processes, are numbers of subjects of this Act, as the implementation of the government policy on climate change mitigation and the long-term planning of measures for climate change adaptation; the functioning of the National Green Investment Scheme and the functioning of the National System of Inventories of Emissions of Harmful Substances and Greenhouse Gases in the Atmosphere incl. from waste disposal sites; the measures to reduce greenhouse gas emissions from liquid fuels and energy for transport, etc.
- The Act puts in place a rolling cycle of statutory national risk assessments and a resulting Adaptation Programme that must address the risks.

Third National Action Plan on Climate Change for the Period 2013-2020 (NAP, 2012), developed in the frame of the Norwegian Cooperation Programme for Economic Growth and Sustainable Development in Bulgaria.

- The plan provides specific measures for reduction of greenhouse gas emissions across all sectors consistent with both the national policy on climate change and the potential of the national economy to reduce emissions. The aim of these measures is to ensure the implementation of the commitments taken and the achievement of the legally binding European objectives.
- The Plan presents global trends and scenarios on climate change and their basic aspects relating to Bulgaria - facts, scenarios and possible consequences.
- This plan is important for consideration in relation with the national important activities, including RWM activities.

Long-term climate change mitigation strategy until 2050 of the Republic of Bulgaria (MEW, 2022).

- The plan presents Bulgaria's climate targets are set out in Bulgaria's Integrated Energy and Climate Plan for the period to 2030. In this sense, the document is related and important to be considered for the climate changes impact on RWM, given that RWM issues are mainly considered in the country's energy sector.
- The long-term strategy presents the Bulgarian position and priorities with regard to the low-carbon economy and the achievement of climate neutrality by 2050.
- Presented are the scenarios considered and the modelling assumptions used (Chapter 4), strategic measures to reduce GHGs emissions (Chapter 5), assessment of the impacts of existing and planned policies and measures, incl. regards waste management (Chapter 7), etc.

France

Construction and operational phases

Existing facilities in operational phase

For existing nuclear facilities, the analysis of the risks of external hazards, including natural hazards, is reassessed during safety reviews (every 10 years). The reassessment must take into account new knowledge on hazards, feedback from the experience of the 2011 Fukushima Dai-ichi accident (including the implementation of the "hard core" of safeguard equipment protected against extreme hazards), the expectations of regulations (decree of February 7, 2012) and the recommendations of the Western European Nuclear Safety WENRA. Climate change constitutes one of the issues discussed during the safety reviews. There is no specific guide for the radioactive waste disposal however considered as a nuclear facility. (INB Decree, 2012) (WENRA, 2014) (IAEA, 2020)

New facilities in construction and in operational phases

For new nuclear facilities, analysis of the risks of external hazards, including natural hazards, is usually carried out at the planning application stage. Unlike existing facilities, natural external hazards exceeding the design basis are taken into account in the safety demonstration from the design stage, in accordance with ASN guide no. 22 (ASN, 2017) on the design of pressurized water reactors, drawn up jointly with IRSN (now ASNR). Climate change must be integrated into the design by operators when choosing the site, when designing operational systems and when anticipating the levels of hazards to be considered over the entire lifetime of the facilities. With regard to the impact of climatic changes on safety, it is also important to ensure that the design is capable of adapting to any changes in hazards (flooding, heat waves, tornadoes, snow etc.) on the site.

After the facility is commissioned, these levels are analyzed at each periodic review (10 years) in the light of new knowledge related to climate change and updated as necessary (see § 1.1). In particular, it will be verified that any potential changes remain covered by the generic decoupled level considered at the design stage.

If not, a strengthening of the design provisions will be proposed to meet the facility's safety objectives. There is no specific guide for the radioactive waste disposal however considered as a nuclear facility. (IAEA, 2020)

Post-closure phases

There is a Safety Guide concerning the disposal of radioactive waste in a deep geological formation (the last one is the version of 12/02/2008) (ASN, 2008).

Fundamental objective / Reference situation

For the reference situation following closure of the disposal facility, the calculated individual effective doses shall not exceed the value of 0.25 mSv/year for prolonged exposure related to events that are certain or highly probable. The individual exposure evaluations shall be based on a model of the evolution of the disposal system, in particular of the packages and engineered components, as well as on a model of the circulation of underground waters and the migration of the dissolved and gaseous radioactive substances. The events to be considered are a range of probable natural events (climatic cycles, subsidence, tectonic uplift, seismic motion).

Demonstration of safety following closure of the disposal facility, situations considered. The selection of the situations studied comprises the following steps:

- Identification of the events liable to occur;
- Classification of the events according to their probability, their origin (the disposal facility, human activities, natural processes);
- The situations resulting from these events or a possible combination thereof;
- Sorting of the situations into families;
- Selection of the representative situations.

This selection differentiates between the reference situation representative of the probable events and the altered situations corresponding to the occurrence of uncertain but plausible events. With regard to the positioning of these situations over time, the following periods will be referred to:

- An initial period characterised by significant decay of the activity of the short or intermediate lived radionuclides. The presumed conservation of the memory of the repository, for which provisions shall be made, will make any human intrusion during this period highly unlikely;
- An intermediate period, during which stability shall be demonstrated. This is characterised by the absence of major glaciation and the establishment of a reducing chemical environment in the vicinity of the disposal structures;
- The period subsequent to the previous period, for which the occurrence of major glaciation is considered.

Reference situation: The events to be considered are:

- A range of highly probable natural events (climatic cycles, “greenhouse effect” linked to human activity, seismic activity, subsidence or tectonic uplift). Climatic cycles (external geodynamics) are accompanied by processes such as erosion/sedimentation cycles and modification of the surface hydrology and water circulation at depth.

Altered situations

The events studied in order to define these situations will be either events of the same type as those used to define the reference situation, but on an exceptional scale, or events for which the date of occurrence and how they develop are highly uncertain. These events will be divided into two categories, natural events and those linked to human activity.

The natural events to be considered include climate change of exceptional amplitude, exceptional seismic activity, exceptional subsidence or tectonic uplift, diapirism, magmatic activity, meteorite falls. Depending on the site chosen, some of these events may be ignored further to an appropriate analysis.

(Appendix 2) Selection of the situation to be studied for the safety analysis: Reference situation / Evolution of the system as a result of natural events

The chosen evolution for the reference situation corresponds to that resulting from probable natural events.

Climatic cycles: The succession of climatic cycles as set out in the Milankovitch theory shall be envisaged as the entire site is within a periglacial context. The influence of the presence of permafrost or a drop in sea levels (by about 100m) on erosion and its possible consequences on water flow at depth shall be evaluated. The effects of “greenhouse” type climate change linked to human activity, with the notable consequence being a rise in sea levels, shall be taken into consideration (interglacial period).

Situations referred to as altered: The events to be considered shall be divided into two categories, natural events and those linked to human activity.

Altered situations linked to natural events / Climatic cycles of exceptional amplitude: Exceptional amplitudes shall be taken into consideration for the climatic cycles liable to occur until such time as the activity contained in the disposal system has significantly decayed.

Andra's approach and practice for all surface, subsurface and deep storage sites/projects

Climate change, which could extend into the next million years, was addressed and processed by considering two phenomenologically plausible scenarios, obtained as part of the BIOCLIM project[4], and aimed at framing the range of possible climate changes. These two scenarios, which constitute the envelope of all possible climate changes that could occur over the next million years, are:

- An "A4" scenario of natural climate change, which was established by taking into account the current level of CO2 in the atmosphere (partly due to current anthropogenic activities);
- A "B4" scenario of climate change severely disrupted by anthropogenic activities, which was established based on a maximalist assumption regarding CO2 emissions over the next three centuries (destocking and release of 5,000 Gt of fossil carbon into the atmosphere) and the atmospheric CO2 cycle.

These two envelope climate change scenarios are converted into bioclimatic change scenarios (e.g. Köppen-Geiger, Köppen-Trewartha, etc.), which are themselves converted into bioclimatic geographic zones with their associated biospheres.

Two research themes are being explored:

- The biosphere is the last link in the chain for modeling the transfer of radionuclides and chemical toxins to humans and assessing their impact. Scenario development involves making choices concerning the biosphere(s) to be considered, the potentially exposed group(s) to be considered, their composition including age classes, lifestyle habits, dietary behaviours, transfer and exposure pathways, and the models used.

[4] project description and all reports available at www.andra.fr/bioclim

- Natural analogues already studied worldwide and/or described in the literature in terms of erosion rates, denudation, alteration, etc. for a given type of substratum are assigned for each bioclimatic geographic zone.

Modelling (assessments) of the local and regional evolution of geomorphology and hydrological and hydrogeological flows are carried out for all disposal sites and projects (surface, subsurface, deep) according to the timescales of interest (from a few thousand years to millions of years) to constrain:

- For surface and subsurface disposal facilities: e.g., robustness of disposal facility depth and upper and lower depth and thickness of sound bedrock;
- For deep geological disposal facility: e.g., radionuclide trajectory and migration time, following the various phases of incision, appearance of potential deep aquifer outlets in the bottoms of neighbouring valleys.

Finland

STUK (Säteilyturvakeskus, Finnish Radiation and Nuclear Safety Authority) has approved the Onkalo repository, emphasizing its resilience to future climate changes, including glacial periods and rising groundwater levels. The agency requires continuous monitoring and modeling of climate impacts to ensure long-term safety. STUK's regulations align with IAEA standards, incorporating climate change as a key factor in waste management planning. Summary of the regulations in STUK relevant to waste management and disposal facilities that mention climate change explicitly;

Law on Environmental Impact Assessment Approach 252/2017 (LAW, 2017)

This law applies to projects and changes that are likely to have significant environmental impacts. The law applies also to radioactive waste management and disposal facilities and specifically the impact of the hazard and according to Appendix 2 of the law concerning properties of the project that need be addressed includes major accident and/or disaster risks that are relevant to the project, including risks caused by climate change, based on scientific knowledge needs to be addressed.

STUK Regulation Y/4/2018 (STUK, 2018)

According to Section 30, the long-term safety of disposal must be based on mutually complementary barriers so that the degradation of one or more long-term safety functions or a foreseeable change in the bedrock or climate will not jeopardize long-term safety.

YVL Guide D.5/2018 (YVL, 2018)

According to the Section 30 of the STUK Regulation Y/4/2016, the long-term safety of disposal shall be based on long-term safety functions achieved through mutually complementary barriers so that the degradation of one or more long-term safety function or a foreseeable change in the bedrock or climate will not jeopardize the long-term safety.

- (A04) The scenarios used in assessing alternative evolutions of the disposal system shall be systematically created to cover any events and factors that may be of relevance to long-term safety and that may arise from: a. external factors, such as climate changes, geological events or human actions; b. radiological, mechanical, thermal, hydrological, chemical, biological and radiation-related factors internal to the disposal system; and c. quality non-conformances in the barriers and the combined effects of all the aforementioned factors.

- (A08f) Whenever possible, the consequences and probabilities of rare events impairing long-term safety referred to in paras. 316 and 316a shall be assessed quantitatively; otherwise, their significance shall be assessed qualitatively.

Further, definition of a Rare event impairing long-term safety; Rare event impairing long-term safety shall refer to a potential event significantly reducing the performance of barriers that has a very low probability of occurring but that may jeopardize long-term safety in case of occurrence. Such rare events may be caused by geological phenomena, climatic phenomena or human action.

Germany[5]

Roles and responsibilities in the German radioactive waste management programme

Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety - Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit (BMUKN; formerly BMUV)

BMUKN as programme and legal supervisor also bears the overall political responsibility in the area of final disposal. On behalf of the federal government, the Ministry acts as sole shareholder of BGE (see Federal Company for Radioactive Waste Disposal - Bundesgesellschaft für Endlagerung (BGE)) and also supervises BASE (see Federal Office for the Safety of Nuclear Waste Management - Bundesamt für die Sicherheit der nuklearen Entsorgung (BASE)).

Federal Office for the Safety of Nuclear Waste Management - Bundesamt für die Sicherheit der nuklearen Entsorgung (BASE)

BASE, as the regulatory authority, exercises legal supervision for interim storage and disposal facilities. It is responsible for public participation in, and provides information to the public about the site selection procedure for high-level radioactive waste (HLW) in a dedicated internet platform. Within this framework, it examines the proposals regarding sites for further investigation and the site proposal of the BGE (see Federal Company for Radioactive Waste Disposal - Bundesgesellschaft für Endlagerung (BGE)) and determines (at the end of every phase by means of an official notice) whether the previous procedure was carried out in accordance with the provisions of the Repository Site Selection Act.

Federal legislator (Bundestag and Bundesrat)

In the course of the site selection procedure for HLW, the federal legislator is called upon to take action at the end of each phase: At the end of the current Phase I, a decision must be made on which siting regions are to be explored in more detail. At the end of the procedure, a decision will be made on the site on which the repository will be constructed.

Federal Company for Radioactive Waste Disposal - Bundesgesellschaft für Endlagerung (BGE)

The federally owned BGE is responsible for the planning, construction, operation, and closure of repositories. BGE implements the site selection procedure for HLW and operates the Asse II mine, the Konrad repository, and the Morsleben repository. It identifies a proposal for a site for a repository for high-level radioactive waste through sub-areas, siting regions, and sites in accordance with the Repository Site Selection Act (see Act on the Search for and Selection of a

[5] Including input by GRS as German project partner from the TSO college: This text presents information on the regulatory and institutional framework in Germany in regards to the Konrad repository and the future repository for high-level radioactive waste. Further regulations apply to other facilities (e.g., Morsleben repository, Asse II mine) but are not presented in the EURAD-2 WP CLIMATE.

Site for a Repository for High-Level Radioactive Waste (Repository Site Selection Act); 2017, last revised 2023), prepares and conducts the respective exploration programmes, carries out safety investigations for potential sites.

Federal Company for Interim Storage - Gesellschaft für Zwischenlagerung (BGZ)

The federally owned BGZ is responsible for operation of the Ahaus and Gorleben storage facilities. On 1 January 2019, the licensed, decentralised storage facilities at the locations of Germany's nuclear power plants were handed over to BGZ. Since 2020, BGZ has also managed storage facilities for low- and intermediate-level radioactive waste at the locations of German nuclear power plants. With this, responsibility for storage of radioactive waste from power companies has been brought under one roof.

Nuclear Waste Management Commission - Entsorgungskommission (ESK)

ESK advises BMUKN in matters of nuclear waste management (conditioning, storage and transport of radioactive materials and waste, the decommissioning and dismantling of nuclear facilities, and disposal in deep geological formations).

National Citizens' Oversight Committee - Nationales Begleitgremium (NBG)

NBG is an independent, pluralistically composed social board. The task of the NBG is to support the search for a repository for high-level radioactive waste in an independent, transparent and citizen-oriented manner. The NBG has a comprehensive right of inspection of files at the BGE.

Lower Saxony Ministry for Environment, Energy, Construction and Climate Protection - Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz (NMU)

NMU is the competent licensing authority and the highest water regulatory authority in German state of Lower Saxony (where the Konrad repository is located). It supervises the LBEG (see State Authority for Mining, Energy and Geology - Landesamt für Bergbau, Energie und Geologie (LBEG)) from an administrative and technical perspective. The NMU approves operating plans for the Konrad repository by issuing a decree to the LBEG (see State Authority for Mining, Energy and Geology - Landesamt für Bergbau, Energie und Geologie (LBEG)).

State Authority for Mining, Energy and Geology - Landesamt für Bergbau, Energie und Geologie (LBEG)

As an approval, licensing and supervisory authority under mining law, LBEG is also an immission control and waste management authority for activities and facilities that fall under mining authority control. The LBEG inspects the Konrad repository on a regular basis.

Laws / Ordinances / Regulations / Guidelines / Recommendations[6]

Overarching Laws / Ordinances / Regulations / Guidelines / Recommendations

Act on the peaceful use of nuclear energy and protection against its dangers (Atomic Energy Act); 1959, last revised 2022 (Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren (Atomgesetz – AtG)) (AtG, 2022)

[6] General selection and focus on climate events and processes: The regulatory framework in Germany stipulates to apply the state of the art in science and technology and to incorporate further developments and increasing knowledge. This includes the knowledge of climate change and its impacts (in the short and long term). Many other regulations and requirements have to be considered for the safe construction of facilities, above and below ground, the handling of radioactive waste, the treatment of workers, the consideration safety in all aspects or consideration of protection of the environment. The following section introduces the most relevant regulations for the EURAD-2 WP11 Climate and puts the emphasis on the consideration of weather- and climate-related events, processes and scenarios and their predicted,

AtG section 2c addresses the National Waste Management Programme, which is updated on a regular basis (at least every ten years) based on progress in science and technology as well as recommendations from expert review. Principles of nuclear waste management (section 2d) are that radioactive waste shall be disposed of safely, taking into account the aspects of passive safety with regard to long-term safety.

The responsibilities for the final disposal of radioactive waste are regulated in the Atomic Energy Act. According to section 9a (3) AtG, the German federal government must set up facilities for the final disposal of radioactive waste. BMU (now BMUKN) transferred this responsibility to BGE on April 25, 2017.

The transitional provision in section 58 AtG establishes the responsibility for supervision of the state authorities (NMU) for the Konrad repository. BASE's responsibility for Konrad will change as soon as operations commence. BASE will then become the licensing authority.

Act on Protection against the Harmful Effects of Ionizing Radiation (Radiation Protection Act); 2017, last revised 2024 (Gesetz zum Schutz vor der schädlichen Wirkung ionisierender Strahlung (Strahlenschutzgesetz – StrlSchG)) (StrlSchG, 2024)

StrlSchG part 2 chapter 1 section 8 defines the principle of avoidance of unnecessary exposure and dose reduction. Any unnecessary exposure or contamination of humans and the environment is to be avoided. Further, any exposure or contamination is to be kept as low as possible even below the respective limit values. Depending on the task/activity, the state of science and technology or the state of technology has to be taken into account.

Ordinance on Protection against the Harmful Effects of Ionizing Radiation (Radiation Protection Ordinance); 2018, last revised 2024 (Verordnung zum Schutz vor der schädlichen Wirkung ionisierender Strahlung (Strahlenschutzverordnung – StrlSchV)) (StrlSchV, 2024)

StrlSchV implements Council Directive 2013/59/Euratom of 5 December 2013, laying down basic safety standards for health protection of individuals against the dangers arising from exposure to ionizing radiation.

Laws / Ordinances / Regulations / Guidelines / Recommendations relating to high-level radioactive waste

Act on the Search for and Selection of a Site for a Repository for High-Level Radioactive Waste (Repository Site Selection Act); 2017, last revised 2023 (Gesetz zur Suche und Auswahl eines Standortes für ein Endlager für hochradioaktive Abfälle (Standortauswahlgesetz – StandAG)) (StandAG, 2023)

StandAG governs the site selection procedure for high-level radioactive waste. The site selection procedure aims to identify the repository site in Germany that ensures the best possible safety for one million years based on a participatory, science-based, transparent, self-questioning and learning, staged, comparative and reversible process. StandAG entered into force in 2013. The Act was substantially amended in 2017 after the Repository Commission had spent two years discussing the selection criteria for a repository, as well as public participation in repository site selection, and subsequently presented corresponding proposals. In Germany, three types of host rock shall generally be considered for the final disposal of high-level radioactive waste in accordance with StandAG: rock salt, claystone, and crystalline rock. Exclusion criteria, minimum requirements, and geoscientific weighing criteria, defined in StandAG, must be applied repeatedly in all phases of the site selection procedure. In addition to these criteria and requirements, preliminary safety analyses (vorläufige Sicherheitsuntersuchungen – vSU) play a central role.

possible or unlikely evolution on various timescales and how this is approached in the German radioactive waste management programme.

Their purpose is to assess the extent to which the safe containment of radioactive waste can be expected using the geological site conditions.

Climate change is not explicitly mentioned in StandAG. Nevertheless, it can be derived that the climatic situation and its evolution have to be considered:

Exclusion criterion “large-scale vertical movements” (StandAG Chapter 3 section 22 (2) 1.)

Pursuant to StandAG Chapter 3 section 22 (1) an area shall not be deemed suitable as a repository site if at least one of the exclusion criteria under (2) is met in this area. Exclusion criteria under (2) are: 1. Large-scale vertical movements, 2. Active fault zones, 3. Influences from current or previous mining activities, 4. Seismic activity, 5. Volcanic activity, 6. Age of groundwater.

Large-scale vertical movements can be caused by isostatic adjustments as the result of e.g. the formation and subsequent melting of ice sheets. Since formation and melting of ice sheets is directly controlled by climatic conditions (esp. temperature and precipitation) it is important to consider changed conditions and their potential future evolution (see also Ordinance on Requirements for Conducting Preliminary Safety Analyses in the Site Selection Procedure for the Disposal of High-Level Radioactive Waste (Disposal Safety Analysis Ordinance); 2020 and Ordinance on Safety Requirements for the Disposal of High-Level Radioactive Waste (Disposal Safety Requirements Ordinance); 2020).

Minimum requirements “Minimum depth of the containment-providing rock zone” (StandAG Chapter 3 section 23 (5) 3.)

Pursuant to StandAG Chapter 3 section 23 (2) areas which do not fulfil an exclusion criterion pursuant to section 22 shall only be suitable as a repository site if all the minimum requirements specified in (5) are fulfilled. Minimum requirements specified in (5) are: 1. Rock permeability in the containment-providing rock zone, 2. Thickness of the containment-providing rock zone, 3. Minimum depth of the containment-providing rock zone, 4. Area of the repository, 5. Preservation of the barrier effect.

Regarding the minimum depth of the containment-providing rock zone, StandAG Chapter 3 section 23 (5) 3. requires that the top of a containment-providing rock zone must lie at least 300 metres below ground level. In areas where exogenous processes are to be expected during the assessment period, such as, in particular, intensive erosion during future ice age(s), the direct or indirect impacts of which could lead to the integrity of a containment-providing rock zone being impaired, the top of the containment-providing rock zone must lie deeper than the greatest anticipated depth of such impacts. BGE commissioned the research project “Suchtiefe” to provide clarification on the greatest anticipated depth of such impacts. The findings are summarised in the final report (Breuer, 2023) and include a study of Pleistocene tunnel valleys in northern Germany attaining depths of more than 500 m. The regional distribution of these Pleistocene tunnel valleys provides a basis for the assessment of potential future (1 million years) subglacial erosion events. A regionally variable minimum depth for the containment-providing rock zone can be aligned with the depth zones presented in the study “Suchtiefe”.

Ordinance on Requirements for Conducting Preliminary Safety Analyses in the Site Selection Procedure for the Disposal of High-Level Radioactive Waste (Disposal Safety Analysis Ordinance); 2020 (Verordnung über Anforderungen an die Durchführung der vorläufigen Sicherheitsuntersuchungen im Standortauswahlverfahren für die Endlagerung hochradioaktiver Abfälle (Endlagersicherheitsuntersuchungsverordnung – EndlSiUntV)) (EndlSiUntV, 2020)

The implementation of the preliminary safety analyses (vSU) is regulated in EndlSiUntV. The ordinance can be further substantiated by additional guidelines. Climate change is not explicitly mentioned in EndlSiUntV and no specific requirement is presented on how to consider climate change in the implementation of the vSU.

Nevertheless, section 7 provides details on the analysis of the disposal system. Pursuant to section 7 (1), the basis for the analysis of the planned disposal system in the investigation area shall be the geosynthesis according to section 5, the preliminary safety concept according to section 6 (1) and the preliminary design of the disposal facility according to section 6 (2). The geosynthesis contains the documentation and interpretation of all geoscientific information on an investigation area. The aim of the geosynthesis is a consistent representation of the geoscientific conditions relevant for the safety of the disposal facility (section 5 (2)). Furthermore, section 7 (3) stipulates that the operational safety and the long-term safety of the disposal facility shall be analysed according to sections 8 and 9.

Section 8 provides details on the operational safety analysis, which shall cover all facility conditions of the disposal facility, including the surface facilities, during construction, operation and closure in accordance with section 17 of the Disposal Safety Requirements Ordinance. For the operational safety analysis the probability of external and internal influences on the safety-related systems, subsystems and individual components, of failures of these systems, subsystems and individual components and of deviations of these systems, subsystems and individual components from normal operation shall be estimated in accordance with section 17 (1) no. 1 of the Disposal Safety Requirements Ordinance.

Section 9 details the requirements for the long-term safety analysis. It needs to cover the safe containment of the radioactive waste in accordance with section 4 of the Disposal Safety Requirements Ordinance as well as (among others) the integrity and robustness of the containment-providing rock zone in accordance with section 5 of the Disposal Safety Requirements Ordinance and the robustness of the further barriers and other components of the disposal system over the entire assessment period of one million years from the planned sealing of the disposal facility. In the long-term safety analysis, the behaviour of the disposal system as a whole shall be considered and presented according to the expected and deviating evolutions of the disposal facility system.

Ordinance on Safety Requirements for the Disposal of High-Level Radioactive Waste (Disposal Safety Requirements Ordinance); 2020 (Verordnung über Sicherheitsanforderungen an die Endlagerung hochradioaktiver Abfälle (Endlagersicherheitsanforderungsverordnung – EndlSiAnfV)) (EndlSiUntV, 2020)

Disposal safety requirements are regulated in EndlSiAnfV. The developments in the state of science and technology have to be respected for all aspects outlined in the ordinance. The ordinance can be further substantiated by additional guidelines (see Recommendations of the Nuclear Waste Management Commission (Empfehlungen der Entsorgungskommission)). Climate change is not explicitly mentioned in EndlSiAnfV. Nevertheless, it can be derived that the climatic situation and its evolution have to be considered:

Expected and deviating evolutions (EndlSiAnfV Chapter 2 section 3)

Pursuant to EndlSiAnfV Chapter 2 section 3 (1), the assessment period for long-term safety is one million years from the planned sealing of the disposal facility. For this time period, expected and deviating evolutions of the disposal system and the geological situation at the disposal site (defined as occurring “certainly or usually” and “not expected but can occur”, respectively) are to be systematically determined, described and classified. Evolutions shall be classified as expected or deviating with regard to (among others) the geological and climatic situation.

In addition, hypothetical evolutions (defined as evolutions, which can be excluded, even under unfavourable assumptions, according to human judgement) shall be described, provided that their consideration can serve to further optimise the disposal system or to test the robustness of the disposal system.

Safety during construction, operation and decommissioning of the disposal facility; facility conditions (EndlSiAnfV Chapter 5 section 17)

(1) The facility conditions relevant for the safety of the disposal facility during construction, operation and decommissioning shall be systematically determined, described and classified as 1. normal operation, 2. abnormal operation, 3. design basis accidents, or 4. beyond design basis accidents and events. (2) For these facility conditions, graduated defence and protective measures shall be developed and implemented as part of the safety concept. (4) The measures must not significantly and no more than inevitably impair the long-term safety of the disposal system.

Calculation Basis for Dose Estimation for the Disposal of High-Level Radioactive Waste (Berechnungsgrundlage für die Dosisabschätzung bei der Endlagerung von hochradioaktiven Abfällen) (CBDE, 2022)

The Calculation Basis for Dose Estimation for the Disposal of High-Level Radioactive Waste is to be applied in the site selection procedure during the further-developed and the comprehensive preliminary safety analyses (Chapter 4 section 4 EndlSiUntV). The additional mean effective annual dose for humans has to be estimated as part of the long-term safety analysis for each investigation area pursuant to chapter 9 section 1 (3) EndlSiUntV. For this purpose, the calculation basis aims to provide a concretisation of regulatory requirements and the determination of the course of action.

In the calculation basis for the dose estimation cool-temperate climate is assumed as the default climate (with several calculation parameters given for this climate). Other possible climates and the transition between different climate states at a site during the assessment period shall be considered, too.

Recommendations of the Nuclear Waste Management Commission (Empfehlungen der Entsorgungskommission)

The Nuclear Waste Management Commission publishes various documents in their role as advisor of BMUKN. (The following guidelines are of relevance for the EURAD-2 WP11 CLIMATE.)

Guideline for the Safe Operation of a Repository for High-Level Radioactive Waste (May 2023) (Leitlinie zum sicheren Betrieb eines Endlagers für hochradioaktive Abfälle) (Guideline, 2023)

This guideline substantiates the EndlSiAnfV and EndlSiUntV. Further developments of this guideline are anticipated. This guideline specifies requirements for the general operation of a repository for high-level radioactive waste and explicit requirements for surface facilities, the access to the underground space and the underground facilities.

The guideline specifies that the safety-technical design requirements according to the ESK Guidelines for Interim Storage (see Guidelines for the Dry Interim Storage of Irradiated Fuel Elements and Heat Generating Radioactive Waste in Containers (Revised version June 2013) and Recommendations of the Nuclear Waste Management Commission: Guidelines for Interim Storage of Radioactive Waste with negligible Heat Generation (Revised version December 2021) and for the Protection against Flooding (see Guideline regarding the Safeguarding of Repositories against Flooding (December 2018) are effective for surface facilities for a repository for high-level radioactive waste.

Guideline regarding the Safeguarding of Repositories against Flooding (December 2018) (Leitlinie zum Schutz von Endlagern gegen Hochwasser) (Guideline, 2018)

The safeguarding against damage from flooding is a basic requirement on the design of nuclear facilities. The guideline details consequences of flooding on repositories and their relevance for adherence with the safety objective, causes for flooding (local strong rain, surface discharge in local catchments, surface discharge in larger catchments, ice blockage in rivers, mechanically induced waves, locally wind induced waves, sea waves, seiches, tsunami, storm surges, failure of embankment dams and dyke, failure of artificial water reservoirs, high groundwater level), a

guide on how to evaluate the basis for determination and regarding the consideration of climate change as well as regarding the management of uncertainties and potential protection measures.

Because the timeframes for nuclear waste disposal are much longer than for nuclear power plants and interim storage facilities (especially for the repository for high-level radioactive waste), according to ESK, the influence of climate change and new insight regarding extreme weather conditions for the determination of the design flood have to be considered in a site-specific manner. Climate change is expected to lead to further sea level rise and storm surge water level rise as well as more frequent and more intense strong rain events.

Guidelines for the Dry Interim Storage of Irradiated Fuel Elements and Heat Generating Radioactive Waste in Containers (Revised version June 2013) (Leitlinien für die trockene Zwischenlagerung bestrahlter Brennelemente und Wärme entwickelnder radioaktiver Abfälle in Behältern) (Guideline, 2013)

This guideline collects safety-technical requirements for the dry interim storage of irradiated fuel elements and heat generating radioactive waste in sealed metallic containers.

External influences due to natural factors are to be considered as operational burden or as design basis accidents. The design load for natural impacts are to be determined according to site-specific conditions: The design against storm, rain, snowfall and frost is to be based on the most adverse weather conditions to be expected at the respective location. Regarding flooding, the guideline recommends sites without flooding. If flooding is not possible to exclude, the facilities have to be protected against inflow of water with suitable technical methods according to KTA 2207 (KTA 2207, 2014).

Laws / Ordinances / Regulations / Guidelines / Recommendations relating to low and intermediate-level radioactive waste

Plan Approval Decision for the construction and operation of the Konrad mine in Salzgitter as a facility for the disposal of solid or compacted radioactive waste with negligible heat generation from May 22 2002 (Plan Approval Decision) (Planfeststellungsbeschluss für die Errichtung und den Betrieb des Bergwerkes Konrad in Salzgitter als Anlage zur Endlagerung fester oder verfestigter radioaktiver Abfälle mit vernachlässigbarer Wärmeentwicklung vom 22. Mai 2002 (Planfeststellungsbeschluss – PFB)) (PFB, 2002)

The application for the initiation of a planning approval procedure for the construction of the Konrad repository was submitted in 1982. The Plan Approval Decision was granted by the state of Lower Saxony on May 22, 2002 and became final in 2007 after the last appeal instance. Since 2007, the Konrad mine has been converted into a repository in accordance with the PFB.

Potential changes occurring during future ice ages/colder climate and during warmer climate conditions are described in the documents on which the PFB is based. Neither change is deemed to pose a risk to the safe containment of the disposed radioactive waste.

Recommendations of the Nuclear Waste Management Commission: Guidelines for Interim Storage of Radioactive Waste with negligible Heat Generation (Revised version December 2021) (Empfehlungen der Entsorgungskommission: Leitlinien für die Zwischenlagerung von radioaktiven Abfällen mit vernachlässigbarer Wärmeentwicklung) (Guidelines, 2021)

The Nuclear Waste Management Commission publishes various documents in their role as advisor of BMUKN. This guideline aims to collect all safety-relevant influencing factors, which are of relevance for the interim storage of radioactive waste with negligible heat generation.

This guideline considers (among others) nuclear accident analyses due to external influences due to natural factors, e.g. storm, rain, snowfall, frost, lightning, flooding, earthquakes. The guideline requests the floor of the storage building to be positioned above the water level for centennial flooding, otherwise construction measures are to be implemented against the inflow of

water. Temporal measures are to be planned for flooding expected every ten thousand years. The state of science and technology has to be considered for the determination of the design flood.

Italy

Radioactive Waste

Most of the radioactive waste existing in Italy has been generated from the past production of electricity in nuclear power plants (definitively closed in 1987 following a national referendum), from the decommissioning activities and from the re-entry in Italy of the conditioned ILW, HLW, resulting from the spent fuel sent abroad for reprocessing. A minor fraction of waste is referred to the production by medical, industrial and research activities.

Regulatory Body, WMO

The National Inspectorate for Nuclear Safety and Radiation Protection (ISIN) is the Italian regulatory authority for nuclear safety and radiation protection, stated by the Legislative Decree n. 45/2014 (Decreto, 2014). Sogin S.p.a is the state owned company responsible for decommissioning of the nuclear facilities and the management of radioactive waste from energy production. The management of the waste coming from sanitary, research and industrial activities, as well as the radioactive sources, is entrusted to the so-called Integrated Service, managed by ENEA and Nucleco S.p.a. The classification of radioactive waste is based on its radiological content, in line with IAEA classification scheme (Decreto, 2015).

Policy and National Repository

The national policy was originally established in 2004. On December 2019 the National Programme for the implementation of the policy for the management of spent fuel and radioactive waste has been adopted, as established by the Legislative Decree n. 45/2014, artt. 7-8 (actually under revision by Italian Ministries). The current policy is focused on the decommissioning of the nuclear facilities, radioactive waste management and the realization of a near-surface repository (Italian National Repository) for disposal of LLW, SL-ILW and for the interim storage of LL-ILW and HLW. The siting, design, construction and management of the facility are entrusted to Sogin (Legislative Decree n. 31/2010, Art. 25 (Decreto, 2010) Actually, almost all the waste generated is stored in the sites of origin, while the siting procedure for the National Repository is currently underway.

Geological disposal is considered for long-lived ILW, HLW and spent fuel, even if the current National Programme does not provide a scheduled and detailed plan for an Italian DGR; as previously underlined, the Programme is under revision, taking into account also the possibility of the so-called ”dual-track approach” in the disposal of this type of waste.

Legislation and climate change

In the Italian legislation on radioactive waste management, no specific indication regarding the management of the impacts of climate change on nuclear sites is reported. Despite this, as described below, assessments of future scenarios in the management of radioactive waste and the risks induced by climate change will be a logical consequence of the safety analyses and will be taken into account indirectly.

Authorizations for the operation of nuclear plants (i.e. final repositories) or for activities in the nuclear field are issued after checking the suitability of the proposed site from the point of view of radiation protection, taking into account the current state of meteorological and climatological conditions (i.e. Legislative Decree 101/2020, art. 59 (Decreto, 2020). Since this legislation has the purpose of guaranteeing the nuclear safety in the long term, it is necessary that the safety

analysis for new nuclear plants will evaluate these impacts also for the future. Assessments of the local current climatological and meteorological conditions are also a determining topic in the drafting of emergency plans, in the management of radioactive waste (Annex XXXII). The safety analysis must also consider the international regulations and technical guides, where aspects related to the impacts of climate change are taken into due consideration.

Nuclear plants and related activities are subject to the environmental impact assessment procedure, as required by Italian and European legislation and specifically by Decree (Decreto, 2020). Article 28 provides for a single authorization by the competent Ministry, after consulting the nuclear safety authority (ISIN), but also including the environmental impact assessment.

In the context of the environmental impact assessment, Italian legislation does not expressly provide for assessments of future climate impacts (Decreto, 2006); however, such assessments are inherent in the technical assessment procedures for particularly significant infrastructures, especially if the realization, exercise and post-closure phases last for decades. In this regard, it is necessary to take into account European indications such as the Communication from the European Commission Technical guidelines on climate-proof infrastructures in the period 2021-2027 (EC, 2021) as well as the technical rules for the environmental impact studies-Annex 2, published by the National System for Environmental Protection (SNPA, 2020), which reserve a central role for the climate issue, to be taken into consideration in all phases of the environmental compatibility assessment.

ISIN Technical Guides and climate change

Technical Guides issued by ISIN are regulatory documents, disclosing best practices, operational and technical measures to implement legislative provisions for nuclear safety, radiation protection, criteria and methodology for control activity (assigned to ISIN by Legislative Decree n 101/2020, art. 236 and by Legislative Decree 45/2014, art. 2).

The Technical Guide 29 Siting Criteria of a near surface disposal facility for low and intermediate level waste (ISIN, 2014) uses area Exclusion Criteria in siting, to limit the possible impacts of natural events on the infrastructure and to limit phenomena that may affect its safety and the safety of activities carried out during the operation, closure and post-closure phases. The exclusion criteria are implemented by excluding areas that may present critical issues, such as coastal areas, areas subject to hydraulic phenomena, areas characterized by geomorphological risks, areas characterized by steep slopes, etc. These exclusion criteria are therefore useful to indirectly avoid, or in any case limit the impact of future climate changes on the surface repository. The Identification Criteria, defined to allow the evaluation of the areas identified following the application of the Exclusion Criteria, refer to the recommendations developed by international bodies and in particular by the IAEA and take into account, among other things, the aspects of protection of the repository from extreme weather conditions, and therefore indirectly from natural future events induced by climate change.

The Technical Guide 32 Safety and radiation protection criteria for radioactive waste surface disposal plants (ISIN, 2022) takes into account the most up-to-date international standards to establish objectives and general criteria for the safety and radiation protection for the qualification of the site, the design, construction, operation, closure and post-closure of surface disposal facilities for radioactive waste. The Technical Guide (§ 5.4) specifies that for the safety analysis of the post-closure phase and for the purposes of assessing the radiological dose to people, climate changes must also be taken into account, considering the evolution of the environment, with a long-term perspective in relation to the lifespan of the work. To this end, it is expected that the reference scenarios to be considered must be defined by identifying the characteristics, events and processes that can influence the safety of the disposal system in the long term, and therefore also future climatic conditions and their impact on the repository.

The investigations for the qualification of the site (Technical Guide 32 Annex 1) (ISIN, 2022), must include studies on the meteorology of the site and on the effects that meteorological features could have on the design of the disposal plant. Suitable areas must be assessed on the basis of the severity of the effects of such events; therefore, suitable areas must be indirectly assessed considering the extreme natural phenomena induced by climate change. In Annex 3 of the Technical Guide, climate is one of the fundamental elements to be considered in the safety analysis, within the description of the main characteristics of the site.

The Technical Guides also refer to the in-depth studies required by international legislation (i.e. IAEA Safety Guides), which obviously considers future climate changes impact and relative risk scenarios.

Spain

The CSN (Consejo de Seguridad Nuclear) mandates that waste storage sites be evaluated for risks related to extreme weather, such as droughts and heavy rainfall. The agency supports the development of centralized temporary storage facilities (e.g., El Cabril) with enhanced climate resilience measures. Long-term disposal plans are being developed with climate change as a critical consideration.

In Spain, there is currently no specific regulation on how nuclear waste management facilities must account for climate change. The first and main regulation addressing nuclear energy, Law 25/1964 on Nuclear Energy (Law, 1964) in Article 38 bis.4 states that, “The State will assume ownership of the radioactive waste once it has been definitively disposed of. It will also take on responsibility for any monitoring that may be required following the closure of a nuclear facility, once the period established in the corresponding closure declaration has elapsed.”

Furthermore, the near-surface repository “El Cabril” in Southern Spain must comply with the Royal Decree 102/2014 (Royal Decree, 2014), which regulates the responsible and safe management of spent nuclear fuel and radioactive waste at all stages. However, this Royal Decree doesn’t include any provisions regarding climate change. In Article 4.4, it mandates that the Spanish Government will take responsibility for the environmental monitoring in the post-closure phase.

On the other hand, Law 7/2021 on Climate Change and Energy Transition (Law, 2021) urges critical infrastructure to incorporate measures in their planning, design, and management to adapt to and be resilient against the challenges posed by climate change. This ensures their operability while contributing to environmental sustainability.

Spain’s climate policy framework is defined by the Integrated National Energy and Climate Plan (PNIEC) (PNIEC, 2021), which outlines the country’s strategy for decarbonisation and climate resilience. With regard to radioactive waste management, the PNIEC refers to and aligns with the provisions of the General Radioactive Waste Management Plan (PGRR) (PGRR, 2023), which establishes the national policy and strategy for the safe management of radioactive waste and spent fuel. The 7th Radioactive Waste Management Plan, affirms that “In line with the analyses carried out to assess the safety and performance of such facilities, the actions planned for the post-closure period of final disposal sites—grouped under the general concept of "institutional control" (a set of activities aimed at monitoring the evolution of environmental and radiological parameters at a site during the period established by the competent authorities, once the facility has been closed)—include radiological and environmental monitoring, control of meteorological and hydrogeological data, knowledge transfer and information preservation using available media, site maintenance, and physical security control.”

According to Law 21/2013 on Environmental Assessment (Law, 2013), facilities intended exclusively for the disposal of radioactive waste are subject to a mandatory ordinary Environmental Impact Assessment (EIA). These projects are explicitly listed in Annex I of the law,

which includes activities with potentially significant environmental effects that require a full EIA procedure.

The Strategic Environmental Assessment of the 7th Radioactive Waste Management Plan, in Chapter 5.8 (SIA, 2022), states that “Potential evolution of the most significant environmental elements during the implementation of the plan, taking climate change into account”. This takes into account the following aspects related to climate change and nuclear repositories:

- Impacts on soil that recommend avoiding natural areas to reduce the loss of vegetated land (which mitigates CC through carbon sequestration),
- Impacts on biodiversity that recommend avoiding natural and protected areas. Reminds that the El Cabril facility is expected to increase mitigation as it will contribute to revegetation,
- Impacts on radioactive waste transportation states that “Some negative impacts of climate change on infrastructure include damage to bridges, slopes, and road surfaces due to increased rainfall; slope erosion caused by flash floods; flooding of road surfaces due to insufficient drainage capacity; the formation of ruts in pavement under arid conditions; and disruptions to traffic caused by wildfires along road margins. Positive impacts have also been identified, such as a reduction in winter maintenance operations due to fewer snowfalls and icy days.” No references or scientific sources are included.

Switzerland

The Swiss Federal Nuclear Safety Inspectorate (ENSI) (ENSI, 2024) specifies and supplements the safety-related requirements for the planning, construction and later closure of deep geological repositories. In accordance with the ENSI regulations, deviations from these specifications are permitted if the proposed solution is at least equivalent in terms of nuclear safety.

In Switzerland, a deep geological repository (DGR) is, according to Art. 3 of the Nuclear Energy Act of March 21, 2003 (KEG, 2023), a facility in the geological subsurface that can be sealed, provided the permanent protection of people and the biosphere is ensured by passive barriers. It is a nuclear installation and comprises the main repository, the pilot repository and the test areas (Art. 64 of the Nuclear Energy Ordinance of December 10, 2004 (KEV, 2004). According to Art. 49 para. 5 KEG (KEG, 2023), a nuclear installation also includes the access facilities and installation sites associated with construction and operation.

For the construction and operation of the DGR, detailed probabilistic safety analyses (PSA) are required (similar to other Swiss nuclear installations). In terms of climate (or rather, weather), these PSAs include, but are not limited to, droughts, harsh winter or summer conditions, low/high river water levels and other extreme weather events. The requirements are detailed in the ENSI guidelines A05 (ENSI, 2024).

With respect to the long-term safety of the DGR (after sealing), the aspect of climate change is generally mentioned (e.g. in the SGT (SGT, 2008)) but no pre-determined limits concerning different climate-related parameters are defined. Rather, the SGT states in general terms that “the site for a geological disposal facility shall be characterized at a level of detail sufficient to support both a general understanding of the characteristics of the site, including its past evolution and its probable future natural evolution over the period of interest with regard to safety, and a specific understanding of the impact on safety of features, events and processes associated with the site and the facility”. According to this, and since climate, or climate changes, can have a significant impact on DGR safety, e.g. through erosion, Nagra had to show that climate driven processes (such as during future glaciations) do not lead to a reduction of the barrier effect of the

host rock or the effective containment of rock zone; or to an exposure of the repository within the period under consideration (100,000 years for low- and intermediate-level wastes or 1 million years for high-level wastes). Probable evolutions of the climate in the (distant) future were taken into account by using alternative (conservative) climate projections.

Ukraine

Introduction

The issue of radioactive waste (RW) management safety in the context of climate change is becoming increasingly significant. As a country with advanced nuclear energy infrastructure and numerous RW management facilities, Ukraine recognizes climate change as a crucial factor that must be addressed throughout the entire lifecycle of RW management facilities. The national regulatory and technical framework mandates consideration of climate factors and their potential impacts on RW management facility safety across all lifecycle stages – from site selection and design through construction, operation, closure, and post-operational monitoring.

Climate Change and Its Potential Impact on RW Infrastructure

According to the Ukrainian Hydrometeorological Institute (UkrHMI), Ukraine is projected to experience the following climate changes in coming decades:

- Elevated average annual temperatures
- Higher frequency of extreme weather events (including intense precipitation, storms, floods, and droughts)
- Fluctuations in groundwater and subsurface water levels
- Intensified wind loads, increased air humidity, and accelerated soil erosion

These phenomena pose direct threats to disposal engineered barrier integrity, potentially causing accelerated material degradation and increasing risks of radionuclide release into the environment.

Legislative Framework

Law of Ukraine "On Radioactive Waste Management" (UkrLaw, 1995)

This legislation establishes the legal, organizational, and financial foundations of state policy regarding radioactive waste management to protect human life, health, and the environment. The Law stipulates long-term safety requirements that incorporate consideration of natural factors, including climate change, throughout all phases of RW management facilities – site selection, design, construction, operation, closure, and post-closure monitoring. Key provisions include:

- Ensuring complete isolation of RW from the biosphere
- Implementing defense-in-depth protection principles resistant to external influences, including climatic factors
- Maintaining compliance with radiation, environmental, and engineering safety standards that account for natural hazards during planning and implementation of RW management projects

Law of Ukraine "On Environmental Impact Assessment (EIA)" (UkrLaw, 2017)

This Law establishes mandatory environmental impact assessment procedures for activities with potential significant environmental impacts, particularly in RW management. Entities involved in site selection, design, construction, operation, reconstruction, repurposing, or decommissioning

of RW storage or disposal facilities must prepare comprehensive EIA Reports. These reports must analyze climate impacts, including greenhouse gas emissions scale and nature, as well as operational sensitivity to climate change. The EIA must also consider climate change forecasts, extreme weather scenarios, and necessary adaptation measures to ensure long-term facility safety. Activity permits cannot be issued without a positive EIA conclusion.

Technical Regulatory Framework

NP 306.4.219-2018: "General Safety Provisions for Radioactive Waste Disposal" (NP, 2018)

This regulation defines requirements for assessing extreme natural events and climate change forecasts with occurrence probabilities of at least 10E-6 per year that could affect repositories over extended timeframes, as well as combinations of natural and anthropogenic hazard sources.

NP 306.4.213-2017: "General Safety Provisions for Radioactive Waste Management Before Disposal" (NP, 2017)

This document regulates consideration of extreme weather conditions during RW disposal design processes, or alternatively, justification for their non-consideration.

NP 306.4.142-2008: "Requirements for the Structure and Content of the Safety Analysis Report for RW Storage Facilities" (NP, 2008a)

Contains specific requirements regarding regional climate descriptions, extreme weather condition characterizations, atmospheric parameter documentation, and methodologies for incorporating these factors into design and emergency planning procedures.

NP 306.4.223-2020: "Requirements for the Structure and Content of the Safety Analysis Report for Surface and Near-Surface Radioactive Waste Disposal Facilities" (NP, 2020)

Defines requirements for mandatory detailed meteorological justification of site suitability, comprehensive consideration of climate changes (precipitation patterns, temperature variations, evaporation rates, wind characteristics), and long-term safety modeling incorporating projected climate scenarios.

NP 306.4.149-2008: "Requirements for Site Selection for Radioactive Waste Disposal Facilities" (NP, 2008b)

According to these requirements, RW repository sites must be located in areas with minimal climatic risks, ensure barrier isolation from extreme events (hurricanes, intense precipitation, groundwater level fluctuations), and remain suitable for safe operation while preserving barrier integrity for a minimum of 300 years. This regulation also specifies requirements for geological repository placement at depths providing adequate protection from climatic influences.

Construction and Climatological Standards

DBN A.2.2-1:2021: "Composition and Content of Environmental Impact Assessment (EIA) Materials" (DBN, 2021)

This document establishes requirements for EIA section composition and content within project documentation for new construction, reconstruction, and major renovations of buildings and structures for any purpose. It mandates inclusion of a "Climate and Microclimate" section in EIA materials, documenting principal climatic characteristics of facility location areas and current/projected climate changes. This includes assessment of facility impacts on microclimate and analysis of potential conditions unfavorable for atmospheric contamination dispersion.

DBN A.2.1-1-2008 (DBN, 2008) and DBN A.2.1-1-2014: "Engineering Surveys for Construction" (DBN, 2014)

These documents regulate engineering-meteorological survey implementation, including studies of extreme weather phenomena (storms, heavy precipitation, droughts, tornadoes), analysis of potential climate risks, and forecasting their impacts on facility safety. They also mandate consideration of changes in temperature regimes, moisture conditions, wind loads, and other parameters potentially affecting engineering structure durability and stability.

DSTU-N B V.1.1-27:2010: "Construction Climatology" (DSTU, 2010)

Establishes required climatic parameters for consideration during building and structure design, particularly under climate change conditions. For RW management facilities, essential considerations include:

- Temperature regimes affecting material durability and protective barrier stability
- Humidity levels and precipitation quantities significant for repository sealing integrity
- Snow load magnitudes and wind characteristics critical for architectural and technological solutions at RW storage facilities

Institutional Framework[7]

- Ministry of Environmental Protection and Natural Resources of Ukraine (MEPR) formulates climate policy and ensures implementation of EIA procedures.
- State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) conducts licensing, control, and supervision of safe RW management.
- Ukrainian Hydrometeorological Institute (UkrHMI) —provides scientific support for extreme meteorological phenomena analysis and climate forecasting for long-term safety assessment.

Practical Climate Change Considerations

Ukrainian regulations require RW management facility designers and operators to account for:

- Temperature increases potentially leading to material degradation
- Increased frequency and intensity of extreme weather events (floods, droughts, dust storms, tornadoes, etc.)
- Groundwater level changes potentially affecting disposal and storage facilities sealing integrity
- Elevated humidity and associated corrosion hazards that compromise isolation systems
- Accelerated erosion processes and long-term degradation scenarios

Safety assessments must address both normal operating conditions and climate change-induced scenarios, including:

- Risks associated with extreme meteorological events
- Projected climate change patterns

[7] [MEPR] Ministry of Environmental Protection and Natural Resources of Ukraine (MEPR), https://mepr.gov.ua/

[SNRIU] State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) https://snriu.gov.ua/kontakti/derzhatomregulyuvannya

[UkrHMI] Ukrainian Hydrometeorological Institute (UkrHMI) https://www.uhmi.org.ua/

- Impacts on long-term barrier integrity (minimum 300-year timeframe)

RW repository design and safety documentation must contain:

- Climate change forecasts (temperature patterns, precipitation regimes, wind loads, snow loads, groundwater level changes, erosion processes, etc.)
- Identification of facility vulnerabilities to extreme weather events (hurricanes, intense precipitation, droughts, tornadoes)
- Justification of protection system effectiveness throughout all operational stages, closure, and post-closure periods of RW management facilities

United Kingdom

In the United Kingdom, regulation of radioactive waste disposal is managed through a combination of legislation, regulatory guidance, and planning frameworks. The UK Government and Devolved Administrations are responsible for policy development and implementation regarding radioactive substances and nuclear decommissioning. The Nuclear Decommissioning Authority (NDA), oversees decommissioning and clean-up of nuclear sites.

The main regulators are:

- Office for Nuclear Regulation (ONR); and
- The environment agencies, with Environment Agency (EA) regulating radioactive waste disposal in England, Natural Resources Wales (NRW) in Wales, and the Scottish Environmental Protection Agency (SEPA) in Scotland.

Key radioactive waste legislation includes:

- Nuclear Installations Act (NIA, 1965),
- Environmental Permitting Regulations (EPR) 2016, in England and Wales (EPR, 2016) and
- Environmental Authorisations (Scotland) Regulations 2018, in Scotland (EAR, 2018).

The UK has adopted a graded approach to regulation for all practices involving ionizing radiation, and this is embodied in the policy and regulatory framework. The UK policy framework (UK, 2024) for managing radioactive substances and nuclear decommissioning was updated in 2024. It aims to provide a clear direction of travel and to drive earlier, more cost-effective nuclear decommissioning and effective management of radioactive substances, including radioactive waste. Radioactive waste policy differs in Scotland (SG, 2025) to the rest of the UK in that they do not opt for geological disposal of higher-activity radioactive waste (HAW) and instead opt for near-surface management close to the site of production. In England and Wales, the policy is to manage the most hazardous radioactive waste through geological disposal.

