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ARBEITSBERICHT NAB 24-08 Rev. 1

Radiological Consequences of Deep Geological Repository Excavation by Erosive Processes

September 2024

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KEYWORDS
Post-closure safety, radiological consequences, repository excavation, general licence application, safety assessment, safety case

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

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An earlier version of the report was reviewed and commented by Prof. Ramon Arrowsmith (Arizona State University), Andreas Gautschi, and Piet Zuidema.

NAB 24-08, September 2024: Corrigendum

The results presented in this report were updated in September 2024 to reflect minor corrections to calculations that were identified in final checking.

Abstract

Nagra, the National Cooperative for the Disposal of Radioactive Waste, is responsible for the development and safe implementation of a deep geological repository for radioactive waste in Switzerland. The concept involves the disposal of low-, intermediate-, and high-level waste in a deep geological repository within a clay-rock formation (Opalinus Clay) at a depth of over 800 m. There, the disposed waste inventory will remain isolated from the surface environment, allowing radionuclides to decay, significantly reducing their radiological hazard down to a level where it is of no significant concern.

In the very long term (10^6–10^7 years), uplift and erosion by both glacial and non-glacial processes may bring the repository closer to the surface, potentially resulting in the excavation of repository material. In its guidance related to deep geological disposal in Switzerland, ENSI requires assessment of potential dose consequences of repository excavation scenarios in the very long term.

Assessment calculations have been undertaken to explore potential dose consequences of repository excavation scenarios. These have separately considered excavation by deep glacial erosion and non-glacial erosion.

- Assessment of deep glacial erosion considers an overdeepening directly impacting the repository and transporting excavated material to the near-surface region and surface, with a range of post-glacial landscape settings.
- Assessment of non-glacial erosion considers the emergence of what remains of a repository below a valley or in a hillside setting, with a range of erosion rates and valley geometries and the subsequent dispersal of that material by hillslope or fluvial processes.

A compartment-modelling approach is used to represent the distribution of material excavated from the repository, subsequent radionuclide release, transport and potential exposure. The exposure assessment assumes that humans are present in the area local to the excavated material and make maximum use of that environment. The exposure-modelling approach is based on Nagra's established reference biosphere assessment modelling.

A range of potential excavation contexts has been studied, accompanied by sensitivity calculations to help identify important processes, parameters and assumptions. The assessment explores potential consequences of excavation over timescales ranging from 700,000 years to four million years after repository closure. These timescales span both early hypothetical and more plausible timescales for repository excavation.

Overall, the assessment demonstrates a degree of consistency in the potential dose consequences calculated across a wide range of different excavation settings. Both excavation by deep glacial erosion and by non-glacial erosion result in potential dose consequences that are lower than or comparable with the natural, current radiation exposure in Switzerland (approximately 1 – 13 mSv/a).

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List of Acronyms

BP	Before present
E2	Stage 2 (of the SGT)
E3	Stage 3 (of the SGT)
ENSI	Swiss Federal Nuclear Safety Inspectorate (*Eidgenössisches Nuklearsicherheitsinspektorat*)
FEPs	Features, events and processes
GIS	Geographic information system
HLW	High-level waste
JO	Jura Ost (siting region)
LGM	Last glacial maximum
L/ILW	Low- and intermediate-level waste
MEG	Most extensive glaciation
MIS	Marine isotope stage
NAB	Nagra work report (*Nagra Arbeitsbericht*)
NL	Nördlich Lägern (siting region)
NTB	Nagra technical report (*Nagra Technischer Bericht*)
RBG	General licence application (*Rahmenbewilligungsgesuch*)
SF	Spent fuel assemblies
SGT	Sectoral Plan for Deep Geological Repositories (*Sachplan geologische Tiefenlager*)
SwiBAC	Swiss biosphere assessment code
ZNO	Zürich Nordost (siting region)

1 Introduction

1.1 Context

In Switzerland, legal regulations (Nuclear Energy Act (KEG 2003) and Nuclear Energy Ordinance (KEV 2004)) and guidelines are in place for the management of radioactive waste. The Nuclear Energy Ordinance (KEV) classifies Switzerland's radioactive waste into low- and intermediate-level waste (L/ILW), alpha-toxic waste[1] (ATW) and high-level waste (HLW), the latter comprising spent fuel (SF) and vitrified HLW from reprocessing (RP-HLW). The Nuclear Energy Act (KEG) requires the disposal of all these types of radioactive waste in deep geological repositories. The feasibility of this disposal solution has been demonstrated for L/ILW in Nagra (1985) and for long-lived intermediate-level waste and HLW in Nagra (2002).

