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Executive Summary

This White Paper presents challenges and limitations regarding climate change issues in radioactive waste management (RWM) and presents a set of recommendations and proposals for actions to address identified gaps and limitations as a basis for the development of subsequent studies. This White Paper is the outcome of the EURAD-2 Strategic Study “Impact of climate change on nuclear waste management” (CLIMATE), which brought together experts and specialists from 23 organisations from 13 countries representing all colleges and civil society organisations to identify the significant challenges common to the respective National Programmes on this topic.

Climate change and the associated increase in extreme weather events affect *every* facility type in *every* country on *all* timescales relevant to RWM. Surface installations of deep geological repositories (DGR)s, pre-disposal and interim storage facilities, near-surface and surface repositories rely on infrastructure and equipment threatened by climate extremes. Similar disposal concepts across Europe imply shared vulnerabilities to natural climate variations and anthropogenic climate change. Natural and engineered barriers show sensitivity to water-table changes, dry-wet cycles, freeze-thaw cycles, and erosion. For all climate zones and facility types, similar constraints were encountered, including inadequate spatial and temporal resolution of climate data, limited site- and facility-specific characterisation data, knowledge on timing, magnitude and rate of climate-related processes, challenges in modelling interdependent events and cascades, as well as a scattered landscape of methodological approaches and regulatory frameworks.

The overarching way forward therefore focuses on better understanding of climate change impact over all timescales up to one million years through coordinated Research and Development (R&D) and methodological innovation across partner countries. The recommended R&D and adaptation will substantially strengthen the resilience of construction, operation, and long-term post-closure management of RWM facilities. By combining improved data foundations, advanced modelling, targeted engineering upgrades, continuous monitoring and interaction with civil society, the RWM community will be better positioned to demonstrate robust climate resilience to regulators and stakeholders. Proactive adaptation will reduce long-term operational risk, avoid expensive redesigns, ensure worker safety, and safeguard repository integrity under evolving climatic conditions. This coordinated approach will also promote harmonisation across European programmes, contributing to consistent and defensible safety cases for all facilities.

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1. Introduction

Within the framework of EURAD-2, the Strategic Study "Impact of climate change on nuclear waste management" (CLIMATE) brought together experts and specialists from 23 organisations from 13 countries representing all colleges and civil society organisations to identify the significant challenges common to the respective National Programmes on this topic. As key outcome of this work package (WP), this White Paper presents challenges and limitations regarding climate change issues in radioactive waste management (RWM) and presents a set of recommendations and proposals for actions to address identified gaps and limitations as a basis for the development of subsequent studies.

The topic of climate change impact on RWM aligns with multiple knowledge domains of the EURAD Strategic Research and Knowledge Management Agenda (SRA; EURAD Bureau, 2023). Primarily, it addresses EURAD goal breakdown structure (GBS) domain 4.3.2 *Climate change* (Enhanced treatment of climate change, land-use and parameter derivation in biosphere models). In this context, the SRA calls for enhanced understanding of site evolution (landscape, hydrology, biosphere) at several spatial and temporal scales for the different disposal types.

Across Europe, RWM programmes rely on a spectrum of facility types, including pre-disposal, interim storage, surface and near-surface repositories, as well as deep geological repositories (DGRs), each with long planning horizons and operational periods typically spanning 100 years or more and assessment periods of up to 1 million years. Climate change introduces hazards and perturbations affecting all facility types for all waste types, in all climate zones and on all relevant timeframes. Although transport infrastructure is expected to be impacted by climate change in similar ways, it is not considered in the Strategic Study CLIMATE due to its extensive geographic extent in comparison to localised facilities. Increased frequency and intensity of extreme weather events, changes in temperature and precipitation patterns, sea level fluctuations, as well as long-term geological and hydro(geo)logical changes may affect safety functions, including natural and engineered barriers, in varying and not always well-understood ways. This problem is further aggravated by interdependent sequences of events, which lead to a possibly non-linear aggregation of related risks. Existing legal frameworks and currently applied methods to incorporate climate induced hazards and perturbations into safety assessments for RWM vary greatly in degree of detail and across different European countries. This fragmented landscape of regulatory guidance and methodological approaches arises from multiple limitations and uncertainties, resulting in diverse ways of incorporating climate-induced impacts on RWM into national programmes. Climate change aspects in RWM have mostly been addressed on a country-level, at least in the case of advanced programmes, and less on a continental or even global scale.