Key guidance on radioactive waste disposal includes:

- Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation (GRA-NSD, 2009) and

- Geological Disposal Facilities for Solid Radioactive Wastes: Guidance on Requirements for Authorisation[8] (GRA-GDF, 2009).

The fundamental protection objective stated in these guidance documents is to "ensure the protection of human health and the environment from radiological hazards both at the time of disposal and in the future." This objective is achieved by developers or operators of disposal facilities for solid radioactive waste by meeting the five key principles:

1. Level of Protection: Maintain protection against radiological hazards.
2. Optimization: Keep radiological risks as low as reasonably achievable.
3. Non-radiological Hazards: Protect against non-radiological hazards.
4. Reliance on Human Action: Minimize reliance on human intervention.
5. Openness and Inclusivity: Engage with stakeholders and the public.

As set out in the guidance for near-surface facilities, the environmental safety case needs to take into account the potential for climate change. It acknowledges the high level of uncertainty in future climate projections, so guides the developer/operator to consider a range of possibilities. The potential consequences of climate change that should be considered in assessments include changes in rainfall patterns (which can affect watercourses and aquifers), changes in sea level, increased rates of erosion including coastal erosion, glacial cycling and glaciotectonic movements.

For geological disposal facilities, the guidance sets out that climate evolution scenarios should be modelled over timescales up to 1 million years. Developers must show that future climate effects will not compromise containment. For example, performance assessment modelling is required, which may include factors such as:

- Glacial and interglacial cycles;
- Sea level rise;
- Permafrost development; and
- Increased rainfall or groundwater flow.

The environment agencies have also worked together with the Office for Nuclear Regulation to produce guidance on the use of the latest climate projections: UKCP18: Use of UK Climate Projections 2018 Position statement, Office for Nuclear Regulation, Environment Agency, Natural Resource Wales and Scottish Environment Protection Agency (UKCP18, 2022).

This states that dutyholders in the nuclear industry must integrate UKCP18 projections into their climate change assessments, ensuring that their facilities are resilient to future climate impacts. This involves transitioning to UK Climate Projection 2018 (UKCP18, 2022), using Representative Concentration Pathways (RCPs), conducting extreme value analysis (EVA), considering credible maximum scenarios, adopting a managed adaptive approach, and using post-2100 sea level rise scenarios. Specific guidance for the construction or operational phase, and for post-closure are set out below.

<u>Construction/Operational Phase</u>

1. Transitioning to UKCP18:

[8] Note: update to both guidance document is underway, and re-publication is expected in Spring 2026

- Dutyholders are expected to incorporate UKCP18 projections into their climate change assessments at all stages of the facility lifecycle, including design, planning, construction, and operation.
- For new build sites, safety cases must be updated to reflect UKCP18 within a reasonable timeframe, with a program of work describing when and how this will be done.

2. Representative Concentration Pathways (RCPs):
   - Dutyholders should use RCPs to assess climate change impacts, with specific guidance on selecting appropriate RCPs for different scenarios.
   - Probabilistic projections at 25km spatial resolution over land are available for RCP 2.6, 4.5, 6.0, and 8.5.
3. Extreme Value Analysis (EVA):
   - Dutyholders are expected to use EVA techniques to assess the probability of extreme climate events, which helps in deriving design basis events for natural hazards.
4. Credible Maximum Scenarios:
   - Dutyholders should consider credible maximum scenarios, which are high-end, plausible climate change scenarios, to assess the impacts of low probability, high impact climate events.
   - These scenarios help in sensitivity testing different adaptation options over time periods appropriate for the nuclear industry.
5. Managed Adaptive Approach:
   - A managed adaptive approach is recommended for long-term climate change planning, involving taking action based on observed trigger points and building flexibility into options and decisions to adapt to future climate changes.
   - Components of a managed adaptive approach include:
     i) Understanding the full range of risks that might need to be managed. This comes from performing analysis of climate change using a range of climate scenarios, annual exceedance probabilities and sensitivity studies. This should include consideration of the credible maximum scenario. The regulators expect dutyholders to use the most up to date credible maximum scenarios in any new analysis of climate change.
     ii) Understanding how much flexibility and what options might be needed, and when, depending on the different climate change projections, so as to not foreclose modifications needed to enhance resilience in the future.
     iii) Iterative decision-making (evaluating results and adjusting actions on the basis of what has been learned).
     iv) Feedback between monitoring and decisions (learning). Knowing when a decision will be needed given the changing risks and the lead time to make an adjustment, or implement a new option.
     v) The sustainability of the managed adaptive approach must be demonstrated. In other words, that the responsibility for adaptation can reasonably and effectively be passed on to future dutyholder(s).

<u>Post-Closure Phase</u>

1. Exploratory Post-2100 Sea Level Rise Scenarios:
    - For nuclear sites with lifetimes extending beyond 2100, dutyholders should use exploratory post-2100 sea level rise scenarios provided by UKCP18.
    - These scenarios account for the continued rise in sea levels and the associated uncertainties.
2. Long-Term Climate Resilience:
    - Dutyholders must demonstrate that their proposals have a high level of climate resilience built-in from the outset and can be adapted over their predicted lifetimes to remain resilient to credible maximum climate change scenarios.
    - This includes ensuring that adaptation of Structures, Systems, and Components important to safety would be possible.
3. Sustainability of Managed Adaptive Approach:
    - The managed adaptive approach must be sustainable, meaning that the responsibility for adaptation can reasonably and effectively be passed on to future dutyholders.
    - For aspects covered by the nuclear safety case, these can be controlled on an ongoing basis by the nuclear site licence and attached licence conditions.

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Appendix B. Climate risk screening indicators

Climate risk examination employs an indicator-based approach to quantify hazard intensity, facility exposure, and system vulnerability for each climate hazard. The following subsections synthesise indicator frameworks across climate groups, organised by hazard type.

Heavy Rainfall and Flash Flooding

- Hazard Indicators include maximum daily precipitation exceeding 20, 50, or 100 mm/day thresholds, the 98.5th percentile of daily precipitation distribution, maximum 1-hour and 3-hour precipitation intensities, and the number of days per year with extreme precipitation events. Climate projections indicate a 10-30% increase in extreme precipitation intensity across most European regions by the end of the century under RCP8.5.
- Exposure Indicators quantify facility elements vulnerable to precipitation impacts, including total area of surface infrastructure and waste emplacement zones, drainage system capacity expressed as design return period, proximity of facilities to drainage channels, and total length of exposed conveyance systems and pipelines.
- Vulnerability indicators evaluate system sensitivity and adaptive capacity, including the ratio of design drainage capacity to projected extreme precipitation intensity, the height of surface facilities above grade, the age and condition of existing drainage infrastructure, and the availability of emergency response procedures for extreme weather events.
- Expected impacts across climate groups include overwhelming drainage systems, leading to surface ponding and potential waste package submersion, increased infiltration through protective covers and into disposal cells, erosion of surface barrier facilities and earthen structures, and disruptions to construction or operational activities during extreme events.

River Flooding

- Hazard Indicators quantify riverine flood risk using return period flood levels (such as 10-year, 100-year, and 500-year events), projected changes in the annual maximum discharge, seasonal shifts in flood timing caused by snowmelt or precipitation regime changes, and the potential for compound flooding from coincident heavy precipitation and high river water levels.
- Exposure Indicators include facility elevation relative to flood level, distance to the nearest major river or stream, area of the facility within the mapped floodplain, and critical infrastructure elements in potentially flooded zones.
- Vulnerability Indicators evaluate flood protection adequacy by examining the height of flood protection structures relative to projected future flood levels, the capacity of sump pumps and dewatering systems, the structural resistance of buildings to hydrostatic and hydrodynamic loads, and the waterproofing integrity of below-grade cover structures.
- Expected impacts include flooding of surface facilities with potential contamination of operational areas, structural damage to buildings and infrastructure from flood forces,

disruption of access roads and supply chains, and long-term elevation of the groundwater table affecting underground structures.

Coastal Flooding and Sea Level Rise

- Hazard Indicators for coastal facilities include mean sea level rise projections, storm surge heights for various return periods, extreme water levels combining mean sea level, tide, and surge, wave run-up and overtopping potential, and coastal erosion rates.
- Exposure Indicators identify coastal facilities through elevation above current mean high water, distance from coastline, presence of natural or engineered coastal protection, and area of facility potentially inundated under various sea level rise scenarios.
- Vulnerability Indicators include height of coastal protection structures with design life considerations, foundation depth and stability under erosion conditions, drainage system capacity to manage increased groundwater levels from sea level rise, and material corrosion resistance to saltwater exposure.
- Expected Impacts include increased risks from rising sea levels, more frequent and severe storm surge flooding, saltwater intrusion into groundwater affecting facility operations, coastal erosion threatening the facility's integrity, and the loss of coastal protection ecosystems.

Heat Waves and Extreme Heat

- Hazard Indicators measure thermal stress using maximum daily temperature, the number of days exceeding critical thresholds (30°C, 35°C, 40°C), the duration of heat wave events defined as consecutive days above these thresholds, and nighttime minimum temperature as an indicator of recovery periods.
- Exposure Indicators identify heat-vulnerable systems, including HVAC system capacity and efficiency ratings, cooling water demand and availability, electronic systems and control equipment sensitive to temperature, and outdoor work requirements during hot conditions.
- Vulnerability Indicators assess thermal resilience through HVAC design capacity margin above maximum historical temperature, backup cooling system redundancy, building insulation and passive thermal management, and worker heat stress protocols and monitoring systems.
- Expected Impacts include HVAC system failures or decreased efficiency during peak demand, worker heat stress reducing operational capacity and safety, elevated concrete curing temperatures affecting structural quality during construction, accelerated degradation of temperature-sensitive materials and electronic components, and increased electricity demand stressing the power infrastructure.

Drought and Water Scarcity

- Hazard Indicators characterise drought intensity through Standardised Precipitation Index (SPI) or Standardised Precipitation-Evapotranspiration Index (SPEI), consecutive dry days, soil moisture deficit, and streamflow statistics.
- Exposure Indicators quantify water-dependent operations, including cooling water demand, concrete mixing and curing needs, dust suppression requirements, worker water supply, and vegetation irrigation for erosion control.
- Vulnerability Indicators evaluate drought resilience by examining on-site water storage capacity, access to alternative water sources, water efficiency and recycling systems, and drought contingency plans for the facilities.
- Expected impacts include insufficient water availability for cooling operations, compromised concrete quality during construction in dry conditions, increased airborne dust affecting air quality and equipment, vegetation failure on engineered cover materials leading to erosion, and soil moisture changes impacting barrier performance through shrinkage and swelling cycles.

Windstorms and Extreme Wind

- Hazard Indicators for wind hazards include maximum wind gust speed, number of days with wind exceeding damage thresholds, directional exposure to prevailing storm winds, and compound wind-precipitation events.
- Exposure indicators identify wind-sensitive infrastructure, including the height and surface area of tall structures, temporary construction elements with high wind loads, overhead power lines and communications infrastructure, and stored materials or waste that are vulnerable to wind-driven debris.
- Vulnerability Indicators assess wind resistance by comparing structural design wind loads to projected extreme winds, evaluating roof and cladding securement integrity, assessing the risk of tree fall on structures and power lines, and examining emergency power backup capacity for wind-driven outage events.
- Expected Impacts include structural damage to buildings and equipment from extreme winds, power outages affecting critical operational systems, wind-driven debris causing damage to facilities and vehicles, and construction delays during high wind events.

Soil Erosion

- Hazard Indicators quantify erosion drivers through rainfall erosivity (R-factor in RUSLE), wind erosivity for arid regions, freeze-thaw cycles, and vegetation productivity under a changing climate.
- Exposure Indicators identify erosion-vulnerable features, including total area of engineered soil covers, slope gradient of cover systems, length of drainage channels and ditches, and areas of disturbed soils during construction.

- Vulnerability Indicators measure erosion resistance based on soil erodibility, vegetation cover percentage, root depth, erosion control measures (such as geotextiles and surface treatments), and slope stabilisation structures.
- Expected Impacts include progressive thinning of protective cover layers potentially exposing waste, gully formation and concentration of surface flow causing accelerated erosion, sedimentation of drainage systems reducing capacity, and long-term cover system failure requiring remediation.

Water Table Variations

- Hazard Indicators characterise groundwater changes through projected mean water table depth, seasonal water table fluctuation amplitude, frequency of water table reaching critical levels, and long-term trends in groundwater recharge.
- Exposure Indicators identify water-table-sensitive components including depth of underground structures relative to water table, presence of clay barriers requiring specific saturation state, drainage and dewatering systems, and foundation systems.
- Vulnerability Indicators assess groundwater impacts through structural waterproofing integrity, dewatering system capacity and reliability, barrier tolerance to saturation cycling, and groundwater monitoring network adequacy.

Expected impacts include an increase in hydrostatic pressure on underground structures, enhanced contaminant transport potential, and degraded performance of clay barriers through repeated wetting-drying cycles.

Appendix C. Group documents Task 3

Surface disposal in subarctic climates (Finland, Lithuania, Ukraine)

Group description

Group: 3Sa

Disposal type (Name): surface (1.Olkiluoto-FI, 2.Ignalina B19-LT, 3. Ignalina B25-LT, 4. ENSDF L3-UA)

Nuclear waste type: VLLW/LILW

Current climate: Dfc

Countries: Finland, Lithuania, Ukraine

Partners: VTT, Mitta, GTK, FTMC, SSTC NRS **Time window for construction and operation**: 100 a AP

Location/Type of waste/Surface facilities/Distance from the shoreline

Location:

Olkiluoto: 61N(Latitude), 21E(Longitude), 5-10 m(Altitude)

Ignalina B19: 55.35N (Latitude), 26.33E(Longitude), 150 m(Altitude)

Ignalina B25: 55.35N(Latitude), 26.33E(Longitude), 150 m(Altitude)

ENSDF L3 :55-50N(Latitute), 30-35E(Longitude),100-200m(Altitude)

Type of waste: VLLW and LILW

Olkiluoto: Very low level waste

Ignalina B19: Very low level radioactive waste (VLLW)

Ignalina B25: Low- and intermediate- level short- lived radioactive waste (LILW SL)

ENSDF L3 : Disposal of solid radioactive waste: conditioned radioactive waste consisting of processed products from the Solid Radioactive Waste Treatment Plant and Liquid Radioactive Waste Treatment Plant; radioactive waste accumulated during the ChNPP operation and generated during the decommissioning process

Surface facilities:

Olkiluoto: Possibly some storage facility

Ignalina B19: Landfill Facility for Very Low Level Radioactive Waste- Project B19 is operated in the area close to Ignalina Nuclear Power plant. A purpose of B19 Project is to construct infrastructure for final disposal of very low level radioactive waste. B19 Project consists of two sub-projects for construction two structures:

• Project B19-1 – Buffer Storage of 4000 m3 capacity. The Storage has been constructed on a territory of INPP and being operated since 2013;

• Project B19-2 – ,,Landfill“ type repository for placing 60000 m3 of very low level radioactive waste.

The Landfill repository consists of three Disposal Modules of 20000 m3 each. Generally, the Ignalina NPP site accommodates several facilities related with the radioactive waste management and operation of NPP, which is under decommissioning now. The first unit of INPP was shut down on December 31, 2004 and the second unit- on December 31, 2009. The unloaded from the Units 1 and 2 nuclear fuel is intended to keep in Interim Spent Fuel Storage Facilities (ISFSF). The newly built dry type ISFSF B1 was designed, constructed and installed as a complex of systems and equipment, necessary to pack the spent nuclear fuel into the special casks CONSTOR®RBMK1500/M2, to seal them and to transport them from the Units to the ISFSF. spent nuclear fuel will be safely stored at the ISFSF for 50 years according to

the established requirements of the Republic of Lithuania, EU standards and IAEA recommendations, with the possibility of extending the shelf life (if necessary) or placing into deep geological repository (DGR). Forecast completion of DGR is 2078. Bituminised Waste Storage Facility B20 is located in the north-western part of the protected Ignalina NPP industrial site. Storage Facility is designed for acceptance and storage of bituminised RW. The bituminised RW are attributed to “B” and “C” classes of RW, i.e., short-lived low and intermediate level RW to be placed to the near-surface repository. The Storage Facility is connected to Building 150 (LRW processing, bituminisation and cementation buildings), by pedestrian and process galleries from the east and to Building 158/2 (Cemented LRW Interim Storage Facility) from the west. Solid Waste Management and Storage Facilities (SWMSF) B2/3/4 is design and constructed for retrieval, treatment and temporary storage of INPP solid radioactive waste. The facility will treat the solid radioactive waste generated until final shutdown of Unit 2 (end of 2009), as well as the waste generated as the result of INPP decommissioning activities. Very low-level SRW, suitable for disposal in a surface repository, will be packaged and transported to B19-1 Facility for temporary storage. Later the VLLW will be transferred to B19 Landfill. Whereas, after solid RW treatment in SWMSF (fragmentation, incineration, pressing) final packages with short-lived low and medium level SRW will be formed, placed in SWSF-SLW (B4) and then transported to the near surface repository (B25 Project) for disposal. Long-lived low and medium level SRW after sorting and characterization will be transported to SWSF-LLW for temporary storage until construction of the near surface repository is completed (term for storage of SLW and LLW packages in SWSF – up to 50 years).

Ignalina B25 : Officially named by- Near Surface Repository For Low And Intermediate Level Short-Lived Radioactive Waste - Project B25 is erected in the area (Stabatiškė village) close to Ignalina Nuclear Power plant and scheduled to start operation in 2025. 36 reinforced concrete vaults are planned for final disposal of 100 000 m3 of final packaging of radioactive waste (concrete containers with cemented radioactive waste. Reference: https://www.iae.lt/en/activity/decommissioning-projects/155

ENSDF L3 : Centralized Long-term Storage Facility for Spent Ionizing Radiation Sources (CLTSF) is operational, the Centralized Spent Fuel Storage Facility (CSFSF) of the dry type is being commissioned

Distance from the shoreline

Olkiluoto: <1 km

Ignalina B19: 350 km

Ignalina B25 : 350 km

ENSDF L3 : 10-20km, The distance to the Pripyat and Uzh rivers is 8 and 18 km respectively. (555 km to Odesa, Black Sea coast - 46.5° N, 30.7° E)

Current phase/EBS/Host rock

Phase:

Olkiluoto: Applied for Environmental Impact Assessment (2021)

Ignalina B19: Operation

Ignalina B25: Construction

ENSDF L3: Operation

EBS:

Olkiluoto: Typical landfill type design

Ignalina B19:

Buffer Storage B19-1– temporary, roofed, radioactive waste accumulating structure, that serves as interim Storage and occupies area of 0.2 ha. The Facility is equipped with a waste characterization unit and all other necessary means (software and hardware, handling and transportation equipment). After the Storage gets full of waste, Landfill disposal campaign will

be organized. 15 campaigns are planned, each of disposal of 4000 m3 capacity packages with very low level radioactive waste.

Landfill type Waste Disposal Modules B19-2 – ferroconcrete base-slab (foundation plate) with rainwater collection system installed, that serves as monitoring mean and controls water pollution every time before discharge, although Design foresees no exceeding of permittable limits of pollution. Main waste packages, that are planned to be disposed over the base-slab, are half-height ISO containers, plastic bales, flexible plastic containers (FIBC package). The packages will be placed on the stepped structure to form a roughly “hill shaped” stack, which will then be covered by layers of different natural and fabricated materials to achieve a smooth, hill-shaped form. Finally, hydro-isolation, drainage and protective layers will be laid on top to prevent water penetration into the waste stack and washout of radionuclides from the waste to the environment. Modules will occupy 4.4 ha area.

Ignalina B25 :

According to the national strategy on radioactive waste treatment, a repository B25 for disposal of short-lived low and intermediate level radioactive waste should be designed and constructed in Lithuania. According to the prepared Technical Project, 36 reinforced concrete vaults are planned for final disposal of 100 000 m3 of final packaging of radioactive waste (concrete containers with cemented radioactive waste. The repository, its protective areas and auxiliary structures required for operation will occupy the area of about 45 hectares. Since waste will be disposed for a long time (about 20 years), the repository will be divided into three groups of vaults (12 vaults per group) in order not to build all vaults at the same time. First of all, only one group of vaults will be constructed. The construction of the third group of vaults will be decided at a later stage of INPP decommissioning.

The engendered barriers consist of:

•Concrete container for the cemented radioactive waste.

•Concrete vaults for the placement of the containers.

•Filling of the free space between containers with concrete solution.

•Concrete ceiling of the vault.

•Several layers of clay, gravel, sand, pebble, vegetative ground will be installed over vault ceiling, the total thickness of which will be about 7 meters.

Reference:https://www.iae.lt/en/b25-project.-near-surface-repository-for-low-and-intermediate-level-short-lived-radioactive-waste/470

ENSDF L3: The system includes the following natural and engineered barriers:

The first barrier consists of containers and cement compound (a matrix with embedded waste).

The second barrier comprises the disposal facility's engineered structures, including: reinforced concrete compartments, waterproof bottom coverings of the compartments; water collection systems in disposal facility compartments; concrete compartments; sand-concrete mixture for radioactive waste fixation; waterproof screening.

The third barrier is formed by the aeration zone soils beneath the disposal facility and their ability to retain radionuclides. To enhance the protective properties of the third barrier, the design incorporates a multi-layer anti-filtration screen under the foundation of disposal facility sections and includes a collection system for any water that might seep under the repository compartments

Host rock/Basement rock:

Olkiluoto: Metamorphic (0-20m from surface to the top of the host rock and >100 m from top to bottom of host rock)

Ignalina B19: Granite and GnMixed (mixed glacial and post glacial deposits at the depth of 0-100 m from the surface composed of till, clay and sand; deeper ~100-720 m transitioning to layers of sandstone, limestone, shales and claystone; laying at 720 m on the ancient crystalline basement rock of Granite and Gneiss)

Ignalina B25: Mixed (mixed glacial and post glacial deposits at the depth of 0-100 m from the surface composed of till, clay and sand; deeper ~100-720 m transitioning to layers of sandstone, limestone, shales and claystone; laying at 720 m on the ancient crystalline basement rock of Granite and Gneiss)

ENSDF L3: Consolidated clay with quaternary fluvioglacial quartz sands and glacial (moraine) layers (100-250m from surface to the top of the host rock and >100m from top to bottom of host rock)

The referenced data is not applicable to the near-surface disposal facility and was sourced from the research study on geological repository potential:

Current climate /Current land use/Geology/Hydrology/Geomorphology/Porewater

Köppen-Geiger:

Olkiluoto: D

Ignalina B19 : Dfb

Ignalina B25 : Dfb

ENSDF L3 : Dfb (the climate is characterized by multiple soil freeze-thaw cycles. Water infiltration into the formed fissures impacts the structural integrity of the upper containment, complicating their properties)

Köppen-Trewartha:

Olkiluoto: E

Ignalina B19: Dc

Ignalina B25: Dc

ENSDF L3 : **Dc**

(0-100 years AP)

Olkiluoto: The local climate at Olkiluoto is largely affected by the sea; southern winds prevail on average, and the annual average wind speed is 8.0 m/s. The annual average temperature and precipitation are 6.1 °C and 590 mm respectively using the statistics of 1992 – 2016 (Sojakka et al. 2018). The return levels of extreme daily precipitation are 70-95 mm on the 100-year time scale and 90-150 mm on the 500-year time scale. The corresponding extreme hourly precipitation return levels are 30-40 mm and 35-45 mm, respectively. All these return levels are expected to increase in the next 100 years due to climate change; in other words, heavy rains are expected to get even heavier. On the other hand, heavy snow loading (> 20 kg/m2) occurring concurrently with high wind speed (> 8 m/s) occurs in current climate once in 2-5 years. It is projected that such conditions will become somewhat more frequent in southern and eastern Finland during the current century. However, the level of understanding for the precipitation and snow loading trends can be considered only moderate (Tietäväinen et al. 2012). The projections of sea level change in the Finnish coast estimate that at the Olkiluoto region land uplift may dominate over the sea level rise during the next 100 years (Kahma et al. 2014, Johansson et al. 2014).

Ignalina B19: Lithuania has a temperate maritime climate, which is influenced by its proximity to the Baltic Sea. This climate is characterized by distinct seasons, with relatively mild winters and cool summers. For the future 0-100 Years (to 2125):

(Temperature) Average air temperature increase of +2.6–2.9 °C (under high-emission scenarios). More frequent heatwaves and tropical nights (≥ 20 °C). Severe frosts (< −25 °C) may disappear entirely. Longer and hotter summers.

(Precipitation) Increase in total annual precipitation, especially in winter and spring. More frequent heavy rain events (≥ 20 mm/day). Possible drier summers, raising drought risks.

(Snow & Freeze–Thaw) Significant reduction in snow cover duration and depth. Fewer freeze–thaw cycles (−18% to −42%), impacting infrastructure durability.

(Hydrology) Higher winter and spring river runoff. Lower summer flows, increasing seasonal drought risk. Possible changes in groundwater levels.

(Wind) Decrease in average wind speeds (~8–9%).

(Vegetation) possible change in dominating vegetation types.

Ignalina B25 : the same as for Ignalina B19.

ENSDF L3 :0–100 Years (to 2125)

(Warming) ENSDF-3 will experience significant warming, with mean annual temperatures projected to rise by 2–4°C above late 20th-century levels, depending on global emissions pathways.

(Precipitation) Winters are expected to become wetter (10–20% increase in precipitation), while summers may become drier, increasing the risk of droughts and heatwaves.

(Extremes) More frequent and intense extreme events are likely, including heavy rainfall, river flooding, and longer, more severe heatwaves.

(Ecosystem and hydrology) Increased risk of forest loss, soil erosion, and changes in groundwater recharge patterns. Freeze–thaw cycles will remain common but with milder winters.

(Sea level) No direct marine flooding risk for ENSDF-3 due to its inland location, but river flood risk may increase due to more intense precipitation events

Hydrology:

Olkiluoto: Perennial, surface water dominated mostly from precipitation)

Ignalina B19: Perennial, surface water dominated (river water is mostly from precipitation)

Ignalina B25 : Perennial, surface water dominated (river water is mostly from precipitation)

ENSDF L3 : Mixed Hydrological System with both significant surface water and groundwater components: high base flow from groundwater (50-60%); significant seasonal surface water contribution; complex aquifer interconnection; strong seasonal variation in total flow

Current land use:

Olkiluoto: Built-up

Ignalina B19: Built-up

Ignalina B25 :Tree cover

ENSDF L3 : Tree cover

Geomorphology:

Olkiluoto: Low relief topography: rather flat landscape

Ignalina B19: Low relief topography: rather flat landscape

Ignlaina B25 : Low relief topography: rather flat landscape

ENSDF L3 : Low relief topography: rather flat landscape

Geology above host rock/basement rock:

Olkiluoto: Thin Glacial deposits

Ignalina B19: Sedimentary

Ignalina B25: Sedimentary

ENSDF L3 : Sedimentary

Geology below the host rock/basement rock:

Olkiluoto: Metamorphic

Ignalina B19: Metamorphic

Ignalina B25: Metamorphic

ENSDF L3 : Mixed

Hydrogeology above the host rock/basement rock:

Olkiluoto: shallow water systems

Ignalina B19: Phreatic sedimentary aquifer

Ignalina B25: Phreatic sedimentary aquifer

ENSDF L3 : Artesian sedimentary aquifer

Hydrogeology below the host rock/basement rock:

Olkiluoto: Fractured crystalline rock

Ignalina B19: Aquitard

Ignalina B25 : Aquitard

ENSDF L3 : Mixed

Porewater of the host rock/basement rock at the RWM site/facility:

Olkiluoto: Fresh

Ignalina B19:Fresh

Ignalina B25: Fresh

ENSDF L3 : Fresh

Porewater of the host rock above the RWM site/facility:

Olkiluoto: Does not apply, no host rock above facility

Ignalina B19: Fresh

Ignalina B25: Fresh

ENSDF L3 : Fresh

Porewater of the host rock below the RWM site/facility:

Olkilutoto: Fresh

Ignalina B19: Fresh

Ignalina B25: Fresh

ENSDF L3 : Fresh

Impact of sea level:

Olkiluoto: No, not during the next 300 years

Ignalina B19: No

Ignalina B25: No

ENSDF L3 : No, The Exclusion Zone is located at a significant distance and elevation from the Baltic and Black Seas, minimizing the likelihood that sea level changes would affect the hydrogeological regime or storage system.

Screening

Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

☒ Coastal flooding(x)

☒ Cold spells

☒ Droughts(x)

☐ Desertification
☒ Flash flooding(x)
☒ Heavy rainfall(x)
☒ Heat waves(x)
☒ Landslides
☐ Permafrost thaw
☒ River flooding(x)
☒ Sea level rise(x)
☒ Soil erosion(x)
☒ Water table variations(x)
☒ Windstorm(x)
☐ Wildfires
☐ Others (please specify): ____Strong winds_____

Interdependencies and Cascading Risks:

- Heavy rainfall → Flash flooding → Soil erosion (sequential degradation)
- Coastal flooding + Sea level rise (compound saltwater intrusion)
- Heavy rainfall → Soil saturation → Landslide

Please, indicate the data source (for climatic, sea level,.), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
Baltic Sea SLR Projections	Copernicus Marine Home | CMEMS	1993-2022	2030	2050	2100	RCP8.5	Yes	No	Regional	Gulf of Finland/ ENSDF L3
EURO-CORDEX Regional Models	EURO-CORDEX EURO-CORDEX	1981-2010	2021-2040	2040-2070	2071-2100	RCP2.6/4.5/8.5				Baltic Sea Region

Comments:Baltic-Sea-Climate-Change-Fact-Sheet_2024.pdf

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use?

*Which **hazard indicator** would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)? Which **exposure indicator** would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones? Which **vulnerability indicator** would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks? Finally, for each hazard,*

indicate the expected impact(s) *on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.*

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impacts
Heavy rainfall	- 98.5th percentile daily precipitation intensity (mm/day);	- Surface facility drainage system design capacity vs. projected storm intensities ; - Disposal cover slope gradients and lengths ; - Critical infrastructure elevation ;	- Landfill cover erosion resistance (tons/ha/year); - Storm drainage system design capacity margins;	- Increased groundwater infiltration into disposal modules through compromised cover systems; - Enhanced erosion of stepped repository protective covers; - Slope instability in landfill-type repository designs; - Drainage system performance degradation and potential overflow; - Landslide filling the disposal modules or relocating the disposal material;
Flash flooding	- Sub-daily precipitation intensities >50mm/hr; - Peak discharge rates exceeding drainage capacity;	- Facility elevation relative to local drainage network; - Access road vulnerability to inundation;	- Emergency response capability and equipment availability; - Backup drainage system capacity; - Access road flood resistance design	- Rapid inundation of surface-founded access structures and control buildings; - Accelerated erosion of protective earth covers and slope failures; - Restricted emergency access and evacuation routes
River flooding	- 100-year flood levels relative to facility elevation (m);	- Distance to major rivers and tributaries (km); - Site elevation above 100-year flood level (m);	- Site-specific flood protection design level;	- Flooding of surface facilities and operational access routes; - Extended operational shutdowns and waste handling delays;

		- Historical flooding evidence at facility sites;		
Coastal flooding	- Significant wave height during storms (m); - Wave run-up heights at shoreline;	- Facility elevation relative to mean sea level (m); - Horizontal distance to coastline (m);	- Steel component corrosion rates in brackish/saline conditions; - Concrete durability under marine exposure;	- Direct inundation of low-elevation surface-founded processing and storage facilities; - Saltwater intrusion into shallow aquifer systems affecting barrier chemistry; - Accelerated corrosion of steel components and reinforcement; - Electrical system failures and instrumentation damage ;
Sea Level Rise	- Long-term absolute sea level change (m); - Regional sea level trends; - Vertical land movement rates;	- Underground repository depth below current mean sea level (m); - Coastal infrastructure foundation elevation; - Distance from current shoreline;	- Barrier material long-term degradation rates; - Structural component design life under marine conditions;	- Progressive submersion of coastal facility infrastructure; - Increased groundwater salinity affecting engineered barrier performance; - Enhanced coastal erosion compromising site stability;

Heatwaves	- Maximum daily temperature >25°C frequency (days/year); - Multi-day heatwave duration and intensity;	- Surface infrastructure total exposed area (m²); - HVAC system capacity ratings and design temperatures; - Heat-sensitive equipment inventory and locations ;	- Construction material thermal expansion limits and coefficients; - Equipment maximum operating temperature ratings; - Worker heat stress thresholds and safety protocols;	- Accelerated corrosion and thermal degradation of metal waste containers; - Equipment overheating, derating and failure in surface processing facilities; - Thermal stress-induced cracking in concrete structures
Droughts	- Consecutive dry days >90th percentile; - Drought severity-duration-frequency analysis ;	- External water source dependencies for cooling and operations; - Potential dust generation areas and pathways; - Air-cooled system capacity and efficiency ratings;	- Water supply system redundancy and storage capacity; - Dust suppression system effectiveness	- Reduced heat rejection efficiency of air-cooled systems and equipment; - Increased airborne dust generation and dispersion from desiccated covers; - Water supply shortages affecting operations and dust control;
Windstorms	- 100-year wind speed return levels (m/s); - Extreme wind speed probability distributions;	- Above-ground structure exposure area and height; - Temporary storage facility structural specifications; - Electrical transmission line proximity; - Tree fall potential zones around facilities;	- Structural wind load design limits (Pa); - Waste container anchorage specifications and testing; - Power transmission system storm resilience design; - Debris impact resistance of critical components;	- Physical damage to temporary storage structures and waste handling equipment; - Wind-borne debris impact on waste packaging and containers; - Power grid disruptions affecting monitoring, control and safety systems; - Communication tower and antenna system outages;

Soil erosion	- Universal Soil Loss Equation parameters; - Erosion potential index;	- Multi-layer cover slope angles and aspect; - Vegetated surface area density and establishment; - Total area exposed to erosive precipitation;	- Cover layer composition, thickness and compaction adequacy; - Root penetration barrier effectiveness;	- Progressive loss of multi-layer cover system integrity; - Exposure of underlying waste packages to direct precipitation;
Water table variations	- Seasonal groundwater level fluctuation amplitude (m); - Water table depth variability; - Hydraulic head fluctuations;	- Disposal module depth relative to seasonal water table fluctuations; - Site-specific hydrogeological setting complexity; - Engineered drainage system capacity; - Seasonal variation sensitivity;	- Engineered barrier performance under variable saturation conditions; - Drainage system capacity safety margins; - Foundation settlement sensitivity to water table changes;	- Fluctuating engineered drainage system performance and efficiency; - Cover stability issues during rapid saturation/desaturation cycles; - Monitoring well interference and data quality degradation
Cold Spells (Coldwaves)	- Days <0°C ; - Minimum temperature ; - Coldwave duration ;	- Heating system dependency; - Worker exposure hours - Heat-sensitive equipment; - Concrete structures; - Steel structures;	- Material temperature limits;	- Heating system overload; - Concrete degradation; - Steel degradation; - Electronic failures;

Historical Evidence:

- 2018 Baltic Sea heatwave (Finnish coastal facilities)
- 2017 Nordic extratropical cyclone (storm surge impacts)
- 2010 extreme rainfall (Ignalina region flooding)
- 2021 compound heatwave-precipitation events (Finland)

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Triple coastal flooding threat: Sea level rise + storm surge + heavy rainfall for coastal facilities

Multi-hazard infrastructure damage: Wind storms + heavy rainfall causing simultaneous impacts

Barrier coupling effects: Temperature + precipitation changes affecting engineered barriers and drainage system while accelerating chemical degradation processes in engineered barriers.

Infrastructure cascades: Power failures(outage) during cooling demands (ventilation and monitoring equipment)

Transportation disruptions may prevent access for emergency response(delivery of critical materials) or routine maintenance activities.

How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

Semi-Quantitative Risk Scoring Option

Risk Score = (H × E × V) where:

- H = Hazard likelihood (1-5 scale)
- E = Exposure level (1-5 scale)
- V = Vulnerability degree (1-5 scale)

Example of the Scoring Criteria:

Score	Hazard Likelihood	Exposure Level	Vulnerability
5	>80% in 100yr	Critical assets exposed	No resilience measures
4	60-80% in 100yr	Important assets exposed	Limited measures
3	40-60% in 100yr	Moderate assets exposed	Some measures
2	20-40% in 100yr	Low value assets	Good measures
1	<20% in 100yr	Minimal exposure	Excellent measures

Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Climate Data Constraints:

Spatial resolution constraints: It limits the ability to capture local microclimate features affecting individual facilities. Regional climate models with 12.5 km resolution may not accurately represent site-specific microclimate conditions, such as sea-land breezes, lake effects, and topography. This can lead to potential misclassification of site exposure, especially for coastal flooding and localized cloudbursts, which are significant for coastal facilities influenced by sea-land interactions.

Temporal resolution limitations: Daily data often overlook short bursts of heavy rain lasting 15 to 60 minutes. These bursts can lead to flash floods, block culverts, and cause erosion channels. As a result, the warning signs for heavy rain and flash floods are often underestimated.

Short observational records: About 50 years of reliable extremes complicate stable estimates of several hundred-year design values. Tails of distributions for sub-daily rainfall and wind remain uncertain, increasing confidence bounds in screening.

Large ensemble spread for precipitation: Disagreements among EURO-CORDEX climate models are most significant when it comes to predicting precipitation intensity. Relying solely on average results from multiple models can obscure the potential for extreme rainfall events, which are crucial for designing effective drainage systems, covers, and vaults.

Engineering and Vulnerability Data Gaps:

Engineering parameter uncertainty: Proprietary or preliminary design parameters (materials, thickness, slopes) increase variability in scoring; without limits, screening scores appear more accurate than they truly are. Limited public access to detailed engineering specifications restricts quantitative risk modeling.

Material degradation data: Some barrier materials may not perform the same under climate change. Limited data on concrete, liners, and covers in harsh conditions like wet-dry cycles, freeze-thaw, and salty aerosols makes it hard to predict their performance.

Compound event modeling: The lack of multivariate extremes characterization restricts the ability to analyze joint rain-wind-surge-high GW events, so vulnerability might be underestimated where co-occurrence leads to failure modes (e.g., overflow combined with wind damage).

Site-specific microclimate: Lack of site-specific climate adjustments can misrepresent the exposure of certain assets (such as access roads, drainage inlets, crane yards), affecting scoring.

Monitoring and Validation Constraints:

Limited baseline monitoring data: Limited data hinder understanding of the current facility's vulnerability to climate changes. There are not enough on-site gauges and groundwater loggers, which makes it difficult to accurately measure hazards and exposure. Also, using gauges that are far from the site can lead to errors in the data we collect. Instrument limitations during extreme weather events may create data gaps precisely when information is most critical.

Validation data scarcity for extremes: Instrument outages or insufficient sub-hourly logging during extreme events hinder the validation of flash floods, erosion, wind indicators, and return period estimates.

Cross-facility comparison challenges: Differences in age, design, and operational histories complicate benchmarking, and harmonizing screening procedures could reduce key site-specific weaknesses if not properly documented.

Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Assessment Trade-offs:

Screening vs. detailed assessment: Rapid, consistent scoring during screening might overlook localized or micro/scale vulnerabilities (e.g., a low spot in an access road, a slightly undersized culvert, a poorly graded swale, or a low doorway threshold) that do not trigger alarms and could increase operational risk during extreme conditions.

Static vs. dynamic vulnerability: Without time-staging, improvements or degradation (such as cover settlement) are not reflected, resulting in outdated scores and misprioritized mitigation.

Multi-hazard integration challenges: Proposed screening matrices primarily evaluate hazards separately; joint probability or conditional cascades (rain + wind + high GW) are not quantified, which could underestimate the hazards.

Uncertainty propagation: Aggregating uncertainties from climate, hydro, and engineering is not formalized in the screening step; risk bands lack confidence intervals and can seem more definitive than they actually are.

Scale and Integration Issues:

Hazard interaction complexity: Fully integrated compound-risk quantification requires copulas (statistical tools that model dependence between variables like rainfall and storm surge) or event-based frameworks (simulate entire "storm events" with all drivers together), which demand detailed data and modeling beyond a screening process.

Scale mismatch problems: Translating global and regional projections into facility-scale indicators introduces structural uncertainty. Screening should identify where convection-permitting or site-specific models are necessary next.

Improvement Strategies (Recommendations):

Enhanced monitoring networks: Prioritize installations that directly address weak indicators (e.g., sub-hourly precipitation for flash floods; shoreline levels and surge sensors), and enhanced monitoring could provide better validation data for risk model development.

Integrated modeling approach: Plan the detailed phase to couple climate downscaling, hydrologic/hydraulic models, and geotechnical/structural models with shared boundary conditions and uncertainty ensembles.

Participatory assessment methods: Conduct structured sessions with operators, maintenance, and safety teams to identify undocumented vulnerabilities, such as recurring localized ponding and wind debris paths. Incorporate these findings into scoring to enhance stakeholder engagement.

Standardized assessment protocols: Maintain a consistent scoring rubric, indicator list, and documentation package across sites so regulators can compare like-for-like, while allowing site annexes for specific hazards and for cross-facility comparability.

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

☒ Coastal flooding (FI)

☐ Cold spells
☐ Droughts
☐ Desertification
☒ Flash flooding
☒ Heavy rainfall (All) (High)
☒ Heatwaves (All) (High)
☐ Landslides
☐ Permafrost thaw
☒ River flooding (High)
☒ Sea level rise (FI) (High)
☒ Soil erosion
☒ Water table variations (High)
☒ Windstorm
☐ Wildfires
☐ Others (please specify): _____

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Heavy rainfall	- High-resolution hydrological modeling; - Drainage capacity analysis;	- Enhanced drainage systems (150% design capacity); - Early warning systems; - Retention ponds;
Heat waves	- Thermal stress analysis; - Equipment performance modeling;	- Enhanced cooling systems, - Heat-resistant materials; - Modified work schedules; - Backup power;
River flooding	- Flood hazard mapping; - Hydraulic modeling;	- Improved flood protection; - Elevated critical infrastructure; - Emergency access routes;
Water table variations	- Groundwater flow modeling; - Barrier performance assessment;	- Enhanced monitoring networks - Flexible barrier systems; - Improved foundation drainage;
Sea level rise	- Coastal vulnerability assessment; - Long-term projections;	- Coastal protection upgrades; - Drainage system modifications; - Infrastructure relocation;

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

High-resolution precipitation data for extreme event modelling

Current regional climate models (12.5-50 km resolution) cannot capture that the driving factors behind flash flooding, erosion, and drainage system overtopping, as well as sub-daily precipitation intensities (15-60 minute bursts >30-50 mm/hr), are critical for facility drainage design but are poorly represented in daily climate datasets.

These gaps and uncertainties may lead to an underestimation of flash flood risk for surface facilities and access routes, result in inadequate sizing of drainage systems, culverts, and retention ponds, and hinder the validation of erosion models for multi-layer cover systems.

Site-specific soil and groundwater characteristics

The current understanding of hydraulic conductivity, porosity, and flow paths within layered till-sand-bedrock sequences is limited. Additionally, there is insufficient data regarding seasonal groundwater fluctuation patterns and how these patterns respond to extreme precipitation events. Furthermore, gaps exist in the understanding of groundwater-surface water interactions during flood events.

These gaps and uncertainties may lead to uncertain predictions of water table fluctuations that impact engineered barriers, insufficient modeling of contamination transport pathways, and inaccurate estimates of foundation settlement and structural stability risks.

Long-term performance data for engineered barrier systems

This highlights that there is limited operational experience, generally less than 30 years, with multi-layer cover systems, concrete vaults, and drainage systems under Nordic and Eastern European climate conditions, coupled with insufficient data on barrier degradation rates, joint performance, and redundancy failures, as well as a lack of standardized monitoring protocols for assessing barrier integrity.

These gaps and uncertainties may cause high uncertainty in long-term containment performance projections, difficulty in calibrating engineering models for barrier degradation, and an inadequate basis for maintenance scheduling and replacement planning of EBS.

Material degradation rates under projected climate conditions

The report highlights that there is limited accelerated aging data for materials such as concrete, bitumen, geosynthetics, and metals under conditions involving intensified wet-dry cycles, freeze-thaw, and thermal cycling, along with insufficient testing of barrier materials within the projected temperature increases of 2-4°C and precipitation changes of 10-25%, compounded by gaps in understanding the synergistic effects of multiple climatic stressors including thermal, chemical, and mechanical factors.

Historical performance data from comparable facilities

The gaps indicate that there are limited operational analogues with similar designs, waste types, and climate conditions, and highlight insufficient documentation of climate-related incidents and failures, as well as a lack of standardized reporting for extreme weather impacts on radioactive waste facilities.

For the 3Sa climate group, operational analogues can include Swedish repositories (Forsmark, Ringhals, with different designs and regulatory frameworks), French facilities (Aube, with different

climate conditions and operational practices), and UK coastal facilities (Sellafield, with different geological and engineering contexts).

Local microclimate and topographic effects on facility operations

This gap includes insufficient characterization of site-specific wind patterns, temperature variations, and precipitation distribution; limited understanding of how topography influences drainage, snow accumulation, and erosion; and a lack of data on vegetation interactions with engineered systems.

Mitigation Strategies for Data Gaps

Enhanced monitoring networks: Install high-resolution meteorological stations with 1-5 minute precipitation logging, wind sensors, and groundwater level monitoring.

Rapid site characterization: Conduct targeted geotechnical investigations for critical flow paths and foundation conditions.

Material testing programs: Initiate accelerated aging tests for key barrier materials under projected climate conditions.

Collaborative data sharing: Establish agreements with research institutions and international facilities for performance data exchange.

Standardized monitoring protocols: Develop consistent barrier integrity assessment methods across 3Sa facilities.

Site-specific climate downscaling: Commission high-resolution climate projections using convection-permitting models.

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Model resolution constraints: Inadequate representation of local-scale phenomena

Regional climate models with a resolution of 12.5 km cannot resolve coastal gradients, lake effects, urban heat islands, or convective hotspots that impact individual facilities. Similarly, hydrological models may overlook local drainage features, preferential flow paths, and microtopographic controls on runoff. Engineering models might fail to capture stress concentrations, joint behavior, and localized failure modes.

The report highlights the presence of systematic bias in hazard indicator estimates specific to site conditions, which can lead to the missed identification of critical failure modes and vulnerability hotspots, thereby reducing confidence in the effectiveness of proposed adaptation measures.

To address these gaps, several practical approaches can be used: first, statistical downscaling involves using weather generators and stochastic models to create site-specific climate series; second, nested modeling links regional climate models with high-resolution local models; and third, proxy data integration merges model outputs with local observations and empirical relationships.

Multi-hazard modeling: Limited tools for assessing compound risk interactions

Most modeling frameworks typically evaluate hazards independently, which can overlook critical interactions such as rain, wind, and surge. Estimating joint probability distributions for multiple hazards is challenging due to limited observational data. Additionally, cascading failure modes, such as drainage failure leading to flooding, erosion, and containment breaches, necessitate integrated modeling approaches.

To address these gaps, several practical approaches can be employed, including copula-based methods that model statistical dependence between hazards using copula functions, event-based simulation which generates synthetic storm events with correlated hazards through stochastic weather generators, and system dynamics modeling that represents facilities as interconnected systems featuring feedback loops and cascading effects.

Temporal scale mismatches: Connecting long-term projections with operational decisions

Climate projections extend to the year 2100 in Task 3; however, operational decisions require guidance for the near-term, spanning several decades. Facility lifespans, which typically last several hundred years, serve as a bridge across multiple climate projection time horizons that present varying degrees of uncertainty. Additionally, design standards and safety margins must incorporate considerations for both gradual climate trends and potential extreme events.

Expected challenges for operational decision-making include determining optimal timing for investments in adaptation measures amid uncertain climate trajectories, establishing appropriate safety margins to account for deep uncertainty in long-term projections through design redundancy, and structuring decision processes to facilitate learning and adjustments over time via adaptive management.

Engineering model integration: Coupling climate and facility performance models

Climate models produce meteorological variables, while engineering models require specific loading conditions such as stresses, pressures, and chemical concentrations. Model interfaces must reliably manage different temporal and spatial resolutions. Additionally, validating coupled model chains is challenging due to limited system-level performance data.

The anticipated technical challenges include variable transformation, which involves converting climate variables into engineering loads, like transforming precipitation data into hydraulic head measurements. Ensuring boundary condition consistency is also essential for maintaining compatible assumptions across various model interfaces. Finally, representing feedback mechanisms is vital for understanding how modifications to facilities can affect local climate conditions.

Validation constraints: Limited historical data for model verification

Extreme events are inherently rare, which results in limited validation data for analyzing such extreme behaviors. Historical climate data may not accurately predict future conditions, thereby restricting the applicability of validation datasets. Additionally, facility monitoring records are often of insufficient length to enable robust statistical validation.

The expected challenges for model validation include the validation of extreme values, which is complicated by limited sample sizes for return periods (for example, the period of greater than 50 years). Additionally, non-stationarity poses a challenge, as historical validation may not be applicable under changing climate conditions. Finally, validating integrated model chains against observations at the system level is difficult due to the complexity of the models.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

Near-Surface Repository Systems (Olkiluoto, ENSDF L3):

Forsmark and Ringhals repositories (Sweden): 25+ years operational experience with Nordic climate conditions (**Time periods**: 1990s-present)

Evidence: Engineered barrier performance, drainage system effectiveness, freeze-thaw impacts

Limitations: Different facility designs, varying regulatory standards

Concrete Vault Systems (Ignalina B25):

French repositories (Aube): Similar vault designs in temperate climate (**Time periods**: 1990s-present)

Evidence: Long-term concrete performance, groundwater interaction patterns

Limitations: Different climate conditions, varying operational practices

Landfill-Type Systems (Ignalina B19):

Nordic landfill covers: Experience with multi-layer cover systems (**Time periods**: 1980s-present)

Evidence: Cover stability under freeze-thaw cycles, erosion resistance

Limitations: Different waste types, regulatory requirements

Coastal Nuclear Facilities (Olkiluoto):

Sellafield (UK): Long-term coastal nuclear waste storage experience (**Time periods**: 1950s-present)

Evidence: Sea level rise impacts, storm surge effects, saltwater corrosion

Limitations: Different geological settings, facility designs

Historical Climate Analogues :

2018 Baltic Sea heatwave: Finnish coastal facilities experience

2017 Nordic extratropical cyclone: Storm surge impacts

2010 extreme rainfall: Ignalina region flooding events

2021 compound heatwave-precipitation events: Finland multi-hazard impacts

References

Climate change in the Baltic Sea 2024 Fact Sheet Baltic-Sea-Climate-Change-Fact-Sheet_2024.pdf,https://helcom.fi/wp-content/uploads/2024/10/Baltic-Sea-Climate-Change-Fact-Sheet_2024.pdf

KYT SURFACE Near Surface Repositories in Finland, VTT-R-00124-20, 2020 Research report, https://kyt2022.vtt.fi/raportit_2020/SURFACE_Near%20Surface%20Repositories%20in%20Finland%202019%20vuosiraportti.pdf

IAEA-NS-ARTEMIS, Mission to Finland, 2022

Surface disposal in oceanic climates (France, Belgium, UK)

Group Description

Group: 3Sb

Disposal type (Name): Surface (1.CSM/CSA-F, 2.Dessel-B, 3.LLWR-UK)

Nuclear waste type: LILW

Current climate: Cfb

Countries: France, Belgium, UK

Partners: Andra, ASNR, BGRM, SCK CEN, NWS

Time window for construction and operation: 100 a AP for Dessel-B

Location/Type of waste/Surface facilities/Distance from the shoreline

Location:

CSM/CSA :50-45N(Latitude), -2E(CSM)(Longitude), 80m(CSM)(Altitude)

Dessel : 51°13'23.4"N(Latitude), 5°04'37.5"E(Longitude), 20-50m(Altitude)

LLWR :55-50N(Latitude), 5-0W(Longitude), 10-20m(Altitude)

Type of waste:

CSM/CSA : ILW-SL for CSM, LILW-SL for CSA

Dessel : Low and intermediate level short-lived waste (LILWSL)

LLWR : Low Level Waste Repository (LLWR)

Surface facilities:

CSM/CSA : CSM : Closure - CSA : In operation

Dessel : Belgoprocess: storage facility (nuclear facility), Caisson factory: waste package factory (non-nuclear facility), IPM: Installation for the production of monoliths (nuclear facility), Entrance cluster: control room for remote-controlled operations on-site and administration (non-nuclear facility), Water collection buildings: storage tanks of the drainage system of the disposal modules (non-nuclear facility), Maintainance building: work place (non-nuclear facility)

LLWR : Railway bay; grouting plant; seven closed disposal trenches covered with an interim cap; two engineered disposal vaults (open air); leachate management system; marine holding tank for liquid discharges; monitoring infrastructure; operations infrastructure; office accommodation. No pre-disposal management is done on the site other than grouting. A major capping programme is starting with preparatory works now underway. Reference (for basic site information - more up-to-date references are available but they are not available online): LLWR Site History and Description, LLWR/ESC/R(11)10018, May 2011. https://webarchive.nationalarchives.gov.uk/ukgwa/20170412103307/http://llwrsite.com/national-repository/esc-permit-approval/

Distance from the shoreline:

CSM/CSA : 3 km (CSM) & 300 km (CSA)

Dessel : 100-200km

LLWR : <1km

Current phase/EBS/Host rock

Phase:

CSM/CSA : Monitoring after closure for CSM, Operation for CSA

Dessel : Construction

LLWR :Operation

EBS:

CSM/CSA : CSM - multi-layers engineered barrier (see Andra files), CSA - Concrete containers infilled with sand

Dessel : Multi-layer cover consisting of an earth cover resting on an impervious concrete top slab. Earth cover is 4.5 m thick and consists of a biological layer (sandy loam), a bio-intrusion barrier (coarse inert material), an infiltration barrier (compacted clay) and a drainage layer (sand). Modules in fiber-reinforced concrete. Monoliths (fiber-reinforced concrete), back-filled with mortar.