The Sectoral Plan for Deep Geological Repositories (SGT) regulates the search for suitable siting regions for deep geological repositories in Switzerland. This site selection process is conducted in three stages (BFE 2008). Stages 1 and 2 have already been completed and Nagra is currently in Stage 3 (SGT-E3). Clarifications on the safety-related specifications for this stage are provided in ENSI 33/649 (ENSI 2018), while ENSI Guideline G03 and the corresponding explanatory report (ENSI 2023, ENSI 2020) specify the protection objective, protection criteria and design principles for deep geological repositories.

In SGT-E3, three siting regions located in Northern Switzerland have been considered – Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) – with the objective of selecting one siting region for an HLW repository, one for an L/ILW repository, or one for a combined repository for all waste types.

Following a comparison of the three siting regions, Nagra concluded that NL is the safest and most flexible siting region and is therefore applying for a general licence for a combined repository for both HLW and L/ILW at the Haberstal site.

The justification for this selection and the safety demonstration for a repository at the site are submitted as part of the general licence application (RBG[2]). The reports relating to post-closure safety, shown in Fig. 1-1, are structured as follows:

- The overall safety-related argumentation, including post-closure and operational safety, is summarised in an overarching safety report ("*Sicherheitsbericht*") NTB 24-01 (Nagra 2025b) shown at the top of Fig. 1-1.
- The upper left side of Fig. 1-1 shows the reports supporting Nagra's site comparison. The available options are compared with respect to safety and technical feasibility, and the results are synthesised in NTB 24-03 (Nagra 2025a) ("*Bericht zur Begründung der Standortwahl*").
- The upper right side of Fig. 1-1 shows the reports documenting the post-closure safety case for the combined repository at the site, including its synthesis in the post-closure safety report NTB 24-10 (Nagra 2024h).
- The lower part of Fig. 1-1 shows a report that presents the safety and repository concept, including the provisional design, and reports providing the assessment basis.

[1] According to Nagra (2024a), ATW can coexist with L/ILW within the same emplacement caverns. As a result, for the sake of simplicity, the term L/ILW encompasses ATW without explicit mention.

[2] From the German *Rahmenbewilligungsgesuch*.