Potential solutions to these challenges include early mitigation and adaptation measures to improve RWM facilities to withstand short-term climate-related hazards. Recommended research and development (R&D) activities may also improve data availability and validation, better understanding of (long-term) climate processes, more detailed hazard characterisation and uncertainty reduction, as well as methodology development and harmonisation between practices applied in various member states. Interactions with civil society will also contribute to reinforce safety, notably by integrating societal concerns in the development of potential solutions.

Unless otherwise stated, all information presented in this White Paper are direct outcomes of the WP. Rationale, methodology and detailed outcomes of the strategic study are summarised in the Synthesis Report on Climate Change Impacts on Nuclear Waste Management Facilities (D11.2).

2. Challenges

Climate risk assessment for radioactive waste disposal facilities encompasses complex interactions between physical climate hazards, facility exposure, and system vulnerability across Europe. Depending on location, facility type and phase of facility development, climate effects can include heavy rainfall, heatwaves and extreme temperatures, cold spells and (wind)storms possibly leading to hazards such as flash floods, river flooding, coastal flooding, sea-level rise, water-table variations, droughts, wildfire exposure, soil erosion, landslides. These even occur as sequences of interdependent hazards, e.g. heavy and/or prolonged rainfall increasing recharge and groundwater levels, and in some cases also causing river flooding, which together may lead to partial or full repository saturation. Over longer periods of time of up to 100,000 years, climate risk assessment for radioactive waste disposal systems needs to include an evaluation of significant alterations and/or perturbations in the geological, hydro(geo)logical and geomorphological environment. In principle, the basic climatic processes are well understood (Marcos and Liakka, 2026). However, due to couplings of processes and cascading effects, large uncertainties regarding future anthropogenic greenhouse gas (GHG) emissions and the resulting effect of future climatic changes, safety analyses and impact assessments for RWM facilities are not straightforward. Identified limitations highlight insufficient and/or inadequate data, limited understanding of processes and their representation in models, as well as inconsistent methodologies and regulations.

Data-related gaps include the total absence of required data or insufficient temporal and/or spatial resolution of existing data. On top of being rarely produced, projections beyond 2100 have low confidence, especially for long-term hydro(geo)logical and geomorphological impacts due to reliance on extrapolated or generalised projections. For several specific processes, detailed impact assessment requires climate data at spatial resolutions of kilometres to meters and temporal resolutions of hours to minutes, substantially finer than current regional climate model outputs. Whilst understanding of paleoclimate records is used in model calibrations, climate impact models are typically calibrated and validated using recent historical observations only. Natural and historical analogues as well as paleo-records provide valuable qualitative insights necessary for model validation, but in some cases, the lack of sufficiently extensive quantitative data may be an obstacle.

Relating to EURAD GBS sub-theme 4.1 *Site description*, and 6.2 *Site investigation and confirmation*, site-specific measurements, including soil hydraulic properties, groundwater monitoring, and local climate data often exhibit spatial coverage limitations or short record lengths, insufficient for calibration and validation of detailed models. Extrapolation from regional monitoring stations to facility locations introduces additional uncertainty. This issue is even more problematic for extreme conditions, as few facilities maintain comprehensive monitoring during extreme climate events, providing empirical vulnerability data. Data requirements for extreme value analysis often exceed available observational monitoring record lengths, particularly for regional climate models. Such limited availability of validation data for testing model predictions under extreme conditions reduces confidence in projections.

Limitations related to process understanding and representation in models highlight the limited predictability of human impact on climate, the failure to consider coupled events and simplified assumptions about ice-sheet and climate behaviour in current climate models. Existing climate models provide valuable insights into such long-term climatic trends. Current climate projections assume that, beyond approximately 2300-2500 CE, humans will cease to alter the climate significantly (Meinshausen et al., 2011). However, this assumption is recognised as a major source of uncertainty.