LLWR : Trenches: The first trench, Trench 1, was opened in 1959. It was dug into clay in a railway cutting made for the Royal Ordnance Factory (ROF) and the waste was placed by tumble tipping. Subsequent trenches were dug up to Trench 7, placing BES at the bases where natural clay was not present or sufficient. Trench 7 continued in operation until 1995. The current interim cap was placed over Trenches 1 to 6 in 1989 to 1990 and over Trench 7 in 1995. / Reinforced concrete open Vaults; Vault 8 was commissioned in 1988 and is very close to full as of 2025. Its capacity is around 308,000 cubic metre. The Vault 8 design has a basal liner of a minimum of 1 m of in situ clay, or at least 300 mm of Bentonite Enriched Soil (BES) where in-situ clay was not present. The majority of wastes are packed within ISO-freight containers and grouted. Containers are stacked to either 4 or 6 high. Vault 9 was constructed from 2008 to 2010. Its capacity is around 247,000 cubic metre. It is currently accepting waste, mostly in grouted ISO-freight containers. The design for vault 9 incorporates a double composite barrier of geomembrane on BES base, designed (with the vault walls) to contain any infiltration for as long as possible. Should Vault 9 eventually fill with leachate ('bathtub'), overtopping leachate would be directed to a leachate management system. Vault 9A is a planned extension to Vault 9. Future vaults are currently anticipated up to Vault 12. /Capping Operations: The entire area of vaults and trenches will be closed in sequence from north to south with a unified multi-layered barrier system, comprised of a highly engineered, single dome final cap (~>5m thick), cut-off-wall (COW) and associated engineering. This will be constructed in strips across each vault and adjacent area of trenches, as soon as practicable after closure of each vault. The cap is designed to provide the best practicable impermeable barrier to infiltration of rainwater and to intrusion, and to maintain its functions for as long as possible. A COW will be constructed to provide a low permeability vertical barrier around the facility./Leachate Management: Engineered drainage pathways are provided by the sub-base features associated with the vault design (e.g. under-base drainage blanket), with the aim of maintaining low saturation conditions within the disposed wastes. /Reference: LLWR Engineering Design, LLWR/ESC/R(11)10020, May 2011, https://webarchive.nationalarchives.gov.uk/ukgwa/20170412103307/http://llwrsite.com/national-repository/esc-permit-approval/

Host rock:

CSM – Metamorphic (CSM - In surface), CSA – Sand (CSA - In surface)

Dessel : -

LLWR : No 'host rock' per say as no safety function is assumed for the geology. The local geology consists of Quaternary age deposits (up to 2.6 million years old) overlying older bedrock. Quaternary deposits at the LLWR site are a result of complex glacial processes, which were responsible for the deposition of a sequence of deposits of clay, sands and gravels up to 60 m thick. The Quaternary deposits overly Triassic Ormskirk Sandstone (around 240 million years old)./Reference: LLWR Hydrogeology, LLWR/ESC/R(11)10022, May 2011. https://webarchive.nationalarchives.gov.uk/ukgwa/20170412103307/http://llwrsite.com/national-repository/esc-permit-approval/

Current climate /Current land use/Geology/Hydrology/Geomorphology/Porewater

Köppen-Geiger:

CSM/CSA : Cfb

Dessel : Cfb

LLWR : Cfb

Köppen-Trewartha:

CSM/CSA : Do

Dessel : Do

LLWR : DOf

(0-100 years AP)

CSM/CSA: CSM (Cfb) CSA (Cfb from 0 to 97y, and Csb from 98 to 122y)

Dessel: Trewartha: Do, possibly Cs (NIROND-TR 2009–07E Version 2 19 October 2018)

LLWR: Expected to retain temperate oceanic humid climate (class DOf, Köppen-Trewartha classification).

IPCC SSP2-4.5 is used as reference scenario, SSP1-2.6 low emission scenario, SSP5-8.5 high emission scenario.

Potential evapotranspiration expected to increase by 7% to 22% for low and high emission scenarios (reference emissions scenario, 13%).

Temperature change (°C) up to 100y After Present (AP) relative to site baseline:

Low emission scenario: 1.8 (range 1.3 to 2.4)

Reference emission scenario: 2.7 (range 2.1 to 3.5)

High emission scenario: 4.4 (range 3.3 to 5.7)

Reference: Nuclear Waste Services, Climate Projections for the 2026 ESC, Analysis and Supporting Information, QRS-10128A-NAM, December 2023 - sent by email.

Current land use:

CSM/CSA : Grassland

Dessel : Grassland, cropland and built area

LLWR : Shrubland

Hydrology:

CSM/CSA : Perennial, surface water dominated (river water is mostly from precipitation)

Dessel : Perennial, groundwater dominated (rivers are mostly fed by groundwater)

LLWR : Perennial, surface water dominated (river water is mostly from precipitation)

Geomorphology:

CSM/CSA : Low relief topography: rather flat landscape

Dessel: Low relief topography: ratherlandscape

LLWR: Low relief topography: rather flat landscape

Geology below the facility:

CSM/CSA : CSM - Metamorphic & Ignous, CSA – Sedimentary

Dessel : Sedimentary

LLWR : No 'host rock' per say as no safety function is assumed for the geology. Surface based facility for LLW.

Hydrogeology below the facility:

CSM/CSA : CSM – Phreatic, CSA - Phreatic

Dessel : Aquifer phreatic

LLWR : Aquifer phreatic

Porewater below the RWM site/facility:
CSM/CSA: Fresh
Dessel: Fresh
LLWR: Fresh
Impact of sea level:
CSM/CSA : No
Dessel : yes
LLWR : Yes

Screening

Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

- ☒ Coastal flooding (x)
- ☒ Cold spells (x)
- ☒ Droughts (x)
- ☐ Desertification (x)
- ☒ Flash flooding (x)
- ☒ Heavy rainfall (x)
- ☒ Heatwaves (x)
- ☐ Landslides
- ☐ Permafrost thaw
- ☒ River flooding (x)
- ☒ Sea level rise (x) (XXX)
- ☒ Soil erosion (x) (XXX)
- ☒ Water table variations (x)
- ☒ Windstorm (x)
- ☒ Wildfires (x)
- ☐ Others (please specify):

Interdependencies and Cascading Hazards:

- Coastal Storm → Storm Surge → Coastal Flooding → Groundwater Intrusion
- Heavy rainfall→ River Flooding → Slope Instability → Infrastructure Damage
- Heatwave → Drought → Soil Desiccation → Barrier Degradation
- Windstorm → Power Failure → Cooling System Failure → Temperature Excurse

Please, indicate the data source (for climatic, sea level,….), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
CCI-HYDR	bwk.kuleuven.be/hydr/CCI/Reports/cci-hydr-iib-climatechangescenarios-extinbo.pdf	1961-1990			2071-2100	SRES	Yes	n/a	Yes	Belgium
Cordex.be	KMI - De klimaatvooruitzichten voor 2100	1976-2005		2036-2065	2070-2100	RCP2.6, 4.5, 8.5	Yes			Belgium
UK Climate Projections	UKCP18[8]	1981-2010	2020-2050	2050-2080	2080-2125	RCP2.6, 4.5, 8.5	Yes (2.2km)	Yes	Yes	UK

Comments:

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use?

*Which **hazard indicator** would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)?*

*Which **exposure indicator** would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones?*

*Which **vulnerability indicator** would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks?*

*Finally, for each hazard, **indicate the expected impact(s)** on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.*

Hazard	Hazard Indicator	Exposure Indicator	Vulnerability Indicator	Expected Impact(s)
River Flooding	- 100-year flood depth (m); - Annual exceedance probability;	- Facility elevation above river; - Distance to water bodies; - Critical infrastructure in flood zone;	- Drainage system capacity; - Emergency response time; - Backup power elevation;	- Inundation of storage areas; - Loss of access roads; - Power supply disruption;
Coastal Flooding	- Storm surge height (m);	- Distance from shoreline; - Coastal defense infrastructure;	- Erosion protection measures; - Evacuation procedures; - Waste package water resistance;	- Direct inundation of facilities; - Erosion of protective barriers;
Sea Level Rise	- Rate of rise (mm/year); - Projected total rise by 2125;	- Current elevation buffer;	- Adaptive capacity of barriers; - Design life vs. SLR projections;	- Permanent inundation risk; - Groundwater table rise; - Infrastructure undermining;

Windstorms	- Peak gust speed (m/s); - Storm frequency; - Duration of extreme winds;	- Exposed structures; - Crane operations; - Temporary structures; - Power lines;	- Building design standards; - Anchoring systems; - Redundant power supply; - Storm shutdown procedures;	- Structural damage; - Flying debris hazards; - Power outages; - Operational delays;
Heatwaves	- Days >30°C; - Maximum temperature; - Heat wave duration;	- Cooling system dependency; - Worker exposure hours; - Heat-sensitive equipment; - Concrete structures; - Steel roof;	- Cooling redundancy; - Worker heat protocols; - Material temperature limits; - Emergency cooling capacity;	- Cooling system overload; - Concrete degradation; - Electronic failures;
Cold spells(waves)	- Days <0°C; - Minimum temperature; - Coldwave duration;	- Heating system dependency; - Worker exposure hours; - Heat-sensitive equipment; - Concrete structures; - Steel roof/structures;	- Material temperature limits;	- Heating system overload; - Concrete degradation; - Steel degradation; - Electronic failures;
Droughts	- Standardized Precipitation Index; - Consecutive dry days;	- Water consumption needs; - Fire risk areas;	- Water storage capacity; - Alternative water sources; - Drought contingency plans;	- Construction delays; - Dust mobilization; - Increased fire risk; - Barrier desiccation;

Water Table Variations	- Groundwater level change (m); - Seasonal fluctuation range; - Trend analysis;	- Depth to waste packages; - Foundation design; - Barrier systems;	- Drainage system capacity; - Waterproofing integrity;	- Barrier saturation; - Chemical degradation; - Radionuclide mobility;
Heavy rainfall	- Intensity-duration-frequency of precipitation;	- Infiltration barriers;	- Performance of engineered drainage system;	- Concrete engineered barrier degradation; - Leaching;
Flash flooding	- Rainfall intensity (mm/hr);	- Catchment area (km²); - Topographic depression areas;	- Drainage system response time; - Surface water management; - Early warning systems;	- Inundation/re-saturation of shafts and underground galleries; - Rapid inundation; - Erosion channels; - Sediment deposition; - Infrastructure overwhelm;

Historical Extreme Events:

LLWR-UK: Flooded during Hurricane Idalia (2023)

European facilities: 2021 flood events, 2018 drought impacts

Construction Phase Impacts:

Work stoppages due to extreme weather

Material delivery disruptions

Quality control challenges in extreme conditions

Worker safety incidents

Operational Phase Impacts:

Disrupted waste receipt and handling

Monitoring system failures

Emergency response impediments

Accelerated infrastructure degradation

Most Vulnerable Components:

Surface water management systems - First point of failure in flooding

Power supply infrastructure - Critical for cooling and monitoring

Multi-layer cover systems - Sensitive to extreme temperatures, extreme precipitation events and moisture

Access routes - Essential for emergency response

Monitoring instrumentation - Vulnerable to extreme conditions

Component-Specific Vulnerabilities:

Engineered barriers (EBS): Clay desiccation, concrete carbonation

Container integrity: Corrosion acceleration, thermal cycling

Drainage systems: Capacity exceedance, blockage

Interim caps: Erosion, settlement, cracking

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Coastal Storm + High Tide + Heavy Rainfall

- **Mechanism**: Storm surge prevents river drainage while heavy rainfall overwhelms inland capacity
- **Amplification** : 2-3x flooding extent compared to single hazard
- **Consequences**: Complete site isolation, multi-pathway contamination risk

Drought + Heatwave + High Winds

- **Mechanism**: Dry conditions enable dust mobilization during high winds, while heat stresses personnel and equipment
- **Amplification**: Increased airborne contamination risk, worker safety challenges
- **Consequences**: Operational suspension, enhanced monitoring requirements

Sea Level Rise + Groundwater Rise + Intense Precipitation

- **Mechanism**: Reduced vertical drainage capacity as water table rises to meet surface flooding
- **Amplification**: Permanent saturation of previously unsaturated zones
- **Consequences**: Accelerated barrier degradation, buoyancy risks

Sequential Storms During Recovery

- **Mechanism**: Second storm impacts before recovery from first event (Example: Winter 2023/24 European storm sequence)
- **Amplification**: Cumulative infrastructure damage, depleted response resources
- **Consequences**: Extended operational disruptions, cascading failures

Power Grid Failure + Extreme Temperature Event

- **Mechanism**: Regional power failure during heatwave or cold spell (Critical dependencies: Cooling systems, monitoring equipment, access controls)
- **Amplification**: Loss of multiple safety systems simultaneously
- **Consequences**: Potential for unmonitored conditions, temperature excursions

How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

Semi-Quantitative Risk Scoring System:

Risk Score = (H × E × V) where:

H = Hazard likelihood (1-5 scale)

E = Exposure level (1-5 scale)

V = Vulnerability degree (1-5 scale)

Example of the Scoring Criteria:

Score	Hazard Likelihood	Exposure Level	Vulnerability
5	>80% in 100yr	Critical assets exposed	No resilience measures
4	60-80% in 100yr	Important assets exposed	Limited measures
3	40-60% in 100yr	Moderate assets exposed	Some measures
2	20-40% in 100yr	Low value assets	Good measures
1	<20% in 100yr	Minimal exposure	Excellent measures

Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☒ Coastal flooding
- ☐ Cold spells
- ☐ Droughts
- ☐ Desertification
- ☐ Flash flooding
- ☒ Heavy rainfall
- ☒ Heatwaves
- ☐ Landslides
- ☐ Permafrost thaw
- ☒ River flooding
- ☒ Sea level rise
- ☐ Soil erosion
- ☒ Water table variations
- ☒ Windstorm
- ☒ Wildfires
- ☐ Others (please specify): _____

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Sea Level Rise and Coastal Flooding	- Assessment of erosion mechanisms including undercutting vs. direct wave attack scenarios based on facility elevation relative to projected cliff base;	- Potential relocation of critical infrastructure to higher elevations; - Construction of enhanced sea defenses where feasible; - Development of waste retrieval contingency plans for accelerated exposure scenarios;
Heavy Rainfall	- Detailed hydrological modeling incorporating engineered drainage system capacity assessment and multi-layer cover performance	- Upgrading drainage system capacity with enhanced pumping stations and larger collection systems; - Implementation of improved multi-layer cover designs with

	analysis under extreme precipitation events; - Detailed near-field modelling;	enhanced infiltration barriers using advanced geomembranes; - Installation of real-time precipitation monitoring and early warning systems; - Monitoring of humidity inside disposal cells; - Development of temporary cover systems for extreme weather events;
Heat waves	- High-resolution temperature and humidity modeling with assessment of duration and intensity of future extreme temperature events; - Analysis combining climate projections with system vulnerability including design limits and material resilience under temperature stress; - Evaluation of cooling system performance under projected temperature increases of +1.8°C to +4.4°C over 100 years;	- Upgrading HVAC (Heating, Ventilation, and Air Conditioning) systems to ensure adequate cooling capacity under extreme temperatures; - Installing thermal insulation or passive cooling solutions; - Adjusting operational schedules to limit exposure during peak heat hours; - Enhanced backup power systems for cooling infrastructure;
Water Table Variations	- 3D hydrogeological modeling incorporating climate change effects on groundwater recharge rates and seasonal fluctuation patterns; - Analysis of groundwater level changes relative to waste package depth and foundation design; - Assessment of drainage system capacity under varying water table conditions and potential for barrier saturation;	- Enhanced groundwater monitoring networks with automated alert systems; - Installation of improved drainage systems with adaptive capacity; - Waterproofing upgrades for critical infrastructure; - Implementation of groundwater control measures including potential dewatering systems where appropriate; - Elevation of critical infrastructure above projected flood levels;
River Flooding	- Flood risk modeling using updated precipitation projections and catchment-scale hydrological models;	- Elevation of critical infrastructure above projected flood levels; - Construction of flood barriers and improved site drainage;

	- Assessment of 100-year flood depths and facility elevation buffers; - Analysis of emergency response time and access route vulnerability during flood events;	- Development of emergency response protocols including alternative access routes; - Installation of flood-resistant equipment housings;
Windstorms	- Structural vulnerability assessment of buildings and infrastructure under enhanced wind loading conditions;	- Structural reinforcement of buildings and infrastructure to meet enhanced wind load requirements; - Securing of loose materials and equipment; - Installation of wind-resistant building materials and designs; - Enhanced maintenance protocols for post-storm inspections;
Wildfires	- Modelling tools to estimate frequency and intensity of wildfires;	- Landscape should be deforested Firelanes;

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Temporal Resolution and Coverage Limitations: High-Resolution Climate Data

Sub-daily data availability remains insufficient for detailed hydrological modeling, especially limiting the ability to simulate extreme precipitation events at the necessary temporal scales for infiltration and drainage system analysis.

Spatial Resolution and Local-Scale Process Representation: Spatial Downscaling

The 25km grid resolution inadequately captures local microclimate variations, especially for coastal facilities affected by complex land-sea interactions. Coastal process representation remains limited at the facility level, with insufficient spatial resolution to accurately model storm surge propagation, coastal erosion, and groundwater-surface water interactions in nearshore areas.

Complex topography influences on local climate patterns are inadequately represented, creating systematic biases in precipitation and temperature projections for facilities located in topographically complex terrain.

Process-Based Modeling Data Gaps: Material Property Evolution Data

The degradation behavior of facility materials under changing climate conditions lacks empirical validation datasets, which introduces fundamental uncertainties in barrier performance projections over the targeted time period.

Waste form behavior under evolving climate conditions remains poorly characterized, particularly regarding radioactive material mobility and containment performance under unprecedented temperature and precipitation regimes.

Validation and Calibration Data Limitations: Observational Record

Historical baseline periods for model calibration vary significantly between climate datasets (1961-1990 for CCI-HYDR, 1981-2010 for UKCP18), creating systematic inconsistencies in bias correction and model validation procedures.

Limited analogues for comparable RWM facilities restrict model validation opportunities, particularly for unique disposal system configurations and operational environments.

Recommended Mitigation Strategies:

Implementation of ensemble modeling approaches utilizing multiple climate models and scenarios to bound uncertainty ranges systematically.

Application of formal uncertainty quantification methodologies including Monte Carlo approaches for parameter sensitivity analysis.

Integration of enhanced observational networks for real-time model updating and bias correction procedures.

Development of adaptive monitoring trigger systems linking observational data to predetermined response protocols.

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Process Coupling and Multi-Physics Integration Limitations: Complex System Interaction Modeling

Limited capability to quantitatively model multi-hazard cascade interactions, especially for sequences involving coastal storms, groundwater rise, and extreme precipitation events happening close together.

Groundwater-surface water interaction modeling in coastal environments shows inadequate coupling between marine and terrestrial hydrological processes.

Scale Integration and Temporal Extrapolation Challenges: Temporal and Spatial Scale Mismatches:

Process-based models calibrated using short-term historical data (decades) require extrapolate over assessment periods much longer than calibration timescales, which leads to the buildup of systematic uncertainty.

Spatial scale integration between regional climate projections (25 km resolution) and facility-scale process models (meter-scale resolution) introduces systematic downscaling errors that propagate through assessment chains.

Recommended Methodology Enhancement Priorities:

Implementation of formal model ensemble approaches combining multiple modeling frameworks with systematic bias assessment and uncertainty quantification.

Development of process-integration methodologies better coupling climate, hydrological, and geotechnical modeling systems with explicit uncertainty propagation.

Establishment of adaptive modeling frameworks that incorporate observational data for periodic model updating and parameter refinement.

Enhanced validation strategies utilizing natural and artificial analogue systems for extended temporal validation of model projections.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

FAVL studies serve as an analogue for climate evolution, with the climate evolution model used for CSA being validated through these studies. These studies are relevant due to the similar geological and climatic conditions present. The time applicability of this model extends to medium-term projections, spanning hundreds of years. However, there are limitations, including differences in facility design and waste characteristics.

The climate evolution model used for the CSA has been used for FAVL studies as analogue

References

Use of UK Climate Projections 2018 (UKCP18) 2022-UK-NWS-ukcp18-position-statement-rev-2-1.pdf https://www.onr.org.uk/media/ismlkpqi/ukcp18-position-statement-rev-2.pdf

Extension of CCI-HYDR climate change scenarios for temperature and wind speed, 2009, https://bwk.kuleuven.be/hydr/CCI/Reports/cci-hydr-iib-climatechangescenarios-extinbo.pdf

Climate Projections for the 2026 ESC, Analysis and supporting information, LLWR Environmental Safety Case, 2023

Coastal Evolution Projections, LLWR Environmental Safety Case, 2024

Surface disposal in Mediterranean climates (Spain, Italy)

Group Description

Group: 3Sc

Disposal type (Name): surface (1. El Cabril-ESP, 2. Deposito Nazionale, National Repository-IT)

Nuclear waste type: VLLW and LILW

Current climate: Csa for Köppen-Geiger clasification

Countries: Spain, Italy

Partners: Amphos 21, ENEA**Time window for construction and operation**: until 2073 for EL Cabril. 0-100 a AP

Location/Type of waste/Surface facilities/Distance from the shoreline

Location:

El Cabril : 40-35N(Latitude), 10-5E(Longitude),200-500m(Altitude)

Deposito Nazionale (national repository): to date, the siting process for the national repository and Technology Park is ongoing. The initial phase identified 51 potentially suitable areas (CNAI - National Chart of Potentially Suitable Areas) across multiple regions in Italy. These areas can be grouped into the following 5 macro areas based on their geographical location: NORTH (Piedmont region), CENTER (includes areas in the Lazio and Tuscany regions), SOUTH (includes areas in the Basilicata and Puglia regions), ISLANDS (includes areas in the Sicily and Sardinia regions). The designation of these areas has been subject to public consultation and further technical assessment as the project advances.

Type of waste:

El Cabril : VLLW and LILW

Deposito Nazionale: Disposal of LLW, ILW-SL; interim storage of ILW-LL and HLW

Surface facilities:

El Cabril : The main surface facilities associated with the storage site are the personnel offices and the reception, treatment, and conditioning plant. The radioactive material arrives already immobilized in 220-liter concrete drums. At this facility, the drums are placed into concrete containers holding 18 drums each.

Deposito Nazionale: the extension of the site is approximately 150 hectares, divided into two distinct physically separated areas:

the Disposal Area (110 ha), dedicated to the management of radioactive waste and to the hot laboratory;

the Technology Park (40 ha), that will house the non-radioactive laboratories, common structures and services, an applied research center (free from radioactive contamination).

In the Disposal Area, the following facilities will be built: the complex for the definitive disposal of VLLW, LLW; the module packaging plant; the treatment plant for solid waste produced; the module production plant; the cell production plant; the complex dedicated to the long-term interim storage of ILW-LL, HLW and irradiated fuel; the plant for the quality control of radioactive waste and radiochemical analyses; a research laboratory on radioactive materials (hot laboratory); structures for supporting services, necessary for carrying out the activities of the repository.

Distance from the shoreline:

El Cabril : 100-200 km

Deposito Nazionale : 50-100 km

Current phase/EBS/Host rock

Phase:

El Cabril :Operation

Deposito Nazionale: Site selection

EBS:

El Cabril : The packages received are left in concrete casks. When a cask is at full capacity, it is immobilised by means of injected mortar, forming a compact block. This block is deposited in the disposal vault. Once the disposal vault is full, it is sealed with a slab made of reinforced concrete and waterproofed. Once all the structures in a platform are full, it will be sealed with a final cover made up of various drainage and waterproofing layers and topped with a final layer of topsoil to enable integration into the environment. The site's monitoring and surveillance phase begins at this time. It lasts approximately 300 years.

Deposito Nazionale: four components constitute the engineered barriers system:

the Container, that includes the conditioned waste form (the waste itself, immobilized within a cement or other solid matrix) and the surrounding metal or concrete container;

the Disposal Module, that is the large, reinforced concrete structure into which multiple waste packages are placed; the remaining void spaces within the module are filled with grout (cement mortar) to immobilize the container;

the Storage Cell that houses the assembled modules (designed to contain the modules and provide structural protection);

the Multilayered Cover that is the complex, multi-layered engineered cap that will be built over the storage cells after the repository is filled and closed, to prevent water infiltration, limit erosion, and protect the underlying cells.

Host rock:

El Cabril : Metamorphic (0-20m from surface to the top of the host rock and >100m from top to bottom of host rock)

Deposito Nazionale: It's not possible to provide a single, consistent description of the host rock or common geological characteristics that apply uniformly across all 51 potentially suitable areas, or rock features common to the 5 macro areas, because they are quite different.

Current climate /Current land use/Geology/Hydrology/Geomorphology/Porewater

Köppen-Geiger:

El Cabril : Csa

Deposito Nazionale: All the five macro areas have the same Köppen-Geiger classification: C – temperate: s "dry summer": and a "hot summer".

Köppen-Trewartha:

El Cabril : Cs

Deposito Nazionale: The five macroareas have different Köppen-Trewartha classification

NORTH: Piedmont region – Do

CENTER: Lazio/Tuscany region – Cw and Cf

SOUTH: Basilicata/Puglia region – Cw and Cf

ISLAND: Sicily – Cs

ISLAND: Sardinia – Cw and Cf

(0-100 years AP)

El Cabril : 1) Future Kopper Geiger climate: BSh. Annual precipitation in southern Spain is expected to decrease by up to 20–30% by the end of the 21st century. Spring and summer will see the most significant reductions, with precipitation declining by more than 20%, leading to

prolonged dry periods. Winter and autumn rainfall could drop by 10–15%, affecting water recharge cycles. 2) Summer days (>25°C) may increase by up to 35 days/year, and extreme heat days (>35°C) by 20–30 days/year.

Deposito Nazionale: More arid respect to now:

Köppen-Geiger classification: from C “temperate” to B “arid”;

Köppen-Trewartha classification: from C to B.

Hydrology:

El Cabril : Ephemeral (rivers run dry each year or during consecutive years)

Deposito Nazionale: it’s not possible to provide uniform hydrological characteristics for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because of the wide-ranging geological and hydrogeological diversity across Italy.

Current land use:

El Cabril : Shrubland

Deposito Nazionale: it’s not possible to provide uniform current land use information for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because the areas span different geographic and productive regions of Italy. Land use across the candidate sites will naturally reflect the varied national landscape, ranging from areas dominated by agriculture to those with less intensive development.

Geomorphology:

El Cabril : Hilly topography: elevated areas can clearly be recognized in the landscape

Deposito Nazionale: it’s not possible to provide uniform geomorphology information for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because Italy's territory is geomorphologically diverse, with highly varied landforms and active processes. However, all candidate areas share a fundamental set of exclusionary geomorphological constraints which are more critical than their specific landforms. The rigorous application of the siting criteria (ISPRA Technical Guide No. 29) guarantees that all 51 areas are defined by the absence of high-risk geomorphological features. Therefore, while the specific geomorphology (e.g., a low-relief plateau versus a gently rolling plain) may vary among the suitable areas, they all demonstrate a baseline of high geomorphological stability and low susceptibility to natural hazards as a result of the systematic screening process.

Geology above host rock:

El Cabril : The metamorphic rocks on which the facilities are located outcrops at the surface

Deposito Nazionale: It’s not possible to provide uniform geology above host rock information for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because Italy's regional geology is highly diverse. The shallow geological formations will naturally differ based on the macro-area and local processes. However, a fundamental commonality is that the geology above the host rock must meet strict requirements related to the overall safety and integrity of the faility. The application of the Exclusion Criteria (EC) and Investigation Criteria (IC) during the siting phase ensures that all suitable areas share the safety and integrity characteristics.

Geology below the host rock:

El Cabril : Metamorphic

Deposito Nazionale: it’s not possible to provide uniform geology below host rock information for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because Italy's highly diverse and complex regional geology. However, the deep geological formations beneath the near-surface facility must satisfy stringent requirements to function as the ultimate natural barrier against radionuclide migration.

Hydrogeology above the host rock:

El Cabril : no surface facililty

Deposito Nazionale: It's not possible to provide the hydrological characteristics required for all 51 suitable areas, or provide characteristics common to the 5 macro areas, because they are quite different.

Hydrogeology below the host rock:

El Cabril : Fractured crystalline rock

Deposito Nazionale: it's not possible to provide uniform hydrogeology information above the host rock for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas due to the highly variable nature of shallow hydrological systems across the Italian territory. However, all candidate areas share the fundamental requirement of minimizing water infiltration, groundwater interactions with underground structures and protecting the engineered barriers.

Porewater of the host rock at the RWM site/facility:

El Cabril : Fresh

Deposito Nazionale: it's not possible to provide a uniform porewater of the host rock at the RWM site/facility for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because the chemical composition of the porewater is inherently dependent on the specific mineralogy and geological history of the host rock, which varies across the Italian territory. Despite this variability, all acceptable sites must demonstrate that their porewater chemistry fulfills a set of strict, functionally uniform safety requirements for the host rock, which acts as a fundamental natural barrier.

Porewater of the host rock above the RWM site/facility:

El Cabril : surface facility

Deposito Nazionale: It's not possible to provide a uniform porewater of the host rock above the RWM site/facility for all 51 potentially suitable areas, or provide characteristics common to the 5 macro areas, because the chemical composition of the shallow porewater is highly variable, depending on local factors such as climate, vegetation, proximity to the surface, and type of lithology.

Porewater of the host rock below the RWM site/facility:

El Cabril : Fresh

Deposito Nazionale: It's not possible to provide the hydrological characteristics required for all 51 suitable areas, or provide characteristics common to the 5 macro areas, because they are quite different.

Future climate at the end of operation (1,000 years) and the sea level

Climate in 100-10,000 years:

El Cabril : -

Deposito Nazionale (100-200 years AP) The available climate projections end at 2100; at the moment there has been no need to carry out more in-depth climate studies until the definitive site has been identified.

Deposito Nazionale (200-10,000 years AP) Not applicable at the future Italian near-surface repository, considering that, at the moment, the safety of the facility is considered to be guaranteed for about 300 years. In fact, based on the preliminary long-term safety assessment, the institutional control phase will continue for approximately 300 years after which, thanks to the radioactive decay, the site will be available for other uses (negligible radiological impact). At the end of the siting phase, once the site will be identified, a more detailed and specific safety analysis of the future repository (safety case) will be carried out; therefore, the institutional control period and the period of safety guaranteed for the repository will be eventually reevaluated, based on the detailed information and available updates.

Impact of sea level:

El Cabril : No

Deposito Nazionale : Considering that the safety of the surface disposal facility must be guaranteed for about 300 years and that the site must satisfy the Exclusion Criterion of being located above 20 meters above sea level (m a.s.l.) and outside of the 5 km coastal buffer zone, it is expected to remain above future sea level throughout the assessment period. This criterion explicitly accounts for the long-term effects of eustatic sea level rise, local land subsidence/uplift, and potential coastal retreat.

Screening

Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

- ▱ Coastal flooding
- ☐ Cold spells
- ☒ Droughts (SP)
- ☒ Desertification (SP)
- ☐ Flash flooding
- ☒ Heavy rainfall (IT and SP)
- ☒ Heatwaves (IT and SP)
- ☐ Landslides
- ☐ Permafrost thaw
- ☒ River flooding (SP)
- ☐ Sea level rise
- ☒ Soil erosion (IT and SP)
- ☒ Water table variations (IT and SP)
- ☒ Windstorm (IT and SP)
- ☒ Wildfires (SP)
- ☐ Others (please specify): _____

Please, indicate the data source (for climatic, sea level,….), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
AdapteCCa	AdapteCCa*	1995-2004	2011-2040	2041-2070	2071-2100	RCP4.5 RCP8.5	Yes	Yes	Yes	Spain
Med-CORDEX	ISPRA, 2015. Il clima futuro in Italia: analisi delle proiezioni dei modelli regionali. Stato dell'Ambiente 58/2015. ISBN 978-88-448-0723-8, luglio 2015	1971-2000	2025-2050	2041-2070	2061-2090	RCP4.5 RCP8.5	Yes		Yes	Italy

Comments: https://escenarios.adaptecca.es/ provides ensemble data from the CMIP6 experiment for Spain

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use?

*Which **hazard indicator** would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)?*

*Which **exposure indicator** would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones?*

*Which **vulnerability indicator** would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks?*

*Finally, for each hazard, **indicate the expected impact(s)** on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.*

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impact(s)
Heavy rainfall(IT)	- Frequency of high intensity precipitation events (extreme events);	- Post closure phase: multilayer coverage; - Operational phase: ground and underground facilities;	- Post closure phase: vulnerability dependent on the type of materials used for multilayer coverage and its emplacement; - Operational phase: vulnerability related to the management system of runoff water;	- Post closure phase: exposure of the underground facilities; - Operational phase: flooding of ground and underground facilities;
Heavy rainfall(SP)	- Maximum precipitation in 24h; - 95 percentile of daily precipitation; - Maximum precipitation in 5 days;	- Historical floods; - Operation protocols for heavy rain episodes;	- Multilayer cover hydraulic conductivity; - Drainage system capacity;	- Slope instability of the multilayer cover; - Erosions of the multilayer cover; - Water infiltration in the facility;
Heatwaves(IT)	- Number of days with temperature well above the summer average;	- Presence of monitoring instrumentation; - Presence of workers during construction and operational phases of the repository;	- Vulnerability related to the type of instruments; - Vulnerability related to the working and environmental conditions of workers;	- Impact on monitoring instruments sensible to heat; - Impacts on workers during the construction and operational phases of the repository;
Heatwaves(Extreme heat) (SP)	- Maximum temperature;	- The average historical summer maximum	- Presence of workers during construction and operation;	- Heat stress for workers;

	- Extreme maximum temperature; - Summer nights (Tmin > 20ºC); - Longest heatwave duration;	temperature is above 33ºC; - The average historical extreme maximum temperature is above 41ºC;	- Surface facility, affected by changes in air temperature. For instance, thermal expansion of concrete/steel structures;	- Concrete cracking due to thermal expansion;
Soil erosion (IT)	- Frequency of high intensity precipitation events (extreme events); - Thickness of multilayer coverage eroded;	- Multilayer coverage;	- Vulnerability dependent on the type of materials used for multilayer coverage and its emplacement;	- Exposure of the underground facilities during the post-closure phase;
Soil erosion (SP)	- Total dry days (pr<1mm); - Maximum number of consecutive dry days; - Maximum precipitation in 24h;	- Slope of the multicover layer is exposed to erosion; - Sparse vegetation;	- High slope of the multi-cover layer;	- Slope instability of the multilayer cover; - Erosions of the multilayer cover;
Water table variation (IT)	- Reduction of rainfall;	- Underground facilities in relation with groundwater;	- Vulnerability related to the geochemistry of the host rock and groundwater, to the features of materials used to build underground facilities;	- Impact on the geochemistry of water table and its interaction with underground facilities and with the dynamic of radionuclide migration;

Water table variations (SP)	- Daily precipitation; - Average temperature;	- Current water table;	- Chemical stability of facility materials; - Corrosion;	- Groundwater infiltration in the facility;
Windstorm (IT)	- Increase in frequency of extreme windstorm events;	- Ground facilities;	- Vulnerability related to the exposure of ground facilities during the construction and operational phases;	- Damage of ground facilities (construction and operational phase);
Windstorms (SP)	- Tornado frequency; - Wind speed;	- Historical wind damage;	- External cover of facilities; - Roof anchorages during operation;	- Damage due to debris impacts on structures and facility covers; - Soil cover erosion; - Power grid disruption during storms;
Drought (SP)	- Daily precipitation; - Total dry days (pr<1mm); - Maximum number of consecutive dry days;	- Arid conditions (1.7 mm/day); - Annual (285 dry days per year); - Longest dry period(80 days);	- Water demand during construction and operation;	- Soil cover erosion; - Water level variations; - Water supply disruption;
Desertification (SP)	- Average temperature; - Summer nights (Tmin > 20ºC); - Total dry days (pr<1mm);	- The average historical summer maximum temperature is above 33ºC; - The average historical extreme maximum	- Water demand during construction and operation;	- Soil cover erosion; - Larger wildfires frequency; - Water supply disruption;

	- Maximum number of consecutive dry days;	temperature is above 41ºC; - Arid conditions (1.7 mm/day); - Annual (285 dry days per year); - Longest dry period(80 days);		
River flooding (SP)	- Maximum precipitation in 5 days; - Maximum number of consecutive rainy days;	- Historical floods;	- Multilayer cover hydraulic conductivity; - Drainage system capacity;	- Slope instability of the multilayer cover; - Erosions of the multilayer cover; - Water infiltration in the facility;
Wildfires (SP)	- Wind speed; - Wildfire indicator; - Consecutive dry days;	- Historical wildfire damage;	- External materials composition;	- Power grid disruption; - Supply chain disruption; - Damages to the facility;

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

(IT) Soil erosion and flooding are typically related to heavy rainfall (extreme weather events) and may lead to a combined impact on both surface and subsurface (ground and underground) facilities.

(SP) The combination of extreme heat, droughts, desertification and wildfires poses a serious threat to the vegetation cover of the structure, potentially affecting the multi-layer cover. The alternation of dry periods followed by extremely intense precipitation, leading to soil cap erosion, might affect the performance of the multi-layer cover.

How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

(IT) Step1: develop a Risk Assessment Matrix "RAM" (occurrence probability of the event on the site vs its impact on facilities) to perform an initial quantitative risk screening.

Step 2: conduct an in-depth analysis on the most probable and dangerous risks identified as highest propriety or most critical by RAM; i.e. one of the methods employed in Quantitative Risk Assessment — such as probabilistic modeling— for a systematic and rigorous evaluation of the magnitude of the quantitative risks (e.g., probability of failure, expected annual damage) related to particular events.

(SP) Step 1: Risk assessment matrix (provide quantitative value to hazard, exposure and vulnerability and from the combination of these three factors, quantify risk).

Step 2: provide an in-depth assessment of the risks with the highest scores. The type of assessment depends on the risks identified (for instance, assessing extreme precipitation-related risks requires a different approach than desertification-related).

Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

(IT) The initial screening phase, which relies on a Risk Assessment Matrix to perform a qualitative assessment, is inherently limited by the characteristics of the readily available data used to estimate occurrence probability and impact at a national or regional scale. The primary limitations encountered during the screening phase relate to data scale and specificity: scale and resolution of geospatial data; reliability of extreme event history; lack of site-specific subsurface data.

(SP) The climate projection data used is considered appropriate and of good quality for the screening phase, particularly given the time horizon (up to 2100), the spatial resolution (5 km grid), and the fact that the data has been downscaled and bias-corrected.

Climate projections still carry the inherent uncertainties of the underlying models. Using the ensemble mean helps to mitigate some of this uncertainty; however, it can smooth out extreme events, making it unsuitable for more detailed analyses where continuous high-frequency time series are required.

A notable limitation may be the lack of detailed historical records of past climate events, which constrains the ability to accurately assess hazard exposure based on empirical recurrence.

The evaluation of the vulnerability of specific structural components remains incomplete and will require further engineering-based assessment in the next detailed phase.

The involvement of the key actors with in-depth knowledge of the infrastructure is critical for the assessment of the vulnerability.

Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

(SP) The screening methodology struggles to fully integrate compound and cascading risks. It is complex to integrate hazard interactions.

The evaluation of vulnerability requires a close stakeholder collaboration to consider contextual vulnerabilities or local concerns, especially those related to long-term institutional continuity or social acceptance.

To mitigate these limitations, a refined stakeholder engagement strategy should be implemented early in the detailed phase. It is essential that key actors with in-depth knowledge of the infrastructure, its materials, and operational context are involved, to help identify potential impacts and site-specific vulnerabilities.

The adoption of hybrid approaches that combine qualitative and quantitative data (e.g. scenario building, expert elicitation) will help fill data gaps.

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☐ Coastal flooding
- ☐ Cold spells
- ☐ Droughts
- ☐ Desertification
- ☒ Flash flooding
- ☒ Heavy rainfall
- ☒ Heatwaves
- ☐ Landslides
- ☐ Permafrost thaw
- ☐ River flooding
- ☐ Sea level rise
- ☒ Soil erosion
- ☒ Water table variations
- ☐ Windstorm
- ☒ Wildfires
- ☐ Others (please specify): _____

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Heatwaves	- In detail high-resolution models of temperature and humidity variation; - Assess the duration and intensity of future events; - Combine that information with the vulnerability of the system (e.g., design limits, resilience of materials and components); - Assess potential impacts to quantify the possible consequences of heatwave exposure, including: Equipment failure or reduced efficiency, increased cooling demand and energy use, material degradation, health risks for personnel etc.;	- Upgrading HVAC (Heating, Ventilation, and Air Conditioning) systems to ensure adequate cooling capacity under extreme temperatures for personnel; - Installing thermal insulation or passive cooling solutions; - Adjusting operational schedules to limit exposure during peak heat hours;
Flash flood	- The assessment should start with updated intensity–duration–frequency (IDF) curves derived from local rainfall records and downscaled climate projections. Based on this IDF the expected maximum precipitation for different return periods and rain duration can be defined; - Hydrological models can then be applied to simulate runoff across the cover, benches, and drainage channels; - Hydraulic calculations help to verify whether existing drains, outlets, and protective armoring can withstand future peak flows; - In addition, unsaturated flow models can estimate percolation into the cover under saturated conditions;	- Improve the capacity of the drainage system; - Protect exposed areas with more resistant surface materials; - Design controlled overflow areas so water can escape without damaging the cover;
Wildfires	- The assessment should start with a fire-weather baseline from local observations, fire-season	- Maintaining fuel breaks and vegetation clearance zones

	length, and hot-dry-windy hours (concurrent high temperature, low humidity, and strong wind). Use climate models to evaluate future projections for temperature, humidity and wind; - Evaluate exposure by mapping fuels (vegetated land) within 10 km of the site;	around infrastructure and access roads; - Conducting periodic removal of dry biomass and undergrowth within and near the facility boundaries; - Maintaining firebreaks and access paths in good operational condition to facilitate emergency response; - Ensuring the availability of fire-fighting equipment and water sources; - Coordinating with local and regional emergency services for fire surveillance and response planning; - Prepare a post-fire emergency plan to slow runoff, trap sediment, and protect the cover until vegetation recovers;
Soil erosion	- Develop an erosion model with observed rainfall erosivity, growth-layer soil properties, and current vegetation to estimate annual soil loss; - Update rainfall erosivity rates (mm/y) with future climate projections;	- Reinforce erosion control with rock mulch or micro-roughness; - Select deep-rooted native species ; - Periodically restore the surface layer if loss is detected; - Reinforce outlets and chutes to prevent gully initiation;
Heavy rainfall	- Detailed hydrological modelling to evaluate extreme precipitation events;	- Upgrading drainage system capacity with enhanced pumping stations and larger collection systems; - Implementation of improved multi-layer cover designs with enhanced infiltration barriers using advanced geomembranes; - Installation of real-time precipitation monitoring and early warning systems; - Monitoring of humidity inside disposal cells;

Water table variations	- Assessment of the effect of climate change on groundwater recharge rates and seasonal fluctuation patterns; - Assessment of drainage system capacity under varying water table conditions and potential for barrier saturation;	- Groundwater monitoring; - Installation of improved drainage systems; - Implementation of groundwater control measures including potential dewatering systems where appropriate; - Elevation of critical infrastructure above projected flood levels;

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

(IT) The Detailed Assessment (Safety Case) has not been developed for the Italian national repository but it will face constraints typical of any long-term engineered solution situated within a dynamic natural environment. These limitations primarily stem from the need to predict geological, hydrogeological, and climatic processes over the required institutional control period and beyond.

Uncertainties in regional climate predictions (e.g., changes in seasonal precipitation intensity, temperature) directly affect erosion and the water balance within the cover system. Global climate models used for projection often lack the necessary resolution for site-specific predictions of extreme events (e.g., flash floods, intense storms).

These gaps and uncertainties fundamentally impact the assessment's reliability in two main ways:

- Model simplification using conservative model assumptions (e.g., maximum erosion rates, minimum barrier lifetimes). While this increases safety margins, it may overestimate long-term risks, potentially reducing the applicability and realism of the results.
- Safety margin reliance on the performance of the multi-barrier system to compensate for uncertainties in the natural barrier. Any uncertainty in the engineered components' longevity therefore has a high impact on the overall confidence in the long-term safety case.

Future work should focus on reducing the key uncertainties through specific research and characterization efforts, especially in the long-term hydrogeological monitoring at the selected site and at relevant natural analogues to collect continuous data on erosion, infiltration, and groundwater fluctuations over several years. This approach improves the calibration of surface-process models and reduces uncertainty in the long-term water balance calculation.

(SP) A major limitation encountered in the detailed assessment is the lack of long-term, site-specific climatic and meteorological datasets with sufficient temporal and spatial resolution to calibrate impact models. While the meteorological station at El Cabril has been operating since 1987, its record length still limits the reconstruction of multi-decadal variability and extreme event recurrence. For Italy, the absence of a definitive site for the Deposito Nazionale constrains the use of truly local data, requiring reliance on regional or ensemble model outputs. Consequently, many projections are based on downscaled and bias-corrected climate datasets, which, although

robust, may not fully capture local microclimatic variability, topographic effects, or compound events such as flash floods following wildfires.

To mitigate these uncertainties, future work should focus on expanding and integrating local meteorological and hydrological monitoring networks, improving model calibration using continuous observational data, and performing sensitivity and uncertainty analyses to propagate climate variability through the different impact models. The adoption of coupled hydro-climate models would enhance understanding of feedbacks between precipitation, recharge, and groundwater flow.

The involvement of facility engineers, environmental specialists, and climate experts is essential to accurately assess the vulnerability of infrastructure components to climate-driven stressors and to design effective adaptation measures. This close collaboration will help bridge the gap between climate modelling and operational safety, ensuring that adaptation strategies are technically feasible and aligned with site characteristics.

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

(IT) The Detailed Assessment (Safety Case) has not been developed for the Italian national repository but the facility design makes it highly sensitive to changes in meteorological parameters. The main gaps and uncertainties in the detailed assessment methodology related to climate change are:

- **Low-resolution climate projections using GCM**. These models often lack the spatial resolution to accurately predict site-specific changes in key parameters for erosion and flooding (maximum daily rainfall intensity, antecedent soil moisture, etc.). This gap creates uncertainty in the Erosion Rate Models used for the multilayer cover, potentially under or overestimating the rate at which the protective soil layers will be removed over 300+ years.
- **Modeling of extreme events**: the Italian context is shifting towards "rarer but more intense" precipitation events. The models must simulate the effects of extreme events (e.g., 500-year flood or prolonged drought) over long periods (centuries). Unfortunately, current methodologies struggle to integrate the frequency distribution of extreme events over centuries, instead often relying on a single, worst-case scenario.
- **Coupling Climate and Biological Processes**: vegetation cover reduces erosion on the repository cover. Climate change affects the species and density of this cover. Unfortunately, actual methodologies face difficulty in coupling projected changes in soil moisture and temperature with biogeochemical models that predict the viability and effectiveness of protective vegetation (bioremediation/stabilization). These uncertainties in the long-term stability of the bio-cap adds risk to the mechanical integrity of the underlying cover layers.

(SP) The detailed assessment methodology presents several limitations and uncertainties related to the simplifications inherent in current modelling approaches:

- The modelling approaches rely on assumptions that may oversimplify complex processes such as hydrological dynamics, soil erosion, or fire behaviour under changing climate conditions. For example, intensity–duration–frequency (IDF) curves or simple erosion models are based on empirical relationships that may not fully capture non-linear feedbacks or compound events (e.g. flash floods following wildfires). Similarly, many models are calibrated under present-day conditions, which may reduce their reliability when applied to future climate scenarios that fall outside historical ranges.

- Another limitation lies in the difficulty of integrating multiple hazards within a consistent framework. Heat waves, floods, wildfires, and erosion are often assessed separately, while in reality their impacts may interact.

To mitigate these gaps, future work should invest in multi-hazard and system-level modelling, strengthen the coupling between climate projections and engineering performance models, and develop sensitivity and uncertainty analyses to explicitly quantify model limitations. Comparative modelling with different approaches, as well as regular updates in line with advances in climate science, would help align assessments with regulatory expectations and reinforce their credibility for stakeholders.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

(IT) The Italian national repository is a near-surface facility, in which natural analogues are essential long-term evidence used to support the safety assessments, particularly concerning the stability of the engineered structures and the performance of the natural geological barrier over centuries.

The Italian climate in the potentially suitable areas is typically temperate or Mediterranean, characterized by intense, concentrated rainfall events and associated high hydrogeological risks. Analogues must address how these conditions affect the repository's long-term surface stability:

- **Badlands (calanchi) and erosion**: The widespread presence of badlands in Italy's clay-rich Apennine and Southern regions is a critical natural analogue. These formations, sculpted by intense surface runoff and gully erosion over millennia, provide quantitative data on:
    - **Long-term erosion rates**: Crucial for predicting the degradation and longevity of the engineered multi-layer cover, which must remain intact to prevent water infiltration.
    - **Slope stability**: Demonstrating how clay formations behave under heavy seasonal rainfall and freeze-thaw cycles, informing models for the national repository overall landscape evolution.
- **Infiltration and runoff dynamics**: Studies of ancient Quaternary and Plio-Pleistocene sedimentary sequences provide insights into deep infiltration patterns and the performance of natural soil layers in draining or storing water, which is relevant to the site's overall hydrogeology.

While natural analogues increase confidence, they have inherent limitations that are magnified by Italy's unique geological features. The Italian natural systems are complex. The specific lithology and geological fabric (microstructure, fractures) of the final national repository site will be unique. This inherent heterogeneity limits the exact quantitative transferability of data from a general analogue site to the specific repository location.

(SP) Climate-related natural analogues for the El Cabril facility can be identified in several regions that share similar semi-arid to arid conditions. These are particularly relevant for future climate projections that foresee a transition from temperate to BSh climates:

- **South and South East Spain (Tabernas in Almeria or Guadalquivir hillslopes):** where seasonal droughts and episodic intense rainfall coexist, can help evaluate erosion

rates, infiltration dynamics, and vegetation recovery under conditions similar to those foreseen for the El Cabril.

- **North African steppe and desert margins (such as northern Morocco, Algeria, Tunisia)** provide analogues for hotter BSh conditions with reduced rainfall and strong seasonal contrasts. They apply to near- and mid-term projections of increasing aridity in southern Spain. Evidence from these regions includes observations on soil erosion, flash flood impacts, and vegetation stress, which can inform assessments of cover stability and surface processes. The main limitation is that these regions may be more arid than El Cabril is expected to become in a few decades, leading to potential overestimating of certain risks.

The limitations of the natural analogues is that not all key factors driving a process are identical than in the facility. In this case, transferability is constrained mainly by lithology and fabric (natural badland terrains and engineered multilayer covers), and the fact that engineered multilayer covers do not have perfect natural counterparts.

References

Analysis of Climate Change Effects on Precipitation and Temperature Trends in Spain https://doi.org/10.3390/land14010085

Future changes of hot extremes in Spain: towards warmer conditions https://doi.org/10.1007/s11069-022-05306-x

El Cabril Disposal Facility https://www.enresa.es/eng/index/activities-and-projects/el-cabril

Real Decreto 102/2014, de 21 de febrero, para la gestión responsable y segura del combustible nuclear gastado y los residuos radiactivos. https://www.boe.es/boe/dias/2014/03/08/pdfs/BOE-A-2014-2489.pdf

Ley 7/2021, de 20 de mayo, de cambio climático y transición energética https://www.boe.es/buscar/pdf/2021/BOE-A-2021-8447-consolidado.pdf

Surface disposal in humid continental climates (Bulgaria)

Group Description

Group: 3Sd

Disposal type (Name): Surface (Radiana – BG)

Nuclear waste type: LILW

Current climate: Dfa

Countries: Bulgaria

Partners: GI-BAS, TUS**Time window for construction and operation**: 60 years AP

Location/Type of waste/Surface facilities/Distance from the shoreline

Location: 43N(Latitude), 23E(Longitude),50-100m(Altitude)

Type of waste: Low- and Intermediate-Level Short-lived RAW

Surface facilities: Concrete Disposal Cells, Buffer storage building, Building for acceptance of RAW containers, Auxiliary facilities

Distance from the shoreline: 350 km to the Black Sea, 3.5-4 km to the Danube River

Current phase/EBS/Host rock

Phase: Construction

EBS: The multi barrier system for isolation of NDF-Radiana Site comprises the following parts:

the first engineering barrier is the waste form (steel drums fixed with cement mortar);

the second engineering barrier is the reinforced concrete container with thick walls, bottom slab and a cover slab;

the third engineering barrier includes the reinforced concrete disposal cells, the foundations, the closing slabs and the filling material;

the fourth engineering barrier includes the loess-cement cushion (5 m thick cement modified loess layer) and the protective multilayer cover;

the fifth (natural) barrier is the natural characteristics of the repository site.