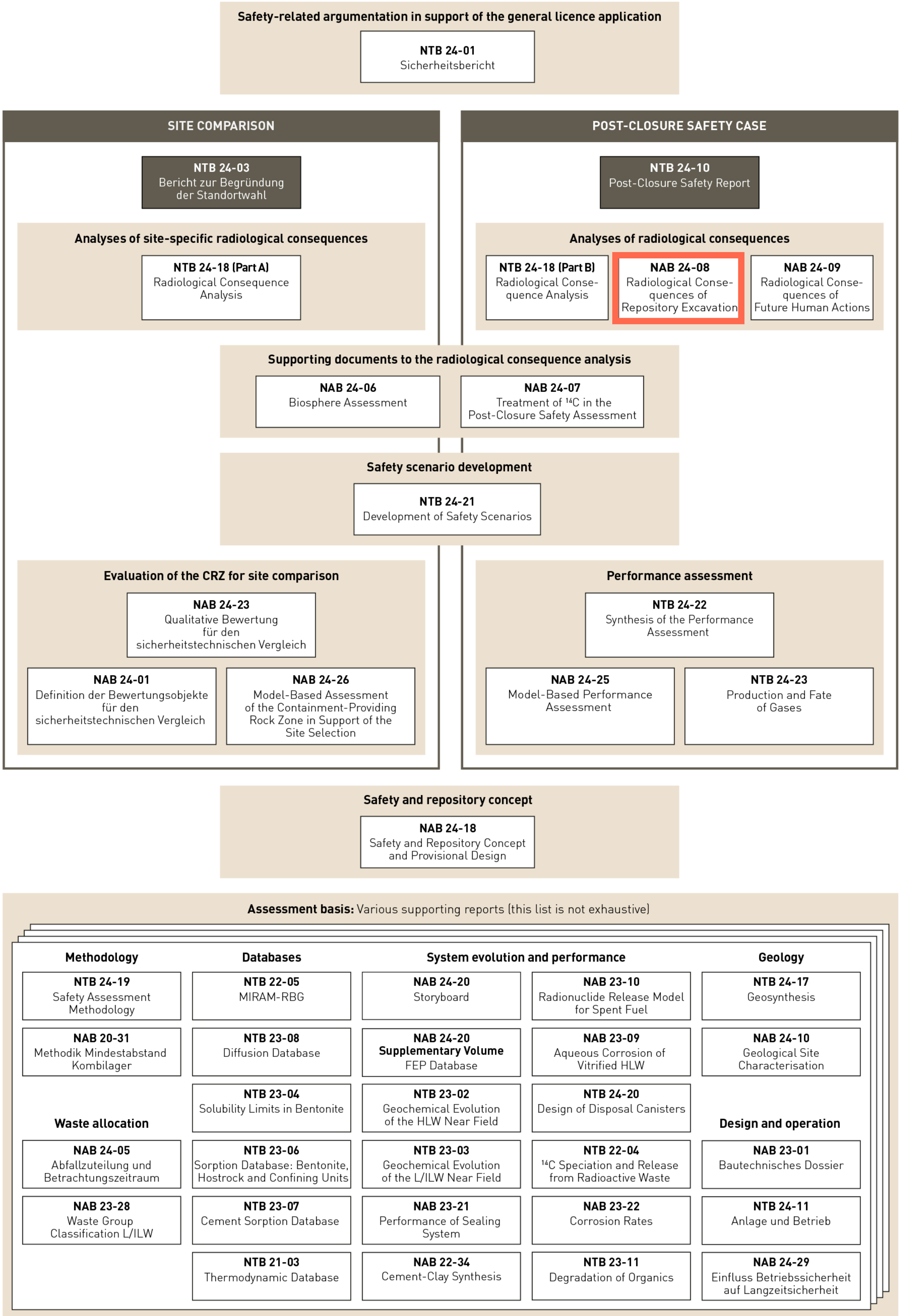

Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

The present report is bordered in red in Fig. 1-1 and is part of the analyses of radiological consequences in support of the post-closure safety case for the combined repository at the site.

The landscapes in the siting regions considered in SGT-E3 are continuously eroded by uplift-related fluvial incision and coupled hillslope denudation. These regional erosion processes result in downcutting. This will be intensified during future glaciations when glacial processes dominate erosion and so-called overdeepened valleys could be excavated. Northern Switzerland has a number of overdeepened valleys, where the total local erosion due to past glacial processes has been deeper than the regional erosion base. The current Nagra investigations of the present geological situation (Nagra 2024e) include scenarios for the future evolution due to erosion processes, detailed in NAB 24-15 (Nagra 2024d).

In the context of the site selection process, this knowledge is used to reduce the likelihood of the repository being impacted directly by future glacial erosion. However, uplift and erosion by both glacial and non-glacial processes may bring the repository closer to the surface, potentially also resulting in the excavation of repository material in the very long term (10^6-10^7 years).

This study evaluates the potential radiological consequences of two hypothetical safety scenarios for different points in time, in which erosive processes *excavate* the deep geological repository. The first safety scenario considers repository excavation by glacial processes, the second considers repository excavation by non-glacial processes.

1.2 Regulatory requirements and guidance

This section describes regulatory guidelines relevant for this work. The original ENSI guidelines were written in German. While an English translation exists for most of them, it is provided for information purposes only and has no legal force. For this reason, this section quotes the original German text of the guidelines and provides an English translation immediately below.