Detailed modelling of coupled (or interdependent) events involving multiple coincident climate hazards requires multivariate statistical analysis and physically based process coupling, challenging current capabilities. Limited theoretical or empirical basis exists to assess how global climate change affects interdependencies between climate variables, although it is expected that the magnitude of climatic events will change. Cascading risks propagating through interconnected facility systems require integrated modelling spanning multiple physical domains (hydrology, structural mechanics, thermal processes, electrical systems) with different temporal and spatial scales. Computational challenges and interface complexity between models limit comprehensive cascade assessment. Other major limitations include coastal processes, such as storm surge, wave dynamics, coastal erosion, and contributions to sea level rise from melting land-ice, which are currently incompletely coupled to climate models. Additionally, complex non-linear feedbacks in snow and ice processes are not accurately represented in climate models, resulting in significant variation in model predictions of snow depth, snowmelt timing, and soil freezing, as well as the configuration of future ice-sheets, which is of highest importance to the nordic countries and northernmost parts of mainland Europe (e.g., Posiva, 2021; Liakka & Näslund, 2025, Chapter 4)

Statistical and dynamical downscaling introduce additional uncertainty in projections and often rely on assumptions about scale relationships with limited empirical validation. When using climate data for hydrological or erosion modelling, describing only the average climate state with monthly temperature and precipitation is inadequate. Modelling tools that allow taking perturbations into account are needed to create realistic meteorological time series suitable for process-based simulations. In addition, sea-level rise projections remain highly uncertain and strongly depend on cumulative GHG emissions assumed in the scenarios although generally sea-levels are currently rising and continued increase is expected for several centuries to millennia (Fox-Kemper et al., 2021).

Climate impact assessment and modelling is closely linked to site evolution. Natural analogues, especially from the Arctic, provide a better understanding of cold-region processes (e.g., permafrost-groundwater interactions), but analogues for extended global warming and future interglacial scenarios have not been identified and studied so far. Specifically, at process level they could provide crucial information for conceptual understanding needed for modelling. These could include, for example, deep groundwater responses to extended meteoric or marine water infiltration or land stability and erosion topics.

Touching on EURAD GBS domain 3.4.1 *Engineered Barrier System* (EBS), climate stressors (e.g., higher temperature, higher overall and/or more intense precipitation) and their potential future intensification have been identified to heavily impact barrier material performance (especially bentonite, concrete, multi-layer covers for surface or near-surface facilities). In some cases, material-related limitations have been found and concern the insufficient knowledge of material behaviour under certain climate stressors and particularly of multiple stressors. Experimental and natural analogue studies are required to close the gaps in some material performance questions and extrapolate the data sets for long-term performance, which requires the choice of realistic climate stressors and their potential future evolution.

Screening methodology-related gaps described in this WP include the lack of inclusion of interdependent sequences and cascading risks, as well as temporal dynamics in hazard screening methods and the subjective component to scoring the relevancy of risks. Furthermore, classification-based description of climate states (e.g., Köppen climate types) limits the power of risk evaluations, as changes in precipitation or temperature (average climatic parameters) do not always correspond to meaningful class transitions. This allows the identification of general risks but cannot capture extreme events, short-term variability, or local-scale phenomena, which are required for the assessment of site-specific risks.

Legacy facility documentation, particularly for older facilities and mining residues (e.g., uranium tailings, Naturally Occurring Radioactive Materials (NORM)/radioactive materials, open pit bentonite mines) varies in completeness and accessibility, complicating vulnerability assessment of existing infrastructure. Facility documentation-related limitations describe the absence of clear documents of facility properties and construction details of already existing infrastructure, including drainage system capacities, structural design margins, material specifications, and emergency systems and hence, the problematic estimation of whether such facilities can withstand future climatic change. Additionally, regulatory frameworks typically require demonstrated compliance with quantitative safety criteria, potentially challenged by large uncertainties in climate risk assessment. Safety cases must convincingly address "what if" scenarios, including climate change impacts, but uncertainty ranges may span orders of magnitude for some risks. Regulatory precedents and guidance for climate change integration into nuclear safety assessment remain evolving.