Host rock: Consolidated clay (20-50 m from surface to the top of the host rock and 50-100 m from top to bottom of host rock)

Current climate (Köppen-Trewartha) / Current land use / Geology / Hydrology / Geomorphology / Porewater

Köppen-Trewartha: Dc, Cfa based on the data for the period 1991-2020, Dfa based on the data for the period 1950-2000

(0-100 years AP) Climate change is expected to increase the frequency and magnitude to extreme weather events in the area, namely, extreme precipitation and temperature, storms, fogs and drought. The main hazards in the area include drought, extreme heat, storms. Projected increases in temperatures are likely to exacerbate the existing risks of temperature related hazards such as heat waves, droughts, and fire. Projections estimate an increased risk of a longer fire season as a result of higher temperature and variation in rainfall.

(0-100 years AP) Climate change is expected to affect water availability with decreases in river flows. In addition to changes in precipitation, changes in regional hydrology can be associated with risk of extreme events such as drought and flooding. The changes in regional precipitation is expected to impact existing patterns of river flow by increasing peak discharge rates for major catchments such as the Danube in Bulgaria's northern border.

Hydrology: Perennial, surface water dominated (river water is mostly from precipitation)

Current land use: Shrubland

Geomorphology: Low relief topography: rather flat landscape

Geology above host rock: The NDF foundation is constructed on 5 m thick loess-cement cushion which is palced over the host rock (Pliocene consolidated clayey sediments)

Geology below the host rock: Sedimentary

Hydrogeology above the host rock: the facility is near surface, no aquifer above it

Hydrogeology below the host rock: Aquitard and Aquifer phreatic beneath

Porewater of the host rock at the RWM site/facilitiy: Fresh

Porewater of the host rock above the RWM site/facilty: the facility is near surface, no aquifer above it

Impact of sea level: No

Screening

Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

- ☐ Coastal flooding
- ☐ Cold spells
- ☒ Droughts
- ☐ Desertification
- ☐ Flash flooding
- ☒ Heavy rainfall
- ☒ Heatwaves
- ☐ Landslides
- ☐ Permafrost thaw
- ☐ River flooding
- ☐ Sea level rise
- ☒ Soil erosion
- ☐ Water table variations
- ☒ Windstorm
- ☐ Wildfires
- ☐ Others (please specify):

Combined and cascading relationships:

- Heatwaves → vegetation stress → reduced erosion protection → greater erodibility during subsequent heavy rainfall → cover damage and sediment mobilization.
- Drought → cracking/desiccation of near-surface soils → preferential flow during intense rain after drought → local infiltration spikes and erosion.
- Windstorms during saturated soils after heavy rain → increased cover slope instability and debris damage to roofs and equipment.
- Extreme precipitation in catchment → Danube high stage events → potential access limitations, stormwater backwater in local networks, and strain on regional drainage systems, though the repository elevation reduces direct flood hazard to cells

Please, indicate the data source (for climatic, sea level,….), time horizon for the different periods to be analysed (historical,

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
NIMH (ISIMIP Fast Track)	Climate variation and climate change projection for Bulgaria. 2024. 47 p., ISBN: 978-954-394-408-8	1961-2020	2021-2050		2070-2099	RCP4.5 RCP8.5	Yes	Yes	-	Bulgaria
World Bank	Climate Risk Profile: Bulgaria (2021): The World Bank Group.	1901–2020	2020-2039	2040-2079	2080-2099	RCP4.5 RCP8.5	Yes	-	-	Bulgaria

short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Comments:

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use?

*Which **hazard indicator** would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)?*

*Which **exposure indicator** would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones?*

*Which **vulnerability indicator** would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks? Finally, for each hazard, **indicate the expected impact(s)** on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.*

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impact(s)
Drought	- Daily precipitation; - Total dry days (pr<1mm); - Maximum number of consecutive dry day;	- Dry periods lasting more than 20 days; - Annual number of dry periods;	- Water shortage during operation;	- Soil cover erosion; - Water level variations; - Water supply disruption;
Heavy rainfall	- Maximum precipitation in 24h; - Maximum precipitation in 5 days;	- Historical floods; - Operation protocols for heavy rain episodes;	- Multilayer cover stability and durability; - Drainage system capacity;	- Water infiltration in the facility; - Slope slippage of the multilayer cover; - Erosion of the multilayer cover;
Heatwaves (Extreme heat)	- Maximum temperature; - Extreme maximum temperature; - Summer nights (Tmin > 20ºC); - Longest heatwave duration;	- Air temperature attains temperatures of up to +43 ºC; - Maximum daily temperatures exceed +30 ºC on average during 40-45 % of the summer days;	- Presence of workers during operation; - Facilities affected by changes in air temperature (thermal impact on concrete/steel structures);	- Heat stress for workers; - Concrete cracking due to thermal expansion; - Malfunctioning of some instruments due to high temperature;

		- Historical extreme maximum temperatures are above 40ºC;		
Soil erosion	- Maximum precipitation in 24h; - Frequency of high intensity precipitation events (extreme rainfalls); - Thickness of vegetation and anti-erosion layer of multilayer cover;	- Durability of multilayer cover exposed to erosion;	- Appropriate anti-erosional vegetation on the top of multilayer cover;	- Slope instability of the multilayer cover; - Erosion of the cover;
Wind storm	- 100-year wind speed return levels (m/s); - Extreme wind speed probability distributions;	- Above-ground structures exposure area and height; - Temporary storage facility structural specifications; - Electrical supply lines proximity;	- Structural design limits of wind load; - Mobile roof anchorages during operation;	- Damage due to debris impacts on structures and facility covers; - Soil cover erosion; - Power grid disruption during storms; - Damage of surface monitoring equipment;

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Heavy rainfall (extreme events) and soil erosion may lead to combined impact on surface and near-surface facilities.

The combination of heat waves, droughts, and wind storms presents a serious threat to the vegetation cover of the multi-layered cover.

The alternation of dry periods followed by extremely heavy rainfalls, leading to slope erosion, might affect the normal operation of the facilities and performance of the multi-layer cover.

How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

Step 1: Risk assessment matrix (provide quantitative value to hazard, exposure and vulnerability and from the combination of these three factors, quantify risk); Scorecard or composite index (risk = hazard × exposure × Vulnerability); hazard likelihood (1-5 scale); exposure level (1-5 scale); vulnerability degree (1-5 scale)

Step 2: Provide an in-depth assessment of the risks with the highest scores. The type of assessment depends on the risks identified (for instance, assessing extreme precipitation-related risks requires a different approach than droughts).

Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

The climate projection data used is considered appropriate and of good quality for the screening phase, particularly given the time horizon (up to 2099), the spatial resolution (3 km grid), and the fact that the data has been downscaled and bias-corrected.

Climate projections still carry the inherent uncertainties of the underlying models. Using the ensemble mean helps to mitigate some of this uncertainty; however, it can smooth out extreme events, making it unsuitable for more detailed analyses where continuous high-frequency time series are required.

A notable limitation may be the lack of detailed historical records of past climate events, which constrains the ability to accurately assess hazard exposure based on empirical recurrence.

Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

The screening methodology may miss local vulnerabilities. It is complex to integrate hazard interactions.

Correct quantification of risk assessment could be improved by modeling approaches combining climatic, hydrological, and engineering data.

The evaluation of vulnerability requires a close involvement of all stakeholders.

It is essential that key actors with in-depth knowledge of the infrastructure, its materials, and operational context are involved, to help identify potential impacts and site-specific vulnerabilities.

The adoption of hybrid approaches that combine qualitative and quantitative data (e.g. scenario building, expert elicitation) will help fill data gaps.

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☐ Coastal flooding
- ☐ Cold spells
- ☐ Droughts
- ☐ Desertification
- ☐ Flash flooding
- ☒ Heavy rainfall
- ☒ Heatwaves
- ☐ Landslides
- ☐ Permafrost thaw
- ☐ River flooding
- ☐ Sea level rise
- ☒ Soil erosion
- ☐ Water table variations
- ☒ Windstorm
- ☐ Wildfires
- ☐ Others (please specify): _____

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Heavy rainfall	- Update site-specific IDF curves using downscaled/bias-corrected projections for 10–100 yr return periods under RCP4.5/8.5; - 2D overland flow and infiltration modeling on as-built topography and cover slopes;	- Increase drainage conveyance and inlet capacity; - Add redundancy and debris guards; - Define exceedance flow paths away from critical assets;

Soil erosion	- Erosion potential assessment using The Revised Universal Soil Loss Equation(R-USLE) or equivalent calibrated to local soils and projected rainfall erosivity changes; - Vegetation survivability modeling under drought–heat;	- Multi-layer armoring strategy(for example, topsoil with bioengineering plus geotextiles and localized hard armoring on steeper slopes); - Construction sequencing to minimize exposure;
Heatwaves	- Thermal load analysis for concrete elements using projected Tmax and diurnal ranges; - Occupational heat stress assessment or equivalent indices for work-rest schedules under projected heat extremes;	- Shading/ventilation for equipment (for example, operational heat plans: hydration, cooling stations, adjusted shifts);
Windstorm	- Review anchorage of mobile roof and temporary structures; - Fragility assessment for exposed equipment; - Scenario testing for debris impact and power loss; - Resilience of monitoring networks;	- Enhanced anchorage, tie-downs, and stow procedures for mobile roof; - Wind fences or shields for sensitive equipment; - Hardened enclosures for monitoring stations;

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Convection-permitting projections at the site scale may be subject to limitations. Additionally, translating regional extremes into Intensity-Duration-Frequency (IDF) updates involves methodological challenges.

Local soil parameters for erosion and infiltration under evolving climate (e.g., crusting after drought) may require new field testing; vegetation performance data under future heat/drought is uncertain.

Wind projection deltas for design-level gusts are not consistently available across all cases; therefore, conservative code-based approaches may still be applied

The ranges in predicted peak intensities and wind loads may serve to widen safety margins. Therefore, the adaptation process should be designed to be robust against uncertainty rather than relying solely on specific predicted values.

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Multi-hazard interactions are inherently difficult to quantify together, especially because of the challenges related to sequential effects, like drought followed by flooding.

Additionally, uncertainty remains in modeling structural responses to extreme events.

Furthermore, predicting the behavior of materials subjected to combined heat, moisture, and wind load cycles over extended periods is difficult; thus, reliance on performance monitoring becomes essential beyond established codes.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

Vast region in North Bulgaria (Danube plain) is covered by eolian sediments. Their stratigraphy represents a real record of the climatic evolution during the last 800 000 years. During the Middle and Late Pleistocene, the glacial and interglacial processes in North Europe reached the Danube plain in the form of alternating cold and warm epochs. In the Danube river banks in South Eastern Europe, loess sediments with a series of up to seven fossil soils (paleosols) have been climatostartgraphically characterized. The sequence of loess horizons and respective paleosols between them is an evidence for the alternation of worm and cold climate epochs. The study of these climatostartgraphical benchmarks allow the dating of past climatic geohazards which could take place during the post closure period of the RAW disposal facilities. [App. B.4.6]

References

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The National Disposal Facility A Status of the Art Solution for Bulgaria's Radioactive Waste https://inis.iaea.org/collection/NCLCollectionStore/_Public/45/079/45079187.pdf

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Near-surface disposal in oceanic climates (Belgium- Olen, France-FAVL)

Group Description

Group: 3NSb

Disposal type (Name): Near surface (1. Olen-B, 2. FAVL-F)

Nuclear waste type: LILW

Current climate: Cfb/Do

Countries: Belgium, France

Partners: SCK CEN, Andra, BGRM, ASNR**Time window for construction and operation**: a 100 AP

Location/Type of waste/Surface facilities/Distance from the shoreline

Location:

Olen : 55-50N(Latitude), 5-10E(Longitude),10-20m(Altitude)

FAVL : 50-45N(Latitude), -2-5.42E(Longitude),80-400m(Altitude)

Type of waste:

Olen : Ra-bearing waste within preliminary threshold levels of 15-1000 Bq/g Ra-226

FAVL : LILW-LL

Surface facilities:

Olen : Not known yet, but probably a characterisation, separation, conditioning (optional) and buffer storage facility (ER-1374N)

FAVL :-

Distance from the shoreline:

Olen : 50-100km

FAVL : no constraint

Current phase/EBS/Host rock

Phase:

Olen : Initiation

FAVL : site selection

EBS:

Olen : Not known yet, but probably a combination of engineered barriers such as concrete and clay (ER-1374N).

FAVL : not defined

Host rock:

Olen : Neogene sand formation

FAVL : Plastic clay

Current climate /Current land use/Geology/Hydrology/Geomorphology/Porewater

Köppen-Geiger:

Olen : Cfb

FAVL : Cfb

Köppen-Trewartha:

Olen : Do

FAVL : Do

(0-100 years AP)

Olen : Trewartha: Do, possibly Cs (NIROND-TR 2009–07E Version 2 19 October 2018)

FAVL : Cfb to Cfa after 50 yr / Do through the next 100 yrs (standard scenario)

Hydrology:

Olen : Perennial, groundwater dominated (rivers are mostly fed by groundwater or springs)

FAVL : Perennial, surface water dominated (river water is mostly from precipitation)

Current land use:

Olen : Tree cover, grassland, wetland, built-up area (industry)

FAVL : Grassland

Geomorphology:

Olen : Low relief topography: rather flat landscape

FAVL : Low relief topography: rather flat landscape

Geology above host rock:

Olen : Sedimentary

FAVL : Sedimentary

Geology below the host rock:

Olen : Sedimentary

FAVL : Sedimentary

Hydrogeology above the host rock:

Olen : Phreatic sedimentary aquifer

FAVL : Phreatic

Hydrogeology below the host rock:

Olen : Aquitard

FAVL : Phreatic

Porewater of the host rock at the RWM site/facilitiy:

Olen : Fresh

FAVL : Fresh

Porewater of the host rock above the RWM site/facilty:

Olen : Fresh

FAVL : Fresh

Porewater of the host rock below the RWM site/facilty:

Olen : Fresh

FAVL : Fresh

Future climate at the end of operation (1,000 years) and the sea level

Climate in 100-10,000 years:

Olen : (100-5,000 years AP) Trewartha: Do, Cs (5,000-10,000 years AP) Trewartha: Do, Cs, Cs with sea level rise

FAVL : (100-200 years AP) Cfa and alternation Cr/Cs (200-500 years AP) Cfa and alternation Cs/Bs (500-1,000 years AP) Cfa and alternation Cr/Cs/Bs (1,000-5,000 years AP) Cs

Impact of sea level:

Olen : Yes

FAVL : No

Screening

*Which **climate hazards** would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards*

- ☐ Coastal flooding
- ☐ Cold spells
- ☒ Droughts
- ☐ Desertification
- ☒ Flash flooding
- ☒ Heavy rainfall
- ☒ Heatwaves
- ☐ Landslides
- ☐ Permafrost thaw
- ☒ River flooding
- ☒ Sea level rise - Sea level rise as an indirect driver via regional base-level and groundwater impacts
- ☒ Soil erosion
- ☒ Water table variations
- ☒ Windstorm
- ☐ Wildfires
- ☐ Others (please specify): _____

Interdependencies and cascading:

- Heavy rainfall → flash/river flooding → overtopping of drainage, infiltration to underlying soil or structure ; rain plus windstorms increase structural and operational risks. (Olen)
- Intense precipitation on clay-rich cover/soils → surface runoff, rilling/gullying → erosion and infiltration risks. (FAVL)
- Drought/heatwaves → soil shrink-swell cycles in fine-grained backfills; thermal loads on surface facilities; drought followed by extreme rainfall exacerbates erosion, preferential flow and runoff peaks.(Olen, FAVL)
- Windstorms → debris, power loss, damage to HVAC critical for controlled storage; storms coincident with heavy rain amplify risk.(Olen)

*Please, indicate the **data source** (for climatic, sea level,….), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.*

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
EURO-CORDEX (CMIP6/CMIP5) RCMs	CLIMAAX-recommended downscaled ensembles [1]	1981–2010	2021–2040	2041–2060	2061–2100	SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5 (or RCP2.6/4.5/8.5 if CMIP5)	Yes (0.11°)	Yes (ISIMIP/quantile)	Multi-model	Western Europe; Belgium/ France domains

Comments: Downscaling and bias correction per CLIMAAX/ISIMIP methods; final selection tailored to national regulator expectations (FANC, ASN) and ONDRAF/NIRAS methods.

*For each identified climate hazard, indicate **how you will examine the risk**. Which hazard, exposure and vulnerability indicators would you use?*

Which **hazard indicator** would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)?

Which **exposure indicator** would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones?

Which **vulnerability indicator** would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks?

Finally, for each hazard, **indicate the expected impact(s)** on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impact(s)

Heavy rainfall and flash flooding	- Annual max 1-day and 5-day precipitation, sub-daily extremes if available; - Number of heavy precipitation days; - 10–100-year return levels from extreme value analysis;	- Facility footprint in low-lying areas (drainage density; proximity to ephemeral channels; impervious area fraction; access roads and power infrastructure footprints);	- Drainage capacity vs. design storm (freeboard of ditches/ponds; surface cover erosion resistance; backup power for pumps; dependency on continuous HVAC for storage);	- Overtopping/inundation; - Erosion of covers/embankments; - Infiltration to subgrade; - Operational downtime;
River flooding	- River peak flow quantiles (flood extent depth mapping at 1:100–1:1000);	- Site elevation relative to nearby river floodplain; - Critical facility elevations; - Access route crossings;	- Flood protection standards; - Watertightness of storage buildings; - Redundancy of access;	- Inundation; - Access disruption; - Potential buoyancy loads on foundations;
Water table variations	- Groundwater level percentiles; - Correlation to local precipitation(rainfall)/regional sea-level boundary; - Drought-rewet cycles;	- Foundation depth vs seasonal high water table; - Presence of buried utilities; - Sumps and basements;	- Waterproofing; - Sensitivity of (radium) waste storage to humidity;	- Uplift/floatation risks; - Moisture ingress; - Corrosion or degradation of near-surface EBS elements;
Soil erosion	- Common indicators (Rainfall erosivity (R-factor); - Wind erosivity; - Slope length-steepness factors; - Vegetation cover index);	- Area of bare soils; - Newly constructed embankments; - Cover slopes;	- Material erodibility; - Drainage linings; - Maintenance regimes;	- Loss of cover thickness; - Exposure of engineered layers; - Increased infiltration;
Heatwaves	- Total number of hot days, - Heatwave duration/intensity indices; - Wet-bulb temperature thresholds for worker safety;	- Outdoor work schedules; - HVAC-dependent storage; - Thermal loads on buildings;	- Cooling redundancy; - Indoor climate control margins; - Worker protection protocols;	- Worker safety constraints; - HVAC stress; - Thermal expansion effects, especially on clays/cementitious materials;
Droughts	- SPEI (Standardized Precipitation Evapotranspiration Index) and SSI	- Clayey covers/seals; - Water-dependent dust suppression;	- Desiccation susceptibility; - Cracking propensity of clays; - Settlement risk;	- Cracking of covers/seals; - Preferential pathways on rewetting;

	(Standardized Soil Moisture Index/Standardized Streamflow Index); - Consecutive dry days;			- Dust and air quality issues;
Windstorms	- 10 m wind gust return levels; - Storm-track statistics;	- Tall structures, Cranes during construction; - Power lines;	- Structural ratings; - Tie-down and redundancy; - Emergency power;	- Damage to buildings/equipment; - Power outages; - Accidental releases via building envelope failures (non-radiological first);

*Which **compound risks do you anticipate**?* Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Pluvial-fluvial compounding occurs when intense local precipitation (pluvial flooding) coincides with elevated river discharge or saturated catchment conditions, creating amplified flood peaks and prolonged inundation.

Drought–rewet cycles: desiccation cracking in clayey materials followed by intense rainfall leading to preferential flow and erosion.

Windstorm–rain coupling: envelope damage and simultaneous heavy rain causing water ingress.

Elevated groundwater plus river flooding: reduced drainage gradients increase inundation persistence.

Heatwave–drought: thermal and moisture stresses reducing material performance and worker productivity.

*How would you **quantify the risks**? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.*

> *In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.*

*Did you encounter any **limitations with the data used for the screening phase**? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?*

No problem

*Did you encounter any **limitations related to the screening methodology**? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?*

No problem

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☐ Coastal flooding
- ☐ Cold spells
- ☐ Droughts
- ☐ Desertification
- ☒ Flash flooding (FAVL)
- ☒ Heavy rainfall (Olen, FAVL)
- ☒ Heatwaves (Olen, FAVL)
- ☐ Landslides

☐ Permafrost thaw
☒ River flooding (FAVL)
☐ Sea level rise
☐ Soil erosion
☒ Water table variations (Olen)
☐ Windstorm
☐ Wildfires
☐ Others (please specify): _____

*Indicate which **detailed assessment methodology** you would follow for each of the most critical risks. What **adaptation measures** or design modifications could be considered in response to the identified risks?*

Risk	Methodology	Adaptation measurements
Pluvial(heavy rainfall)-fluvial(river overflow) compound flooding (Olen)	- Coupled pluvial-fluvial modeling with high-resolution digital elevation models(DEM); - Design storms from downscaled EURO-CORDEX ensembles; - Non-stationary frequency curves; - Compound scenario analysis with saturated antecedent conditions;	Elevate critical assets above compound flood levels; Increase drainage capacity with controlled discharge; Flood barriers for facility entries; Lined channels with retention ponds; Backup pumping with emergency power;
Pluvial(heavy rainfall)-fluvial(river overflow) compound flooding (FAVL)	- Flash/river flooding modeling with clay surface runoff coefficients; - Compound inundation scenarios; - Surface water-groundwater interaction modeling in plastic clay terrain;	- Site platform above design flood levels; - Perimeter drainage with compound scenario capacity; - Surface water management to minimize infiltration; - Emergency access route elevation;
Drought-rewet cycles affecting clay barriers(Olen)	- RUSLE (Revised Universal Soil Loss Equation) and WEPP (Water Erosion Prediction Project) with projected erosivity; - Desiccation-cracking models for clay barriers; - YDMI(Yearly Drought Magnitude Index) drought index application; - Crack network modeling with preferential flow analysis; - Multi-cycle degradation assessment;	- Multi-layer barrier systems with geomembranes; - Low-plasticity clay selection; - Active moisture control systems (irrigation, vapor barriers); - Crack-resistant clay-aggregate mixtures; - Performance-based maintenance scheduling;
Drought-rewet cycles affecting	- Plastic clay shrink-swell modeling under Cfb-to-Cfa transition;	- Composite barrier systems with redundant layers;

clay barriers(FAVL)	- Desiccation crack propagation in plastic clays; - Preferential flow pathway development; - Long-term barrier performance assessment;	- Anti-desiccation strategies including moisture-retentive layers; - Vegetative covers for moisture retention; - Crack-resistant clay formulations; - Inspection and maintenance triggers;
Heavy rainfall and drainage performance (Olen)	- Sub-daily precipitation extreme analysis from EURO-CORDEX; - Drainage capacity vs design storm assessment; - Erosion-resistant cover performance modeling;	- Erosion-resistant covers (armored, vegetated); - Staged construction with temporary controls; - Enhanced drainage freeboard;
Heavy rainfall and drainage performance (FAVL)	- Clay-rich cover erosion modeling under intense precipitation; - Surface runoff coefficient analysis; - Infiltration modeling through plastic clay covers; - Maintenance interval determination;	- Multi-layer erosion protection systems; - Gentle slope design with armored toe; - Vegetation management for erosion control; - Surface water diversion systems; - Regular inspection and maintenance;
Windstorm damage and power loss (Olen)	- Gust load assessments using reanalysis/Regional Climate Model (RCM)-informed extremes; - Reliability-based structural design; - Envelope integrity analysis during wind-driven rain events; - Power system redundancy evaluation;	- Wind-resistant cladding and structural design; - Secured crane protocols during storms; - Redundant HVAC systems; - Storm preparedness protocols;
Windstorm damage and power loss (FAVL)	- Wind load analysis for plastic clay terrain; - Structural envelope assessment; - Power loss impact on operations; - Backup system reliability under extended outages;	- Enhanced structural design for regional wind conditions; - Bckup power systems with extended autonomy; - Storm response protocols; - Equipment securing procedures;
Heatwave/HVAC reliability (Olen)	- Indoor thermal modeling with wet-bulb risk assessment; - HVAC capacity checks against late-century extremes; - Worker safety protocol development; - Thermal stress analysis on storage systems;	- HVAC redundancy with backup cooling systems; - Heat stress protocols for workers; - Thermal stress-resistant materials; - Emergency cooling procedures;

Heatwave/HVAC reliability (FAVL)	- Heat stress analysis for clay cover performance; - Thermal expansion effects on plastic clay seals; - Operational heat protocol development; - Cooling system redundancy assessment;	- Enhanced cooling systems for extreme heat events; - Thermal performance monitoring of clay barriers; - Heat-resistant material selection; - Worker safety protocols;
Erosion of covers and surface barriers (Olen)	- Slope stability analysis with climate-adjusted erosivity; - Cover thickness loss distributions; - Staged construction erosion control;	- Armored surface covers with vegetation; - Temporary protective measures; - Enhanced drainage capacity;
Erosion of covers and surface barriers (FAVL)	- Multi-layer clay cover erosion analysis; - Gentle slope optimization; - Armored toe design; - Robust surface water management system design;	- Multi-layer erosion protection and vegetative stabilization; - Comprehensive surface water management;

*Did you encounter any **limitations regarding the data used for the detailed assessment**? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?*

Sub-daily extremes and convective processes : Limited convection-permitting climate projections and incomplete radar archives create significant gaps in the characterization of sub-daily precipitation extremes, leading to under-resolved pluvial flood peaks that can affect the sizing of drainage systems for radioactive waste facilities. Mitigation strategies include using convection-permitting model subsets, stochastic storm generators, and radar-informed Intensity-Duration-Frequency (IDF) curves with climate deltas to address these issues. This approach ensures regulatory compliance through conservative design margins that account for the inherent uncertainties in extreme precipitation estimates over the operational periods.

Material behaviour under cyclic hydro-thermal loads : Limited long-term performance data for engineered materials under drought-rewet cycles and temperature changes creates uncertainty in degradation forecasts and maintenance planning for radioactive waste barriers. Mitigation strategies include laboratory accelerated aging tests, field demonstration projects, and performance-based maintenance with ongoing material property tracking. The framework combines mechanistic modeling with empirical validation while setting performance-based triggers for adaptive barrier management throughout the operational period.

River–pluvial compounding datasets : Inadequate joint probability characterization of concurrent precipitation-discharge events limits accurate compound flood risk assessment, potentially affecting protection system design in complex hydrological environments. Copula-based modeling, scenario-based stress testing, and multi-source data integration provide mitigation by propagating uncertainty and establishing probabilistic design bounds. This approach ensures transparent communication of uncertainty while maintaining conservative design principles for safety-critical applications.

*Did you encounter **any limitations with the detailed assessment methodology**? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?*

Model coupling and feedbacks : Achieving full coupling between atmosphere, catchment, groundwater, and infrastructure systems remains difficult at the facility level, leading to gaps in representing cascading effects that may underestimate compound risk interactions. Iterative coupling methods and targeted high-fidelity modeling for critical scenarios help partially address these issues, but complete system integration remains computationally demanding and methodologically complex for operational phase assessments.

Non-stationary design standards : Current risk assessment codes mainly assume stable climate conditions, which causes a disconnect with changing hazards over the operational lifespan of radioactive waste facilities. Adaptive pathway strategies that include trigger-based design changes and regular standard reviews provide mitigation options, but regulatory frameworks fall behind the latest methodological capabilities for handling non-stationary design challenges.

Representation of maintenance and human factors : Limited integration of operations, maintenance resilience, and human performance factors into quantitative risk assessment can lead to an underestimation of operational disruption impacts during extreme climate events. Incorporating operations and maintenance fragility functions, workforce performance models, and emergency response protocols offers mitigation, although standardized methods for quantifying human factors in climate risk assessments are still underdeveloped.

Validation under future conditions : The lack of empirical verification options for future climate extremes leads to ongoing model structural uncertainty that cannot be fully addressed through traditional validation methods. Multi-model ensemble techniques, expert opinions, and conservative safety margins serve as strategies to manage uncertainty, but inherent limitations in validating future conditions require adaptive management approaches with ongoing model improvements.

Natural Analogues

*Which climate-related **natural analogues** would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?*

CSM/CSA facilities are natural analogues concerning FAVL French disposal. Both sites have been studied.

References

ONDRAF/NIRAS, Long-term climate change and effects on disposal facility, geosphere and biosphere, NIROND-TR 2009–07E Version 2 19 October 2018

ONDRAF/NIRAS launches public consultation on long-term management of radioactive, radium-containing waste 02 December '24 https://www.sckcen.be/en/news/ondrafniras-launches-public-consultation-long-term-management-radioactive-radium-containing-waste

https://www.niras.be/eindberging/ondiepe-berging

Near-surface disposal in Mediterrenean climates (Malvesi-F)

Group Description

Group: 3NSc **Disposal type (Name)**: Near surface (Malvesi-F) **Nuclear waste type**: LILW **Current climate**: Cs **Countries**: France **Partners**: Andra, BGRM, ASNR**Time window for construction and operation**: 100 years
Location/Type of waste/Surface facilities/Distance from the shoreline **Location**: 43.1-43.3N (Latitude), 2.9-3.1E (Longitude), 5-10 m (Altitude) **Type of waste**: low activity - long lived **Surface facilities:** not determine at that step but some industrial building for sure **Distance from the shoreline (Mediterranean Sea):** 10-20 km **Distance from the Aude river:** 3 km **Current phase/EBS/Host rock (exact site not yet selected)** **Phase**: Site characterization **EBS**: no engineered barriers present in the last concept **Host rock**: Consolidated clay, red marl or grey marl in Oligocene (option in the grey marl would be an old mine); impermeable to semi-impermeable marl or permeable conglomerate **Above Host Rock** : Quaternary, Alluvial deposits , Alluvial water table **Below Host Rock** : Jurassic, Limestone, karstic aquifer exploited upstream

Screening

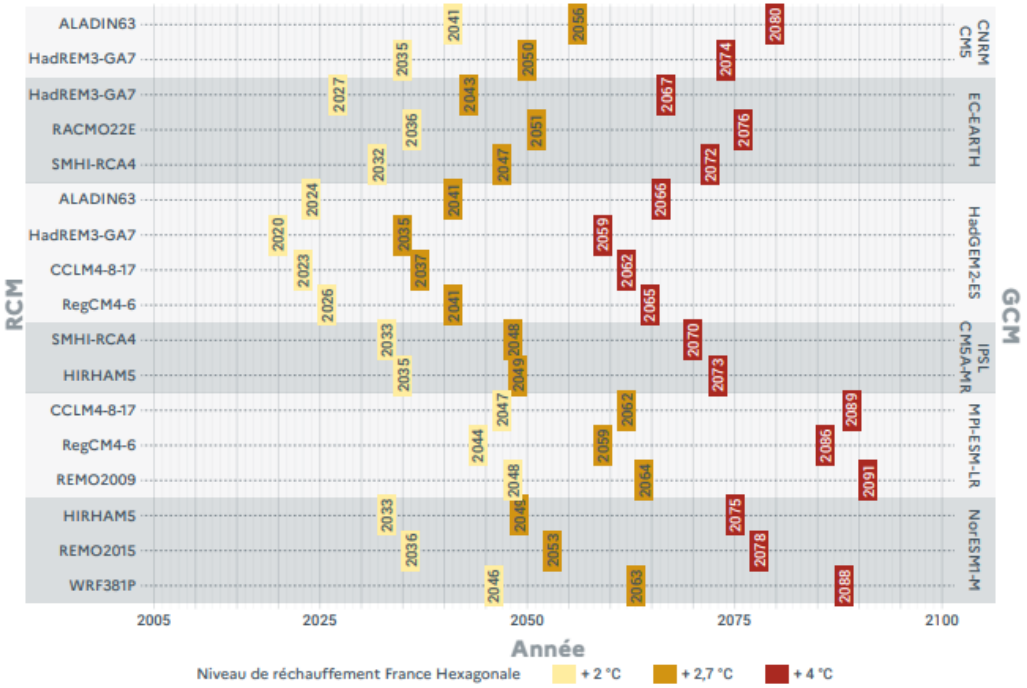
Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

- ☒ Coastal flooding
- ☐ Cold Spell
- ☒ Droughts
- ☐ Desertification
- ☒ Flash flooding
- ☒ Heavy rainfall
- ☐ Heatwaves
- ☐ Landslides
- ☐ River flooding
- ☒ Sea level rise
- ☒ Soil erosion
- ☒ Water table variations
- ☐ Windstorm
- ☒ Wildfires
- ☐ Others (please specify): _____

Please, indicate the data source (for climatic, sea level,….), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
Explore 2	PROJECTIONS HYDROLOGIQUES : RECHARGE POTENTIELLE DES AQUIFERES (https://doi.org/10.57745/ZQPNIE)	1976-2005	H1 2021-2050 (2° increase in European France)	H2 2035-2064 (2.7° increase in European France)	H3 2059-2091 (4° increase in European France)	RCP8.5	No (upscaled)	Yes	Yes	European France

Comments: The time windows H1 (2021-2050), H2 (2035-2064) and H3 (2059-2091) are large because of the discrepancies between the Regional Climatic Models in terms of temperature increase prediction in European France as explained in the figure below.


RCM
GCM
ALADIN63
HadREM3-GA7
HadREM3-GA7
RACMO22E
SMHI-RCA4
ALADIN63
HadREM3-GA7
CCLM4-8-17
RegCM4-6
SMHI-RCA4
HIRHAM5
CCLM4-8-17
RegCM4-6
REMO2009
HIRHAM5
REMO2015
WRF381P
CNRM CM5
EC-EARTH
HadGEM2-ES
IPSL CM5A-MR
MPI-ESM-LR
NorESM1-M
2005
2025
2050
2075
2100
Année
Niveau de réchauffement France Hexagonale
+ 2 °C
+ 2,7 °C
+ 4 °C

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use? Which hazard indicator would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)? Which exposure indicator would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones? Which vulnerability indicator would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks? Finally, for each hazard, indicate the expected impact(s) on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impact(s)
Coastal flooding	- Percentage of disposal system exposed to brackish water (5-30 ppt)	- Percentage of containers in ground gallery exposed to brackish water	- Materials susceptible to corrosion - Engineered barriers or radioactive materials	- Saltwater or brackish water intrusion in the aquifers below the disposal - Accelerated corrosion of the container in underground gallery (if the old Mavési mine is used)
River flooding and Flash flooding	- Annual max 2-day and 5-day precipitation, sub-daily extremes if available; - Percentage of disposal system exposed to river flooding with a 10-, 20-,	- Percentage of surface disposal area exposed to river flooding with a 10-, 20-, 50- and 100-year return period	- Surface infrastructure (e.g. backup batteries at ground surface) - Thickness of earth cover	- Workers safety during the flooding? - Accessibility to the disposal - Progressive soil erosion can compromise the

	50- and 100-year return period			stability of multilayered covers
Droughts	- Average soil moisture anomaly	- Average soil moisture anomaly in subsurface at the depth of the disposal	- Built-up areas of the disposal - River catchment	- Shrink/swell process and impacts on the buildings of the disposal facility
Water Table Variations	- Recharge variations	- Percentage of the disposal desaturated or resaturated	- Integrity of the engineered barrier to the variations	- Usage conflict for water use
Wildfires	- Amount of burned area around the disposal system	- Percentage of near-surface disposal facilities located in areas at risk of burning	- Accessibility to the disposal	- Workers safety
Erosion	- Percentage of disposal system exposed to river flooding with a 10-, 20-, 50- and 100-year return period	- Percentage of surface disposal area exposed to river flooding with a 10-, 20-, 50- and 100-year return period	- Thickness of earth cover	- Progressive soil erosion can compromise the stability of multilayers covers

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Combined risk of droughts in summer and heavy rainfall during the spring with the resulting risk of runoff (soils that cannot absorb large amounts of water after a long dry period).

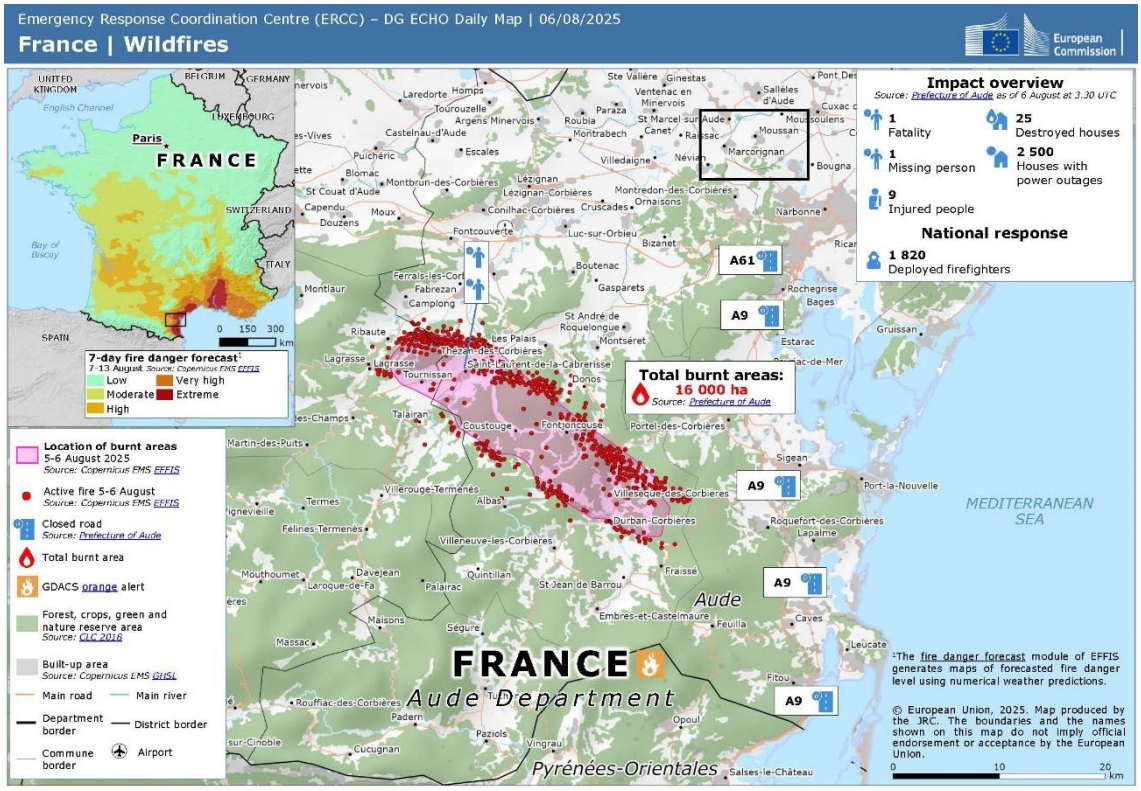
Combined risk of flooding and erosion in near-surface disposal facilities. The combined risk of extreme flooding (due to intense rainfall and river overflow) and **progressive soil erosion can compromise the stability of multilayers covers**.

How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

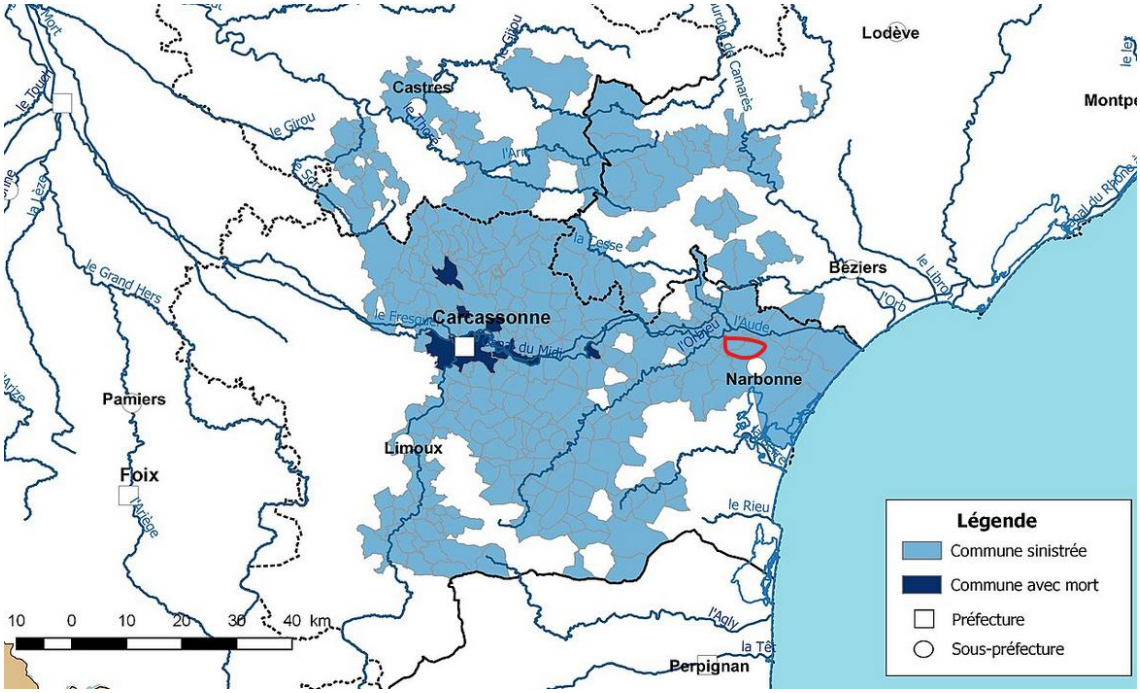
Qualitative comment:

A forest fire broke out on August 5, 2025 in the Corbières massif in the Aude department and strong winds from the locally common Tramontane had caused the fire to spread to over 16,000 hectares and several communities between the cities of Carcassonne and Narbonne) were evacuated. It was the largest fire in France since 1949. By that time, one person had died and 18 had been injured, including 16 firefighters. In addition, at least 36 homes and 40 vehicles were destroyed or damaged.



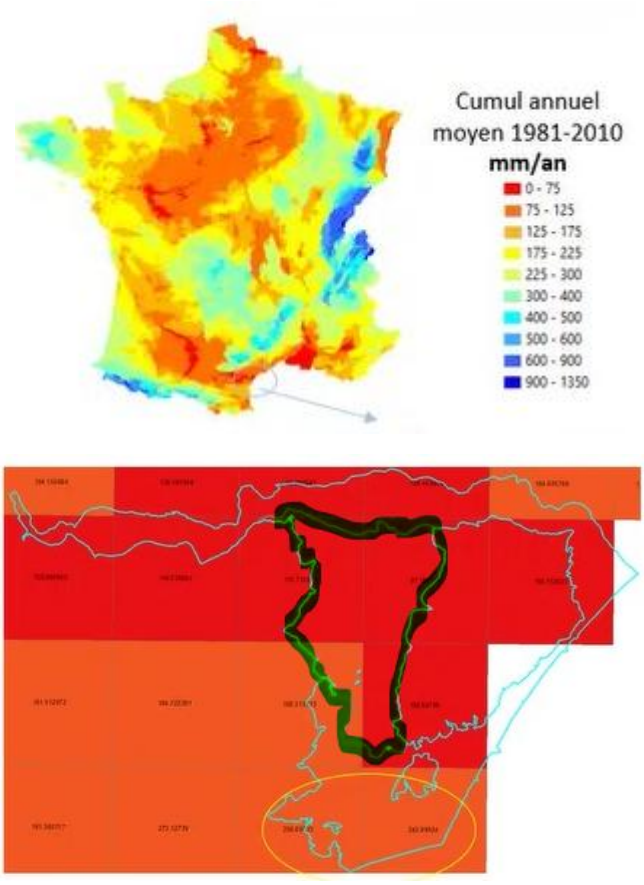
The most critical risk seems to be the proximity to the Aude river (e.g. 3 kms between the Orano Malvesi site and the Aude river) and the **combined risk of flooding and erosion of the cover of the future subsurface disposal**. Below the impacted area (in blue) following the flooding event of 15 October 2018 in the lower valley of the Aude River (studied area of storage in red), reminiscent of the devastating and deadly Mediterranean storm that took place between

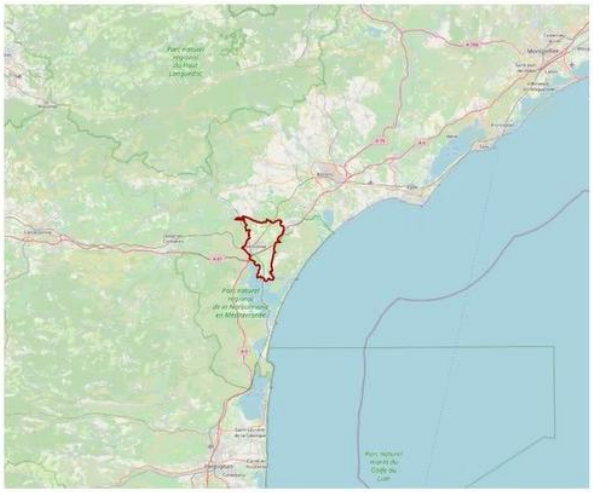
November 11 and 14, 1999, in France, affecting significant material damage and causing the deaths of 35 people.



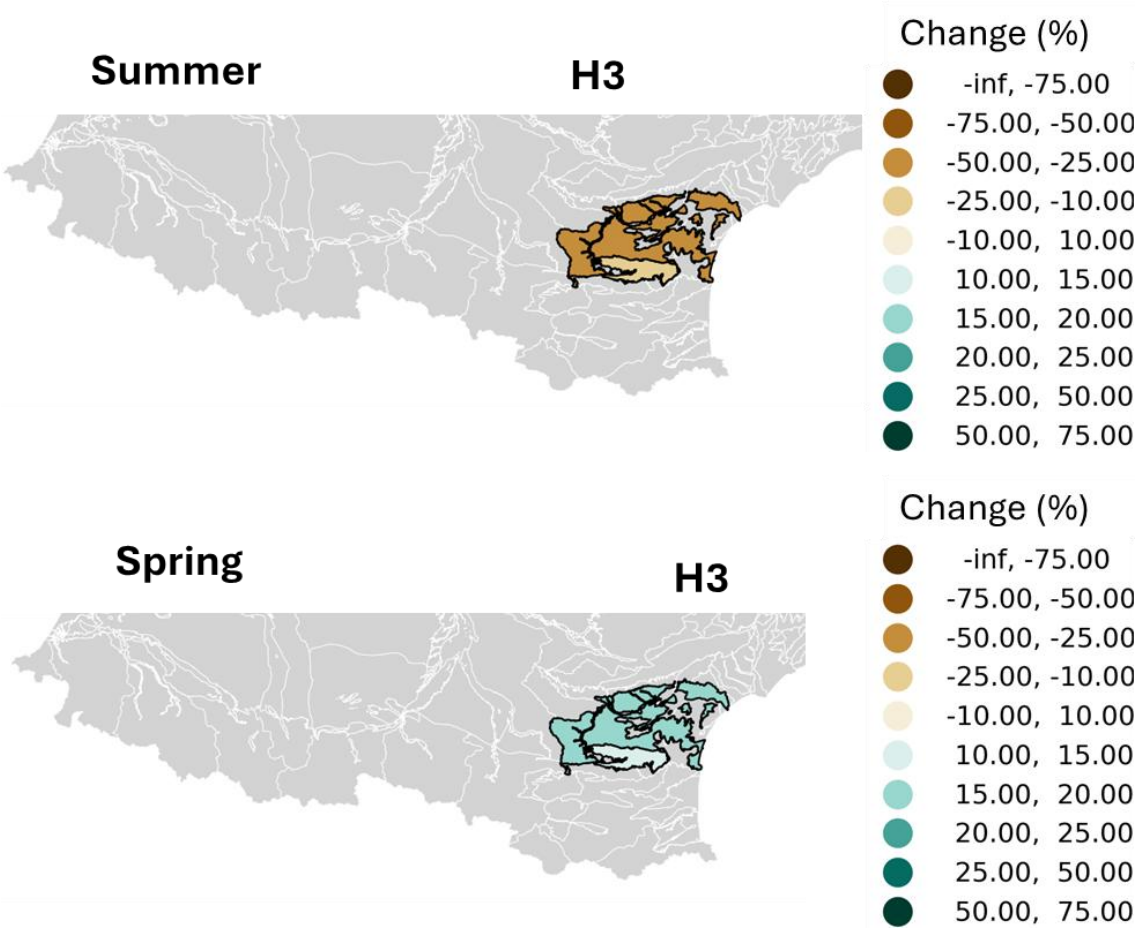
Quantification of the recharge in the studied area:

For the recent period **(1981-2010)**, the effective recharge in European France (and the zoom around the Malvési site) is calculated by BRGM in the following map (in mm/an means millimeter per year):



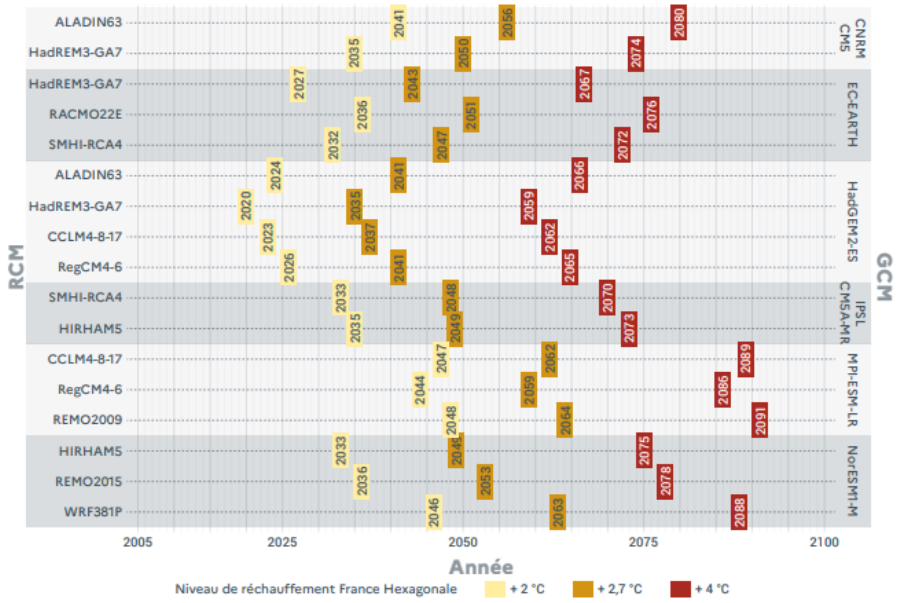


Explore 2 modeling result for the **H3 period (2059-2091)** in Summer (decrease of the recharge **between 25% and 50%**) and Spring (increase of the recharge **between 15% and 20%**) in the studied area around Malvesi site.



Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

The time horizon for the different periods to be analysed (historical, short, medium, long term) are not so easy to define precisely. To better understand, in yellow the time window to attain +2°C (~2021-2050) among the different Regional Climate Models (left), in orange the time window to attain 2.7°C (~2035-2064), and to attain 4°C (~2059-2091)



Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

A first limitation is that **the depth of the near-surface disposal** is unknown at this stage for the future disposal site. A second limitation is that, only the prediction of recharge for three future time horizons (H1, H2, H3) were calculated in Explore2 in the specific zone of the site of Malvési, not the variations of piezometric levels due to the absence of a spatial aquifer model (neither a global model). Therefore, the variations of piezometric levels should be obtained by developing regional subsurface aquifers models or alternatively global models (e.g with Gardenia/Rameau software of BRGM).

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☐ Coastal flooding
- ☐ Droughts
- ☐ Desertification
- ☒ Flash flooding
- ☒ Heavy rainfall

☐ Heatwaves
☐ Landslides
☒ River flooding
☐ Sea level rise
☒ Soil erosion
☐ Water table variations
☐ Wildfires

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Heavy Rainfall and Flooding	- Prediction of the stability of multilayered covers;	- Site selection (distance to the Aude river) and design modification (Depth of the disposal and thickness of the earth cover)
Pluvial-fluvial Compound Flooding	- Prediction of the stability of multilayered covers;	- Site selection (distance to the Aude river) and design modification (Depth of the disposal and thickness of the earth cover)
Erosion of multi-layer covers	- Prediction of the stability of multilayered covers;	- Site selection (distance to the Aude river) and design modification (Depth of the disposal and thickness of the earth cover)

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

A first limitation is that **the depth of the near-surface disposal** is unknown at this stage for the future disposal site.

The main limitation is that, only the prediction of recharge for three future time horizons (H1, H2, H3) were calculated in Explore2 in the specific zone of the site of Malvési, not the variations of piezometric levels due to the absence of a spatial aquifer model (neither a global model). Therefore, the variations of piezometric levels should be obtained by developing regional subsurface aquifers models or alternatively global models (like the tools Gardenia/Rameau of BRGM).