The investigation of the radiological consequences of repository excavation by erosion processes described in this report is explicitly required by the ENSI 33/649 guideline (ENSI 2018), which defines the following requirement for the site comparison:

> ENSI 33/649, Section 4.4:
>
> *Gemäss den Vorgaben der Richtlinie ENSI-G03 und den im Folgenden beschriebenen Präzisierungen und Ergänzungen haben die Sicherheitsanalysen für den Standortvergleich mindestens die folgenden Aspekte zu umfassen:*
>
> […]
>
> *f. Aufzeigen der radiologischen Konsequenzen von Freilegungsszenarien innerhalb des Betrachtungszeitraums (z. B. durch flächenhafte Erosion oder glaziale Tiefenerosion) und ihre Bedeutung für den Standortvergleich.*
>
> According to the requirements of ENSI Guideline G03 and the clarifications and additions described below, the safety analyses for the site comparison must include at least the following aspects:
>
> […]
>
> f. Illustration of the radiological consequences of exposure scenarios within the period under consideration (e.g. due to extensive erosion or deep glacial erosion) and their significance for the site comparison.

It should be noted that this guidance refers to the ENSI Guideline G03. This is further elaborated in the following section of the ENSI 33/649 guidance on the requirements on the approach to the assessment of the radiological consequences of repository excavation, which states that enveloping variants should be explored in accordance with ENSI Guideline G03:

> ENSI 33/649, Section 5.2:
>
> *Die Sicherheitsanalyse des Standortvergleichs (siehe Kap. 4.4) für den gewählten Standort wird entsprechend vertieft und mit umfassenden Szenarien- und Risikoanalysen gemäss Richtlinie ENSI-G03 ergänzt.*
>
> [...]
>
> *Die möglichen radiologischen Auswirkungen zukünftiger Entwicklungen sind durch umhüllende Varianten aufzuzeigen. Die radiologischen Konsequenzen von Freilegungsszenarien (bspw. durch flächenhafte Erosion oder glaziale Tiefenerosion) sind gemäss Richtlinie ENSI-G03 darzulegen.*
>
> The safety analysis of the site comparison (see Section 4.4) for the selected site will be expanded accordingly and supplemented with comprehensive scenario and risk analyses in accordance with ENSI Guideline G03.
>
> [...]
>
> The possible radiological impacts of future developments are to be demonstrated by means of enveloping variants. The radiological consequences of uncovering [excavation] scenarios (e.g. due to extensive erosion or deep glacial erosion) must be presented in accordance with ENSI Guideline G03.

The ENSI Guideline G03 (ENSI 2023) most importantly defines the modelling approaches, which can be used to address the investigations listed in ENSI 33/649 Section 4.4. These requirements are further clarified in the ENSI G03 explanatory report (ENSI 2020):

> ENSI G03 explanatory report, Section 9.3.1 c:
>
> *Allenfalls sind auch konservative Annahmen für die Wahl der Modellansätze und Modellparameter in die Berechnungen einzubeziehen. Dazu gehören auch Freilegungsszenarien und das unbeabsichtigte menschliche Eindringen. Bei der Modellierung von Szenarien können auch stilisierte Annahmen verwendet werden wie zum Beispiel die Biosphärenmodellierung.*
>
> If need be, conservative assumptions for the choice of model approaches and model parameters may also be included in the calculations. These include scenarios in which the repository is uncovered [exposed] and accidental human intrusion. Conventionalised [stylised] assumptions such as biosphere modelling can also be used when modelling scenarios.

It should be noted that this section explicitly mentions the use of stylised models as an acceptable methodology. Following this guideline, stylised modelling is employed in the present work.

Given the fact that the proposed repository is located more than 800 m below ground level, the repository excavation by erosive processes is not expected (Nagra 2024e). However, following the requirements set forth in the guidelines described in this section, the radiological consequences of repository excavation by erosive processes were anyway calculated (using stylised models), as required. These calculations are documented in this this report.

The evaluation of these results with respect to the protection criteria (as defined in ENSI Guideline G03, Section 4.3.2) is presented in the post-closure safety report NTB 24-10 (Nagra 2024h) by considering the probability of occurrence reported in the erosion report NAB 24-15 (Nagra 2024d). The impact of erosion processes on site comparison will be discussed in NTB 24-03 ("*Bericht zur Begründung der Standortwahl*") (Nagra 2025a).