Safety impacts of climate change during the construction and operational phase include potential effects on infrastructure and equipment, as well as on natural and/or engineered barriers. The performance of natural and engineered barriers can be affected by drastic changes in thermal and/or hydrological conditions. For example, when the combination of rain intensity, rain duration and orography leads to increased infiltration and water table rise, leachate generation, humidity and corrosion can occur. Additional safety impacts stem from accelerated degradation of clay-based barriers due to more extreme and/or more frequent cycles of dry and wet conditions. Heatwaves can cause overload of Heating, Ventilation and Air Conditioning (HVAC) systems, leading to reduced cooling efficiency. Wildfires threaten external structures and vegetation, which serves as erosion protection, in turn leading to potential damage of multi-layer covers or other engineered barriers on the surface. **Safety impacts during the post-closure phase** differ by repository type: For deep geological repositories these can include altered host-rock properties and engineered barrier components due to changes in the biosphere, hydrosphere and geosphere caused by e.g., glacial loading and erosion, modification of groundwater flow dynamics (underneath ice-sheets, under permafrost conditions, under global warming, under marine inundation), and terrestrial and marine erosion. For surface and near-surface disposal systems, safety impacts mostly relate to, given the shallow depth, erosion (marine erosion for coastal sites and terrestrial erosion for others), barrier degradation and modification of groundwater dynamics.

Operational impacts across all RWM facility types align with general impacts of climate change on (critical) infrastructure and relate to EURAD GBS Sub-theme 5.4 *Operational safety*. These include, dependent on location, access disruptions from e.g. storms, snowmelt events or flash floods, reduced operational efficiency due to overheating of equipment, exceedance of drainage and personnel safety limits leading to temporary shutdowns. Reduced operational efficiency or shutdowns impact timing and costs.

Time impacts include delays in construction during extreme events, potentially extended licensing times if groundwater and climate modelling remain incomplete or new information must be incorporated. Maintenance cycles may have to be shortened, such as the potentially more frequent need to restore the surface cover layer if loss is detected due to enhanced erosion in surface or near-surface disposal.

Cost impacts include consequences from prolonged time requirements as well as larger expenses for reinforcement, replacement or upgrades to protection systems, infrastructure and equipment and higher operational expenditure from more frequent inspections, vegetation management or emergency interventions.

A better understanding of the impact of climate hazards and a common strategy to integrate those into safety cases needs to be addressed through harmonised R&D because their impact on safety is very significant, with additional impacts on operation, time and cost. In some countries, regulators require climate resilience, while others increasingly expect non-stationary climate analysis. So far, it is not sufficiently described how to incorporate climate-related aspects and their potential impact in RWM safety cases. Addressing this common challenge now would enhance public trust in long-lived disposal solutions, as this requires demonstrable resilience over many decades. Transparency and involvement of publics on safety issues are necessary conditions to ensure trust in RWM processes. Although, different climate hazards are of different importance in different climate zones, cross-climate zone knowledge transfer will allow to create a shared European benefit to address this common challenge together, as coordinated methodologies strengthen consistency, harmonisation and defensibility.

3. Proposed way forward

3.1 Near-Term R&D Priorities (3–5 Years)

The analyses demonstrate that climate-related hazards already affect and will increasingly influence the construction, operation and long-term safety of all RWM facilities across Europe. The overarching way forward therefore focuses on better understanding of climate change impacts on all timescales up to one million years through coordinated Research and Development (R&D) and methodological innovation across partner countries. Aside from R&D needs, especially for existing facilities, early engineering adaptation measures aligned with climate change adaptation measures for all (critical) infrastructure could be implemented promptly, depending on facility characteristics and local climatic and topographic conditions. Such measures directly reduce operational disruption risk and provide immediate and long-term safety benefits. Another near-term priority, in cooperation with respective national weather services, is to expand real-time, site-specific monitoring of rainfall, groundwater, soil moisture, temperature, wind intensity, and coastal water levels as well as to implement or re-evaluate early-warning triggers (e.g., rainfall intensity thresholds, heat-stress metrics). Across all facility types, a major priority for construction, operational and initial post-closure phases, is to implement comprehensive site characterisation programs, filling critical data gaps, establishing long-term high-resolution monitoring networks tracking facility performance, climate parameters and conditions (including extremes) as well as hazard projections. In this way centralised databases integrating engineering, geotechnical, hydro(geo)logical, and operational information supporting modelling and decision-making are to be created. Downscaled climate datasets must be refined to produce updated intensity, duration and frequency (IDF) curves for extreme rainfall, high-resolution thermal projections, and more robust river/coastal flooding scenarios. Convection-permitting (1–4 km) climate models may be developed for rainfall, thunderstorms, windstorms, and interdependent events.