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Prediction of the stability of multilayers covers is not an easy task due to the uncertainties on key parameters.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

Climate states: from C “temperate” to B “arid” (arid soils that cannot absorb large amounts of water)

Time windows: in the recent future

References

Le projet Explore2, des projections hydrologiques pour adapter la gestion de la ressource en eau - INRAE : recherches pour l'agriculture, l'alimentation et l'environnement

Projections hydrologiques : Recharge potentielle des aquifères - Explore2 - Rapports techniques

“Réponse des Eaux souterraines au CHangement climatique dans le bassin AdouR-GaronnE (RECHARGE). Rapport final“ http://ficheinfoterre.brgm.fr/document/RP-67149-FR

https://en.wikipedia.org/wiki/2025_Corbi%C3%A8res_Massif_wildfire

Gaume, E., Livet, M., Desbordes, M., & Villeneuve, J.-P. (2004). Hydrological analysis of the river Aude, France, flash flood on 12 and 13 November 1999. *Journal of Hydrology*, *286*(1), 135–154. https://doi.org/10.1016/j.jhydrol.2003.09.015

https://www.150ansinondations.com/november-1999-the-aude/

Deep geological repositories in humid continental climates (Finland, Switzerland, Czechia, Germany)

Group Description

Group: 3DGRa

Disposal type (Name): Deep Geological Repository (1. Onkalo-FI, 2. Nördlich Lägern.-CH, 3. Czechia (Dunaj) and 4. Germany No site yet)

Nuclear waste type: SF

Current climate: Dfb

Countries: Finland, Switzerland, Czechia, Germany

Partners: VTT, Mitta, GTK, SÚRAO, TUL, Nagra, BGE, GRS**Time window for construction and operation**: 100a AP

Location/Type of waste/Surface facilities/Distance from the shoreline

Location:

Onkalo: 61N(latitude), 21E(Longitude), 5 m-surface facility, 420-520m below surface (repository) (altitude)

Nördlich Lägern. : 47.5N (latitude), 8.5E(longitude), 400 m(altitude)

CZ (Dunaj): 50-45N (latitude), 15-20E (longitude), 540–760m (altitude)

D: 45–55N as no site has been selected yet but must be in Germany (latitude), 5-15E as no site has been selected yet but must be in Germany(longitude), No site defined yet, cannot be specified (altitude)

Type of waste:

Onkalo : SF

Nördlich Lägern. : All

CZ(Dunaj): SNF / HLW and ILW

D: High-level radioactive waste, including spent nuclear fuel

Surface facilities:

Onkalo: Final commissioning phase with trial operation underway (Encapsulation plant).

Nördlich Lägern. : Not finalised yet, regular low-rise buildings (except for shaft-access probably)

CZ(Dujay): The surface area will house the technical facilities and equipment required for the preparation and disposal of SNF and RAW, the facilities and equipment required for the construction of the underground section, accommodation for workers at the site, and security, administration, information services, communication and other adjacent technical buildings. It is expected that the surface area will contain Nuclear facility area, Workshops and warehouses, Fire protection structures, Reinforced excavation rubble dump, Administrative buildings, Information centre, and Other structures to be specified depending on the conditions that prevail at the finally selected site [SÚRAO 2023].

D: (i) Buildings and technical facilities, necessary for the handling and storage of high-level radioactive waste inventory (e.g. storage facility for transport and storage casks, encapsulation plant), (ii) Ramp or vertical shaft of the repository mine, (iii) Buildings and technical facilities, necessary for the operation of the final repository.

Distance from the shoreline:

Onkalo : < 1km, 1-2km

Nördlich Lägern. : ~500 km to North Sea, ~300 km to Mediterranean

CZ(Dunaj) : 420 km

D: No site defined yet, cannot be specified

Current phase/EBS/Host rock

Phase:

Onkalo: Final commissioning phase with trial operation underway.

Nördlich Lägern.: Submitted the general license application (waiting for approval), currently switching from site characterization to planning/construction.

CZ(Dunaj): Site selection

D: Site selection

Operational safety investigations are a part of the preliminary safety analysis (vSU). In the current stage of the site selection procedure for HLW (i.e. Phase I, Step 2), in which the representative preliminary safety analysis (rvSU) is carried out, “the basic possibility of safe operation shall be demonstrated, but a complete operational safety analysis does not need to be performed”, according to Section 7 (6) No. 4 EndlSiUntV [EndlSiUntV 2020]. The basic possibility of safe operation addresses non-radiological (conventional) and radiological aspects of operational safety in varying degrees of detail [BGE 2022].

For the non-radiological aspects of operational safety (such as occupational safety, mining law and fire protection), site non-specific assessment of the regulatory framework and derivation of corresponding measures as a requirement for the preliminary repository design in accordance with Section 6 (4) EndlSiUntV [EndlSiAnfV 2020] is carried out. The indication of the basic possibility of safe operation with regard to the non-radiological aspects is also site non-specific and based on the assumption that safe operation is possible by complying with the regulatory requirements. A detailed analysis of the non-radiological aspects of operational safety is thus not necessary within the framework of the rvSU and will only be carried out in the next phase of the site selection procedure (i.e. Phase II).

In case of the radiological aspects of operational safety (i.e. radiation protection and release of radioactive substances), a generic catalogue is developed in the first step. The catalogue summarises possible external and internal impacts during construction, operational and closure phases as well as measures for meeting operational safety requirements, taking into account developed repository concepts and assumed operational processes. The external impacts are defined according to BMUB 2015 [BMUB 2015] as “impacts induced outside of the facility area, caused by conditions in its proximity or natural events or any other civilisation-related impacts”. The internal events are “impacts resulting from events on the facility area, inside or outside buildings”. Interactions between the impact categories are not considered in the rvSU. The possible effects of the external and internal impacts are investigated for defined repository subsystems (surface installations, access points (shaft, ramp), underground infrastructure areas, emplacement areas and access galleries), taking into account facility conditions “intended operation” (normal operation, abnormal operation) and “accident” (design basis accidents, beyond design basis accidents and events) according to Section 17 (1) No. 1 [EndlSiAnfV].

The influence of the external and internal impacts is considered to be relevant for the operational safety if conditions for the intended operation are not met. The following external impacts, relevant to nuclear law and radiation protection law and related to climatic drivers, are identified in the generic catalogue for operational safety in the framework of the rvSU:

For repository subsystems “surface installations and access points (shaft, ramp)”: flood events, mass movements (landslide, debris flow, rockfall, etc.), sinkholes, external fire and lightning strike.

For flood events, the following climatic and non-climatic drivers have to be considered, based on ESK (2018) [ESK 2018]: local heavy rainfall, surface runoff in local catchment areas, surface runoff in large catchment areas, ice jams on rivers, mechanically-induced wave, local wind-induced wave, sea waves, seiches, tsunami, storm surge, failure of dams and dikes, failure of artificial water reservoirs and high groundwater table.

For repository subsystem “surface installations”: wind load and snow load.

For repository subsystems “access points (shaft, ramps), underground infrastructure areas, emplacement areas and access galleries”: flooding of a mine, which can result from the external impact “flood events”.

EBS:

Onkalo: Copper-iron canister, bentonite buffer surrounding the canister and backfill of bentonite in tunnels with disposal holes, in addition, concrete plugs at the end of the tunnels, otherwise the facility is backfilled with clay/crushed rock mixtures, (crushed)rock and concrete plugs

Nördlich Lägern.: Canister surrounded by bentonite placed in clay-rich rocks, optimization phase ongoing

CZ(Dunaj): The Czech SNF/HLW disposal concept is based on the Swedish KBS-3 concept as adapted to the crystalline rock environment of the Bohemian Massif. Unlike the Swedish concept, the Czech concept assumes the use of steel waste disposal packages and Czech Ca-Mg bentonite. The concept of the ILW waste disposal will most probably be based on disposal chambers in special waste packages and then surrounded with the other engineered barriers and components [SÚRAO 2023].

D: § 4 (2) EndlSiAnfV stipulates [EndlSiAnfV 2020]: The intended disposal system shall ensure the safe containment of the radioactive waste passively and maintenance-free through a robust, graded system of different barriers with different safety functions. According to § 4 (3) EndlSiAnfV, the essential barriers to achieving safe containment of radioactive waste are 1. one or more containment-providing rock zones or 2. in the case of the host rock crystalline rock, provided that no containment-providing rock zone can be identified, technical and geotechnical barriers suitable for the respective geological environment. Further barriers hinder or prevent the migration of radionuclides in addition to and in coaction with the essential barriers. Pursuant to § 5 (4) EndlSiAnfV, the properties of technical or geotechnical barriers required for long-term safety shall be specified in the safety concept. The (preliminary) safety concept is part of the (preliminary) safety analyses, which are currently ongoing in the German site selection procedure for a high-level radioactive waste repository. Concepts for engineered barriers are currently worked on and will be published in 2027. Separate concepts are being developed for all three considered host rock types (claystone, crystalline, rock salt). Broadly speaking, the engineered barriers consist of the disposal container as well as buffer, backfill and seals. Wherever possible, material from excavation will be reused to produce material most similar to the surrounding host rock. As in virtually any other country’s engineered barrier system, also bentonite will be used in various forms due to its high swelling capacity and hence good sealing properties.

Host rock:

Onkalo: Metamorphic (250-500 m from surface to the top of the host rock and >100 m from top to bottom of host rock)

Nördlich Lägern.: Shale (800 - 900 m from surface to the top of the host rock and 100 - 120 m from top to bottom of host rock)

CZ(Dunaj): Igneous (0-20 m from surface to the top of the host rock and >100 m from top to bottom of host rock)

D: No site selected yet, cannot be specified. Could still be rock salt, claystone or crystalline rock (No site selected yet, cannot be specified. Legal minimum host rock depth 300m from surface to the top of the host rock and >100 m from top to bottom of host rock)

Current climate/Current land use/Geology/Hydrology/Geomorphology/Porewater

Köppen-Geiger

Onkalo: Dfb, that is cold without dry season and warm summer

Nördlich Lägern. : Cfb/Cfa

CZ(Dunaj): Dfb; Cfb

D: Most likely Cfb or Dfb (predominant classifications in Germany)

Köppen-Trewartha:

Onkalo: Dc, that is temperate

Nördlich Lägern. : Cf

CZ(Dunaj): Do; Dc

D: D (Do or Dc (predominant classifications in Germany))

(0-100 years AP)

Onkalo: Nearly like present; probably more rainy. Also depends on the scenario. [Posiva 2021]

Nördlich Lägern. : Almost like present, most likely gradual warming and increase of extreme events (depending on GHG scenario)

CZ (Dunaj): Change from now to 2090 (ClimRisk scenario aggregation): Mean air temperature increase from 7.9 to 9.9 °C. Annual precipitation increase from 700 mm to 720 mm. Relative humidity from 78.5 % to 77.7 %. Number of hot days (reaching 30 °C) from 6.6 to 20.3. [GCRI 2023] HYMOD-KZ (Vizina et al. 2024) [VIZINA 2024] is, not only, a web-based application that provides climate data (e.g., air temperature, atmospheric precipitation) for small catchment areas in the Czech Republic for the years 2005 to 2085. However, it also includes baseflow, which is a quantity generally equal to groundwater recharge (a key input for groundwater and radionuclide transport models). HYMOD-KZ uses the results of six global climate models and one regional model, ALADIN–CLIMATE/CZ. The Table below shows the average across all models; individual plots correspond to different climate change scenarios. The values shown in the graphs and the table are for the area “Jihlava from the source to the Třešťský stream” (DYJ_0810) for the years 2005, 2030, 2050, 2070, and 2085.

Table: Initial and final values of key variables according to HYMOD-KZ for Dunaj site

Quantity	Units	2005	2085	
			min	max
Air Temperature	°C	7.7	9.2	12.1
Precipitation	mm/month	58	57	67
Base flow	mm/month	7.2	7.4	12.9

D: No site selected yet, cannot be specified. Additionally, large uncertainty due to different model outputs and due to influence of anthropogenic climate change.

Current land use:

Onkalo: Tree cover and also grass and moss and lichen, partly built up. Snow and ice in winter

Nördlich Lägern. : Cropland, tree cover

CZ (Dunaj): Tree cover

D: No site defined yet, cannot be specified

Hydrology:

Onkalo: Perennial, groundwater dominated (rivers are mostly fed by groundwater or springs)

Nördlich Lägern. : Perennial, surface water dominated (river water is mostly from precipitation)

CZ (Dunaj): Perennial, surface water dominated (river water is mostly from precipitation)

D: No site defined yet, cannot be specified

Geomorphology:

Onkalo: Low relief topography: rather flat landscape

Nördlich Lägern. : Hilly topography: elevated areas can be recognized in the landscape

CZ (Dunaj): Hilly topography: elevated areas can clearly be recognized in the landscape

D: No site defined yet, cannot be specified

Geology above host rock:

Onkalo: Above host rock there is a thin quaternary layer, mostly clay and silt.

Nördlich Lägern.: Mesozoic and Tertiary sediments

CZ (Dunaj): Soils and regolith

D:No site selected yet, cannot be specified.

Geology below the host rock:

Onkalo : Metamorphic and magmatic

Nördlich Lägern. : Mesozoic sediments

CZ (Dunaj): Magmatic

D: No site selected yet, cannot be specified.

Hydrogeology above the host rock:

Onkalo : Fractured crystalline rock

Nördlich Lägern. : regional and local aquifers, all separated by relatively impermeable units

CZ (Dunaj): There is no aquifer above the host rock

D: No site selected yet, cannot be specified.

Hydrogeology below the host rock:

Onkalo : Fractured crystalline rock

Nördlich Lägern. : regional and local aquifers, all separated by relatively impermeable units

CZ (Dunaj): Fractured crystalline rock

D: No site selected yet, cannot be specified.

Porewater of the host rock at the RWM site/facility:

Onkalo : Saline

Nördlich Lägern. : Na-Cl-Type with moderate ionic strength

CZ (Dunaj): Fresh

D: No site selected yet, cannot be specified.

Porewater of the host rock above the RWM site/facility:

Onkalo : Fresh to Brackish

Nördlich Lägern. : Na-Cl-Type with moderate ionic strength

CZ (Dunaj): Fresh

D: No site selected yet, cannot be specified.

Porewater of the host rock below the RWM site/facility:

Onkalo: Saline to brine

Nördlich Lägern.: Na-Cl-Type with moderate ionic strength

CZ (Dunaj): Fresh

D: No site selected yet, cannot be specified.

Impact of sea level:

Onkalo : Yes

Nördlich Lägern. : No

CZ(Dunaj): No

D: No site selected yet, cannot be specified.

Screening

Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

☒ Coastal flooding
☒ Cold spells
☒ Droughts
☐ Desertification
☒ Flash flooding
☒ Heavy rainfall
☒ Heatwaves
☒ Landslides (Finland)
☐Permafrost thaw
☒River flooding
☒ Sea level rise
☐ Soil erosion
☒ Groundwater table variations
☒ Windstorm (Germany[9])
☒ Wildfires (Germany)
☒ Others : Sinkholes, Lightning strike, Snow load (Germany)

Sequential Cascading Effects:

- Heavy rainfall events can progress from surface flooding to groundwater infiltration, ultimately compromising long-term repository performance through enhanced radionuclide migration pathways.

Infrastructure Interdependencies:

[9] [Germany] In this questionnaire hazard “windstorm” was selected to represent external impact “wind load”; the latter being a hazard subcategory of the “windstorm”. Hazard “wildfires” was selected in this questionnaire to represent external impact “external fires”, since external fires include wildfires. External impacts “sinkholes”, “lightning strike” and “snow load” were classified in this questionnaire as “other hazards”.

In the next step, the basic possibility of safe operation in context of nuclear law and radiation protection law is investigated for the identified investigation areas. Based on the generic catalogue, possible external impacts to occur in the investigation areas are identified and mapped accordingly. For these purposes, requested and publicly accessible data are used (modelling prediction or climate change not considered in the rvSU). As far as possible, probability of occurrence and quantification of external impacts (e. g. in terms of water volume, water level) in particular for flood events, are determined. The identified climate-related external impacts specific for the investigation areas are identic to the climate-related generic external impacts listed above.

In the last step, robustness of operational safety regarding nuclear law and radiation protection law is investigated, based on the occurrence of the external impacts in the investigation areas.

- Power grid failures during extreme weather events can disable critical cooling systems, while transportation disruption affects waste delivery schedules and emergency response capabilities.
- Communication system failures during storms compromise monitoring systems essential for repository safety oversight.

Compound Event Interactions:

- Storm surge combined with heavy rainfall can overwhelm drainage systems, while freeze-thaw cycles combined with precipitation enhance infiltration through compromised engineered materials.
- Drought-heatwave combinations create synergistic stress on cooling systems and increase wildfire risks in forested areas.

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
EURO-CORDEX RCMs	EURO-CORDEX Data	1950-2020	2020-2050	2050-2100	2100-2300	SSP2-4.5 (primary) SSP1-2.6 SSP5-8.5	Yes	Yes	Yes	Europe
CMIP6 (Coupled Model Intercomparison Project Phase 6) GCMs(General Circulation Models)	IPCC AR6	1950-2020	2020-2050	2050-2100	2100-2300	SSP1-2.6 SSP2-4.5 SSP5-8.5	No	No	Yes	Global
Copernicus C3S	https://www.ngfs.net/system/files/import/ngfs/media/2022/11/21/technical_documentation_ngfs_scenarios_phase_3.pdf	1950-2020	2020-2050	2050-2100	-	Multiple SSPs	Yes	Yes	Yes	Europe

Please, indicate the data source (for climatic, sea level,….), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Comments:

- Onkalo (Finland): Priority is on the Coastal flooding.
- Nördlich Lägern (Switzerland): Priority will probably be on extreme events
- Czech Republic: Priority is on heatwave impacts with specialized of flood frequency analysis for Elbe/Morava basins

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use? Which hazard indicator would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)? Which exposure indicator would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones? Which vulnerability indicator would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks? Finally, for each hazard, indicate the expected impact(s) on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impact(s)
Coastal flooding	- Storm surge height (m); - Return period analysis (10, 50, 100 yr); - Wave height statistics;	- Surface facilities within flood zone; - Access roads elevation(<5m); - Coastal infrastructure distance(<2km from shore);	- Structural flood resistance rating; - Elevation above mean high water; - Drainage system capacity vs. design storm;	- Facility flooding; - Equipment damage; - Access denial; - Emergency response disruption; - Saltwater intrusion; - Corrosion acceleration;

Sea level rise	- Mean sea level rise projections (cm/decade); - Tide gauge records; - Relative sea level change; - Coastal erosion rates (m/yr);	- Coastal facility accessibility; - Saltwater intrusion risk;	- Facility elevation above projected SLR; - Adaptive capacity; - Design flexibility;	- Facility access loss; - Infrastructure submersion; - Monitoring disruption;
Cold spells (waves)	- Days <0°C; - Minimum temperature; - Coldwave duration;	- Heating system dependency; - Worker exposure hours; - Heat-sensitive equipment; - Concrete structures; - Steel structures;	- Material temperature limits;	- Heating system overload; - Concrete degradation; - Steel degradation; - Electronic failures;
Heavy rainfall (with Flash flooding)	- Maximum daily precipitation (mm); - Seasonal distribution patterns; - Annual totals; - Extreme precipitation events (>50mm/day); - Antecedent precipitation index;	- Site drainage capacity; - Underground access points; - Surface facility footprint/Drainage systems; - Stormwater management;	- Stormwater management capacity/Site slope stability factor; - Infiltration prevention; - Building envelope integrity/Early warning system capability/Emergency response time; - Foundation waterproofing;	- Groundwater infiltration; - Waste handling delays; - Drainage system overflow; - Transportation disruption; - Construction delays; - Landslides;

Heatwaves	- Heat Wave Index (HWIS); - Days exceeding 30°C, 35°C, 40°C; - Maximum wet bulb temperature; - Cooling degree days;	- Outdoor worker activities; - Air conditioning systems; - Heat-sensitive equipment; - Worker exposure duration;	- HVAC system capacity; - Heat-sensitive equipment protection; - Worker heat stress protocols; - Cooling redundancy;	- Worker heat stress; - Equipment overheating; - Cooling system strain; - HVAC failure; - Material degradation;
River flooding	- Peak discharge (m^3/s); - Flood frequency analysis; - Drainage capacity;	- Proximity to rivers/streams (<500m); - Low-lying areas; - Critical infrastructure elevation;	- Flood protection adequacy; - Early warning systems; - Structural flood resistance; - Emergency response capability;	- Facility inundation; - Waste handling suspension; - Contaminated water release; - Transportation disruption; - Emergency response complications;
Flash flooding	- Rainfall intensity (mm/hr);	- Catchment area (km^2); - Topographic depression areas;	- Drainage system response time; - Surface water management; - Early warning systems;	- Rapid inundation; - Erosion channels; - Sediment deposition; - Infrastructure overwhelm;
Droughts	- Standardized Precipitation Index (SPI); - Consecutive dry days;	- Cooling water systems; - Surface water dependencies;	- Water storage capacity (days); - Cooling system efficiency;	- Cooling system failures; - Dust generation; - Fire risk increase;

	- Soil moisture deficit; - Groundwater recharge rates (l/s/km²);	- Vegetation cover stability; - Fire protection systems;	- Backup water supply availability;	- Water shortage; - Vegetation loss; - Increased erosion; - Groundwater depletion;
Windstorms	- Maximum wind speed (km/h); - Storm frequency (#/yr);	- Building height and orientation; - Crane operations; - Outdoor storage areas;	- Structural design wind loads; - Emergency shutdown procedures;	- Structural damage to buildings; - Operational disruptions; - Debris generation; - Power outages;

Disposal System Component Vulnerabilities

Surface Infrastructure: Buildings require flood protection, and thermal stress management capabilities. Electrical systems need extreme weather resilience, while ventilation systems must maintain performance under high temperature conditions.

Expected Facility and Operational Impacts

Construction Phase Impacts: Work schedule delays during extreme weather events, material transport disruption during storms, worker safety concerns during heatwaves, foundation stability issues from freeze-thaw cycles, and increased construction costs due to weather-related delays.

Operational Phase Impacts: Waste handling delays during extreme weather, cooling system efficiency reduction during heatwaves, power outages affecting monitoring and safety systems, access road flooding preventing waste deliveries, and increased maintenance requirements for weather-damaged infrastructure.

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Multi-hazard Interaction Analysis

- **Drought-Heatwave Compounds:** Simultaneous water stress and thermal stress create synergistic impacts exceeding individual hazard effects. These combinations overwhelm cooling system capacity, accelerate concrete degradation through desiccation cracking, and significantly increase wildfire risk in forested areas.
- **Flood-Storm Compounds:** Storm surge combined with heavy rainfall generates cascading infrastructure failures when multiple systems are overwhelmed simultaneously. These compound events can lead to contaminated water dispersion during flooding and compromise emergency response capabilities.
- **Freeze-Thaw-Precipitation Interactions:** Enhanced infiltration through thermally-stressed materials accelerates concrete deterioration, disrupts groundwater flow patterns, and compromises foundation stability. These interactions are particularly relevant for facilities experiencing seasonal temperature variations.

Cross-sectoral Risk Amplification

- **Energy-Water-Transport :** Power grid failures during extreme weather affect cooling water pump operations, transportation fuel shortages during extended heat events disrupt facility operations, and water supply contamination impacts cooling system functionality. These interconnected vulnerabilities create systemic risks requiring coordinated adaptation measures.
- **Regional Climate-Ecosystem Feedbacks:** Forest loss can alter local precipitation patterns, and coastal erosion impacts marine ecosystem services supporting facility operations. These feedback mechanisms amplify local climate risks beyond direct physical impacts.

1. *How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.*

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Temporal Resolution Limitations: Limited sub-daily precipitation data constrains flash flood assessment accuracy. Insufficient long-term paleoclimate records limit deep future validation capabilities. Incomplete extreme event documentation in historical records affects return period analysis reliability.

Spatial Resolution Constraints: Coarse global climate model resolution proves inadequate for local impact assessment. Limited high-resolution regional downscaling for complex topography affects mountainous sites.

Process Representation Deficiencies: Incomplete compound event representation in climate models limits multi-hazard assessment capabilities.

Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Temporal Scale Integration Challenges: Limited integration between short-term weather and long-term climate creates assessment discontinuities. Inconsistent temporal resolution across different assessment components affects result synthesis.

Spatial Scale Integration Difficulties: Site-specific microclimate effects remain difficult to represent in regional assessments. Local-regional climate feedback mechanisms lack comprehensive understanding.

Participatory Process Limitations: Engaging diverse stakeholder communities across multiple countries presents coordination challenges. Limited integration of indigenous and local knowledge affects assessment completeness. Balancing expert judgment with stakeholder preferences requires structured engagement protocols.

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☒ Coastal flooding (FI)
- ☐ Cold spells
- ☒ Droughts (CZ)
- ☐ Desertification
- ☐ Flash flooding
- ☒ Heavy rainfall (CH)
- ☒ Heatwaves (CH, CZ)
- ☐ Landslides (CH)
- ☒ Permafrost thaw (FI)
- ☐ River flooding
- ☒ Sea level rise (FI)
- ☐ Soil erosion
- ☐ Water table variations
- ☐ Windstorm
- ☐ Wildfires
- ☐ Others (please specify): _____

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Coastal flooding	- Hydrodynamic modeling with sea level rise scenarios; - Storm surge analysis; - Coastal erosion assessment;	- Elevated infrastructure design; - Flood barriers and drainage systems;

		- Waterproof construction materials; - Emergency response protocols;
Permafrost thaw	- Thermal modeling of ground conditions; - Foundation stability analysis; - Infrastructure impact assessment;	- Insulated foundations; - Flexible infrastructure design for ground condition; - Monitoring systems;
Heavy rainfall	- Drainage system capacity analysis; - Flash flood risk assessment;	- Enhanced drainage infrastructure; - Surface water management; - Flood-resistant construction; - Early warning systems;
Compound risks	- Multi-hazard probabilistic assessment; - Cascading failure analysis; - System resilience modeling;	- Redundant systems design; - Flexible operational procedures; - Multi-hazard emergency protocols; - Adaptive management strategies;

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

High-Resolution Data Gaps: Limited availability of site-specific meteorological and hydrological data restricts model accuracy. Insufficient ground truth validation data impacts model calibration and uncertainty assessment.

Long-term Datasets: Insufficient historical records of extreme events impact return period estimates. Limited paleoclimate data hinder understanding of long-term variability patterns.

Process Understanding: Limited understanding of compound event mechanisms hampers accurate risk assessment. Lack of data on infrastructure performance during extreme conditions impacts vulnerability evaluation.

Future Scenario Limitations: Large uncertainties in emission pathways and climate sensitivity impact long-term projections. Limited depiction of tipping points and non-linear climate responses.

To address data gaps, enhanced monitoring networks, improved data sharing protocols, and investments in long-term observational systems would improve assessment reliability. Collaborative research initiatives between facilities could address common data needs.

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Model Resolution and Accuracy: Current climate models may not accurately capture local-scale processes essential for site-specific assessments. They also have limited ability to represent changes in the frequency and intensity of extreme events.

Uncertainty Quantification: Incomplete propagation of uncertainties through the assessment chain undermines confidence in results. There are limited methods for combining different types of uncertainties (aleatory and epistemic).

Temporal Integration: Difficulty in aligning short-term operational needs with long-term climate change. Few methods exist for incorporating adaptation timing and effectiveness.

System Complexity: Insufficient portrayal of human-system interactions and adaptive responses. Limited capacity to simulate cascading failures across interconnected systems.

To address these gaps in methodological improvements, developing ensemble approaches, enhanced uncertainty quantification methods, and better integration of multiple assessment scales would tackle current limitations. Investing in next-generation climate models and impact assessment tools is essential.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

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Deep geological repository in oceanic climates (Germany, France, UK, Belgium)

Group Description

Group: 3DGRb

Disposal type (Name): DGR (1. Konrad-D, 2. Cigeo-F, 3. UK and 4. (Northern) Belgium)

Nuclear waste type: HLW, (L)ILW-LL, LILW

Current climate: Cfb

Countries: Germany, France, UK, Belgium

Partners: BGE, GRS, Andra, BGRM, ASNR, NWS, SCK CEN**Time window for construction and operation**: 100 a AP

Location/Type of waste/Surface facilities/Distance from the shoreline

Location:

Konrad : 55-50N(Latitude), 10-15E(Longitude), 50-100m(Altitude)

Cigeo : 48N(Latitude), 5E(Longitude), 200-500m(Altitude)

UK : N/A. Siting process active. No site chosen.

Belgium : Initiation phase, no site chosen

Type of waste:

Konrad : Low- and intermediate-level radioactive waste with negligible heat generation

Cigeo : HLW and ILW-LL

UK : The UK Geological Disposal Facility (GDF) will take higher activity waste. This consists of High Level Waste, Intermediate Level Waste and a small amount of Low Level Waste which is not suitable for disposal at existing surface facilities. For planning purposes, we consider wastes from existing uses of radioactive materials, as well as wastes that would be generated from new nuclear power stations. We also include various nuclear materials in our planning that are not currently classified as waste, since these would need to be managed through geological disposal if it were decided at some point that they had no further use. The inventory for geological disposal is available online. [NDA 2021]

Belgium : Low and intermediate level waste long-lived (LILW-LL; cat B), high level waste (HLW; cat C) and possibly spent fuel in case considered as waste (cat C if not seen as a resource).

Surface facilities:

Konrad [PFB 2002] :

The Konrad repository consists of two shafts. Whereas shaft Konrad 1 is designated for transport of personnel and material as well as inflow of fresh mine air, shaft Konrad 2 is for re-packing and transport of the disposal packages and the outflow of mine air. At both shafts, various surface facilities have been constructed, are currently being constructed and will be constructed in the next few years.

At shaft Konrad 1, surface facilities are the mine shaft house including annex and the hoist frame, administrative building with offices and social rooms, , guard house, engine house south, belt conveyor and loading facility, building for material logistics, engine house north, workshop with switchgear building, heating system with wood pellet storage and standby diesel, diesel oil storage and fuel station, weather station, wood pellet and heating oil storage (under the surface). [PFB 2002, chapter 1.3.1.3 (Konrad 1)]

At shaft Konrad 2, surface facilities include a reloading/transfer facility, which is a group of buildings consisting of a drying facility, workshop 1 and a special treatment room (section A1), the reloading/transfer hall including the connection to the shaft hall (section A2), offices and social buildings (section B), heating system with switching substation and chimney (section C),

buffer hall (section D). Further surface facilities at Konrad 2 include the hoist frame with the shaft hall, ventilation building with a diffusor and exhaust air channel, guardhouse, outdoor power transformer facility, workshop with engine shed and friction winch hall, storage for backup transport means, garage, mine water transfer station, automobile parking garage, control station drying facility, immission measuring station. [PFB 2002, chapter 1.3.2.4 (Konrad 2)]

Cigeo : Site characterisation

UK : No site-specific blueprint/plans exist, as no community/site has yet been selected. The surface facilities of a Geological Disposal Facility (GDF) will handle the reception, inspection, and preparation of radioactive waste before its transfer underground.

Belgium : Initiation, no detailed plan for surface installations available yet

Distance from the shoreline:

Konrad : 100-200km

Cigeo : 344 km

UK : N/A. Siting process active. No site chosen. However, the three Community Partnerships currently involved in the process are all located adjacent to the coast.

Belgium 0-100 km

Current phase/EBS/Host rock

Phase:

Konrad : Construction

Cigeo : Site characterisation

UK : Site selection

Belgium : Initiation

EBS:

Konrad :

The main/primary barriers at Konrad are the geological barriers with their high isolation potential. Nevertheless, the excavation of the mine and operations have damaged the barrier functions. Hence, after the end of operations at Konrad, all cavities in the mine will be backfilled with dumping backfill and slinger stowing backfill (Schütt- und Schleuderversatz) and the surface shafts will be sealed backfilled and sealed in order to re-establishe the barrier function of the rock strata overlaying the repository.

Material used for backfilling of the shafts are required to be invariable over 10,000 years but the sealing remains effective also after this timeframe. Backfill and sealing measures for the Quaternary and Upper Creataceous parts of the shaft mainly serve to seal the shaft off against relatively shallow aquifers. For this part and purpose, a hydrostatic asphalt seal is planned to used. Since the main barrier of the repository is located within the Lower Cretaceous, the backfill material has to pass high requirements regarding its sealing properties. The excavation damage zone around the shaft also has to be treated with a suitable sealing material to prevent hydraulic routing via this path. For this purpose, a mineral seal in the Lower Cretaceous and in the Upper and Middle Jurassic a mineral column support with a horizontal connection to the mine pit are envisaged. Measures have to be undertaken to prevent the leak of the shaft filling into the mine pit via the shaft landing station. The stated requirements have to be met also under seismic impact (earthquake). [PFB 2002, C II.2.1.2.7.1]

Cigeo : Geological deep

UK : Nuclear Waste Services (NWS) is at an early stage of demonstrating technical feasibility of a GDF at potential UK sites, focussing initially on adapting the disposal concepts developed by more advanced waste management organisations. These disposal concepts are captured in NWS' 2016 generic Disposal System Safety Case [NDA 2017].

Belgium : Combination of carbon steel overpack (HLW; Cat C only) and cementitious barriers

Host rock:

Konrad : Host rock is the sedimentary Oxford formation (Jurassic), which is characterised by limestone, clay and ore deposits. (>500m from surface to the top of the host rock and 20-50m from top to bottom of host rock)

Cigeo : Consolidated clay (200-500 m depth) (>100m thickness)

UK : N/A. No site (and therefore host rock) has been chosen (200-1000m depth)

Belgium : Plastic clay (200-600m, 185m depth at Mol site) (50-100m, 100m thickness at Mol site)

Current climate /Current land use/Geology/Hydrology/Geomorphology/Porewater

Köppen-Geiger:

Konrad : Cfb

Cigeo : Cfb

UK : No specific site.

Belgium : Cfb

Köppen-Trewartha:

Konrad : (BGE) Dc

Cigeo : Do

UK : No specific site.

Belgium : Do

(0-100 years AP)

Konrad : Likely somewhat warmer than now but similar to today, still temperate climate.

Cigeo : B4 scenario – BIOCLIM5000 hypothesis, RCP8.5

Do (temperate)

UK : No specific site has been chosen, so no site-specific climate models/scenarios exist.

NWS (previously RWM) funded a PhD 2013-2017 “Projecting long-term past and future climate change within the context of post-closure performance assessments for disposal of radioactive waste”. This developed a tool which can model utilising select CO2 emissions to provide temporally and spatially scaled climate models. This work has subsequently been developed further by SKB, Posiva and KAERI.

Belgium : Alternation of current climate and global warming without marine transgression [SCKCEN 2012] (SCK•CEN-ER-184)

Current land use:

Konrad : Mix of cropland and industrial built-up areas

Cigeo : Grassland

UK : Siting process active. No site chosen

Belgium : Mixed

Hydrology:

Konrad **:** Perennial, surface water dominated (river water is mostly from precipitation)

Cigeo : Perennial, surface water dominated (river water is mostly from precipitation)

UK : Siting process active. No site chosen

Belgium : Perennial, groundwater dominated (rivers are mostly fed by groundwaters)

Geomorphology:

Konrad : Low relief topography: rather flat landscape

Cigeo : Low relief topography: rather flat landscape

UK : Siting process active. No site chosen

Belgium : Low relief topography: rather flat landscape

Geology above host rock:

Konrad : Sedimentary

Cigeo : Sedimentary

UK : No site (and therefore host rock) has been chosen

Belgium : Sedimentary

Geology below the host rock:

Konrad : Sedimentary

Cigeo : Sedimentary

UK : No site chosen

Belgium : Sedimentary

Hydrogeology above the host rock:

Konrad : Aquitard

Cigeo : Aquitard

UK : No site chosen

Belgium : Phreatic sedimentary aquifer and aquitards (mostly)

Hydrogeology below the host rock:

Konrad : Aquitard

Cigeo : Aquitard

UK : No site chosen

Belgium : Artesian sedimentary aquifers and aquitards

Porewater of the host rock at the RWM site/facilitiy:

Konrad : Saline

Cigeo : Fresh

UK : No site chosen

Belgium : Fresh (mostly)

Porewater of the host rock above the RWM site/facilty:

Konrad : Saline

Cigeo : Fresh

UK : No site chosen

Belgium : Fresh (mostly)

Porewater of the host rock below the RWM site/facilty:

Konrad: Saline

Cigeo: Fresh

UK : No site chosen

Belgium : Fresh to brackish

Impact of sea level:
Konrad : No
Cigeo : No
UK : No site chosen
Belgium : Yes

Screening

Which climate hazards would you consider during the screening phase? Please, include interdependencies, cascading and combined hazards

- ☒ Coastal flooding(M)
- ☒ Cold spells (M)
- ☒ Droughts(H)
- ☐ Desertification
- ☒ Flash flooding(M)
- ☒ Heavy rainfall(H), for Germany[10]
- ☒ Heatwaves(H)
- ☒ Landslides(M)
- ☐ Permafrost thaw
- ☒ River flooding(H), for Germany
- ☐ Sea level rise
- ☐ Soil erosion(M)
- ☒ Water table variations(H)
- ☒ Windstorm(M), for Germany
- ☐ Wildfires
- ☐ Others (please specify): for Germany: lightning strike, snow load, ice

Hazard Interdependencies and Cascading Effects

- Heavy rainfall → River flooding → Groundwater table variations → Repository saturation
- Droughts → Heatwaves → Wildfire risk → Air quality impacts

[10] Germany: The following external impacts, relevant to radiological aspects of operational safety and related to climatic drivers, are identified [PFB 2002][ESK 2018][IPCC 2023]: heavy rainfall, flood events (in terms of river/canal flooding), lightning strike, wind, snow load, ice, external fires. Wildfires are not included into external impact "external fires", since there is no forest around the facility site. River/canal flooding is not expected due to the local topography. Fire spreading to the buildings is prevented by maintaining a low fire load in the outdoor areas.

Radioactivity release possibly resulting from the external events, is prevented by appropriate structural, technical, or administrative measures.

In this questionnaire hazard "windstorm" was selected to represent external impact "wind"; the latter being a hazard subcategory of the "windstorm". External impacts "lightning strike", "snow load" and "ice" were classified in this questionnaire as "other hazards".

- Droughts + Heatwaves → Amplified cooling demands and water scarcity
- River flooding → Infrastructure damage → Operational disruption (cascading operational impacts).

Please, indicate the data source (for climatic, sea level,….), time horizon for the different periods to be analysed (historical, short, medium, long term), emission scenario (RCP) and type of climate models you would use for the screening phase.

Data Source	Reference	Baseline	Short term	Medium term	Long term	Emission scenario	Downscaled	Bias-corrected	Ensembled	Geographic coverage
National Meteorological Services	Météo-France, KMI Belgium	1961-1990	2021-2040	2041-2070	2071-2100	RCP4.5, RCP8.5	Yes - station data	Yes	Multi-station	National
CLIMAAX Toolbox Data	CLIMAAX Handbook 2023	1991-2020	2021-2040	2041-2070	2071-2100	RCP2.6, RCP4.5, RCP8.5	Yes - regional	Yes	Multi-model ensemble	Europe
CCI-HYDR	bwk.kuleuven.be/hydr/CCI/Reports/cci-hydr-iib-climatechangescenarios-extinbo.pdf	1961-1990			2071-2100	SRES	Yes	n/a	Yes	Belgium
Cordex.be	KMI - De klimaatvooruitzichten voor 2100	1976-2005		2036-2065	2070-2100	RCP2.6, 4.5, 8.5	Yes			Belgium
Germany (Konrad): Deutscher Wetterdienst (DWD) (Germany's National Meteorological Service)									Multi-station	National, regional

Germany (Konrad) : precipitation	Local weather stations									Local
Germany (Konrad): water discharge	Local water discharge measuring stations									Local

Comments:

For each identified climate hazard, indicate how you will examine the risk. Which hazard, exposure and vulnerability indicators would you use?

Which **hazard indicator** would you use to evaluate the future evolution of the hazard (e.g., climate impact drivers)?

Which **exposure indicator** would you use for evaluating the risk? Is there historical evidence of extreme weather events in the past? Which ones?

Which **vulnerability indicator** would you use for evaluating the risk? To which part of the disposal system do these risks apply (e.g., engineered barrier, earth cover, aquifer above host rock, container in underground gallery, river catchment)? Which disposal system components are most vulnerable to these risks?

Finally, for each hazard, **indicate the expected impact(s)** on the facility and the operation. Impacts are the effects of climate risks on repositories, workers and operations. More than one impact can result from a climate risk.

Hazard	Hazard indicator	Exposure indicator	Vulnerability indicator	Expected impact(s)
Heavy rainfall(H)	- Annual maximum daily precipitation (mm); - Frequency of extreme precipitation events (>95th percentile);	- Surface facilities area (ha); - Drainage system capacity (m^3/s);	- Permeability of surface materials; - Drainage system age and condition; - Surface installation stability factors;	- Surface flooding - Inundation of surface facilities; - Inundation/re-saturation of shafts and underground galleries;
River flooding(H)	- 100-year flood level (m); - Peak discharge rates (m^3/s); - Flood duration (days);	- Distance from nearest river (km); - Elevation above river level (m); - Floodplain extent;	- Flood defense infrastructure; - Emergency response capacity; - Critical equipment elevation;	- Inundation of surface facilities; - Inundation/re-saturation of shafts and underground galleries; - Loss of access roads;

				- Equipment damage;
Heatwaves(H)	- Maximum temperature (°C); - Duration of >35C days;	- Concrete structure exposure; - Cooling system requirements;	- Concrete thermal expansion coefficients; - Worker heat protection measures; - Cooling system redundancy;	- Worker health risks; - Concrete cracking; - Increased cooling demands; - Material degradation;
Cold Spells (waves) (M)	- Days <0°C; - Minimum temperature; - Cold wave duration;	- Heating system dependency; - Worker exposure hours; - Heat-sensitive equipment; - Concrete structures; - Steel structures;	- Material temperature limits;	- Heating system overload; - Concrete degradation; - Steel degradation; - Electronic failures;
Coastal flooding(H)	- Storm surge height (m); - Wave height (m); - Sea level rise projections (mm/yr);	- Distance from shoreline (km); - Site elevation (m Absolute Sea Level (ASL)); - Coastal defense presence;	- Coastal defense condition; - Emergency protocols;	- Saline intrusion into aquifers; - Coastal erosion; - Infrastructure damage; - Access disruption;
Droughts(H)	- Standardized Precipitation Index (SPI); - Soil moisture deficit (%); - Groundwater level decline (m);	- Water supply dependency; - Dust control needs;	- Water storage capacity; - Alternative water sources; - Drought contingency plans;	- Water supply shortage; - Increased dust generation; - Increased fire risk;
Water table variations(H)	- Groundwater level fluctuation (m); - Recharge rate changes (%);	- Repository depth below water table (m);	- EBS degradation potential; - Monitoring system coverage;	- EBS saturation changes;

Windstorms(M)	- Maximum wind speed (km/h); - Storm frequency (#/yr);	- Building height and orientation; - Crane operations; - Outdoor storage areas;	- Structural design wind loads; - Emergency shutdown procedures;	- Structural damage to buildings; - Operational disruptions; - Debris generation; - Power outages;
Flash flooding(M)	- Rainfall intensity (mm/hr);	- Catchment area (km²); - Topographic depression areas;	- Drainage system response time; - Surface water management; - Early warning systems;	- Inundation/re-saturation of shafts and underground galleries; - Rapid inundation; - Erosion channels; - Sediment deposition; - Infrastructure overwhelm;

Historical Evidence of Extreme Events:

France (Cigeo region): The 2003 European heatwave caused operational shutdowns at over 30 nuclear facilities, while recent severe thunderstorm outbreaks in June 2022 produced significant hail damage and flooding across multiple departments. 2016 Seine floods,

Belgium: The July 2021 floods resulted in 38 fatalities and massive infrastructure damage, with climate projections indicating temperature increases up to 3.5°C and over 50 heatwave days per year by 2100

Construction & Operational Phase impact (0-100 years):

- Worker health: Heat stress casualties, flood evacuations
- Construction: schedule delays from extreme weather
- Equipment: Cooling system overloads, corrosion acceleration, flooding of surface and underground facilities
- Access: Road closures from flooding

Which compound risks do you anticipate? Compound risks arise when multiple hazards interact, leading to combined or amplified consequences that exceed the impact of each risk on its own.

Primary Hazard	Secondary Hazard	Interaction Type	Mechanism	Temporal Correlation
Heavy rainfall	River flooding	Cascading	Saturated soils reduce infiltration	Immediate to hours
Droughts	Heatwaves	Synergistic	Reduced evaporative cooling	Concurrent
Heavy rainfall	Soil erosion	Direct causation	Surface runoff exceeds infiltration	Immediate
Sea level rise	Coastal flooding	Amplifying	Reduced storm surge return periods	Long-term trend
Coastal flooding	Water table variations	Cascading	Saline intrusion alters flow	Days to months
Droughts	Wildfires	Enabling	Dry vegetation creates fire conditions	Seasonal lag
Windstorms	Heavy rainfall	Concurrent	Storm systems bring both hazards	Simultaneous
River flooding	Water table variations	Hydraulic coupling	Surface water raises groundwater	Hours to weeks
Heavy rainfall	Water table variations	Hydraulic coupling	Heavy rainfall on saturated soil surface induces local flooding	Hours to weeks

How would you quantify the risks? As described in the introduction, climate risk is a combination of hazard, exposure and vulnerability.

In case of lacking information, this section can be left blank, or you can provide a more qualitative comment.

In Belgium, there is no action undertaken yet to quantify such risks.
Germany: probabilistic analysis of hazards.

Did you encounter any limitations with the data used for the screening phase? What were the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the screening? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Gap Category	Specific Limitations	Impact on Screening	Mitigation Measures	Regulatory Alignment
Temporal /Historical Climate Data	Limited extreme records (<50 years), Sparse spatial coverage	Underestimation of rare events	Paleoclimate proxies, Regional model ensemble	

Site-specific Data	Limited monitoring	Generic assessments only	Sensitivity analysis,	Preliminary assessments only
Compound Events	Limited concurrent hazard data, Unknown interactions	Potential risk underestimation	Expert elicitation, Scenario approaches	Emerging regulatory topic

Temporal Coverage Constraints: Limited records of extreme events (<50 years for most stations) emphasize the temporal constraint, leading to a significant underestimation of rare event frequencies, especially beyond 100-year return periods that are critical for infrastructure resilience. Assuming a stationary climate is invalid amid recent accelerating climate change, making traditional statistical methods ineffective since historical data no longer represent future climate conditions. Seasonal bias in observational data, where winter precipitation records are more reliable than summer extreme rainfall data, further complicates accurate climate analysis due to the historical limitations.

Spatial Resolution Inadequacies: Spatial resolution limits in meteorological and climate modeling are clear due to sparse station networks with typical spacing of 20-50 km, which fail to capture important local climate variations around repository sites. Also, regional climate models often have topographic representation errors that hinder accurate depiction of orographic precipitation enhancement and temperature gradients vital for site-specific assessments. Furthermore, urban heat island effects and land-use changes are poorly represented in gridded datasets, further affecting the accuracy of localized climate analyses.

Site-Specific Information Deficits: In the UK and Belgium repositories, no site selection completion prevents location-specific vulnerability assessments, restricting analysis to general regional methods. Surface facility specifications remain preliminary for all sites except Konrad, limiting the accuracy of exposure quantification. Details of the engineered barrier system are classified or undetermined, hindering detailed vulnerability analysis.

Groundwater monitoring networks have insufficient duration (<10 years) to establish baseline variability and climate sensitivity. Variations in aquitard permeability under climate stress are poorly quantified, which is critical for assessing barrier integrity. Surface-groundwater interaction parameters are inadequately characterized for evaluating compound flood-groundwater risk.

Did you encounter any limitations related to the screening methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Limitation Type	Description	Impact on Assessment	Proposed Solutions	Resource Requirements
Model Resolution	RCMs at 25-50km miss local effects	Underestimate orographic precipitation	Dynamic downscaling <5km	High computational demand

Scenario Selection	Limited to standard RCPs	May miss risk space	Storyline approaches, Stress-testing	Stakeholder engagement
Temporal Mismatches	Climate vs operational timescales	Disconnect near/long-term risks	Seamless prediction systems	Long-term monitoring
Uncertainty Propagation	Cascading through assessment chain	Wide confidence intervals	Robust decision making	Advanced statistics

Model Resolution Limitations: Regional Climate Models (RCMs) operating at typical 25-50 km horizontal grid resolution fundamentally lack the spatial resolution needed to capture critical local-scale processes influencing nuclear waste repository sites. The grid cell averaging effect inherently smooths out sub-grid variability, leading to systematic biases in extreme weather predictions that are crucial for infrastructure risk assessment.

Scenario Selection Limitations: The Representative Concentration Pathway (RCP) framework provides only four discrete emission scenarios (RCP2.6, 4.5, 6.0, 8.5) representing specific radiative forcing trajectories, creating fundamental gaps in risk space exploration for 100-year repository operational planning.

Temporal Scale Integration Problems: Multi-Temporal Risk Assessment : Construction versus operational risk profiles are inadequately integrated, missing vulnerability transitions throughout the facility lifecycle. Climate change acceleration over a 100-year span is poorly represented by linear trend assumptions in screening methodologies. Effects of aging legacy infrastructure on vulnerability development are not systematically included.

Uncertainty Propagation Issues: Methodological Chain and model structure Uncertainty : Compounding uncertainty through climate model → downscaling → impact model → risk assessment chain is inadequately quantified using standard error propagation approaches. Assumptions about the correlation structure between hazards, exposure elements, and vulnerability factors are often unrealistic, leading to bias in combined risk estimates. Tail risk is underestimated because normal distribution assumptions are inappropriate for extreme climate events.

Alternative conceptual models are not systematically explored, leading to hidden structural biases in risk ranking. Interaction effects between parameters are inadequately captured by sensitivity analysis methods designed for independent parameter variation. The inability to validate for 100-year projection periods prevents verification of the methodology's performance.

Detailed Assessment

Based on your knowledge and understanding, which are the most critical risks and would require a deeper analysis in the detailed assessment?

- ☐ Coastal flooding
- ☐ Cold spells
- ☒ Droughts
- ☐ Desertification
- ☐ Flash flooding
- ☒ Heavy rainfall
- ☒ Heatwaves
- ☐ Landslides
- ☐ Permafrost thaw
- ☐ River flooding
- ☐ Sea level rise
- ☐ Soil erosion
- ☒ Water table variations
- ☐ Windstorm
- ☐ Wildfires
- ☐ Others (please specify): _____

Indicate which detailed assessment methodology you would follow for each of the most critical risks. What adaptation measures or design modifications could be considered in response to the identified risks?

Risk	Methodology	Adaptation measurements
Heavy rainfall and flooding	- High-resolution hydrodynamic modeling (1-5km); - Coupled surface-groundwater flow analysis; - Extreme value statistical analysis; - Infrastructure vulnerability assessment;	- Enhanced drainage systems; - Demountable flood barriers; - Elevated critical equipment; - Sustainable drainage solutions; - Adapt elevation of potential flood water entrance points (e.g., shafts);
Heat wave impact on operation	- Detailed thermal finite element modeling; - Material degradation analysis; - Worker heat stress assessment; - Facility thermal response analysis;	- HVAC system upgrades; - Advanced thermal insulation; - Passive cooling solutions; - Modified work schedules during extreme heat;
Drought effect on water supply and cooling	- Integrated water resource modeling; - Alternative supply assessment; - Demand optimization analysis; - Supply chain vulnerability assessment;	- Strategic water reserves; - Advanced recycling systems; - Drought contingency protocols; - Alternative supply infrastructure;

Water table variation on engineered barriers	- Long-term degradation analysis; - Performance assessment integration; - Barrier material testing;	- Enhanced barrier materials; - Active groundwater control systems; - Real-time monitoring networks; - Predictive maintenance protocols;

Did you encounter any limitations regarding the data used for the detailed assessment? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed assessment? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

High-Resolution Climate Data Gaps:

- Spatial Resolution Constraints: Micro-climate characterization around repository sites necessitates climate data with a spatial resolution of less than 1 km, which is currently unavailable from standard meteorological networks. Orographic precipitation enhancement effects are inadequately represented in regional climate models, which is critical for the assessment of extreme rainfall events in complex terrain regions. Additionally, the quantification of urban heat island effects at surface facilities of DGR is hampered by the lack of long-term, high-resolution temperature monitoring data, which is essential for optimizing cooling system design.
- Temporal Resolution Inadequacy: The collection of sub-hourly precipitation data is necessary for flash flood modeling, but is currently limited to fewer than 10 stations within 50 km of the repository sites. The evolution of extreme weather events, including storm development and dissipation patterns, is inadequately characterized due to the lack of continuous high-frequency meteorological observations. Additionally, the analysis of compound event sequencing is hindered by gaps in concurrent multi-parameter extreme weather records.

Infrastructure Response Data Limitations:

- Facility-Specific Vulnerability Functions: Nuclear facility related to extreme weather impacts are mostly proprietary or unavailable, requiring reliance on generic infrastructure response models. Material performance databases under combined thermal, mechanical, and chemical stress conditions are insufficient for analyzing repository-specific barrier systems. Additionally, operational threshold documents describing facility shutdown and emergency procedures are not standardized across European nuclear waste management organizations.
- Engineering System Performance: The efficiency degradation of HVAC systems under extreme temperature conditions is inadequately quantified for nuclear facility applications. The impact of aging drainage infrastructure on the capacity to manage extreme precipitation is insufficiently characterized for specific facility designs. Reliability of backup power systems during prolonged extreme weather events lacks comprehensive testing data under actual operational conditions.