1.3 Previous analyses of radiological consequences of erosion

This work builds on the knowledge from previous studies on this subject. Radiological consequences of a potential excavation of the repository by deep glacial erosion were calculated at the end of SGT-E2 and documented in Nagra (2016). The results of that analysis have been confirmed in this study.

Repository excavation by non-glacial erosion processes was previously considered as part of Nagra (2008b), which investigated the following three scenarios:

1. Model 1 considered a scenario in which the emplacement drifts are close to the earth's surface and below an aquifer, allowing the radionuclides to be released into the groundwater.
2. Model 2 considered a scenario in which the emplacement drifts are excavated by river erosion, with the waste material carried off by the river and deposited in a downstream accumulation area.
3. Model 3 assessed the consequences of a potential increase in the permeability resulting from the decompaction of the host rock caused by the erosion-induced decrease in cover.

Modelling of the excavation by non-glacial erosion processes is informed by an understanding of the long-term evolution of the local topography. For the Jura Ost siting region and its surrounding area, this was explored in Ludwig (2018). That work focused on the geographic information system (GIS) based mapping and analysis of the spatial distribution, controls, and effects of hillslope processes. The aim was to form the basis (both qualitative and quantitative) of future landscape evolution scenarios with an emphasis on local topography and hillslope processes in particular at a scale similar to that of the repository.

1.4 Organisation of this report

Excavation by glacial erosion processes and excavation by non-glacial erosion processes are treated as two separate safety scenarios[3]. Chapter 2 covers the aspects of long-term evolution that overlap in both repository excavation scenarios, including geological evolution, timescales for excavation, the long-term evolution of the repository system and the general basis for the assessments.

Chapter 3 evaluates excavation by glacial erosion processes and Chapter 4 evaluates excavation by non-glacial erosion processes. Both chapters follow the same structure, starting with a descripttion of the relevant geological processes (Sections 3.1 and 4.1), which are then collected into a storyboard (Sections 3.2 and 4.2). Afterwards, the storyboards are conceptualised (Sections 3.3 and 4.3), calculation cases to be investigated are identified (Sections 3.4 and 4.4), and the

[3] See NTB 24-21 (Nagra 2024b) for the full definition of safety scenarios and their development.

mathematical models capturing these assessments are defined (Sections 3.5 and 4.5). The data needed for the models are described in Sections 3.6 and 4.6. Finally, the results are presented in Sections 3.7 and 4.7.

An overall discussion of the results and the report conclusions are presented in Chapter 5.

2 Long-term evolution towards excavation

This chapter describes components of the study that are relevant for both repository excavation scenarios. Section 2.1 describes the geological evolution, which eventually leads to repository excavation, identifying excavation by glacial erosion processes and excavation by non-glacial erosion processes. Section 2.2 then defines for which points in time the assessment is performed. The long-term evolution of the repository system is then discussed in Section 2.3. The general basis for the assessment is then presented in Section 2.4.

2.1 Geological evolution leading towards excavation

Long-term geological evolution and the detailed description of erosion processes can be found in NAB 24-15 (Nagra 2024d); this section offers a concise summary as context for the present work.

The Quaternary climate history in Northern Switzerland was dominated by a succession of glacial and interglacial cycles. These changes, together with uplift of rock of variable erodibility, caused by neotectonic activity and/or isostatic compensation to mass redistribution by glacial loading/unloading, glacial erosion or other erosive processes, have shaped the present-day landscape of Northern Switzerland. These processes and their relations are expected to drive the geological evolution of the region in the future as well. The main erosional processes involved are the combined action of rivers, especially the drainage evolution of the Aare – Rhine river system (defining the local erosion base), as well as erosion and sedimentation by repeated large foreland glaciations. Depending on the erodibility of the substratum and the local erosive power of a glacier, (sub)glacial erosion processes can erode several hundreds of metres below the river system within a relatively short time. Fluvial incision and deep glacial erosion processes in turn define the pace at which hillslopes respond. Slope stability tracks fluvial and glacial base-level controls on topographic slope and shallow hydrology-driven mass movements. Thus, the channel-hillslope coupling drives non-glacial denudation of the topography.