In low-lying or coastal sites, early evaluation of sea-level rise combined with storm surge is required. For regions with limited existing data or ongoing site selection, targeted data acquisition is essential to reduce current screening uncertainties. Method development is needed for uncertainty quantification in downscaled products. Building on screening results, detailed assessments should prioritise the most pressing hazards: heavy rainfall and pluvial/river flooding, heatwaves, droughts, water-table variations, erosion, infiltration and coastal flooding/sea-level rise where relevant. Site-specific hydrodynamic modelling, thermal analyses, infiltration tests, groundwater models, as well as multi-criteria risk matrices and multivariate statistical methods for interdependent event analysis under non-stationary conditions should be developed to quantify thresholds for operational failure. These analyses will provide a technical basis for adapting layout, drainage capacity, cooling loads, and worker protection protocols.

Detailed vulnerability mapping should be undertaken to identify components most sensitive to climate stresses (e.g., drainage systems, ventilation and cooling systems, engineered surface covers). This should be performed for existing facilities as well as planned future facilities. For low-lying sites (<30 m a.s.l.), a complete marine inundation over several 10,000 years cannot be excluded. Therefore, potential impacts of marine and estuarine erosion and saline water intrusion into disposal cells of surface and near-surface repositories should be explicitly assessed, including the use of data obtained from natural analogues, if and where available, or general observations from similar natural environments. This information will allow implementers to prioritise R&D, maintenance, and design modifications.

More extensive experiments (laboratory tests), supplemented with modelling exercises and potential analogue studies, need to further evaluate (barrier) material characteristics under multiple climate stressors and over extended time periods to better understand material degradation under climate stress, for example: bentonite hydration and concrete cracking under recurring heat/drought conditions, thermal cycling or freeze-thaw/permafrost and ice-sheet loading, EBS sensitivity to hydrogeochemical and thermal changes.

Waste Management Organisations (WMOs) lead local Features, Events, Processes (FEP) identification (for example according to NEA (2024)), hazard analysis, design development and integration as well as operational planning and adaptation. Research Entities (REs) develop models, run laboratory programmes, and refine methodologies. Technical Safety Organisations (TSOs) and regulators clarify expectations prior to licensing regarding climate-resilient design and inclusion of climate processes in long-term safety assessments in the Safety Case. Meteorological and hydrological services provide advanced datasets and flood/heatwave projections. Civil society representatives develop and adapt tools of dialogue to enable pluralistic discussions, including different types of publics.

Expected benefits within three to five years include substantial uncertainty reduction in hazard characterisation and early identification of vulnerabilities in drainage, cooling, covers and EBS components. In addition, improved regulatory readiness will lead to defensible early safety cases, including the post-closure phase of near-surface, shallow and deep geological repositories; avoidance of costly reactive redesigns and operational interruptions; enhanced workforce safety and reduced exposure to heat or storm-related hazards. Although these should be near-term priorities, they are expected to be continued well beyond the timeframe set out here for maximal benefit.

3.2 Long-Term R&D Priorities (10–20 Years)

Fully integrated terrestrial, coastal and hydro(geo)logical models might be developed for facilities exposed to sea level rise, storm surge, river flooding or complex groundwater dynamics. For the near-field, integrated models would couple hydrochemical, erosional and infiltration processes. These models should represent non-linear interactions (e.g., between flooding and erosion, between heatwave and drought) to anticipate upper-bound scenarios for facilities on or near the surface, in order to maximize safety margins. An extensive observational network, including past conditions from paleo-records, is required to provide detailed baseline data for the evaluation of such models. Since threats from extreme weather events are not unique to RWM but impact public safety through significant disruption and damage to infrastructure, agricultural productivity, and natural ecosystems, research initiatives may be formed with other actors to leverage synergies.