Coupled System Modeling Data:

- Hydro-Geological Coupling Parameters: Surface-groundwater interaction coefficients during extreme rainfall events require site-specific tracer or impulse-response modelling studies, which have not always been conducted at repository sites. Moreover, rapid water table fluctuations under actual stress conditions are not always understood at specific sites. The long-term impact of groundwater chemistry and temperature on the permeability of engineered barriers is also poorly understood due to limited testing over extended periods.
- Regional Infrastructure Dependencies: The vulnerability of external utility systems—such as power grids, water supplies, and transportation networks—due to extreme weather conditions is inadequately mapped concerning repository operational dependencies. Additionally, regional emergency response capacities during compound events lack quantitative assessments

necessary for supporting nuclear facilities. Furthermore, the patterns of supply chain disruptions during extreme weather events are insufficiently characterized to inform maintenance and operational continuity planning.

Did you encounter any limitations with the detailed assessment methodology? What are the main gaps or uncertainties? How might these gaps and constraints impact the reliability or applicability of the detailed modelling? What steps could be taken to address or mitigate these gaps in future work? How do these limitations align with regulatory or stakeholder requirements?

Coupled Physical Process Modeling Limitations:

- Physics Integration Challenges: The scale-dependent process representation faces challenges in integrating molecular-scale chemical reactions with facility-scale thermal responses and regional-scale hydrological processes within unified modeling frameworks. Additionally, there is significant uncertainty in the constitutive relationships for novel barrier materials subjected to unprecedented stress combinations, including climate-driven thermal cycling, chemical evolution, and mechanical loading, due to the lack of fundamental scientific validation.
- Temporal Scale Integration Problems: The multi-temporal process coupling approach inadequately addresses rapid climate events occurring within hours, which influence long-term barrier performance over decades, primarily due to computational constraints and limitations in process representation. Current modeling approaches, which assume quasi-static system evolution, do not sufficiently capture the acceleration of climate change over a 100-year operational period. Additionally, existing assessment methodologies inadequately track the propagation of legacy effects originating from early operational decisions through the system's long-term performance.

Extreme Event Modeling Deficiencies:

- Compound Event Representation: Modeling non-linear interactions among multiple concurrent hazards surpasses current multi-hazard assessment capabilities, especially for novel climate combinations that have not been observed historically. Additionally, the complexity of cascade pathways through interconnected infrastructure systems necessitates network-scale modeling capabilities that are not yet incorporated into existing repository-specific assessment tools.
- Extreme Value Extrapolation Issues: The assumptions underlying statistical distribution models for extreme climate events are increasingly invalid under conditions of non-stationary climate change. Currently, there is no widely accepted methodological consensus for alternative modeling approaches. The dependence structure, or tail dependence, between multiple hazards is inadequately characterized, resulting in systematic underestimation of the frequency of compound extreme events. Furthermore, the physical limits of extreme weather intensities may not be accurately captured by statistical extrapolation methods, necessitating the development and implementation of process-based modeling approaches that are not yet operationally available.

System Complexity and Emergent Behavior:

- Infrastructure Network Dependencies: Cross-sectoral vulnerabilities encompassing energy, water, transportation, and communications significantly impact repository operations. However, addressing these vulnerabilities necessitates the development of modeling frameworks that extend beyond the scope of single-facility assessments. The evolution of regional infrastructure resilience during prolonged periods of climate stress is inadequately characterized, thereby limiting comprehensive analyses of repository operational dependence. Additionally, supply chain vulnerabilities to compound extreme events currently lack systematic modeling approaches that are suitable for applications involving nuclear facilities.

Validation Data Inadequacy:

- Historical Analogue Limitations: The availability of infrastructure performance data during extreme weather events is restricted due to the infrequency of such events and the proprietary nature of nuclear facility operational records. Furthermore, validating compound events is virtually impossible because of the extreme rarity of multi-hazard combinations pertinent to repository assessment.

Computational and Technical Constraints:

- High-Performance Computing Challenges: Ensemble modeling at specified resolution and complexity levels demands significant computational resources that may exceed available capacity for routine assessment purposes. Furthermore, the data storage and management requirements for high-resolution, multi-parameter, long-term simulations surpass current data infrastructure capabilities. The integration of multidisciplinary tools across climate, hydrological, geotechnical, and nuclear engineering software necessitates the development of standardized interfaces, which are not yet universally available.

Regulatory Framework Adaptation:

- Standards Evolution Needs: The process for approving assessment methodologies has not been sufficiently modified to accommodate innovative climate risk assessment techniques that necessitate the development of regulatory guidance. The criteria for acceptance of uncertainty under conditions characterized by deep uncertainty lack established precedents within the context of nuclear facility licensing. Additionally, the international harmonization of climate risk assessment standards requires coordinated efforts across multiple regulatory jurisdictions, each with distinct risk tolerance levels and assessment traditions.

Natural Analogues

Which climate-related natural analogues would be useful according to site specifications (e.g., type of earth cover or host rock)? For which time periods are these analogues applicable? What evidence or observations from these analogues can inform risk assessment? What are the limitations or uncertainties in using these analogues for the current site? What references or case studies support the selection and use of these analogues?

In the case of the Cigeo site, several studies were conducted to characterize its future evolution. In the latest version, several stations around the world serve as analogue data for characterizing DO, EO, EC, FT, Cr, and Cs climates.

Thus, these studies provide answers for the evaluation of the site and various associated parameters (establishment of biosphere types, hydrogeological regime, and geomorphological evolution over a million years).

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Appendix D. Group documents Task 4

Group 4DGRa

Group number: 4DGRa

Disposal type: Geological

Current climate: Dfb at latitude >50N

Countries: Finland, Germany

Partners: VTT, Mitta, GTK, BGE, GRS

Lead: Mitta

Time window: 0-1000 ka AP (a or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	**Case study/site name**	**Disposal type**	**Waste type**	**Current phase**
Finland	Olkiluoto	Geological	Spent nuclear fuel (SNF)	Construction
Germany	No site	Deep geological disposal facility	High-level radioactive waste, including spent nuclear fuel	Site selection

Case study/site name	**Latitude**	**Longitude**	**Altitude**	**Distance to sea**
Olkiluoto	65-60N	20-22E	0-10	< 1
Germany no site	Approx. 47 to 55 N	Approx. 5 to 15 E	unknown	unknown

Case study/site name	**Climate Köppen Geiger/Köppen-Trewartha**	**Hydrology**	**Land-use**	**Landscape**
Olkiluoto	Dfb/Dc	Fractured crystalline rock	Constructed areas, forest, and agricultural areas, i.e. mixed	Low relief topography
Germany no site	Cfb or Dfb / D (Do or Dc)	unknown	unknown	unknown

Case study/site name	**Host rock (HR)**	**Depth (m)**	**Thickness (m)**
Olkiluoto	Fractured crystalline rock	250-500	> 100
Germany no site	unknown (claystone, crystalline or rock salt)	>300 m (see Subtask 4.1 "Regulatory framework" for further information	>100 m

Case study/site name	Geology above HR	Geology below HR	Hydrogeology above HR	Hydrogeology below HR
Olkiluoto	Metamorphic and magmatic	Metamorphic and magmatic	Fractured crystalline rock	Fractured crystalline rock
Germany no site	unknown	unknown	unknown	unknown

Case study/site name	Pore water HR	Pore water above HR	Pore water below HR
Olkiluoto	Fresh or brackish	Fresh	Brackish or brine
Germany no site	unknown	unknown	unknown

Case study/site name	Describe the engineered barriers
Olkiluoto	Copper-iron canister, buffer bentonite, tunnel backfill, closure materials
Germany no site	§ 4 (2) EndlSiAnfV stipulates: The intended disposal system shall ensure the safe containment of the radioactive waste passively and maintenance-free through a robust, graded system of different barriers with different safety functions. According to § 4 (3) EndlSiAnfV, the essential barriers to achieving safe containment of radioactive waste are 1. One or more containment-providing rock zones or 2. In the case of the host rock crystalline rock, provided that no containment-providing rock zone can be identified, technical and geotechnical barriers suitable for the respective geological environment. Further barriers hinder or prevent the migration of radionuclides in addition to and in coaction with the essential barriers. Pursuant to § 5 (4) EndlSiAnfV, the properties of technical or geotechnical barriers required for long-term safety shall be specified in the safety concept. The (preliminary) safety concept is part of the (preliminary) safety analyses, which are currently ongoing in the German Site Selection Procedure for a high-level radioactive waste repository. Concepts for engineered barriers are currently being worked on and will be published in 2027. Separate concepts are being developed for all three considered host rock types (claystone, crystalline rock and rock salt). Broadly speaking, the engineered barriers consist of the disposal container as well as the buffer, backfill and seals. Wherever possible, material from the excavation will be reused to produce material most similar to the surrounding host rock. Bentonite is expected to be used in various forms due to its high swelling capacity and hence good sealing properties.

Case study/site name	References
Olkiluoto	Posiva 2021a. Operating Licence Application, spent nuclear fuel encapsulation plant and disposal facility. Posiva Oy, Eurajoki, Finland. Posiva 2021b. Safety case for the operating licence application – Selecting climate evolution lines. Eurajoki, Finland: Posiva Oy. POSIVA 2019-21.

Germany no site	EndlSiAnfV: Ordinance on Safety Requirements for the Disposal of High-Level Radioactive Waste (Disposal Safety Requirements Ordinance) of October 6, 2020 (Federal Law Gazette. I p.2094)

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

In the next 1 million years glacial cycles are expected to occur repeatedly. A glacial cycle consists of periods with cold/temperate climate (called interglacials), permafrost, ice sheets and periods when the site is submerged if located near the sea or other water bodies.

The climate scenarios projected into the future account for the latest understanding of the major factors that affect climate variability on long timescales, like insolation and greenhouse gases concentration, especially CO2. The main cause of the forcing differences between the scenarios is the CO2 concentrations, formulated following the representative concentration paths (RCPs) in IPCC AR5 (IPCC 2013).

The CLIMBER-SICOPOLIS EMIC that has been used is a state-of-the-art model system for past and future climate projections up to 100,000 years. CLIMBER-2 has been used in intercomparison studies for the last interglacial climate and found especially suitable for climate simulations covering very long time periods (Bakker et al. 2013). The fair reproduction of the last glacial maximum and of the temperatures during the Holocene (current interglacial) gives confidence in the use of those models and data.

For longer future climate projections, a combination of modelling techniques has been used. These models include a carbon cycle impulse response function used to project atmospheric CO2 concentration in responses to anthropogenic CO2 emissions, a conceptual global sea level model (CGSLM) which estimated future changes in global sea level (GSL) forced by orbital and atmospheric CO2 variations, and a statistical climate emulator used to project the future evolution of a number of climate variables forced by atmospheric CO2 concentrations, orbital variations and global ice sheet volume changes. The results of the emulator were then downscaled using bias-correction and a physical-statistical technique (Posiva 2020).

The current cold/temperate period (interglacial) is assumed to continue until 50,000 years AP in a global warning scenario in the extension of RCP4.5 and then be followed by permafrost and glacial periods. In the extension of RCP8.5 (extended global warming), the current interglacial will last about 200,000 years AP and also be followed by permafrost and glacial periods. It must be noted that in the last 800,000 years, the duration of interglacials has been limited to 10 to 30 thousand years (PAGES 2015).

Subtask 2b – Gaps and constraints

The projections of future atmospheric CO2 and GSL, and hence the climate projections, are based on the assumption that in a few hundred years (approximately 500 years AP) humans will make no other significant changes to the climate. This may occur through emissions of CO2 from the burning of fossil fuels or other processes such as land-use change, or through emissions of other gases that act as radiative forcing agents, such as methane or aerosols. The uncertainty associated with future human activities and the resulting impacts on radiative forcing has been taken into account in the selection of more than one IPCC emissions scenarios. There are two other RCPs, RCP2.5 and RCP6.0. The first was not considered due to that the actual CO2 concentration level is already higher than the ones considered in RCP2.5. The second is in the middle of RCP4.5 and RCP8.5, so two selected scenarios represent a lower and upper bound of future climate (Posiva 2021b).

Other uncertainties are in the assumption that future glaciations will follow the same trajectory of ice sheet development and retreat as was observed during the last Weichselian. It may be that future

glaciations do not demonstrate the same spatial patterns of ice build-up and melt, perhaps due to differences in the orbital parameters or atmospheric CO2.

Subtask 2c – Natural analogues

Extensive set of analogues have been studied over the past few decades to better constrain the potential effects caused by climate change. Climate driven changes are mainly studied via host rock analogues (see Posiva 2021a for external and host rock processes).

Ice sheet formation is directly linked to subsidence and uplift of the crust, which has led to extensive research examining the potential impact of glacially induced seismicity (including syn-and post-glacial faulting) (e.g. Ojala et al. 2017, 2018, 2019; Smith et al. 2018). These analogue studies have been used in determining boundary estimates of earthquake magnitudes (Posiva 2021b) and significantly increase understanding on the multi-slip mode of occurrence of seismic bedrock movements (e.g. Mattila et al. 2019). Sites in the areas of continuous sedimentary cover are more difficult to assess, leading to uncertainty in the spatial distribution. Marine /lacustrine sediment record, or additional inland sites could be further assessed to investigate palaeo events around southern Fennoscandia.

Erosion rates estimates are based on observations made from regional quaternary sedimentology and bedrock features, which are considered as regional analogue data. Based on the studies compiled in Posiva 2021a, the conservative estimate for bedrock erosion is 10m over full glacial cycle. Much lower estimates, <1 m/100 ka, 5–28 m/1 Ma (mid-range), 2–43 m/1 Ma (wider-range) are derived for example for Forsmark (Sweden) (Hall et al. 2019). Cosmogenic nuclide studies could be used to expand areal understanding of the overall erosion rates and increase robustness.

There is no direct evidence from the Olkiluoto region regarding the depth of permafrost. Therefore, global understanding of permafrost formation mechanisms—considering geographical and topographical factors—is applied to model and assess potential permafrost development at Olkiluoto. Significant understanding regarding groundwater – permafrost dynamics have been obtained from The Greenland Natural Analogue for climate state ET (e.g. Kontula et al 2016). Methane hydrate formation is estimated to be limited at Olkiluoto, although theoretically, it could be possible during permafrost periods (Posiva 2021a).

Observations from geological systems support long-term stability of bentonite in the engineered barrier system under conditions of low temperature. For example. The position of large bentonite deposits in Wyoming and Oregon permafrost areas during the last glaciation. Climate implications to groundwater system are based mainly on-site modelling, however, analogues have been studied to better understand the potential effects of glacial cycles (especially in relation to dilute water and or oxygen ingression at depth (see discussion in Posiva 2021a). The extreme potential case of increased dilute water infiltration has been studied in the Saimaa-project, indicated limited effects even in the case of stagnant ice sheet (Kuusisto et al. 2022). Recently, indirect analogue analyses of smectite stability have been undertaken to better assess buffer stability under dilute groundwater scenario (Reijonen et al. 2024).

No analogues to date have been studied to assess potential impacts of extended global warming (analogous sites with extended meteoric water infiltration).

Subtask 2d – Evolution of climate change risks

In Finland, the potential risk of permafrost reaching repository depth was already taken into account in the selection of repository depth between 400 and 500 m in the late 70s and early 80s, though at that time no site was yet selected. After selection of the site about year 2000, the layout of the repository has changed to account for the position of the largest fractures that could carry glacial meltwater to repository depth. Glacial meltwater could damage the properties of the bentonite barrier and jeopardize the containment of radionuclides.

Nature and spatial distribution of receptors

In case radionuclides would reach the biosphere, in the case of Olkiluoto, it has been calculated that for all credible scenarios (not what if), the resulting annual doses to humans are below the radiation dose constraints for most exposed people and other people, as set out by the Finnish regulator, remain generally low by more than two orders of magnitude. The resulting absorbed doses rates to plants and animals imply that any radiological impact of radionuclide releases will be negligible.

Fluxes and patterns of groundwater flow

Groundwater flow rate at Olkiluoto vary depending on depth, type of fractures, and the influence of glacial cycles. Flow rates are generally slow but can be influenced by fracture zones and the current uplift of the landmass. Specific measurements using Posiva Flow Log are used to determine flow direction and rate in fractures at various depths. At repository depth, water flows downwards, but near the shoreline and below the sea, it can flow horizontally or upwards.

During permafrost, groundwater flow is reduced as a consequence of very low hydraulic gradients, although pressure differences between frozen and unfrozen areas do exist. The gradual development of permafrost decreases hydraulic conductivity and fresh-water infiltration, resulting in changes in groundwater circulation not only at shallow depths but also deeper in the repository rock volume. Under permafrost conditions, the hydraulic conductivity of the frozen rock decreases significantly and infiltration is basically non-existent. Changes in groundwater composition are, therefore, also reduced.

During glaciation the pressure of the ice sheet (its profile, retreating rate and direction, NNW in the Olkiluoto case), is the major driving force to the groundwater flow. If the ice sheet is cold-based or if there is permafrost beneath the ice sheet, then infiltration of glacial melt water will be very limited. If the ice sheet is warm-based, as is expected during ice-sheet retreat, infiltration of surface waters through fracturing in the ice layer and melting waters forming below the ice sheet may infiltrate into deep bedrock because of the hydraulic gradients due to variation of hydraulic head between areas below the ice sheet and areas with no ice cover. The hydraulic gradients are expected to be at the highest in the vicinity of the ice margin. Consequently, flow rates at the site are increased and will have an effect on transport paths and groundwater composition. The increased groundwater flow and infiltration of glacial meltwater and sea water in connection with ice-sheet retreat, when the ice sheet is assumed to be warm-based, may also affect groundwater composition, especially in the upper part of the bedrock (Posiva 2013).

Chemistry of groundwater in and around the repository

Groundwater around the repository is brackish. Brine water is found at more than 500m depth. Extensive studies on the interaction of this water and the engineered barrier system have shown no risk of permanent or other damage. Changes in groundwater composition are possible as a result of infiltration of meteoric water during the temperate period, infiltration of oxygen-rich, glacial melt waters, upconing of saline waters during ice-sheet retreat and infiltration of seawater with varying salinity during a submerged period. At the time of the retreat of an ice sheet and after it, Olkiluoto is assumed to be submerged as it was at the end of the Weichselian.

The potential infiltration of meltwater from the melting and retreating of ice sheet may pose a risk to the buffer and backfill materials because of the potential transformation of bentonite to gel that could easely been carried away in groundwater (see Section above on natural analogues).

Surface water

Surface water is fresh water. However, the risk is in the potential infiltration of meltwater from the melting and retreating of ice sheets, as explainded above.

Erosion and sedimentation rate

Erosion rates have been estimated to be low enough to not risk the exposition of the DGR for extremely long periods (see discussion on natural analogues).

Topography

Low topography and the nearness of the see poses a risk for the infiltration of seawater, however, during glacial cycles transgression and regression processes are expected (including infiltration of more saline water), more risk is related to meteoric water infiltration (dilution of groundwater). However. in the case of a DGR at Olkiluoto experiments with water of similar composition to seawater have shown that the buffer bentonite clay surrounding the canister will experience minor effects and no significant damage in the engineered barriers is expected.

Mechanical loading and unloading

The inception of large ice sheets poses a risk for the long-term duration of the canister/s containing spent fuel or HLW. However, if the position of the deposition holes is selected accurately, the risk of breaching due to mechanical loading and unloading can be diminished. Also, the design of the canister accounts for the maximum ice sheet load inferred from the past as it is assumed to have taken into account during the penultimate glacial maximum taken place during the Saalian glaciation (Posiva 2021b).

Subtask 3a – Risk methodology

In the analyses of long-term safety for a geological radioactive waste disposal system, the climate evolution is one of the key issues. Climate is an overarching external FEP (Features, Events and Processes) that, in its evolution and variability, will influence the long-term evolution, and hence, the performance of any geological disposal system for radioactive waste. Climate will, of course, influence also other FEPs that affect the evolution of the natural environment (biosphere and geosphere) and engineered barrier system (EBS). To project climate evolution into the future, an understanding of the dynamics of how past climates evolved is necessary. Climate change forcing mechanisms are many, but in the long times associated to the safety case, the main mechanisms are the incoming solar radiation, i.e. insolation, and atmospheric CO2. Regarding atmospheric CO2, the observed increase out of natural variability is due to anthropogenic contribution since the industrial revolution in the mid 1800's (Posiva 2021b).

Especially, climate-driven surface hydrology (e.g. precipitation, ice sheet development, permafrost formation) gives the boundary conditions for groundwater evolution (flow and chemistry, especially salinity), which influence the performance of the EBS (Engineered Barrier System) and radionuclide release and transport. Further, glaciations affect the rock stresses and thereby stability of the host rock.

The sequence of climate states has been used in the safety case for modelling landscape evolution, the evolving groundwater flow and chemistry. Also, the potential impacts on the safety functions of the EBS is investigated.

Subtask 3b – Needs, gaps and recommendations

The projections of future atmospheric CO_2 and global sea level, and hence the climate projections, are based on the assumption that beyond approximately 2500 AD, humans will make no other significant changes to the climate. This may occur through emissions of CO_2 from the burning of fossil fuels or other processes such as land-use change, or through emissions of other gases that act as radiative forcing agents, such as methane or aerosols. The uncertainty associated with future human activities and the resulting impact on radiative forcing is significant, thus a range of IPCC emissions scenarios have been included to account for the different possible pathways that society might take.

Natural analogues have been used to demonstrate long-term safety, but there is still room to include if not natural analogues per se, but rather observations from natural systems in order to better assess climate-related impact on nuclear waste disposal.

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Group 4DGRb

Group number: 4DGRb

Disposal type: deep geological disposal

Current climate: D-C <50N

Countries: Czechia, Germany, Switzerland

Partners: SÚRAO, TUL, GRS, BGE, Nagra

Lead: TUL (Czechia)

Time window: 0–200 ka AP, 0–1000 ka AP (Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	Case study/site name	Disposal type	Waste type	Current phase
Switzerland	Noerdlich Laegern	Deep geological disposal	all	General license application submitted
Czechia	Dunaj – a cryptic name for a candidate site used in a climate impact study	Deep geological disposal	Spent nuclear fuel (co-disposal of HLW and ILW in shallow horizon)	Site selection (geo-logical survey on 4 candidate sites)
Germany	No site	Deep geological disposal	High-level radio-active waste, including spent nuclear fuel	Site selection

Case study/site name	Latitude	Longitude	Altitude	Distance to sea
Noerdlich Laegern	47.5 N	8.5 E	~400 m asl	300 km
Dunaj (CZ)	49.37 N	15.44 E	540–760 m asl	420 km
Germany no site	Approx. 47 to 55 N	Approx. 5 to 15 E	unknown	unknown

Case study/site name	Climate Köppen Geiger / Köppen-Trewartha	Hydrology	Land-use	Landscape
Noerdlich Laegern	Cfb/Dfb	Surface water dominated	Crops / managed tree cover	Hilly topography
Dunaj (CZ)	Dfb (Cfb nearby) / Do; Dc	Perennial, surface water dominated (river water is mostly from precipitation)	Tree cover	Hilly topography
Germany no site	Cfb or Dfb / D (Do or Dc)	unknown	unknown	unknown

Case study/site name	Host rock (HR)	Depth (m)	Thickness (m)
Noerdlich Laegern	Clay (HR)	800–900 m	100–110 m

Dunaj (CZ)	Igneous (granite)	0–20 m	> 100 m
Germany no site	unknown (clay-stone, crystalline or rock salt)	>300 m (see Subtask 4.1 “Regulatory framework” for further information	>100 m

Case study/site name	**Geology above HR**	**Geology below HR**	**Hydrogeology above HR**	**Hydrogeology below HR**
Noerdlich Laegern	Mesozoic and Tertiary sediments	Mesozoic sediments	Regional aquifer (separated from HR by aquitard)	Regional aquifer (separated from HR by aquitard)
Dunaj (CZ)	Soils and regolith	Magmatic	There is no aquifer above the host rock.	Fractured crystalline rock
Germany no site	unknown	unknown	unknown	unknown

Case study/site name	**Pore water HR**	**Pore water above HR**	**Pore water below HR**
Noerdlich Laegern	Na-Cl-Type with moderate ionic strength	Similar	Similar
Dunaj (CZ)	Ca-SO4, Ca-HCO3	Similar	Na-HCO3
Germany no site	unknown	unknown	unknown

Case study/site name	**Describe the engineered barriers**
Noerdlich Laegern	Canisters surrounded by bentonite
Dunaj (CZ)	Steel canister surrounded by bentonite (Ca-Mg type) for SNF
Germany no site	Broadly speaking: disposal container as well as the bentonite buffer; backfill and seals. — Separate concepts are being developed for all three considered host rock types (claystone, crystalline rock and rock salt).

Case study/site name	**References**
Noerdlich Laegern	NTB 24-17 Geosynthesis of Northern Switzerland. Nagra 2024. TALENTO, Stefanie and GANOPOLSKI, Andrey, 2021. Reduced-complexity model for the impact of anthropogenic CO_2 emissions on future glacial cycles. *Earth System Dynamics*. DOI 10.5194/esd-12-1275-2021.
Dunaj (CZ)	KOLOMÁ K., TRPKOŠOVÁ D., KRÁLOVCOVÁ J., NEŠETŘIL K., MILICKÝ M., GVOŽDÍK L., VENCELIDES Z. (2024): *Geochemical model of the reference deep geological repository site*. MS SÚRAO, TZ 785/2024 KRÁLOVCOVÁ, Jiřina, Jiří MARYŠKA, Tomáš HROCH, Naďa RAPANTOVÁ, Martin MILICKÝ a Matěj ČERNÝ, 2022. *Geotran project: Influence of changes in geospheric properties on the evolution of radionuclide transport from the deep repository area to the biosphere: influence of geological evolution on radionuclide migration in the geosphere. A comprehensive research report.* Liberec: TUL, ČGS, PROGEO, VŠB-TUO. — Unpublished report (in Czech only).

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Germany no site	EndlSiAnfV: Ordinance on Safety Requirements for the Disposal of High-Level Radioactive Waste (Disposal Safety Requirements Ordinance) of October 6, 2020 (Federal Law Gazette. I p.2094)

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

This climatic zone will experience the re-appearance of cold-climate conditions with permafrost development and, depending on the location and altitude, the development of glaciers and ice-sheets.

Climate change scenarios are mostly based on past climatic sequences and reduced-complexity models to screen the possible impact of CO_2 scenarios on future glaciations. For instance, given the highly uncertain influence of the Alps on future climatic conditions, NAGRA did not consider to develop a deterministic climatic sequence for the future, but focus on extreme climates and a more general conceptual understanding of climatic influences on the repository. In Switzerland, the most extreme case involves the advance of an ice-sheet or glacier over the repository, the timing of which strongly depends on future greenhouse gas emissions. It is not expected to occur before 100 kyrs AP. In Czechia, glacial conditions are not expected, but permafrost is considered.

Subtask 2b – Gaps and constraints

No detailed deterministic climatic sequences are available, but the question is if this is needed. Only extreme, pessimistic, climate scenarios are considered so far, such as long permafrost conditions in Czechia, and ice-sheet development in the Alps (Switzerland).

Subtask 2c – Natural analogues

One case is put forward as a useful analogue in Czechia help selecting a suitable site for a DGR: the Rožná deposit. It serves as a natural analogue – uranium has remained stable in the reduced U(IV) form in the rock mass for over 250 million years. Geochemical and isotopic analyses confirm minimal uranium migration even during climatic changes, thus supporting the safety functions of the host rock (granite). Other natural analogues that are proposed and/or mentioned as potentially useful are: natural bentonite and clay deposits (buffer and backfill materials), ancient groundwater systems (groundwater flow and permafrost), geomorphological archives (surface processes: erosion and denudation), past interglacials (MIS11 as an analogue for a long interglacial – as expected for the current interglacial) and analogue climate regions (e.g. mountainous Mediterranean areas as an analogue for future global warming in Switzerland; Greenland as an analogue for future permafrost and/or ice-sheet in Germany).

Subtask 2d – Evolution of climate change risks

Under global warming, and during future interglacial conditions, reduced groundwater recharge and enhanced rock weathering are mentioned as potential risks. Reduced groundwater recharge will slow down groundwater circulation and decrease the cooling rate of the host rock and may alter the geochemistry. Enhanced rock weathering might have an impact on the geochemistry of the disposal system.

Under global cooling, permafrost is expected to reduce groundwater recharge, which increases the residence time and may induce groundwater chemistry changes. Permafrost will also have an impact on the hydraulic conductivity of the host rock and over- and underlying hydrogeological units.

Under extreme global cooling, i.e., ice-sheet and glacier development, the erosion risk increases significantly. Furthermore, increased pressure on the bedrock may induce host rock deformation and changes in permeability and increased loading of the engineered barriers. Unloading and subsequent isostatic rebound may cause erosion, rock deformation and subsequent changes in the hydrogeological system.

Subtask 3a – Risk methodology

An evaluation of the impact of climate (infiltration) and erosion (surface lowering) on groundwater flow and radionuclide transport was performed in Czechia. This evaluation was used for the geochemical evolution model. Long periods of constant conditions (25 ka to 100 ka) allow these effects to manifest; however, the scenario formulation is only preliminary and does not sufficiently screen possible impacts on the safety function. The scenario does not include the explicit effect of anthropogenic CO_2.

Subtask 3b – Needs, gaps and recommendations

Detailed climate sequences for the future, based on EMICs or GCMs are not available for this climatic zone. However, it seems that the approaches applied so far, i.e., a repetition of climatic conditions from the past, or an estimation of extreme climate conditions for the future (based on reduced-complexity models) seemed to be appropriate to screen various climatic risks. However, the impact of some of these climatic conditions (e.g., permafrost on groundwater flow and chemistry) still needs to be analysed in some programs. In general, natural analogues for global warming and future interglacial conditions are not really considered.

Group 4DGRc

Group number: 4DGRc

Disposal type: deep geological disposal

Current climate: Cf

Countries: France, Belgium, Germany, UK

Partners: Andra, Mines Paris, BGRM, ASNR, SCK CEN, BGE, GRS, NWS

Lead: Mines Paris

Time window: 0-1000 ka (a or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	Case study/site name	Disposal type	Waste type	Current phase
France	Cigeo, F	Deep geological disposal	LILW-LL, HLW, spent fuel	License application
Belgium	4DGRc_BE	Deep geological disposal	LILW-LL, HLW, spent fuel	Initiation
UK	No site yet exists	Deep Geological Disposal Facility	The UK Geological Disposal Facility (GDF) will take higher activity waste. This consists of High Level Waste, Intermediate Level Waste and a small amount of Low Level Waste which is not suitable for disposal at existing surface facilities.	Site selection
Germany	4DGRc_Konrad	Deep geological disposal	Low- and intermediate-level radioactive waste with negligible heat generation	Construction

Case study/site name	Latitude	Longitude	Altitude	Distance to sea
Cigeo, F	48N	5E	200-500m	200-500km
4DGRc_BE	No site	No site	0-100 m	0-100 km
UK	No site	No site	No site	No site
4DGRc_Konrad	52°10'N	10°24' E	ca. 95 m asl	ca. 195 km

Case study/site name	Climate Köppen Geiger/Köppen-Trewartha	Hydrology	Land-use	Landscape
Cigeo, F	Cfb/Do	Perennial SW	Grassland	Low relief topography

4DGRc_BE	Cfb/Do	Perennial, groundwater dominated	Mixed	Low relief topography
UK	Cf/Do	No site	No site	No site
4DGRc_Konrad	Cfb/Dc	Perennial, surface water dominated	Mix of cropland and industrial built-up areas	Low relief topography

Case study/site name	**Host rock (HR)**	**Depth (m)**	**Thickness (m)**
Cigeo, F	Consolidated clay	200-500m	>100m
4DGRc_BE	Plastic clay	200-600 m (185 m*)	50-100 m (100 m**)
UK	No site	200-1000 m	No site
4DGRc_Konrad	sedimentary Oxford formation (Jurassic), characterised by limestone, clay and ore deposits	800-1300 m (iron ore formation Korallenoolith)	20-50 m (100 m)

*At the Mol site

**At the Mol site

Case study/site name	**Geology above HR**	**Geology below HR**	**Hydrogeology above HR**	**Hydrogeology below HR**
Cigeo, F	Sedimentary	Sedimentary	Aquitard	Aquitard
4DGRc_BE	Sedimentary	Sedimentary	Phreatic sedimentary aquifers and aquitards (mostly)	Artesian sedimentary aquifers and aquitards
UK	No site	No site	No site	No site
4DGRc_Konrad	Sedimentary	Sedimentary	Aquitard	Aquitard

Case study/site name	**Pore water HR**	**Pore water above HR**	**Pore water below HR**
Cigeo, F	Fresh	Fresh	Fresh
4DGRc_BE	Fresh (mostly)	Fresh (mostly)	Fresh to brackish
UK	No site	No site	No site
4DGRc_Konrad	Saline	Saline	Saline

Case study/site name	**Describe the engineered barriers**
Cigeo, F	HLW is mainly the result of reprocessing spent fuel from nuclear power plants. It is incorporated into a molten glass paste which is poured into stainless steel waste packages.
4DGRc_BE	Combination of carbon steel overpack (HLW only) and cementitious barriers
UK	No site

4DGRc_Konrad	Cavities in the mine will be backfilled with dumping backfill and slinger stowing backfill (*Schütt- und Schleuderversatz*) and the shafts will be backfilled and sealed. Materials used for the backfilling of the shafts are invariable over at least 10,000 years but the sealing remains effective also after this time frame. Backfill and sealing measures for the Quaternary and Upper Cretaceous parts of the shaft serve mainly to seal the shaft off against relatively shallow aquifers. For this part and purpose, a hydrostatic asphalt seal is planned to be used. Since the main barrier of the repository is located within the Lower Cretaceous, the backfill material must pass high requirements regarding its sealing properties. The excavation damage zone around the shaft also has to be treated with a suitable sealing material to prevent hydraulic routing via this path. For this purpose, a mineral seal in the Lower Cretaceous, and in the Upper and Middle Jurassic a mineral column support with a horizontal connection to the mine pit, are foreseen. Measures have to be undertaken to prevent displacement of the shaft filling into the mine pit via the shaft landing station. The stated requirements have to be met also under seismic impact (earthquake).

Case study/site name	**References**
Cigeo, F	Le socle de connaissances scientifiques et techniques du centre de stockage Cigéo. Les référentiels de connaissances. Tome 1 du référentiel de site : l'histoire géologique et l'état actuel
4DGRc_BE	De Craen, M., Beerten, K., Honty, M., & Gedeon, M. (2012). Geo-scientific evidence to support the I2 isolation function (geology & long-term evolution) as part of the Safety and Feasibility Case 1 (SFC1). (0 ed.) (SCK CEN Reports; No. ER-184). SCK CEN.
UK	No site
4DGRc_Konrad	Planfeststellungsbeschluss (PFB) für die Errichtung und den Betrieb des Bergwerkes Konrad in Salzgitter als Anlage zur Endlagerung fester oder verfestigter radioaktiver Abfälle mit vernachlässigbarer Wärmeentwicklung vom 22. Mai 2002 https://www.bge.de/fileadmin/user_upload/Konrad/Wesentliche_Unterlagen/Genehmigungsunterlagen/Planfeststellungsbeschluss_Endlager_Konrad_vom_22_Mai_2002.pdf

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

Scenarios based on BIOCLIM (BIOCLIM d3, 2001) for different greenhouse gas emission hypotheses were applied in Belgium and France, emphasizing on two extremes: A4 (no GHGE) and B4 (~RCP8.5).

The period **up to 10 ky AP**, is considered to be a relatively warm period, with current climate conditions to be continued (BIOCLIM A4 scenario) and/or with episodes of global warming (scenario B4). Marine inundation of various parts of northern Belgium is possible. Cold climates are not expected during this time frame.

Within the next time frame, between **10 ky and 50 ky AP**, relatively warm conditions are expected to continue: 5 out of 6 BIOCLIM models predict the presence of a long interglacial ahead.

Between **50 ka and 170 ka AP,** interglacial conditions are expected to continue, although cold intervals cannot be ruled out completely (BIOCLIM A scenarios). The development of ice caps over Belgium and France is not expected.

The (re-)appearance of cold climate conditions is expected for the time frame between **170 ka AP and 400 ka AP**. This is based on the fact that all BIOCLIM models predict glacial maxima, similar to the Weichselian glaciation, within this time frame. Permafrost may develop during strong glacial maxima, but the presence of ice sheets in Belgium or France is not expected. Episodes of global warming (i.e., warmer than the present climate) may possibly occur in between glacial maxima.

Cold climates are also expected to occur in the time frame between **400 ka and 1 Ma AP.** Glacial maxima of high intensity are predicted by all BIOCLIM models and will alternate with relatively warm interglacial periods, comparable to the current climate or even a warmer climate. Permafrost development is expected while ice-sheet advancement over Belgium and France is unexpected.

While ice-sheets are not expected in Belgium/France, they cannot be ruled out over the northern parts of Germany and the UK.

The models used (EMICs) are those of the European project BIOCLIM which serves as a reference for this type of studies. At the beginning of the 21st century, BIOCLIM modelling results (BIOCLIM Deliverable 3, 2001) were the most recent data available.

Regarding the **evolution of the sea level**, several estimates (more or less precise but consistent) have been proposed. The estimates are mainly based on analogues from the past ((Lisiecki et Raymo 2005), (Jouve 2007) (Cojan et al. 2009)). The sea level fluctuates between +40 m during the warmest periods (subtropical dry/Mediterranean climate - Cs) and -120/-130 m during the coldest periods (tundra climate - FT and FI). A level can be defined for each climate type in the KG and KT classification (see Annex I. Sea level rise evolution).

Subtask 2b – Gaps and constraints

Model output is uncertain, due to the highly uncertain future of CO2 emissions. For example, in the B4 BIOCLIM scenario, the climate is warmer than in A4 (no GHGE) for almost 500 kyr.

In the Belgian approach, uncertainties on future climate states led to the definition of representative future climate conditions, and the time frames during which they are supposed to be relevant, rather than producing a continuous, discrete and/or deterministic time series of climate states. Another approach to deal with these uncertainties was adopted in France. Two extreme scenarios of BIOCLIM were considered: A4 time series (with no GHGE hypothesis) and B4 (~RCP8.5).

The **description of climate type/state** (according to the Köppen-Geiger or Köppen-Trewartha classification) is often insufficient to assess a certain risk, since it only provides a wide range of average temperature and precipitation (for instance). Furthermore, t**here are still gaps in the scientific understanding of climate modelling.** Downscaling techniques, necessary to produce local meteorological time series, often yield non-meaningful results and is still a matter of debate.

Some gaps have to be addressed by **climate scientists** on specific topics: downscaling technics, process modelling, computational techniques... Others can be addressed (temporary or not) by a clear methodology and recommendations. Some proposals are given below.

Improving climate scenario description is necessary to allow a more accurate comparison and a better evaluation of its impacts. It is recommended to use original model output: precipitation (P) and temperature (T), EVT and ice volume if possible. It already avoids misinterpretation of climate type scenarios and allows sensitivity analysis.

To address uncertainties, **several scenarios** must be considered (with different GHG emission assumptions) and “envelope” scenarios must be defined if possible. A **sensitivity analysis** should be performed where possible.

Up-to-date assumptions regarding GHG emissions and climate scenarios could be used. The IPCC's last report was released in 2023 and provides more accurate GHG emission scenarios: SSP's (Shared Socioeconomic Pathways) instead of RCP's (Representative Concentration Pathways).

Subtask 2c – Natural analogues

Geographical (climatic) analogues, past climatic analogues and geological analogues are most commonly mentioned for vegetation, erosion and river dynamics, diffusion (in clay), sea level variations, and permafrost and ice sheet development.

Geographical analogues include those where a similar present-day climate is present as one that is expected (or possible) in the future for a specific case study. For France, e.g., erosion and vegetation data and observations are considered from an analogue Mediterranean Cs climate location in the Guadalquivir basin (Spain) and a Cr climate location in Georgia (USA east coast).

Past climatic analogues such as the last glacial (Weichselian) are considered as an analogue: in France to identify periods of **river incision** and conditions favorable to **slope erosion** ((Bogaart et Van Balen 2000), (Gargani et al. 2006), (Jouve 2007)) in Belgium to assess **permafrost development** from palaeo-temperature proxies as an analogue for future cold climate conditions (Govaerts et al., 2016).

Past erosion rates based on long-term integrated geomorphological proxies were used to scope future erosion rates in northern Belgium (De Craen et al., 2012).

The development of glacial basins and tunnel valleys during the Saalian glaciation in northern Europe can be seen as a **natural analogue of glacial erosion** during future ice-sheet development, if any (De Craen et al., 2012).

Past analogues are also used to determine the **sea level** for different types of climates (see references of sea level previous table). The delta-O18 record (Lisiecki et Raymo 2005) was used in (Jouve 2007) to associate sea level to climates. Analogues from the past (Optimum Miocene, Optimum Pliocene) were used to associate sea level to climates the (Cs and Cr respectively) see (Cojan et al. 2009).

Geological analogues s.s. for this climatic zone include tracer profiles over clay formations (CLAYTRAC, 2009). These represent long-term diffusion processes and thus inherently carry the effects of past climatic changes.

The analogue approach has the advantage of addressing processes over long time periods, thousands to hundred thousands of years, and therefore includes the effect of rare events and incorporates slow and complex mechanisms (as proxies). However, as it may lack precision, the perfect analogue does not exist. All driving factors would have to be identical (except for the one used in the analogy). In most cases, the influence of disturbing factors must be accounted for. For example, the relief in Andalusia is different than the one in the Paris Basin, so relief influence (on climate or erosion) must be quantified and compensated for.

Subtask 2d – Evolution of climate change risks

In this climate region, beyond the influence of ice-sheets, climate evolution introduces changes that influence processes such as erosion and infiltration, whose cumulative effects and their sequencing could have an impact on safety by facilitating the hypothetical diffusion of radionuclides in the environment.

For example, new outcrops may appear in aquifers layers due to river incision and landscape erosion. This can lead to a decrease in the hydraulic head, resulting in an increase in the vertical hydraulic gradient and upward flow in adjacent layers that contain the nuclear waste storage facility. In turn, this may increase flow rates and decrease travel time of radionuclides should they have been released from the host rock. For instance, in the Paris Basin, the dynamics of rivers during the Quaternary period show that climatic cycles caused significant incisions in the bedrock (Cojan et al. 2007).

Climate may change the river dynamics (meandering, braided) over time periods of 10 kyr to several 100 kyr and lead to significant changes in topography. This may trigger a complete reorganization of the river network by river captures (by avulsion or piracy). Some cases were recorded in North of France (the Moselle, Meuse tributary was captured by the Meurthe) and new captures can occur in the next million year (e.g. Meuse may be captured by the Meurthe (Benaichouche et al. 2016)). These events can lead to a profound change in the topography and outcropping layers. This could have an impact on groundwater dynamics.

Global warming as such is not expected to change the geochemical environment, unless it would lead to a complete marine inundation of the disposal facility. This may apply for all (future) sites that are situated in a vertical range of 0-60 m above sea level and are potentially connected to the marine environment. In terrestrial conditions, the landscape can evolve differently depending on the latitude of the site and its proximity to the sea. While in Belgium the landscape is expected to slowly evolve at rates comparable to current values during the next several 10 kyrs, in the Paris Basin sheet erosion is expected to become very high (as under the Mediterranean climate today) due to degradation of the vegetation cover and extreme precipitation events. No incision of the river is expected due to high sediment load and low flow.

A **cold climate without permafrost** is expected not to generate major consequences. For a cold climate with permafrost, **frozen conditions** may influence the uppermost sections of the geological barrier (< 300 m deep) but will most likely not change clay properties on the long-term (in Belgium or in Germany-Konrad). However, denudation and erosion rates will probably increase under permafrost conditions and even more during climatic transitions (warm-cold or cold-warm). For cold-warm and warm-cold transitions **fluvial incision** is expected from rivers gradually changing their planform from braided to meandering and back again. The cumulative effect on topography will depend on the position of the site with respect to the erosional baseline.

Ice-sheet development may have significant impacts, but it is assumed that its development has a very low probability over Belgium and France. However, in more northern latitudes within this climate group, ice-sheet development cannot be ruled out during the next 1 Myrs, as it has been during the past 1 Myrs.

Sea level evolution will change groundwater dynamics. High sea-level may lead to a complete marine inundation of low-lying areas: groundwater flow patterns will be reduced (to zero with flooding). Water-loading may induce subsidence locally (maximum 10 m) and coastal erosion may be not neglectable. Low sea level will change groundwater boundary conditions and increase fluvial incision with a propagation effect in the rivers network. Maximum erosion is bounded by the erosion baseline, which in practice is the continental shelf.

Most of the approaches outlined above are qualitative. However, river erosion and groundwater dynamics were simulated at the Paris Basin scale for Cigeo facility. River erosion was simulated for A4 and B4 climatic scenarios, with 2 hypotheses for tectonic movements. Impact of the landscape evolution and sea-level on the hydraulic boundary conditions of the Callovo–Oxfordian formation has also been simulated (Teles et al. 2007) concluding that new outcrops in aquifers (Oxfordian limestone) may increase in the vertical hydraulic gradient and upward flow in the Callovo-Oxfordian clay layer that contains the nuclear waste storage facility.

Subtask 3a – Risk methodology

For this climate group, all scenarios are based on Bioclim (BIOCLIM 2001). However, they were processed in a different way: a selection of 2 extreme scenarios was made for Cigéo (FR) to define an envelope of possible climate futures, while a synthesis of 6 BIOCLIM scenarios was used in Belgium, leading to the definition of representative climate states for specific time horizons.

The climate scenarios at hand for this group allowed to screen various risks, at least conceptually, but many of them have not been propagated into real risk assessments yet.

Subtask 3b – Needs, gaps and recommendations

The available information in this climate group may be sufficient for qualitative and generic assessments, but probably not for detailed risk assessments. More in particular, uncertainties can only be quantified if a sensitivity analysis is performed with realistic parameterisation of the models, instead of using general KG/KT classification.

As for recommendations, we propose the use of updated climate simulations with updated hypotheses (GHGE, AMOC disappearance...). Efficient climate models (GCM, RCM) and improved downscaling techniques can help reducing the uncertainties and reduce conservatism.

A further recommendation is related to the investigation of natural analogues. We propose to study host rocks under a palaeo-climatic gradient, since many host rock formations have a wide spatial extent where various climatic conditions were prevailing in the past.

The ultimate goal would be to develop dynamically coupled models, in which various components of the biosphere-hydrosphere-geosphere are integrated.

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Annex I. Sea level rise evolution

Regarding the **evolution of the sea level**, several estimates (more or less precise but consistent) have been proposed. The estimates are mainly based on analogues from the past (see references). They are summarized in the table below.

Climate (Köppen-Geiger**)	KT**	Specifications, if possible (1)	Estimated range of sea level rise or fall (2)	Estimated min and max depth of permafrost or ice thickness (3)	Ref.
A (tropical)			n/k		
Af	Ar	Rain forest			
Aw, As	Aw	Savanna			
B (arid)			n/k		
BS	BS	Steppe			

C (temperate)			Cxa: rise< 60-70 m Cxc: drop < 120 m		3
Cs	Cs	Subtropical summer-dry (Hard leave evergreen trees and shrubs)	+40 m		2
Cf	Cr	Subtropical humid (Longleaf trees, slash pines and deciduous forest in inland areas)	+15 m		2
Cf, Cw	Do	Temperate oceanic	0		1,2
D (cold)			(drop< 120 m)		3
Df, Dw, Ds	Dc	Temperate continental	0		1,2
Df, Dw, Ds	Eo	Sub-artic oceanic (Needleleaf)	-50 m	n/k	1,2
Df, Dw, Ds	Ec	Sub-artic continental (Tayga)	-80 m	n/k	1,2
ET (permafrost)	FT	Tundra	-130 m (drop < 120 m)	0-250 m (X/Q)	1,2,3
EF (ice-sheet)	FI	Permanent ice cover	(drop < 120 m)	0 m (X/Q)	1,2,3

*add (X) behind the numbers if at least partially based on modelling; add (Q) if the model outputs are highly uncertain

** The conversion proposed by (de Castro et al. 2007) was used for KT (Köppen Trewartha) to KG (Köppen-Geiger) translation

References:

1. dO18 signal (Lisiecki et Raymo 2005) was used in (Jouve 2007) to associate sea level to climates.
2. Analogues in past (Optimum Miocene, Optimum Pliocene) were used to associate sea level to climates the (Cs and Cr respectively) see (Cojan et al. 2009).
3. De Craen et al. 2012.

Group 4NSb

Group number: 4NSb

Disposal type: Near-surface (shallow geological disposal)

Current climate: Cfb

Countries: France, Belgium

Partners: SCK CEN, ANDRA, Mines Paris, BRGM, ASNR

Lead: SCK CEN

Time window: 0-20 ka (a or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	Case study/site name	Disposal type	Waste type	Current phase
France	Andra/ FAVL	Near-surface disposal facility	LILW-LL	Site selection
Belgium	Olen	Shallow-depth disposal with engineered barriers or a combination of natural and engineered barriers	Ra-bearing waste within preliminary threshold levels of 15-1000 Bq/g Ra-226	Initiation

Case study/site name	Latitude	Longitude	Altitude	Distance to sea
FAVL, F	50-45N	2W-5.42E	No site	No site
Olen	51°13'23.4"N	5°04'37.5"E	20-50m	100-200km

Case study/site name	Climate Köppen Geiger/Köppen-Trewartha	Hydrology	Land-use	Landscape
FAVL, F	Cfb/Do	Perennial SW	Grassland	Low relief topography
Olen	Cfb/Do	Perennial GW	Tree cover, grassland, wetland, built-up area (industry)	Low relief topography

Case study/site name	Host rock (HR)	Depth (m)	Thickness (m)
FAVL, F	Plastic clay	20-50 m	50-100
Olen	Glauconitic sand	0-20 m	50-100 m

Case study/site name	Geology above HR	Geology below HR	Hydrogeology above HR	Hydrogeology below HR
FAVL, F	Sedimentary	Sedimentary	Phreatic	Phreatic

Olen	Sedimentary	Sedimentary	Phreatic sedimentary aquifer	Aquitard

Case study/site name	**Pore water HR**	**Pore water above HR**	**Pore water below HR**
FAVL, F	Fresh	Fresh	Fresh
Olen	Fresh	Fresh	Fresh

Case study/site name	**Describe the engineered barriers**
FAVL, F	At this stage there is no more clarification on the design of the barrier.
Olen	Not known yet, but probably a combination of engineered barriers such as concrete and clay

Case study/site name	**References**
FAVL, F	ANDRA, Collectif. 2019. « Projet FAVL, Référentiel du site de la Communauté de Communes de Soulaines-Vandeuvre ». Document technique FRPASTR190002. FAVL. ANDRA-DRD/TR.
Olen	NOCA 2022-1356 - Milieueffectbeoordeling (SEA) van het ontwerpplan voor het langetermijnbeheer van radioactief radiumhoudend afval

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

The climate scenarios formulated in this group are derived from two sources : (1) future climate modelling that was performed to support the CSA and Cigéo case in France (FAVL is going to be located rather close to the CSA site), and (2) sea-level rise estimates derived from a literature source and quoted in the SEA report for Olen (Belgium).

The available future climate model output is derived from a downscaled EMIC, using different forcings and spanning different time windows. For the short-term (0-1000 yrs AP), scenarios are considered which correspond (but are not totally equal) to RCP8.5 : a so-called standard scenario and an 2aT scenario (assuming a two-fold temperature increase relative to the standard scenario). For the long-term, a natural scenario was considered (no GHG emissions, see BIOCLIM A4) and a perturbed scenario (also corresponding to RCP8.5, see BIOCLIM B4). For the short term, the climate is expected to evolve from Do (Köppen-Trewartha) to Cs/Cr within the next 100-200 years (earlier for the 2aT scenario). After 200 yrs AP, episodes of BS conditions are seen in both scenarios and Do conditions returning in the standard scenario. For the long-term, the A4 scenario predicts a return to a Do climate (until 50 kyr AP) and B4 a continuation of the Cs climate (also until 50 kyr AP).

In the preliminary climate impact assessment (as provided in the SEA) for the future Belgian near-surface disposal facility only sea-level rise was identified as a potential risk. Future global sea-level rise arising from the melting of land ice and steric effects was simulated using an EMIC and ECP scenarios until 2300 yrs AP (covering a complete range from low to high). The simulation shows that sea-level

may rise from 9 to more than 37 m after 10 kyrs. For the highest-forcing scenario, the model uncertainty does not exclude the complete melting of the Antarctic ice sheet during the next 10 kyrs.

Subtask 2b – Gaps and constraints

The transfer of downscaled EMIC output data to other sites, even if they are in a similar region, should at least be verified carefully, i.e., to what extent is the area of downscaling representative for the site? If climatic data are to be used for simulating, e.g., groundwater flow, river flow, fluvial erosion or sheet erosion, the formulation of a climate state only, with monthly precipitation and temperature data, may not be sufficient. In such case, perturbation tools should be applied to generate meteorological time series that are representative for a future climate state and can be used directly for e.g. hydrological modelling or erosion modelling.