Most existing (natural) analogues and models emphasise cold or glacial climates, leaving high-temperature and high-precipitation scenarios underrepresented. Expanding analogue research to include warm-climate analogues would improve the completeness of long-term safety assessments. Continued methodological refinement, inclusion of updated emission pathways, better integration of local processes and cascading or sequential events are essential to reduce uncertainties in future climate scenario development. Further improvements of long-term modelling may be required to develop local models instead of global models and to incorporate possible cooling scenarios (e.g. slowing or collapse of the Atlantic Meridional Overturning Circulation (AMOC) possibly within this century (e.g., Lohmann and Ditlevsen, 2021; Ditlevsen and Ditlevsen, 2023), influence of Milankovitch cycles). Additionally, models should represent hydroclimatic variability more accurately, such as running coupled climate–hydrogeological models to simulate recharge, groundwater heads, and flow regimes. Researching natural analogues and inquiring paleo-records is required to benchmark processes such as erosion, infiltration, and weathering under analogue climatic conditions.

Long-term material and barrier performance research is required to address limitations identified regarding EURAD GBS domain 3.4.1 *EBS system*, where currently applied extrapolation beyond experimental data ranges and the lack of consideration of multiple (climatic) stressors are not sufficient to properly assess degradation mechanisms of barrier material on timescales relevant for waste facilities. Research activities investigating long-term durability of engineered barrier materials under future climate conditions need to also consider combinations of climatic stressors. As these are at least partially location- and facility-specific, R&D efforts might be required to determine sensible choices of climatic stressors to best reflect likely future climatic conditions at the given location and over the relevant timescales. Accelerated ageing tests and multi-decadal performance thermal-hydraulic-mechanical-chemical (THMC)-models should inform maintenance cycles, replacement strategies, and updated barrier designs. This requires investments in experimental facilities enabling controlled testing of components under various climate conditions, including extreme conditions and monitoring programs at operational facilities and test covers providing empirical data on actual long-term performance, informing model improvement. Experiments and modelling may be supplemented by studies of well-characterised natural analogues with comparable climate, vegetation, hydrogeology, and substrate conditions. Natural analogues, and paleo-records, can be seen as unique long-term natural laboratories for RWM, and should be included in safety assessments and safety cases. R&D on climate change impact on RWM should make use of advanced digital tools, including digital twins where appropriate, to benefit from these emerging possibilities.

R&D activities are needed to develop adaptive, climate-resilient engineering solutions. Future designs should move beyond incremental adaptation toward fully climate-optimised infrastructure. Examples include redundant drainage networks, elevated or flood-resistant surface structures, sea-level rise-adaptive berms, heat-resistant vault and cover materials, modular cover layers with planned renewal, or redesigned layouts that minimise exposure to flood pathways. For interim storage, adaptive flood defences or even strategic relocation of susceptible auxiliary systems may be required. By integrating real-time monitoring data, improved climate projections and structural/thermal models, digital twins will enable predictive maintenance, optimisation of inspection intervals, rapid detection of anomalies, and scenario-based stress testing. Digital twins facilitate evidence-based decision-making, particularly for long-term service life management of vaults, covers, drainage networks, and cooling systems.

REs and universities lead the development of high-resolution models, barrier science, and digital twins. WMOs prioritize R&D needs, incorporate results into safety analyses and implement engineering upgrades, long-term monitoring and adaptive management. TSOs and regulators update frameworks, incorporating advanced climate science and multi-hazard complexity. European and international bodies (e.g., Copernicus Climate Change Service (C3S), European Centre for Medium-Range Weather Forecasts (ECMWF), International Atomic Energy Agency (IAEA), European Commission (EC) Joint Research Centre (JRC), Nuclear Energy Agency (NEA)) coordinate shared R&D and standards. Expected benefits within 10 to 20 years include climate-resilient design across all repository types and timeframes; strong confidence in long-term barrier performance and operational continuity; significant lifecycle cost savings through predictive maintenance and reduced emergency interventions; harmonised European standards and improved regulatory efficiency; increased public trust through transparent, science-based climate adaptation strategies.

Applicable to the entire range of climate hazards and impacts, timeframes, waste types and disposal concepts, regulators should progressively adopt non-stationary design requirements, multi-hazard frameworks, criteria for uncertainty acceptance, and periodic climate-scenario update cycles. Tailored guidance documents should distinguish between surface and deep facilities, defining timeframes, data requirements, and acceptable uncertainty thresholds. Development of harmonised methodological approaches, including inter-comparison frameworks assessing model performance and data validation, and requirements across nations (European Union (EU), IAEA, NEA), is essential to ensure consistent standards across similar disposal concepts and to facilitate efficient licensing and safety-case updates. As long-term projection uncertainties will never be fully overcome, recommendations include developing scenario-based assessment frameworks acknowledging deep uncertainties. Further recommendations emphasise adaptive management approaches enabling course correction as conditions evolve, understanding improves and designing inherently robust systems less dependent on accurate long-term prediction.

The proposed R&D and adaptation strategy will substantially strengthen the resilience of construction, operation, and long-term management of RWM facilities. By combining improved data foundations, advanced modelling, targeted engineering upgrades and continuous monitoring, the RWM community will be better positioned to demonstrate robust climate resilience to regulators and stakeholders. Proactive adaptation will reduce long-term operational risk, avoid expensive redesigns, ensure worker safety, and safeguard repository integrity under evolving climatic conditions. This coordinated approach will also promote harmonisation across European programmes, contributing to consistent and defensible safety cases for all facilities.

4. Call to Action

All RWM facilities, in every climate zone, are affected by climate-related processes and climate change on a variety of relevant time scales. Increased intensity, duration and frequency of extreme weather events, changes in temperature and precipitation patterns, sea level rise as well as long-term geological and hydro(geo)logical changes affect and potentially threaten the safety of infrastructure, equipment and personnel as well as the long-term safety functions of natural and engineered barriers. Whilst the future evolution of climate and climate change cannot be predicted precisely, several possible future evolutions of climate and climate change can be modelled. However, the impact on RWM infrastructure of climate-related processes and events as well as changes in their temporal and spatial patterns and interactions between various factors is not fully understood. Additionally, regulatory frameworks and methodological approaches to risk assessments and integration into safety cases vary greatly among member states.

The presented solutions to the challenge of incorporation of climate change issues into risk assessments and safety cases are multi-dimensional and include early mitigation and adaptation measures to improve current infrastructure, harmonised R&D efforts to improve data availability, climate process and hazards characterisation and uncertainty reduction, as well as methodology development and harmonisation between practices applied in various member states. This includes methodologies for enabling pluralistic interactions and the transfer of knowledge with different types of publics.

In view of the need for harmonisation of European practices, consistent, scientifically robust and efficient assessment of climate-dependent impacts on RWM facilities, thereby improving safety, comparability, stakeholder communication and cross-border cooperation, is required as a short-term priority. Joint R&D efforts are required to reach such a harmonised European framework, including safety guidelines and a climate database for better understanding and quantification of climate-related processes (including extreme conditions/events) to support consistent and criteria-based selection of climate scenarios in safety assessments for RWM. Consensus-based climate states and scenarios, safety margins and design and selection criteria for disposal systems are expected to be supportive of safety cases and will facilitate transparent communication of climate-dependent uncertainties and future performance of disposal systems, including civil society engagement. Although necessary harmonisation of approaches is emphasised, additional modelling and experimental/field studies may be required to produce representative case studies as exemplary tests for the database and developed guidelines.

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Appendix A. Keywords

Climate Change; Radioactive Waste Management; Impact Assessment; Process Understanding; Surface Repository; Near-Surface Repository; Deep Geological Repository; Operational Safety; Long-Term Safety; Hazard characterisation; Site-specific modelling; Barrier performance; Multiple climate stressors; Natural analogues; Climate proxies

Appendix B. List of acronyms and abbreviations

AD	Anno Domini
AMOC	Atlantic meridional overturning circulation
a.s.l.	above sea level
CE	Common Era
DGR	Deep Geological Repository
EBS	Engineered Barrier System
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EU	European Union
EURAD	European Partnership on Radioactive Waste Management
FEP	Features, Events, Processes
GBS	Goal Breakdown Structure
GHG	Greenhouse gas
HLW	High-Level Waste
HVAC	Heating, Ventilation and Air Condition
IAEA	International Atomic Energy Agency
IDF	Intensity, Duration, Frequency
JRC	Joint Research Centre
km	Kilometres
m	Meters
NEA	Nuclear Energy Agency
NORM	Naturally Occurring Radioactive Materials
RE	Research Entities
R&D	Research and Development
RWM	Radioactive Waste Management
SF	Spent Fuel
SRA	Strategic Research Agenda
THMC	Thermo-Hydraulic-Mechanical-Chemical
TSO	Technical Safety Organisations

WMO	Waste Management Organisation
WP	Work Package