Predicting future sea-level rise can be done without downscaling, but the numbers are very sensitive to the greenhouse gas emission scenario used, i.e., the cumulative amount of emissions over a given time period.

Subtask 2c – Natural analogues

For terrestrial processes such as erosion, climate data from Cs and Cr (K-T) climate analogues are used to estimate the rate and magnitude of erosion in the FAVL project. For a Cs climate this is the Guadalquivir basin in Spain (Csa in K-G), and for a Cr climate this is the state of Georgia in the USA. It should be noted that these analogues are very specific for the targeted region in the FAVL project and cannot be transferred to other sites (even within the same climate class) without a proper evaluation.

Sites that are located within the altitude range of possible sea-level rise may experience a whole series of phenomena that are very typical for estuary development and subsequent marine erosion. The geodynamics of such estuarines can be evaluated using natural analogues from the geological record (e.g., depth of estuaries), and present-day estuaries with similar morphodynamics as the ones expected for the site.

Subtask 2d – Evolution of climate change risks

In this climate group, the identified risks are related to the isolation of the waste (erosion), and containment of the waste (corrosion). Neither of these processes can be ruled out over the assessment period (up to 20 kyr for Belgium and 50 kyr for France). Fluvial incision is not expected to be significant over the next ca. 50 kyr, given that the climate in general will be subtropical (river incision mostly occurs at glacial-interglacial-glacial transitions). Sheet erosion, however, may accelerate in such a climate, with less but more intensive precipitation events. Overall, a smoothing of the topography may be accepted in that case (denudation of topographic highs, and filling of valleys). In Belgium, the current proposal foresees a minimum depth of 10 m. For locations that are within the range of projected sea level variations, there is a potential risk of estuarine erosion and sea water ingression into the disposal cells. The magnitude of erosion in these settings is difficult to predict, but may be in the order of magnitude of several meters to 10 m. While sea level submergence of the site may reduce the hydraulic gradient and prevent the movement of water through the disposal cells, corrosion of engineered components may accelerate. Furthermore, an episode of saline conditions, followed by flushing of the aquifer or aquitard may pose a combined risk. In summary, while the risk of erosion can be mitigated by adapting the disposal depth, intrusion of sea water cannot really be prevented. Flushing (after an episode of corrosion) may be prevented by choosing an appropriate host rock.

Subtask 3a – Risk methodology

Future sea level projections make it necessary to consider potential impacts related to marine erosion and salt water intrusion for sites in this group that are possibly located within the range of sea level variations (i.e., Olen). For this particular site, the potential impact has not been modelled by erosion models or hydrogeological/hydrochemical/corrosion models. Furthermore, there is still a lot of

uncertainty on the projected sea level rise – these projections are very sensitive to greenhouse gas emissions scenarios.

Screening of the magnitude of terrestrial erosion over a series of consecutive climatic states is very likely needed to justify the disposal depth for near-surface or shallow geological disposal facilities. It cannot be ruled out that such screening efforts lead to an adjustment of the disposal depth. In the case of the FAVL site, such erosion modelling has already been conducted.

Subtask 3b – Needs, gaps and recommendations

Future climate projections, for this climate group, indicate a rather rapid transition from a temperate climate to a subtropical climate. The impact on the isolation function (thickness of overburden) of long-term erosion under various climates or an alternation of various climates should be considered since targeted disposal depths are within several tens of meters. This can be achieved either by numerical erosion modelling, or by carefully selecting analogue situations where long-term erosion rates are known under similar conditions (climate, vegetation, hydrogeology, substrate, fluvial system).

Currently, for sites that are situated at an altitude of less than 30 m asl, and for an assessment timeframe of several ten thousand years, a complete marine inundation of the site cannot be ruled out or is even likely. The impacts of marine/estuarine erosion and/or saline water ingression into disposal cells should be assessed.

Group 4NSc

Group number: 4NSc

Disposal type: Near-surface (shallow geological disposal)

Current climate: Csa

Countries: France

Partners: ANDRA, Mines Paris, BRGM, ASNR

Lead: ASNR

Time window: 0-20 ka (a or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	Case study/site name	Disposal type	Waste type	Current phase
France	Malvesi, F	Near-surface disposal facility	LILW-LL	Selection between 2 lithologies found near the Malvesi site

Case study/site name	Latitude	Longitude	Altitude	Distance to sea
Malvesi, F	45-40N	0-5E	5-10m	10-20km

Case study/site name	Climate Köppen Geiger/Köppen-Trewartha	Hydrology	Land-use	Landscape
Malvesi, F	Csa/Cs	Close to the Aude river	Cropland	Low relief topography

Case study/site name	Host rock (HR)	Depth (m)	Thickness (m)
Malvesi, F	Red marl or grey marl (Oligocene); exact site not yet selected	Variable – a minima under alluvial deposits	100 m for grey marl; 150 m for red marl

Case study/site name	Geology above HR	Geology below HR	Hydrogeology above HR	Hydrogeology below HR
Malvesi, F	Quaternary alluvial deposits	Jurassic limestone	Sedimentary aquifer	Karst aquifer

Case study/site name	Pore water HR	Pore water above HR	Pore water below HR
Malvesi, F	unknown	unknown	unknown

Case study/site name	Describe the engineered barriers
Malvesi, F	Design not determined yet => plan for 2030

Case study/site name	References
Malvesi, F	AVIS IRSN N° 2023-00157

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

Climate scenarios for the Malvési site have to be defined. From generic information, we suppose a future semi-arid climate.

Subtask 2b – Gaps and constraints

The study of climatic scenarios and their impact on the storage project could/should be carried out by the operator, since the region has been determined. This is not yet the case at this stage of the project.

Subtask 2c – Natural analogues

Natural analogues in clay/marl under climatic conditions corresponding to the future climate that needs to be defined.

Subtask 2d – Evolution of climate change risks

Risk of of marine flooding due to very low site elevation (9m NGF):

- +1.25 m in 2100 by Sea Level Projection Tool – NASA Sea Level Change Portal1
- +16 m in 2300 with the worst scenario (= ice cap instability) by Technical Summary2

Risk of river flooding due to the proximity with the Aude river.

Risk of rapid cover erosion due to intense rainfall in an arid climate.

Potential changes in underground flow are completely unknown today.

Subtask 3a – Risk methodology

The main risk identified is that the operator may start studies on climate change and its impacts too late in relation to the development of its disposal project to take these aspects into account properly.

Subtask 3b – Needs, gaps and recommendations

The first requirement would be to initiate these studies for the Malvesi site.

Group 4Sa

Group number: 4Sa

Disposal type: Surface, Near-surface

Current climate: Dfb at latitude >50N

Countries: Finland, Lithuania, Ukraine

Partners: VTT, Mitta, GTK, UTU, FTMC, SSTC

Lead: Mitta

Time window: 0-1000 a AP (a or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	**Case study/site name**	**Disposal type**	**Waste type**	**Current phase**
Finland	Olkiluoto	Surface/Near-surface	VLLW	Applied for operational license
Lithuania	Ignalina B19 Ignalina B25	Surface Surface	VLLW LILW-SL	Operation Construction
Ukraine	ENSDF-3	Near-surface	Solid radioactive waste - LILW-SL	Operation

Case study/site name	**Latitude**	**Longitude**	**Altitude (m)**	**Distance to sea (km)**
Olkiluoto	61.23N	21.47E	5-10	< 1
Ignalina B19 Ignalina B25	55.35N 55.35N	26.33E 26.33E	150 150	350 350
ENSDF-3	55-50N	30-35E	100-200	>500 (555 km to Odesa, Black Sea coast - 46.5° N, 30.7° E)

Case study/site name	**Climate Köppen Geiger/Köppen-Trewartha**	**Hydrology**	**Land-use**	**Landscape/Topography**
Olkiluoto	Dfb/E	Perennial SW	Built up	Low relief

Ignalina B19 Ignalina B25	Dfb/Dc Dfb/Dc	Perennial SW Perennial SW	Built up Tree cover	Low relief Low relief
ENSDF-3	Dfb/Dc	Mixed	Tree cover	Low relief

Case study/site name	**Geology below the facility**	**Hydrogeology below the facility**
Olkiluoto	Metamorphic	Fractured crystalline rock
Ignalina B19 Ignalina B25	Mixed	Mixed (shallow phreatic water table (unconfined groundwater zone) above deeper semi-confined to artesian aquifers)
ENSDF-3	Mixed (deeper sedimentary formations (sands, clays, marls) lie on top of the ancient, crystalline basement rock)	Mixed (shallow, phreatic water table with the deeper artesian aquifers)

Case study/site name	**Porewater below the facility**
Olkiluoto	Fresh
Ignalina B19 Ignalina B25	Fresh
ENSDF-3	Fresh

Case study/site name	**Describe the engineered barriers**
Olkiluoto	The landfill design consists of three main units: 1) a cover layer, 2) waste fill and waste packages (waste forms and containers), and 3) a foundation layer, all featuring multilayer structures and different safety functions. The natural barrier below the repository has its own role in ensuring the safety of the multibarrier system taking into account the local natural barrier conditions of the site. Considering the cover layer, the role of the topmost zone also needs to be considered in the passive repository system. If, for example, growth of a forest at the site is accepted after closure, the cover layer thickness should prevent the ingress of tree roots into the level of the upper drainage layer.
Ignalina B19	Three waste disposal modules – Ferroconcrete base-slab (foundation plate) with rainwater collection system installed, that serves as monitoring mean and

Ignalina B25	control water pollution every time before discharge, although design foresees no exceeding of permittable limits of pollution. Main waste packages planned to be disposed over the base-slat are half-height ISO containers, plastic bases, flexible plastic containers (FIBC package). The packages will be placed on the stepped structure to form a roughly “hill-shaped” stack, which will then be covered by layers of different natural and fabricated material to achieve a smooth, hill-shaped form. Finally, hydro-isolation, drainage and protective layers will be laid on top to prevent water penetration into the waste stack and washout of radionuclides from the waste to the environment. Modules will occupy an area of 4,4 ha. According to current plans, 35 reinforced concrete vaults are planned for the final disposal of 100000 m3 of the packaging of radioactive waste (concrete containers with cemented radioactive waste. After the group of vaults is filled with the radioactive waste packages, engineered barriers (several layers of clay, gravel, sand, pebble, vegetative ground) will be installed over it, the total thickness of which will be about 7 meters. The main function of the barriers is to prevent penetration of water into the vaults and thus minimize the release of radionuclides to the environment.
ENSDF-3	The system includes the following natural and engineered barriers: The first barrier consists of containers and cement compound (a matrix with embedded waste). The second barrier comprises the disposal facility's engineered structures, including: reinforced concrete compartments, waterproof bottom coverings of the compartments; water collection systems in disposal facility compartments; concrete compartments; sand-concrete mixture for radioactive waste fixation; waterproof screening. The third barrier is formed by the aeration zone soils beneath the disposal facility and their ability to retain radionuclides. To enhance the protective properties of the third barrier, the design incorporates a multi-layer anti-filtration screen under the foundation of disposal facility sections and includes a collection system for any water that might seep under the repository compartments.

Case study/site name	**References**
Olkiluoto	Keto, P. R.-H., V., Schatz, T., Kivikoski, H., & Gharbieh, H. (2020). KYT SURFACE Performance of a Landfill-Type Near Surface Repository (VTT-R-00016-21). http://kyt2022.vtt.fi/raportit_2020/SURFACE%20Performance%20of%20a%20LandfillType%20Near%20Surface%20Repository%20VTT-R-00016-21.pdf Posiva 2021. Safety case for the operating licence application – Selecting climate lines of evolution. Posiva 2021-09. Posiva Oy, Eurajoki.

	Thölix, L., Korhonen, H., Ruosteenoja, K. 2019. Climate projections for Olkiluoto. Working report 2018-9. Posiva Oy, Eurajoki.
Ignalina B19 Ignalina B25	https://www.iae.lt/en/activity/decommissioning-projects/b19-project.-landfill-facility-for-very-low-level-radioactive-waste/362 https://www.iae.lt/en/b25-project.-near-surface-repository-for-low-and-intermediate-level-short-lived-radioactive-waste/470
ENSDF-3	The data is sourced from a Safety Analysis Report for the Specially Engineered Near-Surface Solid Radioactive Waste Disposal Facility regarding the operation of modules A2 and D2 (accounting for safety reassessment conducted under special license conditions), State Specialized Enterprise 'Central Enterprise for Radioactive Waste Management https://www.uatom.org/en/the-main-radioactive-waste-management-facilities-in-the-exclusion-zone

Subtask 1 – Regulatory framework

See Appendix A.

Subtask 2a – Climate change scenarios

The extension of the RCPs 4.5 and 8.5 is used in the three locations of Lithuania, Ukraine and Finland.

In Lithuania, under RCP4.5, average annual temperature in Eastern Lithuania is predicted to increase by 1.2–1.3 °C by 2071–2100. Under RCP8.5, the increase is 2.6–2.9 °C, with winter warming even greater (3.2–4.4 °C).

Seasonal precipitation is projected to shift: winter and spring become wetter, while summers and autumns trend drier.

Winters will get wetter (up to ~24% i.e. increase by 50 mm to 740 mm), sleet instead of snow, snow season becoming 2–4 times shorter and thinner.

Slight increases in wind and storminess over the Baltic; heavy precipitation events may rise by ~22%.

A shift from Dfb (Cold) to Dfa (Hot-summer continental) has been considered, as well as a shift from Dbf to Cfb (Oceanic), especially in RCP8.5 warmer winters.

In Ukraine a temperature increase of 1.8 °C to 3.4 °C is expected by 2100 along with an increase in precipitation of 0.5% to 6%. A shift to Dfa (hot-summer continental) after 100 years AP and lasting until 1000 years AP is expected with mean summer temperatures larger than 22 °C.

Moderate (RCP 4.5) to high (RCP 8.5) GHG pathways project site-scale warming of ~2–3 °C (RCP 4.5) to > 4 °C (RCP 8.5) by 2100.

In Finland, the temperatures and precipitation are expected to remain largely as at present (T = 6 °C, P = 650 mm/year) in the global warming scenario (extension of RCP4.5). In the extended global warming scenario (extension of RCP8.5) larger temperature and precipitation values are expected at least in the next 1000 – 2000 years. As a consequence, the sea level rises, and the site is expected to remain under water from about 500 to 900 years AP.

Subtask 2b – Gaps and constraints

The lack of localized models for the timeframe considered is a major constraint for all locations, though in Finland climate data are derived for a meaningful interval of latitude values surrounding the site north and south. Nonetheless, a major limitation remains in the lack of high-resolution, locally calibrated

climate models. Uncertainties in future climates are related to unknown future human-related factors (such as greenhouse gas emission levels and possibilities of their reduction). Furthermore, there are uncertainties related to cloud formation, atmospheric circulation, and feedback mechanisms. These limitations contribute to uncertainties in regional climate projections, particularly regarding future temperature, precipitation, and runoff patterns. Climate change impacts like heavy rainfall, flooding, and erosion can compromise the integrity of near-surface covers and barriers.

Projections beyond 2100 years AP remain scarce, limiting confidence in 100–1000 a AP climate states. Downscaling CMIP6 outputs to site scale introduces uncertainty in local precipitation and temperature extremes. Paleoclimate cycles (e.g., mid-Holocene) are poorly represented, constraining analogues for multi-century assessments.

In Finland for the RCP8.5 extended global warming scenario the response of the ice caps in Greenland and Antarctica is highly uncertain. It was assumed that both ice caps would melt contributing to sea level rise, but there are no references in past climates for the last 2 Ma that this would happen with certainty.

Subtask 2c – Natural analogues

For the timeframe considered, no natural analogues have been applied so far, but they can be identified in the case of Lithuania: Analogues can be identified by examining regions that currently experience similar climatic conditions. For example, current Lithuania's Dfb climate can be broadly compared to other regions in Western Europe, particularly those at mid-latitude with a continental influence. Specifically, it falls within the south-western sub-region of the Atlantic continental forest zone, with its coastal areas having a climate more similar to that of the Southern Baltic region (e.g. SFR site located at Forsmark Sweden). However, the SFR (Final Repository for Short-lived Radioactive Waste) is installed about 50 meters deep within the bedrock below the sea, which differs from the Lithuanian B19 and B25 disposal facilities constructed on the surface on glacial and glaciofluvial deposits.

For the transition of Dfb (warm-summer continental) to Dfa (Hot-summer continental) possible natural analogues could be northern Ukraine, central Poland, and southern Belarus. These can provide insight into: (i) groundwater behavior in glacial deposits under hotter climates; (ii) ecosystem and soil responses to increased temperature and drought, (iii) long-term stability of engineered and natural barriers in a warming world. These analogues are especially relevant for nuclear waste repository planning, landscape evolution modeling, and long-term environmental impact assessments.

For the transition of Dfb (warm-summer continental) to Cfb (Oceanic) the best natural analogues are in northern Germany, Denmark, the Netherlands, and parts of northern Poland — areas with glacial soils, shallow aquifers, and a humid, mild climate. These analogues are useful for: (i) predicting hydrogeological responses under more temperate and humid conditions; (ii) estimating long-term behavior of engineered barriers (e.g. for nuclear waste storage); (iii) understanding future ecosystem and soil evolution.

In Ukraine partial analogues for early warming (< +3 °C) exist in today's Dfa (hot-summer continental) climates of northeastern North America, where July means exceed 22 °C and seasonal precipitation patterns mirror those projected for 100–1000 a AP under high-emissions pathways. Mediterranean Csa regions (e.g., northwest Iberia) provide limited analogues for summer drought and erosion risk, but they lack comparable winter precipitation regimes.

Subtask 2d – Evolution of climate change risks

During institutional control that can be from 300 to 500 years depending on the regulations, any potential risk due to climate change can be mitigated by updating the multi-layer cover and, if necessary, the retrieval and relocation of the waste is possible. Also, measures can be taken in the design and construction phases to account for all potential risk of climate impact.

The risks common to any surface facility due to future climate change are:

Increased surface water infiltration due to extreme precipitation that could also change the flow paths around/below the repository.

Soil desiccation and cracking of engineered caps in case of droughts.

Erosion and cover degradation in case of intense rainfalls, vegetation changes, and freezing-thawing cycles

Increase in the potential release and transport of radionuclides in warmer and wetter conditions

Land use changes in future climates may increase risk of human intrusion

In Lithuania mitigation of the risks during institutional control include the improvement of water drainage systems, weatherproof covers, regular inspection and maintenance, and early adaptation of long-term containment strategies.

Erosion of the multi-layer cover is thought to be avoided by a vegetation cover. Infiltration is to be allowed, but not to reach the inner layer that will cover the waste to avoid releases to the environment. This may be achieved using a hydraulic barrier.

In Ukraine, in case of release of radionuclides, the receptors include groundwater-dependent wetlands and floodplain ecosystems along the Pripyat River corridor, domestic and agricultural water users in settlements within 20 km of ENSDF-3, and soil and vegetation cover (including protective forest belts) across the Polissya region, where forest cover reaches 26.8% of the landscape.

The Pripyat River's flow regime includes spring floods (with recurrence intervals up to ~800 years producing discharges ~11 000 m^3/s at Mozyr), mean annual flow of 450 m^3/s, and low-flow conditions of ~171 m^3/s at the 99% exceedance level. The Pripyat River and its tributaries dominate surface water flow in the ChEZ, with spring floods and summer droughts driving seasonal water dynamics. Surface runoff is the primary pathway for radionuclide migration from contaminated soils to water bodies.

Although ENSDF-3 sits well above coastal inundation zones, regional storm-surge modeling indicates Black-Sea rises of 0.3–0.6 m by 2100 under RCP 8.5, raising extreme river flood stages in the Pripyat catchment. Intensive riverine floods (10%–25% increase in peak discharges) can overwhelm site drainage channels.

In Finland, the Olkiluoto, site is located in a sparsely populated rural area. Should radionuclide releases happen, fauna and flora would be immediately affected before reaching humans.

Groundwater flows through fissures and fractures in the bedrock and there are no springs to the surface.

The chemistry of groundwater around a surface repository is not expected to change in the timeframe of 1000 a AP. Only in case a surface repository would get under seawater, the chemistry would change from fresh to brackish or even saline at Olkiluoto. As this is not expected to occur within the next 300 years, the impact has not been studied. Moreover, if the repository would get under sea water after 300 years or more, dilution will occur in case the repository is affected and radionuclide releases occur.

There are no small water systems in the Olkluoto area, with the exception of a raw water pool constructed in the 1970s for the operation of the power plant; surface water comes from precipitation. It reaches the bedrock through infiltration at 1-2 m depth.

Because of low relief topography the erosion and sedimentation rates are also low. The overburden (i.e., the soil cover on top of the crystalline basement) in the area is 2.5 m thick on average.

In the planned disposal area for very low-level waste, the soil is a load-bearing moraine. Moraine with low relief has been observed to slide in Finnish Lapland when near seismic activity (Ojala et al., 2019. https://doi.org/10.1016/j.geomorph.2017.08.045).

Subtask 3a – Risk methodology

In Lithuania, a defined sequence of future climate states has not been applied as part of the screening process for potential impacts on safety functions within the safety assessment of RW surface disposal facilities. Nevertheless, boundary values of certain parameters—such as extreme temperatures or precipitation events—that could be associated with climate change and affect components like engineered and natural barriers, repository vaults, groundwater infiltration, corrosion, radionuclide transport, and erosion, have been implicitly considered. This was done by analysis of "what-if" scenarios in order to demonstrate the robustness of the repository design and the safety margins of underlying assumptions, but not as a formal climate scenario sequence consideration. However, the systematic integration of comprehensively formulated sets of distinct future climate scenario states (aligned with established values of relevant parameters) would significantly improve the completeness and reliability of the safety assessment for RW disposal facilities.

Subtask 3b – Needs, gaps and recommendations

Climate Models are not integrated with Safety Assessment Frameworks in Lithuania. The considerations concerning climate change are mostly considered fragmentarily relying on simplified "what-if" boundary conditions and RW disposal programmes treat climate change only qualitatively or through limited boundary cases. Therefore, it would be desirable to create methodologies for integrating climate-driven parameters (e.g., temperature, precipitation, sea-level rise, glaciation) into e.g. FEP (Features, Events, and Processes) or safety function analyses in more systematic way.

Capacity Building and Methodological Harmonisation between European states are needed in order to strengthen national expertise in climate modelling for RW disposal safety assessments and align with leading methodologies applied in other EU states.

There is also a need to develop climate evolution scenarios adapted to repository-relevant, site-specific conditions and timescales. Safety assessments usually require plausible future scenarios and associated parameter values that reflect local climate dynamics, rather than relying solely on global trends. Current datasets are often overly generalized and lack sufficient temporal and spatial resolution, introducing significant uncertainties in the downscaling process. Development of site-specific climate evolution scenarios over appropriate timescales (ranging from 10 to 1,000+ years), tailored to distinct European climatic zones (e.g., Mediterranean, temperate, Nordic), is essential. This should be carried out in parallel with the development and validation of downscaling techniques (both statistical and dynamical) to generate high-resolution, site-specific climate inputs relevant to the performance assessment of RW disposal facilities.

Current Dfb (according to Köppen-Geiger classification) Lithuanian climate is predicted to change to Dfa or Cfb until year 2100 (or even to Cfa for the year 2200+). According to Köppen-Trewartha classification might shift from Dcb → Do or Cb. This reflects wide range of variability in the predictions, which require to create methods to incorporate climate scenario uncertainty into safety assessments using probabilistic approaches or consideration of multiple plausible future states.

Group 4Sb

Group number: 4Sb

Disposal type: surface disposal

Current climate: Cfb

Countries: Belgium, UK, France

Partners: SCK CEN, NWS, ANDRA, Mines Paris, BRGM, ASNR

Lead: Mines Paris

Time window: 0-10 ka (a or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	Case study/site name	Disposal type	Waste type	Current phase
Belgium	Dessel	Surface disposal	LILW-SL	Construction
France	CSA, F	Surface disposal facility	LILW-SL	Operation
France	CSM, F	Surface disposal facility	ILW-SL	Monitoring after closure
UK	LLWR-UK	Surface disposal facility (engineered barrier)	LLW currently authorized, possibly less hazardous ILW in the future with further authorizations	Operational

Case study/site name	Latitude	Longitude	Altitude	Distance to sea
Dessel	51°13'23.4"N	5°04'37.5"E	25 m	60-120 km
CSA, F	50-45N	2W-5.42E	100-200m	200-500km
CSM, F	50-45N	2W-5.42E	50-100m	5-10km
LLWR-UK	55-50N	5-0W	10-20 m	< 1 km

Case study/site name	Climate Köppen Geiger/Köppen-Trewartha	Hydrology	Land-use	Landscape
Dessel	Cfb/Do	Perennial, groundwater dominated	Grassland, cropland, heather and built area	Low relief topography, rather flat landscape
CSA, F	Cfb/Do	Perennial SW	Grassland	Low relief topography

CSM, F	Cfb/Do	Perennial SW	Grassland	Low relief topography
LLWR-UK	Cfb/Do	Perennial SW	Shrubland	Low relief topography

Case study/site name	**Geology below the facility**	**Hydrogeology below the facility**
Dessel	Sedimentary	Aquifer phreatic
CSA, F	Sedimentary	Phreatic
CSM, F	Metamorphic and igneous	Phreatic
LLWR-UK	Quaternary glacial deposits overlying Triassic Sandstone (Ormskirk Group; around 240 million years old)	Aquifer phreatic

Case study/site name	**Pore water below the facility**
Dessel	Fresh
CSA, F	Fresh
CSM, F	Fresh
LLWR-UK	Fresh

Case study/site name	**Describe the engineered barriers**
Dessel	Multi-layer cover consisting of an earth cover resting on an impervious concrete top slab. The earth cover is 4.5 m thick and consists of a biological layer (sandy loam), a bio-intrusion barrier (coarse inert material), an infiltration barrier (compacted clay) and a drainage layer (sand). The modules and monoliths are made in fiber-reinforced concrete, while the latter are back-filled with mortar.
CSA, F	The reference concept retained to date is made up from top to bottom 1. cover: Turfed topsoil – Thickness: 0.2 m. 2. protective layer = Albian weathered clay – Thickness: 0.8 m. 3. filter = Upper Aptian sand – Thickness: 0.1 m; 4. biological barrier: anti-intrusion and drainage = crushed non-limestone 40/50 – Thickness: 0.4 m; 5. impermeable barrier: Clay of the lower Aptian – Thickness: 1.5 m; 6. shape layer: Upper Aptian Sand – Variable thickness 0.4 m; The considered slopes are 8% for the sections of the cover in the transverse direction, 1% in the longitudinal direction, and 3 width per 1 height (3H/1V) for the peripheral banks.
CSM, F	Currently, at CSM, engineered barrier is composed of 6 layers, from top to bottom of : 1. 0.2m of « natural » soil, 2. 0.75 to 1.25m of coarse material (shists),an anti-intrusion biological barrier, 3. 0.3m of sand drainage layer,

	4. 5cm waterproof bituminous geomembrane, 5. 0.2m of sand drainage layer, 6. Variable thickness, coarse material shape layer (shist and sandstone).
LLWR-UK	Trenches: The first trench, Trench 1, was opened in 1959. It was dug into clay in a railway cutting made for the Royal Ordnance Factory (ROF) and the waste was placed by tumble tipping. Subsequent trenches were dug up to Trench 7, placing bentonite enriched sand (BES) at the bases where natural clay was not present or sufficient. Trench 7 continued in operation until 1995. The current interim cap was placed over Trenches 1 to 6 in 1989 to 1990 and over Trench 7 in 1995. Replacement of the interim cap across the Southern trenches began in 2025 and work is ongoing. Reinforced concrete open Vaults: Vault 8 was commissioned in 1988 and is very close to full as of 2025. Its capacity is around 308,000 cubic metre. The Vault 8 design has a basal liner of a minimum of 1 m of in situ clay, or at least 300 mm of Bentonite Enriched Soil (BES) where in-situ clay was not present. The majority of wastes are packed within ISO-freight containers and grouted. Containers are stacked to either 4 or 6 high. Vault 9 was constructed from 2008 to 2010. Its capacity is around 247,000 cubic metre. It is currently accepting waste, mostly in ISO-freight containers which are filled with grout upon receipt at the LLWR site. The design for vault 9 incorporates a double composite barrier of geomembrane on BES base, designed (with the vault walls) to contain any infiltration for as long as possible. Should Vault 9 eventually fill with leachate ('bathtub'), overtopping leachate would be directed to a leachate management system. Vault 9A is a planned extension to Vault 9. Future vaults are currently anticipated up to Vault 12 with an expected "final waste emplacement date" of 2135. Capping Operations: The entire area of vaults and trenches will be closed in sequence from North to South with a unified multi-layered barrier system, comprised of a highly engineered, single dome final cap (~>5m thick), cut-off-wall (COW) and associated engineering. This will be constructed in strips across each vault and adjacent area of trenches, as soon as practicable after closure of each vault. The cap is designed to provide the best practicable impermeable barrier to infiltration of rainwater and to intrusion, and to maintain its functions for as long as possible. A COW will be constructed to provide a low permeability vertical barrier around the facility. Leachate Management: Engineered drainage pathways are provided by the sub-base features associated with the vault design (e.g. under-base drainage blanket), with the aim of maintaining low saturation conditions within the disposed wastes.

Case study/site name	**References**
Dessel	NIROND-TR 2009–07E Version 2, 2018. Long-term climate change and effects on disposal facility, geosphere, and biosphere. Project near surface disposal of category A waste at Dessel.

	NIROND-TR 2011-14 Versie 3, 2019. Veiligheidsrapport voor de oppervlaktebergingsinrichting van categorie A-afval te Dessel, Hoofdstuk 14: Veiligheidsevaluatie – Langetermijnveiligheid.
CSA, F	RDS2022/ SURRPACID220002/A.1 – Rapport de sûreté – Centre de stockage de l'aube (INB n°149) Partie II – Volume IV
CSM, F	ANDRA, 2016. Sensibilité de la couverture à l'érosion en fonction du climat. Cas du réchauffement climatique anthropique – Point sur les données disponibles. Rapport technique J.RP.AGES.15.0031/A, Agence nationale pour la gestion des déchets radioactifs. 49 pages
LLWR-UK	LLWR Engineering Design, LLWR/ESC/R(11)10020, May 2011 https://webarchive.nationalarchives.gov.uk/ukgwa/20170412103307/http://llwrsite.com/national-repository/esc-permit-approval/

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

Expected climates for the next thousand years (for high GHG emissions) are roughly similar: Csa (Dry and hot summer) is expected for Dessel (B), CSA (Aube, FR) and CSM (Cotentin, FR), in 100 years for the high emission scenario. For CSA and CSM their durations can reach 35% to 90% of the next thousand years. Csb (Dry and warm summer) and Cfa (hot summer, without dry season) are also expected for CSA and CSM, but they are less critical (lower temperature, lower dryness).

For the United Kingdom, the most pessimistic scenario (SSP5-8.5) leads to climate change by 300 years, shifting from a temperate climate to a humid subtropical climate (Cr in KT) until 3000 years.

These results were obtained using different approaches and models.

For Dessel (B): three hydrological scenarios (P, EVT) were defined (CCI-HYDR) based on 22 GCM (Global Climate Model) simulations from the IPCC AR4 database, with a coarse resolution (150-450 km) for the IPCC A1B, A2, and B2 (from SRES) and 10 RCM (Regional Climate Model) simulations from the PRUDENCE database, with high resolution (50 km) for scenarios A2 and B2.

For the United Kingdom: UKCP18 climate projection data (Met Office Hadley Centre, 2022) was used, along with reference data established for the site (from the local weather station between 1981 and 2010) to project future conditions.

For French facilities (CSA and CSM), ILoveClim, an EMIC (Earth Model Intermediate Complexity) model developed by the Laboratory of Climate and Environmental Sciences, was used. The result obtained on large grids (500 km) is reduced using an original downscaling method ("zoom") to achieve a high resolution (10'x10') of 13x18 km with (P, T) monthly averages. Finally, a sensitivity analysis was performed (anomalies relative to the reference period were increased arbitrarily).

Estimates of maximum **sea level** in 10 kyr also differ. The French approach based on geological analogues (Middle Miocene optimum) gives a higher value (+40 m) than the B and UK estimates using modeling (+20 to +25 m). Sea level increases with 1.5 m in the next century, 14 m in the next thousand years (at the earliest) in the worst case. For Dessel, marine inundation is considered to be possible in the time period between 2-10 kyr AP.

Subtask 2b – Gaps and constraints

The key **uncertainty** is the rate and scale of climate change and since this is a global socio-political issue, it is not possible to reduce this uncertainty. In any case, outdated climate scenarios introduce more uncertainties.

The **description of climate scenarios** using a sequence of climate classes (according to the KG or KT classification) is often insufficient for assessing a risk (e.g., soil erosion) and can lead to misinterpretation (changes in P and T do not always imply a change in class).

The **transfer of scenarios** is not straightforward, as they are linked to local characteristics (climate downscaling technics give different results because of the influence of local conditions).

Climate scenarios are difficult to compare (no standard description) and the **models that generate them are also different**. For example, the LSCE (FR) has noted in 2020 that ILoveClim "underestimates" the temperature increase compared to other models.

Some climate simulators do not take all processes into account (such as EMIC): ice caps, biochemistry, carbon cycle, land use, etc. Some of these processes are avoided because they require complex calculations, others because they are simply not well understood.

There are still gaps in scientific understanding: Downscaling techniques, necessary to consider local characteristics, may yield non-meaningful results. Many techniques are developed (statistical, geometrical…) and must be compared. Downscaling climate or vegetation is still a subject of research.

It should be noted that climate scenarios are defined (here) with a view to assessing certain types of risk, most importantly soil erosion and infiltration.

Uncertainties related to GHGE can lead to an underestimation or overestimation of climate change and compromise scenarios and the assessment of risks and impacts. Furthermore, it is difficult to define a "worst-case" scenario because it depends on the type of risk or impact being examined (e.g., Bioclim A4 is critical for river incision, B4 is critical for slope erosion).

A limited description of climate scenarios may not be suitable for assessing/simulating processes and may make it difficult/impossible to estimate their impacts (e.g., soil erosion) and risks.

Simplified models and techniques (downscaling) can lead to insignificant results or an underestimation/overestimation of climate change.

Some gaps have to be addressed by climate scientists on specific topics: downscaling technics, process modelling, computational techniques. Others can be addressed (temporary or not) by a clear methodology and recommendations. Some proposals are given below.

Improving climate scenario description is necessary to allow a more accurate comparison and a better evaluation of its impacts. It is recommended to use original model output: monthly precipitation (P) and temperature (T), EVT and ice volume if possible. It already avoids misinterpretation of climate type scenarios and allows sensitivity analysis.

To address uncertainties, **several scenarios** must be considered (with different GHG emission assumptions) and envelope scenarios (which include all variants) must be defined if possible. A **sensitivity analysis** should be performed where possible.

Up-to-date assumptions regarding GHG emissions and climate scenarios should be used.

Subtask 2c – Natural analogues

Climate-related natural analogues (in time and space) are already used for different purposes. Examples:

- Guadalquivir basin was used as dry subtropical (Cs in KT) climate analogue for an estimation of soil erosion and vegetation protection, for the Paris basin. For the same purpose, data in the state of Georgia in USA were used as an analogue of wet subtropical (Cr in KT).
- Data from the Ourense weather station (NW Spain) were used as an analogue for the Cs (KT) or Csa (KG) climate for the study of infiltration in the multi-layer cover at the Dessel site (B).
- Anthropogenic analogues, from the Neolithic period to World War II, and Holocene palaeosoil analogues are proposed in Belgium for the study of infiltration (in the multi-layer cover), slope stability, and concrete degradation.
- Climate analogues in the past million years have been used for sea level estimation.

However, precautions are necessary, as analogues cannot (usually) be applied directly. The perfect analogue does not exist. All driving factors would have to be identical (except for the one used in the analogy). In most cases, the influence of disturbing factors must be “neutralized”. For example, the relief in Andalusia or Galicia is different than the one in the Paris Basin or in Belgium, so relief influence (on climate or erosion) must be quantified and excluded/removed.

Subtask 2d – Evolution of climate change risks

Identified potential climate change risks are:

1. Appearance of more contrasted seasons: drier summer and wetter winter (e.g.: Mediterranean climate (Cs or Csa) for CSM and CSA sites),

2. Increasing probability of rainfall events of high intensity, and long durations,

3. Sea level elevation with global warming (and decrease in land ice volume).

These changes may have a direct or indirect impact on the cover (engineered barrier) of the nuclear waste storage facility:

- Degradation of vegetation during dry summers (on the topsoil layer of the engineered barrier),
- Degradation of soil characteristics (appearance of microcracks with dry-wet sequences, compaction, “crusting”, decreased or increased infiltration with pedogenesis, etc.),
- Extreme drought conditions can degrade the clay layer and impair its function as an impermeable barrier (CSA),
- Erosion of topsoil may increase due to soil and vegetation degradation (~2 orders of magnitude between grassland and bare soil), as well as heavy rainfall events. The risk is that the top layer of the soil will be washed away or “pierced” (by gullies).
- Internal erosion may also occur (in engineered barriers), but the impact of climate change is not well known at this stage.

The risk of erosion was studied for the Dessel and CSM sites using **numerical models** (RUSLE type) which gave consistent results. For both sites, which have virtually identical slope configurations (1:3), the average erosion rate is estimated to be between 2.5-10 cm/ky (current climate with dense natural grassland) and 20 cm/ky (in a future Cs Mediterranean climate) and less than 10 cm/ky without vegetation (Cs). The results are similar even though rainfall erosivity is currently higher at CSM (+12%). These results highlight that vegetation cover plays an essential protective role: it has an impact of two orders of magnitude on mechanical water erosion.

For the Dessel site, the impact of water erosion, wind erosion and other degrading processes on the multi-layer cover is considered to be low in the expected evolution and reference scenarios. It means

that during the next 1000 years, the impervious top slab remains intact, as well as other safety function fulfulling SSC's, and consequently no water can penetrate the disposal facility. After 1000 years (expected evolution and reference scenarios), the engineered barriers will degrade slowly and gradually. Some parts of the earth cover will erode faster than others, such that the top slab and the upper part of the module walls become locally exposed to atmospheric conditions quite soon. Thus, water infiltration into the modules will increase gradually and heterogeneously, and is limited in the end only by evapotranspiration from vegetation on the earth cover.

There are two alternative evolution scenarios that consider enhanced and extreme erosion. Enhanced erosion means that the earth cover is fully eroded over timeframes of a few 100 years beyond the control phase (350 years after closure), and gradual degradation of the system as a whole after 650 years (instead of 1000 years). Extreme erosion involves a fully eroded cover shortly after the control period, and gradual degradation of the system as a whole from that time onwards (instead of 1000 years).

The penalizing scenarios start from 2000 years after closure, and involves an instantaneously and fully degraded disposal system subjected to Cs climate conditions (high CCI-HYDR scenario) and relying on calcite sorption only.

The impact of extreme precipitation has recently been addressed for CSM. For this purpose, another approach has been launched for soil erosion risks. Small-scale **laboratory experiments** have been set up to study the sensitivity of some parameters (like precipitation intensity, soil moisture, etc.). Critical rainfall events (return period of thousand-year, of ten-thousand-year, etc.) were simulated on bare soil (see thesis by G. Portzer and EURAD2-SUDOKU). Consistency with the RUSLE model approach has not yet been established.

Although in some cases the increase in **infiltration** into the barrier appears to be low, persistent degradation of the hydraulic barrier over time will eventually lead to increased infiltration. Tests were conducted to validate the cover concept for the CSA under extreme drought conditions. The clay layer (impermeable barrier) resists desiccation well under 1.5 m of protective cover.

The **simulation of infiltration** through the multi-layer cover (of Dessel) and recharge to the underlying aquifer (geosphere) under a future Csa climate (Köppen-Trewartha: Cs) was done with a 2D variably-saturated water flow code HYDRUS-2D.

Hydrogeological modeling has been carried out for CSA and CSM (FR) but only for the current climate (temperate Do). The effects of climate change are not yet taken into account. In Dessel, the risk associated with hydrogeological changes (lowering of the water table) is estimated to be neglectable.

There are potential risks with the sea level rise (+14 m in 1 ky, in the worst case) concerning some low-elevation sites (UK, maybe B):

- Saline water intrusion if strong sea-level rise (+ 25 m in 10 ky),
- Tidal currents (erosion of cover),
- Corrosion of engineered components in saline water and leaching of cement phases.

Some risks appear highly unlikely (earthquakes) or negligible (wind erosion, hydrogeological changes, cement phase leaching, etc.) given the configuration of the facilities and the duration of storage. However, there is no consensus on the impact of extreme rainfall events and the likelihood of gully formation.

Some ideas have already been proposed and can be studied, such as **replacing the topsoil with gravel to limit erosion** of the barrier's top layer (CSM). In Dessel, a test cover will be built in the next years, which represents a 1:1 model of the final multi-layer cover. This test cover will be intensively monitored with regard to infiltration and erosion.

The slope of the cover has already been reduced for the CSM cover in order to improve stability, but space remains limited due to constraints related to the extension of the site itself. Furthermore, an

additional protective top layer is proposed (not planned yet) to increase the long-term stability of the cover.

Subtask 3a – Risk methodology

A comparison of different cases that were developed in this climate group can be found below.

Various greenhouse gas emission scenarios were explored at the four different sites (Drigg (UK), Dessel (B), CSA and CSM (FR)), resulting in different climatic scenarios using different models.

For the UK site: the IPCC SSP2-4.5 scenario is used as the reference scenario, the SSP1-2.6 scenario as the low-emission scenario, and the SSP5-8.5 scenario as the high-emission scenario.

For the Belgian installation in Dessel: Bioclim and older climate data (at the time of the assessment), for example from the IPCC Fourth Assessment Report (AR4), were used.

For the two French facilities (CSM and CSA): the latest LSCE simulations (2020) for high emissions (~RCP8.5) were used for the next millennium (with a time step of one year), as well as Bioclim A4 and B4 where necessary.

In the scenario without human interference, the current climate type (Cfb/Do) remains unchanged for ~50 kyr (according to Milankovich cycles). We will therefore focus on 'critical' scenarios (with high GHGE) that are also critical in terms of risks for storage sites and that see the emergence of a warm climate: a Mediterranean-type climate (Csa/Cs) at the 3 continental sites and subtropical humid (Cr) for UK.

In Belgium (Dessel) and France (CSA & CSM), climate scenarios are broadly consistent: Csa (or Cs in KT) is expected in ~100 years at the earliest (or later in 300 years, depending on the case) and could last for 35% to 90% of the next thousand years. The scenario appears to be wetter in the United Kingdom, with the emergence of a humid subtropical climate (Cr in KT) between 300 and 3000 years and a 52% increase in evapotranspiration.

The existing climate scenario types of information and time steps are not homogeneous across the four sites, making it difficult to make accurate comparisons.

The more precise the scenarios are, the less they are aligned. Small differences (in the variants) can have very significant impacts by modifying biomes (e.g. the appearance of a steppe climate (BSh)). Note the predominant impact of vegetation on erosion.

Local characteristics (altitude, topography, proximity to the sea, wind influence, latitude, etc.) are also important for many processes (e.g., rainfall intensity).

If sea level rise is included in the scenario; estimates are also broadly similar (+14 m in ~1ky and +25 m in ~3ky), with the exception of France, which forecasts a rise of 40 m (instead of +25 m).

Screening of possible impacts on safety functions

Averaged data sets such as annual averages (temperature, rainfall, evapotranspiration, etc.) or characteristic parameters for a given climate (in the KG or KT classification) seem sufficient to identify certain risks (erosion, etc.) and rule out others in the short term, such as: the degradation of clay layers (during periods of drought (CSA)), geochemical alterations caused by infiltration or coastal erosion (Dessel), etc. However, it is not possible to quantify them in detail.

Although the typical climate sequence (in the KG or KT classification) is very useful (thanks to the concept of 'biome'), it remains insufficient:

- It is very sensitive even to small variations in temperature (T) or rainfall (P), as shown by the example of CSM simulations (i.e., large differences in results between the two classifications over the next millennium).

- It does not allow for the estimation of certain risks such as surface erosion (huge standard deviation in the Panagos 2017 table), potential flooding, extreme events, etc.
- It remains very approximate with regard to vegetation cover, and the (climatic) analogy remains "delicate" because erosion and vegetation cover depend on many local characteristics (on a small scale), etc.

Similarly, the analogue approach (climate type) is based on classification and therefore inherits the uncertainties associated with its sensitivity (to parameters T, P).

Therefore, detailed and high-resolution climatic datasets are necessary in order to deal with uncertainties and enable sensitivity analyses. It can also improve the choice of an analogue. Models exist (IloveCLIM for CSA and CSM) that can produce monthly results (T and P) on a 1,000-year scale.

Subtask 3b – Needs, gaps and recommendations

While there is consensus on global warming and the emergence of a Mediterranean climate (Csa/Cs) in Dessel, at the CSM and CSA, and a rather humid subtropical climate (Cfa/Cr) in the UK, this information is currently not sufficient to assess certain risks.

We can illustrate the problem with the example of LSCE climate scenarios for the CSA and the CSM. They clearly show that, depending on the variants (related to the uncertainties of the model used), other climates (than Cs and Cr) may appear, for example steppe-type climates (BSh) whose consequences are very important on vegetation and therefore on infiltration and erosion.

Soil erosion studies were carried out in France and Belgium. They show (in the cases of Dessel and CSM) that the average erosion of the superficial layer of the cover, can increase by about 200% in a Csa climate), but remains reasonable if a vegetation cover, even slightly degraded, is maintained. However, the increase is up to 2 orders of magnitude for bare soil. The underlying layer (anti-bio-intrusion) is considered to be resistant to erosion a priori but this has not been tested explicitly.

These estimates regarding erosion remain 'rough' and do not address the impact of extreme events. Alternative climate scenarios (the variants, related to the uncertainties of the evolution models) have not been considered. Finally, the resistance of the bio-intrusion layer to water erosion has not been tested.

As for recommendations, we can formulate the following ones. While some gaps have to be addressed by climate scientists on specific topics (downscaling techniques, process modelling and computational techniques), other gaps can be addressed within the EURAD-2 community:

Improving climate scenario description is necessary to allow a more accurate comparison and a better evaluation of its impacts.

More precise evaluation of the evolution of the climate (and the associated uncertainties) by a sensitivity analysis, and propagate climate characteristics into estimates of cover degradation and infiltration fluxes.

Investigate the **impact of extreme events** (e.g. rains) that can lead to safety issues. This can be done through combining modelling, (field) experiments and the use of natural analogues (see above, Subtask 2C), for both erosion and infiltration.

Group 4Sc

Group number: 4Sc

Disposal type: Surface

Current climate: Cs

Countries: Spain, Italy

Partners: Amphos21, ENEA

Lead: Amphos21

Time window: > 300 yrs after closure

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	Case study/site name	Disposal type	Waste type	Current phase
Italy	Deposito Nazionale	Surface	Disposal: LLW, ILW-SL Interim storage: HLW, ILW-LL	Site selection
Spain	El Cabril	Surface disposal facility with engineered barriers	VLLW and LILW	Operation

Case study/site name	Latitude	Longitude	Altitude	Distance to sea
Deposito Nazionale	Not known (n/k)	n/k	n/k	50-100 km
El Cabril	40-35N	10-5W	200-500 m	100-200 km

Case study/site name	Climate Köppen Geiger/Köppen-Trewartha	Hydrology	Land-use	Landscape
Deposito Nazionale	Köppen Geiger- Cs Köppen-Trewartha- The 5 areas have different classifications: NORTH (Piedmont): Do CENTER (Lazio/Tuscany):Cw and Cf	n/k	n/k	n/k

	SOUTH (Basilicata/Puglia) Cw and Cf ISLAND (Sicily): Cs ISLAND (Sardinia): Cw and Cf			
El Cabril	Cs	Ephemeral	Shrubland	Hilly topography: elevated areas can clearly be recognized in the landscape

Case study/site name	**Geology below the facility**	**Hydrogeology below the facility**
Deposito Nazionale	n/k	n/k
El Cabril	Fractured crystalline rock	Fractured crystalline rock

Case study/site name	**Pore water below the facility**
Deposito Nazionale	n/k
El Cabril	Fresh

Case study/site name	**Describe the engineered barriers**
Deposito Nazionale	Four components constitute the engineered barriers system, complementary and redundant: 1. the **Container** that includes the matrix and the waste; 2. the **Module and the 'grout'** (cement mortar) that immobilizes the container; 3. the **Storage Cell** that contains the modules; 4. the **Multilayered Coverage** that protects the storage cells. 1. The cylindrical or prismatic **Container** represents the first isolation barrier, as well as the solid matrix for immobilizing radionuclides of the waste. 2. The **Module** constitutes the basic structure for placing waste in the repository; the containers are placed in and immobilized by means of 'grout'. The Module is a parallelepiped container in reinforced concrete (or fiber-reinforced concrete) with external dimensions of 3 m x 2 m x 1,7 m. 3. The **Storage Cell** is a box-shaped structure, with walls and foundation slab in reinforced concrete, with dimensions of approximately 27 m x 15,5 m x 10 m (240 modules are placed inside it, on 5 levels). The spaces between the modules will be filled with inert material (sand, gravel or other material with suitable characteristics) which will immobilize the modules. At the end of the filling operations, the cell will be closed and sealed with a reinforced concrete cover, integral with the body of the cell itself. 4.The storage cells will be further protected by a **Multilayer Coverage** system that constitutes an additional engineering barrier; it will be made up

	of layers of soil with different characteristics and functions, with waterproofing membranes in between. The artificial layers features will ensure their durability for the entire period of institutional control, also through maintenance.
El Cabril	The packages received are left in concrete casks. When a cask is at full capacity, it is immobilized by means of injected mortar, forming a compact block. This block is deposited in the disposal vault. Once the disposal vault is full, it is sealed with a slab made of reinforced concrete and waterproofed paint. Once all the structures in a platform are full, it will be sealed with a final cover made up of various drainage and waterproofing layers and topped with a final layer of topsoil to enable integration into the environment. The site's monitoring and surveillance phase begins at this time. It lasts approximately 300 years. Ref: https://www.enresa.es/eng/index/activities-and-projects/el-cabril

Case study/site name	**References**
Deposito Nazionale	Sogin, 2020. Deposito Nazionale - Progetto Preliminare DNPT - Executive Summary - DN GE 00045, 21/12/2020. https://www.depositonazionale.it.
El Cabril	Ref: https://www.enresa.es/eng/index/activities-and-projects/el-cabril

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

In Italy, climate projections indicate a transition from temperate (C) to arid (B) conditions over the next 0–100 ka. Average temperatures are expected to rise by 1.8–3.1 °C under RCP4.5 and by 3.5–5.4 °C under RCP8.5. Annual rainfall may slightly decrease, with regional variability ranging from –8% to +5% under RCP4.5 and from –15% to +2% under RCP8.5, extreme events will intensify. Especially, a strong increase in summer heat waves is projected: the SU25 index could grow by 19–35 days (RCP4.5) or 37–56 days (RCP8.5), while the TR20 index may rise by 14–35 days (RCP4.5) or 23–59 days (RCP8.5). Furthermore, the intensity of rainfall on the wettest days could slightly increase.

Similarly, in Spain, future scenarios also indicate a shift from temperate (C) to arid (B) conditions, with a Köppen–Geiger classification of BSh projected [1,2]. Annual precipitation in the south may fall by 20–30% by the end of the century, with the sharpest reductions in spring and summer (over 20%), while autumn and winter rainfall could decrease by 10–15%, affecting recharge cycles. Hot conditions will intensify, with up to 35 additional summer days above 25 °C per year and 20–30 more extreme heat days above 35 °C.

Specifically, for El Cabril, two thermoclimatic phases are foreseen for the next centuries: a Supermediterranean stage with temperatures between 8–13 ºC and low precipitation (250–650 mm), followed by an Oromediterranean stage with cooler temperatures (4–8 ºC) and increasing aridity [4]. Moreover, a marked warming trend by the year 2100 is expected [3]. Average annual temperatures are projected to increase by +3.6 to +6.5 °C under high emission scenarios (RCP8.5), with the greatest warming occurring during summer months and accompanied by more frequent and intense heatwaves. Total annual precipitation is projected to decrease between 0–17 %, particularly in spring and summer, while rainfall events will become more irregular and concentrated, resulting in fewer but more intense storms.

Long-term projections from ENRESA [4] for Spain describe a sequence of climatic oscillations over the next 130 kyrThese include temperate conditions (0–2 kyr), rapid cooling and stadial oscillations up to 20 kyr, glacial conditions around 20–25 kyr, alternating stadial and interstadial periods until 64 kyr, a recovery to temperate conditions around 67–72 kyr, a new cooling trend until 108 kyr, glacial conditions between 108–115 kyr, a post-glacial recovery around 115–120 kyr, and finally interglacial temperate conditions between 120–130 kyr. Overall, this sequence is characterised by an alternation between prolonged “cold-wet” and “warm-arid” phases. The initial temperate stage (0–2 kyr) corresponds to the present interglacial context, within which the Supermediterranean and Oromediterranean phases would occur as shorter-term sub-stages reflecting progressive warming and increasing aridity due to increased CO_2 concentration in the atmosphere, before the next cooling transition.

These long-term projections are based on orbital (Milankovitch) forcing, which explains cyclic variations in solar radiation due to changes in Earth’s orbital geometry, further modulated by internal feedbacks such as atmospheric CO_2 concentrations. The sequence of future climatic states was established by combining paleoclimatic and paleohydrological reconstructions from geological records with orbital climate models calibrated against Quaternary marine stratigraphic series (e.g., SPECMAP) [4].

Subtask 2b – Gaps and constraints

Current assessments highlight general gaps such as the lack of site-specific and detailed historical climate data, which limits model accuracy and increases uncertainty in predictions. Reliance on extrapolated data further amplifies this uncertainty, while the combined effects of anthropogenic emissions and long-term insolation remain difficult to project with confidence.

To address these gaps, studies must strengthen uncertainty analysis, refine scenario definitions with different emission and insolation pathways, and expand research on adaptation measures for facilities facing climate change.

Subtask 2c – Natural analogues

For El Cabril, suitable climate-related natural analogues are found in present-day semi-arid steppe and Mediterranean–arid transition zones of southern Spain and North Africa. These environments reflect the projected BSh-type climatic conditions expected during future warm–dry phases and provide insight into long-term processes affecting near-surface repositories. In particular, areas in Andalusia (Guadalquivir Basin) and Murcia–Almería, where seasonal droughts and episodic intense rainfall coexist, can help evaluate erosion rates, infiltration dynamics, and vegetation recovery under conditions similar to those foreseen for the El Cabril post-closure period. Evidence from these analogues may support the calibration of erosion and infiltration models, estimation of cover durability, and evaluation of biotic protection by vegetation under extreme moisture/temperature cycles.

For Spain longer term, potential natural analogues for future climatic conditions can be found in present-day cold-winter steppe and desert regions extending from the Black Sea to the Caspian Sea and Central Asia. These environments may resemble the Iberian Peninsula during past glacial stages (20–25, 56–64, and 108–115 ka AP) and interstadial temperate stages (64–72 and 115–120 ka AP). Given the long timeframes involved, such analogues are particularly relevant for considerations linked to deep geological repositories rather than surface or near-surface facilities.

The limitations of the natural analogues is that not all key factors driving a process are identical as in the facility and its environment. In this case, transferability is constrained mainly by lithology and man-made structures and components (natural badland terrains and engineered multi-layer covers), and the fact that engineered multi-layer covers do not have perfect natural counterparts.

Subtask 2d – Evolution of climate change risks

In Southern Italy, reduced overall rainfall coupled with higher temperatures may alter groundwater chemistry through increased evapotranspiration and solute concentration. The shift toward fewer but more intense precipitation events increases the risk of erosion (runoff) and flooding, potentially

damaging repository covers. Conversely, in Northern Italy, higher mean annual precipitation could increase groundwater recharge, influencing groundwater flow regimes and accelerating the potential migration pathways for radionuclides. At El Cabril, the projected warm–dry phase (Csa to BSh climate), characterized by higher temperatures and equal or reduced mean precipitation, is expected to lead to greater hydroclimatic variability, increased erosive potential, and a general decline in soil moisture and aquifer recharge, resulting in a progressive trend toward increasing aridity in the region. These changes may influence the long-term performance of engineered barriers.

The most relevant risks are associated with the stability of the soil cover and the durability of concrete vault structures. For the soil cover, the main concerns include the loss of the topsoil and vegetation layer due to extreme precipitation, drought and low moisture availability, which cause desiccation and loss of soil cohesion. Moreover, dry–wet oscillations may increase infiltration and cause slope instability, leading to cover erosion or slumping. The concrete vault walls are potentially affected by temperature and humidity cycles [5]: high humidity with low winter temperatures may induce microcracking, while high humidity combined with high summer heat can trigger evaporation–condensation processes. During the current summer period, solar radiation already raises vault surface temperatures up to 55–60 ºC, and the expected additional warming of 3.6–6 ºC by 2100 may exacerbate these internal cycles. However, no significant impact on the waste forms is expected, as the multi-barrier system provides sufficient protection against environmental stresses.

Possible adaptation measures include maintaining and reinforcing vegetation cover, optimizing the slope of the final cover, and substituting top cover materials to enhance erosion resistance. Additional measures such as high-capacity drainage systems, edge protection structures, and instrumented test covers are recommended to monitor and calibrate infiltration and erosion models before final closure, ensuring that the system remains resilient under evolving climate conditions.

Subtask 3a – Risk methodology

For the El Cabril case, the Environmental Impact Assessment analises the impacts of climate change on thermal and precipitation regime variations up to the year 2100, using IPCC predictive models for the most unfavorable case, RCP 8.5 [3]. For longer periods, two alternative scenarios affecting site precipitation are taken into account: a change in the infiltration rate (EC1) and a change in the groundwater table elevation (EC2) [6].

- Scenario EC1 postulates a change in average annual precipitation, leading to a change in the potential infiltration flux through the barriers, affecting the processes of contaminant release and transport within the storage facility and in the geosphere, the characteristics of the biosphere, agriculture/livestock, and human behavior. Depending on the change in average annual precipitation (increase or decrease), the reference scenario will be quantitatively affected, not only in the maximum dose to the critical individual, but also likely in the time in which it occurs.
- Scenario EC2, variation in the water table elevation, a penalizing situation is considered according to the characteristics of the storage site as a whole, and to pessimistic assumptions based on the analysis of the evolution of precipitation at the site, which would lead to the elevation of the water table above the elevation of the storage cells, during the period when cover and engineering barriers are assumed to be degraded. Thus, the scenario is characterized by a rise in the water table such that groundwater comes into contact with the waste, causing the source term to alter with respect to that estimated in the reference scenario.

For near-surface disposal facilities like El Cabril, detailed multi-millennial climate reconstructions are not essential. The centennial-scale formulation combining current IPCC projections with process-based perturbations (EC1–EC2) may be sufficient to test system robustness during the post-closure period.

More detailed oscillatory sequences would be valuable for deep geological repositories but exceed the level of complexity required for surface systems.

The scenarios until 2100 for both Italy and Spain are grounded in IPCC Representative Concentration Pathways (RCP4.5 and RCP8.5) and downscaled regional climate projections. This approach aligns directly with European practice, which mandates reliance on IPCC global scenarios, regional climate projections, and natural analogues for long-term safety assessment. Key elements include:

- Long-term regime shift: Köppen–Geiger climate classification is used to model and describe long-term climatic regime shifts (temperate “C” to arid “B” conditions in both countries).
- Extreme events Iindices: of extreme events: Indices of extreme events,, such as SU25 (number of summer days >25 °C) and TR20 (number tropical nights >20 °C), applied to quantify the intensification of severe weather, particularly in the Italian case.
- Long term oscillatory sequences help to explore conditions over glacial cycles and tens to hundreds of millennia. Screening through alternating cold-wet vs. warm-arid phases helps test repository robustness under very different groundwater and geochemical regimes. Thus, the detailed climate sequence does allow screening possible impacts on safety functions (barrier performance, radionuclide containment, stability of engineered structures). However, the level of detail required depends on the facility type:
- Essential for deep disposal: Long-term oscillatory cycles (ka) are essential for deep geological disposal facilities, which require proof of containment over vast timescales..
- Potentially excessive for near-surface disposal, These detailed sequences may be considered excessive for near-surface facilities (like El Cabril in Spain), which primarily rely on shorter-term projections for their operational and post-closure periods. where shorter-term projections suffice.

For regulatory compliance, both ISIN (Italy) and CSN (Spain) require consideration of climate aspects in site qualification and safety assessments. European guidance on “climate-proof” infrastructures also calls for climate adaptation. Hence, climate scenario formulation is a regulatory necessity.

Subtask 3b – Needs, gaps and recommendations

Needs & gaps identified are:

- Site-specific climate baselines: long and homogeneous meteorological series and paleo-proxies at candidate sites are lacking; reliance on regional datasets and extrapolations raises uncertainty for post-closure performance modelling.
- Hydroclimate linkages underrepresented: limited coupling between climate states and recharge, groundwater levels/flows, geochemistry and erosion at repository scales (cover stability, infiltration, run-off).
- Extremes and cycles: beyond indices like SU25/TR20 and BSh classification, extreme rainfall statistics (IDF/rare storms), multi-year droughts, freeze–thaw and heat-humidity cycles are needed.
- Natural analogues: candidates are identified for Spain (cold-winter steppe/desert from Black Sea–Caspian–Central Asia), but systematic analogue programmes linking observed

geomorphic/hydrogeological processes to quantitative parameters (erosion rates, infiltration factors, weathering rates) are missing.

For surface facilities the present material supports screening and concept-level design checks. For a post-closure fully decision-grade, site-specific extremes, erosion susceptibility, moisture–thermal cycles and coupled hydrogeological response investigations are still needed. For deep geological disposal the long-term oscillatory sequence (to 130 ka) is a good framework, but lacks parameterized boundary conditions.

Climate-related impact assessments that are still needed (post-closure) are:

- Cover and near-surface system durability: thermal–moisture cycles, multi-layer cover erosion modelling and wind deflation under arid phases.
- Hydrogeological evolution: recharge scenarios by climate state; water-table and gradient changes; fast-pathway activation (fractures, karst, colluvial gullies); infiltration and transport sensitivity.
- Geochemical coupling: temperature and redox-driven sorption/solubility changes; cement/clay barrier alteration under variable wetting, ionic strength, and CO_2.
- Extreme events & compound hazards: IDF curves for rare storms, multiyear drought, wildfire impacts on vegetation/erosion/run-off and landslides under intense rainfall.

Some recommendations will be:

- A formalized framework is needed to define and communicate the level of acceptable uncertainty derived from missing site-specific data (baseline and paleoclimate). This includes establishing standardized probabilistic approaches (e.g., using Monte Carlo analysis) for projecting extreme event frequency and translating model uncertainty into quantifiable risk margins.
- Improve the climate scenarios for the next centuries to better represent the expected range of hydroclimatic conditions during the post-closure period.
- Run coupled hydro-climate models to propagate climate states into recharge, heads, flows and calibrate with water-level histories.
- Formalize a natural analogue programme study: benchmark erosion, infiltration, weathering in analogue terrains and translate to parameters with uncertainty bounds.
- Produce fit-for-purpose guidance differentiating surface vs deep requirements, timeframes, and acceptable uncertainty treatments.
- Embed knowledge transfer and data curation to support multi-decadal to centennial learning cycles.

Feedback from regulatory & stakeholder requirements

Italy: expects meteorological/climatological consideration in site suitability and emergency planning. The national regulatory body, ISIN, requires that both meteorological and climatological considerations be thoroughly integrated into both site suitability assessments and emergency planning. Specifically, ISIN guidelines call for detailed analysis of mid- and long-term climate evolution to ensure adequate post-closure safety. Stakeholders, including regional authorities and civil protection agency, demand high assurance regarding site safety, specifically requiring: clear demonstration of hazard management

(explicit evidence that natural-hazard exposure is correctly managed and mitigated); resilience cover (confirmation that facility covers is specifically designed to withstand anticipated extreme events); site-specific evidence (the provision of site-specific data and evidence for all climate and hazard projection, moving beyond generalized national or regional averages.

Spain: requires evaluation of extreme weather, resilience measures, and institutional control post-closure (environmental/radiologicalmonitoring, hydro-met data, security, knowledge transfer). Stakeholders will look for transparent adaptation pathways, monitoring plans with triggers, and Strategic Environmental Assessment consistent mitigation (avoid natural areas, manage erosion, address vulnerabilities of roads/bridges/slopes).

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Group 4Sd

Group number: 4Sd

Disposal type: surface disposal

Current climate: Cfa

Countries: Bulgaria

Partners: GI-BAS, TUS

Lead: GI-BAS

Time window: 0-10 ka (or ka AP; Present = 2025 CE)

This document presents a summary of the individual information sheets for each climate group.

Subtask 0 – Case selection

Country	**Case study/site name**	**Disposal type**	**Waste type**	**Current phase**
Bulgaria	Radiana	Surface disposal	LILW-SL	Construction

Case study/site name	**Latitude**	**Longitude**	**Altitude**	**Distance to sea**
Radiana	43°44'14"N	23°46'07"N	65-85 m	330 km (shortest)

Case study/site name	**Climate Köppen Geiger/Köppen-Trewartha**	**Hydrology**	**Land-use**	**Landscape**
Radiana	Cfa	Perennial, groundwater dominated	Shrubland, built area	Low relief topography: rather flat landscape

Case study/site name	**Geology below the facility**	**Hydrogeology below the facility**
Radiana	Sedimentary (clay and sand)	Aquitard and phreatic aquifer (below)

Case study/site name	**Pore water below the facility**
Radiana	Fresh

Case study/site name	**Describe the engineered barriers**
Radiana	1. waste form (steel drums fixed with cement mortar); 2. reinforced concrete container with thick walls, bottom slab and a cover slab; 3. reinforced concrete disposal cells, the foundations, the closing slabs and the filling material; 4. loess-cement cushion at the bottom (5 m thick cement modified loess layer) and the final multi-layer cover on top.

Case study/site name	References
Radiana	https://www.moew.government.bg/static/media/ups/tiny/file/Industry/EIA/2015/Part_7_EN_final_correct_number_of_figures.pdf http://dprao.bg/images/Annex_1_NTS_EIA_NDF_EN.pdf https://www.bulatom-bg.org/en/archive-conferences/conference-2024/ Challenges in completing the construction and commissioning of NRRAO – Stefanova, Chief Engineer, Specialized Division "NDF" Biurrun, E., Stefanova, I., Gonzalez Herranz, E., & WM Symposia, Inc., PO Box 27646, 85285-7646 Tempe, AZ (United States). (2016). Realization of the National Disposal Facility for Radioactive Waste in Bulgaria -16611. 42. Annual Waste Management Symposium (WM2016), Phoenix, AZ (United States). https://conferences.iaea.org/event/106/contributions/1726/ https://www.bge-technology.de/fileadmin/user_upload/MEDIATHEK/vortrag/Loess_Cement_Cushion_WM_2016__16077.pdf https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1908_web.pdf https://www.osti.gov/b nblio/22837978

Subtask 1 – Regulatory framework

See Regulatory Framework Appendix A.

Subtask 2a – Climate change scenarios

Until 2100, this part of the climate zone Cfa will continue as a Cfa climate, with substantial temperature increases and similar precipitation range (within 10%) under RCP4.5, and substantial temperature increases with wetter winters and springs, and drier summers and autumns under RCP8.5. These data are based on outputs from five CMIP5 GCM's for the period 1950-2099 (uniform grid with 0.5°-0.5° resolution). For longer time periods, covering the next 10 kyrs, Cfa climate is expected to continue.

Subtask 2b – Gaps and constraints

As mentioned above, future climate scenarios for the period beyond 2100 are simply based on extrapolation; long-term climate models need to be developed to overcome this problem.

Subtask 2c – Natural analogues

Loess archives that cover the last 800 kyr are mentioned as a useful natural analogue to analyse geohazards in the past as baseline for future risk assessments.

Subtask 2d – Evolution of climate change risks

Climate change is expected to increase the frequency and magnitude to extreme weather events in the area, namely, extreme precipitation and temperatures, and storms. Associated risks include heatwaves, fires and droughts. Extreme precipitation events will increase the erosion and flood risk.

Subtask 3a – Risk methodology

No input.

Subtask 3b – Needs, gaps and recommendations

No input.

Appendix E. Keynote papers of the Civil Society Workshop 1

Civil Society

Question 1: What are the main challenges and uncertainties related to the impacts of climate change on RWM?

1) Challenges linked to the physical impacts of climate change

- Oceanic currents (deceleration of AMOC and impact on European climates)
- Water rise, coastal impacts and isolation of strategic sites (e.g. storage in NPPs, Sellafield, La Hague, etc.)
- Multiplication and intensification of extreme events (floodings, megafires, etc.)
- Possible hydrogeological effects (groundwater long-term flows)
- Erosion mechanism changes and potential impact on seismic activity
- Impacts of CC on transportation and on infrastructure maintenance
- Water stress and possible impact on cooling of radwaste

2) Challenges linked to modelling, scenarios and safety demonstration

- Articulation between models and the different timescales/phases (Different evaluation of models of different periods before and after closure, possible discrepancies between the times scales of CC models and the phases of RWM, lack of “intermediate timescale” models, etc.)
- Long-term modelling issues (trade-off between spatial precision and long-term changes in models, integration of the changes due to CC in the models in a long-term perspective, etc.)
- Climate change in the short term and operational phase (e.g. the precision of annual or decanal predictions of climate change and consequently the adaptations needed in the short term and for the operation phase)
- Climate change and the impact on the concept itself and the major safety functions (Impact of CC on the proof of the long-term validity of concept based on ice caps or dry environments, impacts of CC on human/non-human intrusion, etc.)
- Coupled effects of climate change and how to model them (e.g. the modelling of long-term erosion decoupled from hydrogeological changes)

3) Impact of RWM on CC

- Possible impacts of RWM on Climate Change? (calculation of footprint)

Question 2: How could these challenges and uncertainties evolve over time, over all phases (Initiation, Site Selection, Site Characterisation, Construction, Operation, Closure) and in a long-term perspective?

1) Specific issue of the end of operational phase and closure

- Impacts of climate change on the conditions for closure and the closure itself
- Possible impact of climate change on recoverability/retrievability

2) Modelling the different timescales/phases and sites

- Link between timescales of models/effects of CC and timescales for different phases (c.f. Q1)

- Site and timescale specific studies to understand the priorities/effects of importance

3) Governance and societal changes linked with CC
   - Change in society regarding decisions linked with CC and possible impact on RWM
   - Migrations / changes in the borders / geopolitical instability / conflicts linked to CC
   - Change in uses of the territory linked with CC (use of new resources, agriculture, etc.)

4) Impact of CC on the whole RWM infrastructure and not only the repository
   - Important not to focus only on the specific repository site: transportations, other infrastructures, etc.

Question 3: What are the main ways to manage these challenges and uncertainties?

The main ways proposed by CS actors in order to collectively build stability in the whole uncertainty of climate change impacts on RWM are: Shared culture for safety and security, Fruitful interactions, Transboundary stewardship culture.

1) Shared safety culture:

Similarly to the recommendations from INSAG-4 on Safety Culture, a certain perspective of complexity grasping could be enhanced regarding the impacts of climate change on RWM. One cornerstone would be to always make sure that all elements of the materiality of RWM are taken into account when addressing these topics : notably transportations, indirectly related infrastructures, etc. Thus it seems important not to focus only on repository sites.

Another cornerstone is the capacity to share transboundary information and governance related to these topics. The outcomes of climate change and its impacts are not solely national, they require a shared culture for collaboration and safety.

2) Fruitful interactions:

The different modalities of interactions, debates, discussions and exchanges tackling the aspects of climate change impacts on RWM should be always considered in their plurality, enabling different framing of exchanges, avoiding possible instrumentalisation of the stakeholders arguments. It requires a dynamic and pluralistic approach for communities and organizations and of individuals, as mutual trust conditions.

3) Transboundary stewardship culture:

A conscious attitude from organizations and individuals regarding the continuous temporal and spatial responsibility brought up by RWM and underlined by climate change impacts on RWM, and thus an attitude of vigilance in uncertainties enabling an appropriate governance.
In further detail, it needs to be highlighted that climate change will very likely induce large migrations, possible changes in borders and thus induce geopolitical instability. Changes in the use of territory will occur, and the need to think already nowadays about modalities for managing these uncertainties along time needs to be built.

Question 4: What could be your role(s) regarding the management of those challenges and uncertainties? Also, what could be the possible roles of other actors for that purpose?

1) CS: should receive and collect information related to climate change and management of uncertainty, following-up R&D results. It implies implementation of processes enabling fair public participation, taking duly into account public recommendations. Question: What means (human, resources, appropriate processes) are available for civil society to evaluate independently Climate Change impacts?

2) Research Entities (and others) should continue R&D all along the RWM process in order to find new technologies or to improve existing ones, enabling to improve safety of the facility regarding impact of climate change.

3) WMO should implement facilities including the possibility to integrate new technological results during operational phase -> RWM should be flexible enough to integrate changes/improvement/new results especially on Climate Change. Question: how climate change is included in their licence application and how do they evaluate it?

4) Regulator / TSO should disseminate largely to the public results on their assessment of the safety case, and notably how Climate Change is included in the Safety Case and what resources do they have to evaluate it.

5) WMO, regulators and ministries: even if there is an agreement on the fact that climate change will have uncertain impacts, how to make sure there will be enough money in the future for tackling those uncertainties? It includes not only resource to evaluate climate changes impacts, but also provisions today for having resource later for tackling CC impacts.

6) All actors: Climate change should push for a better possibility of integrating reversibility of the process and retrievability of the waste.

Question 5: To what extent are the topics of climate change impact on RWM connected to transparency and public participation?

- Some elements of answers are included in the answer to question 4: a transparent and democratic RWM process should include dissemination of information and public participation.
- The public participation should be implemented in a fair way, should start as early as possible (including during R&D as it is done in EURAD programmes) and in a continuous way, not only at some consultative steps (that are also important and mandatory by law). The process should duly take into account the recommendations coming from the consultation (explaining how the recommendations have been integrated in the process or why the recommendation is not included)
- This requires R&D and experimentation on implementation of rolling stewardship culture as it was mentioned in ROUTES, UMAN and MODATS results (EURAD-1).
- Regarding specific issues related to climate changes, transparency will be required for climate change data (e.g. how the environment and notably biodiversity will be affected by the RWM). Will some climate change data be considered as security information? It should clearly explain why.
- There is also the question of modelling. It raises the question: who will have access to the data? The system should include the possibility for the regulatory body to check the data.

Question 6: What are, for the next steps, your main topics of interest to be considered and discussed?

Several transversal topics should be addressed, independently or linked with other topics. These topics could include:

- The issues on the conditions for closure, the retrievability/reversibility and their effective implementation linked to climate change

- The importance of environmental international agreements or convention, such as the Aarhus convention, and their link with climate change
- The mechanisms for provision and money linked to uncertainty management related to climate change
- The impact of (long-term) climate change on transboundary situations, private property, land management and the possible rise of new modes of management (commons, etc.)
- The links between climate change and the nuclear industry in general and the possible indirect impacts on RWM (defence of nuclear power in the eye of CC, impacts on NPPs, etc.)
- The possible use of the PEP as a tool of dialogue to create new or alternative scenarios linked with all these issues.

Research Entities

Question 1: What are the main challenges and uncertainties related to the impacts of climate change on RWM?

Climate change presents significant uncertainties and challenges to the safety of radioactive waste management (RWM). These challenges can be grouped into:

- Slow and Gradual Climate Changes: this affects the long-term design and performance of radioactive waste repositories. It is crucial to accurately assess their potential effects on nuclear safety.
- Increasing of extreme Climate Events/Extreme natural disasters related to climate changes: including storms, heavy precipitation, floods, wildfires, and landslides. The increasing frequency and intensity of these events, especially in area close to near-surface radioactive waste repositories pose a critical hazard. They can cause direct impacts on radioactive waste transportation and storage, as well as direct and indirect effects on regional hydrology, altering rainfall patterns and river flow. Uncertainties regarding probability, frequency, magnitude, return time, quantity parameters of these extreme events, etc. should be prioritised, making it challenging to design safe infrastructure without excessively increasing costs.
- Uncertainty related to future climate change are strictly related to the safety of the RW management facilities and activities, as well as the long-term safety after the facilities are closed. There are uncertainties in the features, events and processes (FEPs) that emerge not only from the limitations in scientific models and analysis tools, limits of measurement instruments, etc. affecting the ability to quantify risks accurately, but also arising from the influence of human actions in the actual and future climate (as demography, economic development, rate of greenhouse gases/aerosol emissions growth, political priorities, etc.). All these uncertainties must be acknowledged and incorporated into the scientific evaluation of climate-related risks. Additional prevention and protection measures for nuclear sites will have to be foreseen, even if they are not currently required by current safety regulation.
- The need to improve share uncertainties information with stakeholders and the public, ensuring transparency in RWM decision-making.

Question 2: How could these challenges and uncertainties evolve over time, over all phases (Initiation, Site Selection, Site Characterisation, Construction, Operation, Closure) and in a long-term perspective?

There are some facts related to the evolve over time:

- Future projections up to the next 300 years indicate an increase in the frequency and severity of extreme climate events, which will affect all phases of RWM, from the design of new repositories to their closure and post-closure. On the other side, climate models for more far future (>300 years) are usually more uncertain, causing that frequency and severity of extreme climate events is currently less known.It is crucial to recognize that the impacts of climate change vary regionally, as damages are not evenly distributed among countries. Additionally, RWM policies and safety regulations differ and evolve across nations, making it necessary to

adapt and calibrate future assessments according to the specific conditions of each country or site.

- In the long term, the lack of reliable climate models for periods of 500, 1000 years or more, combined with uncertainty regarding political and geopolitical decisions and the concern for a climate change mitigation on a global scale, makes it difficult to accurately predict future challenges. However, as knowledge of climate and environmental systems advances, the uncertainties in assessing the impact of climate change on nuclear facilities may gradually decrease.
- It's opportune to underline that the expected projections of climate change, as previously mentioned, are permeated by uncertainties that cannot be completely solved (climate model limitations, available data uncertainty, future social/economical/demographic evolution, uncertainties about the scenarios to be considered, etc.). Moreover, only gradual climate changes in the short term are predictable with a good margin of certainty, while in the long term are more uncertain.

Question 3: What are the main ways to manage these challenges and uncertainties?

The focus when managing challenges and uncertainties is not on preventing climate change itself, but on mitigating its impact on RWM, particularly the risks posed by extreme weather events:

- Comprehensive Data Analysis and Forecasting
  - Maximizing the use of all available meteorological data over the longest possible period and ensuring broad coverage in future forecasts.
  - Enhancing climate change impact assessments using advanced mathematical models and high-performance computing systems (e.g., pre-exascale and petascale supercomputers). This allows for fast and highly reliable evaluations of multiple scenarios based on location, timeframes, site characteristics, and repository design.
- Engineering and Structural Adaptations
  - Designing more resilient engineering barriers to counteract the impact of climate change.
  - Preventing future climate-related risks by avoiding geological and territorial contexts most susceptible to extreme weather events, based on scenario planning.
  - Implementing redundant systems for nuclear site protection, ensuring safety during extreme events such as floods, landslides, seismic hazard and earthquakes, or power supply disruptions. Redundancy should be maintained both in active protection systems and passive safety mechanisms.
- Continuous Monitoring and Early Warning Systems
  - Expanding nationwide and regional meteorological monitoring, particularly in areas surrounding repositories.
  - Establishing multi-level alert systems to detect and respond to extreme weather events (e.g., torrential rain, floods, landslides), enabling timely actions by repository staff and government authorities.
  - Monitoring structural integrity and the condition of storage facilities, particularly sensitive elements that may be affected by climate change and extreme events.
- Scenario Analysis and Sensitivity Assessments
  - Developing diverse climate scenarios to assess different potential evolutions and their consequences on safety guarantees.
  - Integrating sensitivity analysis to identify the most influential factors affecting climate change forecasts and refine predictive models for improved decision-making.

- Emergency Preparedness and Response Plans
    - Establishing comprehensive emergency plans for all RWM phases, including waste treatment, interim storage, transportation, and final disposal.
    - These plans should consider a range of probability-based scenarios, particularly regarding extreme weather events, to minimize risks to repository operations, personnel, local populations, and the environment.

Question 4: What could be your role(s) regarding the management of those challenges and uncertainties? Also, what could be the possible roles of other actors for that purpose?

The primary role of research and educational institutions (REs) is to enhance knowledge on climate change impacts and its uncertainties. This includes understanding the causes, sources of greenhouse gases (GHGs), the human activities and technical, social, and managerial strategies to prevent, mitigate, and adapt to climate change and its consequences. This also applies to extreme weather events, which are increasingly linked to climate change.

The main activities would be:

- The Role of Researchers in Climate Change Management: Researchers play a critical role in deepening knowledge on climate change and its uncertainties to predict the magnitude and likelihood of extreme or continuous events in specific territories. Their contributions help:
    - Increase public awareness and stakeholder engagement by disseminating climate science topics to promote prevention and proactive responses.
    - Support engineering solutions by providing essential data for designing resilient RWM facilities that can withstand extreme events.
    - Develop future climate scenarios and sensitivity analyses to assess risks associated with extreme events.
    - Explore mitigation and adaptation strategies through interdisciplinary research, ensuring that climate-related threats are managed effectively.
    - Increase emergency preparedness in RWM by helping to stablishing probability-based plans.
- Universities and RE play a key role in collaborating with various stakeholders, such as parliament, government institutions, regulatory bodies, media, and NGOs, to help manage climate-related challenges.
- Beyond research, the RE play a role in educating experts to develop scientific work in other institutions
    - Universities and RE serve as a source of executive, management and technic personnel for regulatory bodies, government institutions, NGO's,….
    - Universities and RE act as advisors, consultants, and long-term partners for their alumni in professional practice.

Roles of Other Key Stakeholders:

- Legislative institutions: Active policymaking and regulation by government and municipal institutions, ensuring effective legislation to address climate change, a suitable environment for its application and the control for its implementation in the practice.
- Regulatory bodies: Creation and enforcement of regulations for RWM and preparedness for climate-related uncertainties.
- Media: Dissemination of engaging and informative content on climate change for all age groups.
- Public organizations and NGOs: Promoting awareness and transparency on decisions related to RWM, climate change, and extreme weather events.

Question 5: To what extent are the topics of climate change impact on RWM connected to transparency and public participation?

Climate change and its impact on RWM is not just a scientific issue but also a public health concern. People are more likely to understand and engage with climate change mitigation efforts when presented as a hazard and health issue. Therefore, it is crucial to raise public awareness about the effects of climate change on RWM sites and the surrounding environment, as these impacts directly affect their health and lives.

- Transparency and Public Participation in RWM. The extent to which climate change impacts on RWM are linked to transparency and public participation is significant. Beyond the role of NGOs, two key aspects must be emphasized:
    - Public transparency and participation in RWM are highly dependent on public organizations and NGOs, which play a critical role in ensuring open communication and fostering community engagement.
    - The importance of transparency and participation is essential for public health and environmental protection in RWM. A higher level of public engagement encourages greater accountability from authorities and helps drive concrete actions, including:
        - Reducing climate change causes, such as lowering GHG emissions.
        - Enhancing RWM preparedness across economic, public, and social sectors to address climate change challenges, extreme meteorological events, and mitigate their consequences.
- Addressing Disinformation and Strengthening Public Engagement. A major obstacle in addressing climate change is widespread disinformation, which hinders effective responses. To counteract this, research findings must be simplified and transparently communicated to individuals, communities, and decision-makers. Clear communication fosters public involvement in decision-making, making climate issues more accessible and actionable.

Local communities play a vital role in providing territorial knowledge, including natural characteristics and the potential effects of extreme weather events on RWM sites. Their collaboration is essential for developing effective mitigation measures to reduce climate change impacts on RWM.

However, public engagement remains a communication challenge, considering both the sensitivity of the radioactive waste topic and the importance of climate change in this context. The key to successful public involvement is crafting clear, impactful messages and using effective communication strategies to ensure individuals understand the issue and recognize their ability to contribute to solutions.

Question 6: What are, for the next steps, your main topics of interest to be considered and discussed?

Risk of extreme climate events, including heatwaves, droughts, floods, and storms should be mitigate focusing on territorial adaptation, infrastructure resilience, hydrogeological risk management, and early warning systems to prevent landslides and floods.

Addressing climate change requires cooperation at international, national, and local levels, ensuring knowledge-sharing, technological advancements, and best practices to develop a climate-resilient economy. A joint commitment from institutions, citizens, and the scientific community is essential for long-term environmental sustainability.

The Key Research Priorities should be:

- Understanding historical and contemporary climate change trends: underestimation of climate change or overexposure of its impacts on humans and assets? what is the objective reality?
- Analyzing the relationship between climate change and extreme weather events, identifying patterns and risks.

- Exploring the interconnection between climate change, extreme weather events, demographic shifts,emigration and migration patterns and industrial and energy sectors, including their differences on a continental and global scale.
- Studying how other countries conduct climate change assessments at nuclear repository sites and develop sensitivity analyses for uncertainty management, likely in the Northern coyntries, South Africa and South America is rather different.
- Deepening knowledge of extreme weather impacts on the territory to improve preparedness and mitigation strategies.
- By integrating scientific research, collaborative efforts, and a multidisciplinary approach, countries can develop a sustainable and resilient strategy for managing radioactive waste while effectively responding to climate change challenges.

Technical Support Organisations

Question 1: What are the main challenges and uncertainties related to the impacts of climate change on Radioactive Waste Management (RWM)?

For processing[11] / transit storage [12]/ operating phase of disposal facilities (surface): evolution of levels of natural hazards (flooding, high/low temperature, tornados, …) which could have an impact on safety and on waste package at the repository environment. For long-term management in the post-closure phase:

- change in erosion rate for both surface/sub-surface disposal site covers,
- modification of landscape geomorphology (especially at valley incision) that could lead to modifications in the location of the outlets of groundwater resources (this point concerns all types of disposal),
- increase in seismic activity,
- increased carbonate and silicate rock solubility affecting the barrier systems,
- rise in sea levels and consequent submergence of certain areas,
- rise in groundwater level,
- changes in groundwater chemistry (pH, redox conditions, salinity), potentially affecting radionuclide mobility and engineered barrier performance,
- increased microbial activity in warmer conditions accelerating the degradation of waste containers,
- cascading effects where multiple climate factors interact (e.g., drought followed by intense rainfall creating new infiltration pathways),

can lead to faster-than-expected contact between radionuclides and people, and in higher concentrations than predicted in safety studies. Therefore, the need for re-assessment of safety should be evaluated, and in case safety margins are not sufficient, the safety evaluation process should be restarted. If a safety case would not provide sufficient guarantees to fulfil the legal requirements, the process would be updated. In the worst case, it could be necessary to ensure the safety of the radioactive waste disposal site with some additional technical measures (reinforcement, new engineered barrier, …) or even re-siting of waste.

For systematic continuous monitoring of meteorological and (hydro)geological parameters, tracking changes in the relevant factors, accumulating statistical data and analysing them, it's appropriate to use automated environmental monitoring systems. Installing weather stations and hydrogeological posts directly at radioactive waste repository sites will allow determining parameters such as: total radiation, temperature, precipitation amount, relative humidity, pressure, groundwater level and its pH, and rock stability. However, the longevity and long-term chemical-physical resistance to the environment of the sensors is an additional technical challenge and uncertainty.

The rate of climate change, affecting the development of uncertainties, depends mostly on the amount of released greenhouse gases and mitigation efforts (like success in the green transition), and can accelerate or prolong the onset of negative effects for the RWM, as also can accelerate or slow down the drastic changes (not) giving time to mitigate them appropriately. There is a need to analyse the most severe potential climate change scenarios and their impact on long-term waste isolation safety.

[11] Facility for processing includes pretreatment, treatment and conditioning activities (IAEA glossary).
[12] Transit storage is a space at the separate or disposal location intended for RW packages to be later disposed of.

In the scope of green transition, the reduction of greenhouse gas emissions is foreseen also by replacement of cements by new materials such as “green cements”, “geopolymers” and “alkali-activated materials”. The impact of these new materials on disposal site safety (short and long-term) has not been researched yet, as also these materials are not used in non-nuclear building and civil engineering yet. Therefore, they represent additional uncertainty, especially in connection with climate change, because contact with water represents a challenge leading to efflorescence and rapid deterioration of the materials (alkali-activated materials and geopolymers).

The implications of short-term climate change[13] on the Deep Geological Repository are insignificant when compared to the impacts that surface facilities can endure (floods, storms, tornados etc.). However, long-term climate changes, affecting precipitation and erosion, can affect also DGRs.

If climate change leads to a lack of resources or a collapse of society (like war or other military actions), the maintenance and monitoring of disposal sites will be abandoned. Hence the interest is in disposing of the radioactive waste as quickly as possible and basing their safety on passive barriers.

Question 2: How could these challenges and uncertainties evolve over time, over all phases and in a long-term perspective?

During the operational phase of repository development and periodic safety review, most uncertainties should be known and addressed. However, the time needed to be taken into account is 300 years for LILW repository and several hundred thousand years for GDR, after which the radioactive waste can be considered safe. Nonetheless, climate changes can become significant in an even shorter time and change the landscape through erosion, creating new precipitation paths for ground and surface water, microbial activity in warmer conditions, and changes in groundwater chemistry, which can affect the underground repository, leading to the release of radionuclides into the environment.

Several models are predicting the evolution of climate changes which result in very versatile predictions. The longest time climatologist evaluated is up to the year 3000, IPCC projections up to 2100 for several parameters. The most reliable parameter is the sea level, which is constantly rising, as also the average yearly temperature. With the increase of the temperatures, the rate of permafrost thaw and ice melting are closely connected: first will result in an increase of the release of in-the-permafrost-captured greenhouse gas CH_4, and second in the sea level. Although efforts towards the green transition are ongoing, its effect is still not obvious on the global climate scale.

Therefore, uncertainties, which depend on the rate of climate change, are smaller for the short-term (0-10 years), higher for medium-term (10-50 years), and even higher for long-term (50-1000+ years) periods. While short-term effects (extreme weather events like an increase in the frequency of heatwaves, storms, droughts) can be mitigated by the construction (like flood barriers), medium-term (like sea level rise, permafrost thawing, ecosystem shifts) are already challenging but might be mitigated and reversed, while some impacts of long-term climate changes (like ice melting in Greenland and Antarctica, changes of Gulf stream, ….) are irreversible on a human timescale (global effects will last for centuries and reshape the ground and underground landscape) and call also for appropriate city planning, flood defences, and not just for nuclear waste disposal (selection of disposal site and materials of disposal facility).

However, other uncertainties (not only related to climate change) strongly impact long-term management. For example, sustainability of the barriers chosen, as materials may degrade through mechanisms not fully captured in current models, the potential for threshold effects, where gradual changes suddenly trigger rapid system responses, collective memory, political will, geopolitical and economic changes, societal collapse, technological regression, choices made by future generations for

[13] It is also necessary to provide some connections between periods valid for climate studies and for RWM: like, what are periods duration in climate studies, what is short or long term in this respect, what climate studies are available for really long-term periods, which are relevant for DGR.

the management of these wastes, etc… introduces further complexity in predicting repository performance across millennial timescales.

Question 3: What are the main ways to manage these challenges and uncertainties?

Several and different options could help us to manage these challenges:

- Look at equivalent climates present today in other latitudes and study past climates. Determine the key/most influential parameters in impact assessments to focus efforts on them.
- Consider several scenarios, take margins, and work on the adaptability and flexibility of facilities. For new/future facilities, such changes could be anticipated by integrating the possibility of adapting the facility (for instance, reinforcing walls, improving the venting system, implementing cooling systems, choosing appropriate materials, …) to changes in natural hazards. Harder for ageing facilities, for which such changes have not been anticipated.
- Provide an analysis of threshold values for the parameters such as precipitation amount and intensity, atmospheric stability, probability of hurricanes, tornadoes, groundwater level dynamics, possibility of landslides, erosion and soil subsidence for evaluating the impact of meteorological conditions on normal and emergency operation of repositories.
- Emphasize the importance of knowledge transfer across generations for long-term monitoring programs.

Another way to consider this problem could be, instead of managing these uncertainties related to global warming, not to postpone the creation of disposal facilities and to accelerate their implementation and closure, and having an alternative to close a disposal facility early in case of an unforeseen event.

Question 4: What could be your role(s) regarding the management of those challenges and uncertainties? Do you want to share what could be the possible roles of other actors on that purpose?

As a TSO, we should raise attention to such challenges and ensure the passive nature of the safety of disposal after closure. The WMO should accelerate the implementation of that subject in the safety studies.

We should collaborate with other TSOs and with REs to be able to challenge the propositions made by WMOs, as also share experiences and approaches.

In addition, besides the inclusion of official actors, like WMOs, TSOs (with regulatory authorities) and REs, also interaction with Civil Society representatives is vital for exchanges and obtaining supplementary viewpoints.

Together with the Regulator, TSOs should develop science-based acceptance criteria for how climate change should be addressed in safety cases, help establish requirements for periodic reassessment of climate impacts throughout facility lifetimes and provide updates for the regulatory framework.

Question 5: To what extent are the topics of climate change impact on RWM connected to transparency and public participation?

The nuclear industry is one social issue, climate change is another. The two cannot be reconciled without public involvement.

Topics of climate change are extremely important for a variety of stakeholders, in particular to citizens due to the already present impact on the properties, well-being, …, therefore discussion should be

organised with all elements, like transparency (access to information), public participation and also support for participation.

However, for effective public engagement, it is essential to build climate and nuclear literacy. Therefore, educational programs (accessible materials explaining how climate factors are incorporated into safety assessments, capacity-building initiatives that enable informed participation in technical discussions spanning both domains) that help stakeholders understand the complex intersection of climate science and radioactive waste management are crucial.

Question 6: What are, for the next steps, your main topics of interest to be considered and discussed?

Will it be possible to switch to the post-surveillance phase?

Will countries have sufficient resources to complete the huge project of managing radioactive waste?

What mechanisms should be in place in the post-closure period to be prepared for reactions due to climate changes and impacts on the disposals' safety?

What interdisciplinary expertise (climatology, hydrology, materials science, etc.) do TSOs need to develop internally to adequately assess climate-related safety aspects?

How can TSOs effectively communicate complex technical evaluations of climate-related safety aspects to both regulators and the broader public?

What metrics and indicators should TSOs recommend for monitoring potential climate-induced changes at repository sites?

Possibility of a centralized meteorological (geological) database development to enhance the long-term safety of radioactive waste repositories through improved research, forecasting, and responsive threat management.

Waste Management Organisations

Question 1: What are the main challenges and uncertainties related to the impacts of climate change on RWM?

From implementers' perspective, significant challenges related to impacts of climate change on RWM stem from a variety of issues. Due to the nature of the tasks related to disposal of radioactive waste, different timescales have to be considered. That is short-term timescales in connection with construction, operation and closure of a repository and long-term timescales relating to long-term safety of a repository in the post-closure phase with up to one million years of assessment periods, for which the safe containment of radioactive waste with the aim of isolating the radionuclides has to be demonstrated. Succinctly, the challenge is understanding how climate change will impact on facility performance and safety (i.e. will it be negative, and result in a greater release of radioactivity to people and/or the environment).

Weather phenomena and climate variations occur on a wide range of temporal (from several hours for e.g. storms to several hundred kyr for e.g. glacial – interglacial cycles) and spatial scales (global – regional – local), which renders the prediction of future climatic conditions difficult.

Different climate processes become relevant depending on the considered timescales, which in turn also requires different ways of thinking on these vastly different timescales also in regards to nature and extent of uncertainties.

Nevertheless, some challenges apply to both types of timescales and all processes: Climatic processes are highly coupled and depend on other processes and/or influence other processes. The assessment of the overall repository safety has to consider couplings and inter-dependencies of such processes, which accumulate uncertainties already attached to single processes.

The impact of climate-related processes on repository safety is largely influenced by site-specific characteristics (such as rock strata with different strength to withstand erosion) and the site-specific climatic evolution. Hence, before selection of a repository site, it is necessary to consider processes in a more generic way, which per se leads to larger uncertainty.

Relevant on all timescales and causing challenges is the accumulation of impacts from repeating events. Due to its complex nature compared to single events/processes the uncertainty is larger when considering such re-occurring processes over long(er) timescales.

Regarding short-term climate change mainly relevant to construction, operation and closure phases for repositories, changes in intensity and frequency of extreme events (such as heavy precipitation, droughts, wind gusts, storms), their impact on operational procedures and surface installations of repositories are uncertain to foresee especially due to unknown future (anthropogenic) CO_2 emissions and hence the further development of (anthropogenic) climate change. Thus, judging the relevance of these events for operational safety is very important but not straightforward.

Regarding post-closure periods, uncertainties remain regarding the timing of the onset, duration and the magnitude/extent of the next glaciation especially under consideration of different (anthropogenic) CO_2 emission scenarios as the future path of human action cannot be predicted.

Further uncertainties relating to glacial processes, such as impacts from mechanical load of glaciers and ice sheets possibly causing fractures, reduction of pore space in the underlying rock strata and increased load on the canisters. Glaciers cause strong morphological change at the glacier front and erosion (depth and location) in (formerly) glaciated areas. During transition times (i.e. de-glaciation) processes are less well understood and influence for example the surface water runoff from glaciers and groundwater recharge. Depending on location, a dry climate with very high temperatures may also have an impact on repository safety by changing the hydrogeological setting during interglacial states.

Uncertainties are also attached to permafrost, especially regarding the expectable depth of permafrost and the temperature at repository depth depending on the choice of climate model/future climate scenario and the processes of formation and the safety relevance of taliks.

Repeated sea-level changes are to be expected throughout assessment periods, which can lead to long-term flooding of a repository site depending on its location, salt water intrusion into the subsurface, isostatic adjustments which lead to changes in the pressure regime in the subsurface as well as changes to the hydrogeological conditions and watersheds, which may pose an influence on subrosion.

The relevance of uncertainties relevant mainly to post-closure safety depends largely on the waste inventory and the respective assessment period, site and host rock characteristics and the safety concept and design. Therefore, general statements regarding relevant processes, challenges and uncertainties are not always relevant to specific cases. Each radioactive waste disposal project needs to assess these questions for their own local characteristics in a more detailed sense.

Regulatory and policy changes will undoubtedly play a significant role. Additionally, technological advancements may aid in mitigating the impact of climate change.

Question 2: How could these challenges and uncertainties evolve over time, over all phases (Initiation, Site Selection, Site Characterisation, Construction, Operation, Closure) and in a long-term perspective?

Challenges and uncertainties related to short-term processes occurring at the surface are of high relevance during site selection if the demonstration of safety/safe operation for surface repositories and/or all surface installations is required for construction, operation and decommissioning of the disposal facility. During site selection and the subsequent site characterisation major steps have to be undertaken to reduce the vulnerability of surface installations to short-term hazards through planning of robust countermeasures as part of construction of surface installations.

Operational safety is of specific relevance as radioactive waste is/will be near humans (although exposure to workers is kept at a minimum) and the biosphere during the operational phase. Since short-term processes become less relevant after closure/ in the long-term, especially for deep geological repositories after dismantling of surface installations, related uncertainties become less relevant in a long-term perspective.

On the other hand, uncertainties (and their reduction) of long-term processes are of highest importance during the site selection phase in order to be able to select the site with the smallest (i.e. no harmful) impact on repository (safety). Uncertainties will decrease in subsequent phases, e.g. when a site is being characterised further or in the long-term perspective when future emissions are then known. However, uncertainties need to be small enough already during the site selection phase to decide on a site, which can provide the required safety during the site selection phase.

The challenge of data availability/sparsity evolves over time. There is more available data in the shorter term, as well as established projections up to around 2100 or 2300 (e.g. IPCC). However, beyond these timescales there are fewer data and projections, and increasing uncertainty. Very long-term projections may be more predictable due to the planetary-scale controls on climate but for climate projections on the few-hundred-to-ten-thousand-year scale, this is really challenging in terms of data and uncertainties.

Question 3: What are the main ways to manage these challenges and uncertainties?

In order to manage challenges and uncertainties, those have to be identified and characterised in a systematic manner. Clear documentation of the handling of uncertainties and their effects is required.

In some cases, uncertainties can be avoided or mitigated by e.g. defining site selection criteria and minimum requirements to ensure that any significant effects of (extreme) climatic events on the safety functions fulfilled by the disposal system can be excluded. In regards to glacial erosion and permafrost influence, this could be a required minimum depth of the repository / host rock below the surface in dependence of the expected maximum glacial erosion depth or permafrost depth, including additional

safety margins. Potential impacts on the repository and related uncertainties can potentially be mitigated through specific design requirements.

If avoiding or mitigating uncertainties is not (sufficiently) possible, other possibilities for reducing uncertainties by additional actions need to be identified, documented and enacted. Such possibilities are: research and development, where specific, safety-relevant questions are addressed by various research and/or development methods. Site characterisation to better describe a specific site which allows (e.g.) to use better defined input parameters in models. Scientific exchange, in a national and/or international context, with experts and the interested public, helps to manage challenges and uncertainties. Oftentimes stipulated by law or by ordinances, the consideration of unexpected scenarios/evolutions or even basing the safety case on those, is a possibility to manage challenges and uncertainties. If (repository) safety is demonstrated for less likely and unfavourable evolutions, identified uncertainties become less relevant.

Another way to manage uncertainty is to use a range of climate scenarios in safety assessments and to accommodate the range of outcomes in designs and management decisions. Use of low, moderate and high emission scenarios allows a range of possible future outcomes to be assessed. If safety of the facility can be demonstrated within this range of scenarios, this helps to reduce uncertainty in outcome. There is always residual uncertainty but the use of three scenarios is a reasonably manageable, yet robust approach. This permits some degree of quantification of processes which may impact the facility which can be engineered against.

Question 4: What could be your role(s) regarding the management of those challenges and uncertainties? Also, what could be the possible roles of other actors for that purpose?

WMOs are responsible for the identification and overall management of all challenges and uncertainties with a very good understanding of the overall repository system performance and the occurring processes. This means, they have to identify challenges and uncertainties relevant for repository and operational safety (based on WMO judgement), identify R&D needs to reduce those uncertainties and judge their importance for repository/operational safety. If the R&D needs are deemed relevant, it is the WMOs' task to procure R&D project partners and to finance related R&D projects. In order to do the above described, it is necessary to constantly monitor the state of the art of science and technology throughout the entire procedure and to react accordingly if the state of the art develops.

Furthermore, as part of the site characterisation phase (and regarding planning even before), WMOs need to develop and conduct exploration programmes to properly describe a potential repository site (often as part of a comparison between two or more sites). Furthermore, WMOs need to develop a robust repository system (through design and optimisation, based on the aforementioned R&D) and demonstrate its robustness in a transparent and reliable manner. The repository system needs to be robust against all processes deemed relevant and consider expected as well as unexpected evolutions. For surface facilities where the accepted inventory has an important safety function, waste acceptance criteria guide acceptance decisions.

Part of WMOs tasks is also the scientific exchange with experts and informing CSOs as well as to engage in the (scientific) exchange with the interested public.

In all tasks, WMOs need to keep their focus on implementation of the radioactive waste programme and on application to ensure operational and repository safety.

TSOs should supervise whether WMOs have conducted appropriate management measures in relation to uncertainties and identified challenges.

REs support WMOs in reducing uncertainties through R&D projects financed by WMOs. However, REs also enhance the state of the art of science and technology in general even if the subject is not directly relevant for operational or repository safety (fundamental research).

CS challenge the results/reports, give input to discussions and generally stay connected and involved the WMOs' work and outputs.

Question 5: To what extent are the topics of climate change impact on RW; connected to transparency and public participation?

Due to its extensive impact on all parts of life, climate change has become an omnipresent topic in professional and non-professional/private subjects. Climate change is perceived as a large risk to almost all aspects of life by the majority of people. Nevertheless, risk perception is highly subjective so that "large risk" would be quantified differently for every individual. Hence, deduced actions to minimize the impact of climate change differ largely – not just on an individual basis but for entire nations. Uncertainty related to anthropogenic emissions isn't a topic where uncertainty can really be reduced.

This general societal picture with a focus on short-term/anthropogenic climate change is carried forward to RWM.

These statements are essentially true for anthropogenic climate change on short-term timescales up to maybe a few hundred years. On the other hand, long-term climate change is much less connected to personal fear/risk perception. Hence, it appears that, for example, the concept of robustness, the multiple barrier system as well as the long timescales applied in RWM are not well known/not well understood in the general public.

Therefore, it is important for all RWM actors to transport clear information on different levels of detail to avoid further spreading of wrong information and the build-up of unnecessary worries. Existing questions need to be answered as thoroughly and openly as possible, in which also remaining uncertainties and challenges must not be hidden.

Question 6: What are, for the next steps, your main topics of interest to be considered and discussed?

Highly coupled climatic processes, which depend on other processes and/or influence other processes. For example flooding is influenced by climate change but is primarily a hydrological process. The impact of flooding is furthermore largely dependent on regional/local topography as well as human actions. Glaciations are the result of cold climate conditions, which per se do not necessarily pose a threat to the repository. The safety relevance from glaciations stems from the related processes of e.g., isostatic adjustments, (glacial) erosion, changes to hydrological regimes etc. The assessment of the overall repository safety has to consider couplings and inter-dependencies of such processes, which accumulate uncertainties already attached to single processes considered. Consideration of such accumulated uncertainties is not straightforward and no clear procedure is available.

Repeating events, for example, processes relevant on shorter timescales, such as storms, or long-term processes, such as glaciations, will re-occur many times during an assessment period. Whilst the first occurrence of such an event may not damage safety relevant features, the repeated occurrence may accumulate to damage. Due to its complex nature compared to single events/processes the uncertainty is larger when considering such re-occurring processes over long(er) timescales. It is unclear how to properly assess the accumulated effect and related uncertainty of such recurring events, even more so in combination with other coupled/climate-dependent processes.

Uncertainties in regards to changes in intensity and frequency of extreme events and their impact on surface installations are of high interest as the focus generally lies on long-term climate evolutions in most research works thus far.

As previously mentioned, climate change is a global problem so it is important that, for such relevant topics like storage of radioactive waste, the projections of future climate between the different organizations are compared. The national RWM programmes may have different solutions tailored to their specific needs but the projected climate should be, somewhat, comparable depending on location. This benchmark is, however, part of the EURAD-2 initiative.

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