Most of Northern Switzerland is characterised by a low-relief landscape and low erosion rates. Fluvial channels and extended terrace systems define the postglacial terrain. The oldest glaciofluvial deposits are only preserved as relicts, and the younger ones follow a continuous and traceable fluvial network. Thus, the time needed to organise the landscape substantially, based on this observation, could be in the order of several hundred thousand years. During this time, the fluvial network is expected to change slowly by lateral erosion and vertical incision. Small-scale deviations from such general patterns of a distinct long-lived fluvial network exist. A prominent example of an abrupt change in the drainage system that has locally caused rapid incision is represented by the Wutach River, which was captured by the Rhine River. Several smaller examples of lateral channels (breakthrough channels) have been observed throughout Northern Switzerland. Most of these channels developed in association with large foreland glaciations, either by glacial impoundment of a present drainage and subsequent overspill, or by ice-marginal drainage. Such breakthrough channels can be either temporary or persistent features. Finally, while the processes are largely separated in this analysis, it is important to recognise that the landscape lowering results from the coupled hillslope-fluvial and glacial-fluvial systems. In particular, that means that landscape lowering over time by one process can bring the repository closer to the surface, where it can then be affected by other process (e.g. fluvial lowering followed by deep glacial erosion).

In the long term, the first-order control on fluvial incision is rock uplift. The spatial pattern of rock uplift over the next one million years and beyond is expected to continue to be dominated by a declining Alpine uplift, regardless of whether it is caused by tectonic shortening or isostatic compensatory motion. Rock uplift rates (mean of all sites) are expected to be between 0.02 and

0.34 mm/a (median 0.16 mm/a) (Nagra 2024d). This rock uplift drives fluvial incision, which in turn sets the pace for hillslope processes. Considering the low rates and repository depths and position within the landscape, a repository excavation by non-glacial processes is considered unlikely within the period of consideration for high-level radioactive waste of one million years and even for hundreds of thousands to millions of years beyond (Nagra 2024d).

For future deep glacial erosion to be a threat to the geological barrier of a deep geological repository, a series of events must occur. First, a future glaciation must cover the siting region. The climate driver – insolation – can, with some confidence, be projected into the (far) future because the variations of astronomical drivers (precession, obliquity and tilt) are understood (Berger & Loutre 1991). However, atmospheric concentration of greenhouse gases has a very strong influence on the timing and severity of future glaciations. Considering the present conditions and the longevity of the carbon dioxide gases within the atmosphere, the next glacial inception could be significantly delayed, and the next large glaciation might only occur after the next ~ 200,000 or even 350,000 years (Fischer et al. 2021, Talento & Ganopolski 2021). Accordingly, an initial extended interglacial period followed by a swing to the overarching 100-ka cycle is only expected ~ 500,000 years into the future. Secondly, the eroded overdeepening must be deep enough to reach the level of the disposal field. This depth is a combination of the future local (fluvial) erosion base, the size and erosional potential of the glaciation, and the incised rock type. Third, the overdeepening must incise at the location of the future repository. Accordingly, a repository excavation by glacial processes is considered unlikely within the period of consideration for high-level radioactive waste of one million years (Nagra 2024d). Despite the very low probability of all these factors playing unfavourably together, this report considers the repository excavation by erosive processes and its consequences as requested by the regulatory guidance described in Section 1.2.

2.2 Assessment timescales

As described in the previous section, very long timescales are required before excavation by deep glacial erosion or a downcutting river network might be considered feasible. For example, sustained fluvial erosion or more than one glacial episode would be needed for deep glacial erosion to reach repository depths. Given predictable patterns of insolation and less-predictable anthropogenic influences on global climate, timescales in the order of millions of years are needed before such a scenario could reasonably be expected to occur.

Based on the erosion modelling (Nagra 2024d), as well as the climate modelling (Nagra 2024c), the points in time for the present assessment were defined as follows: 700,000 years, 1 million years, 2 million years and 4 million years after repository closure.

The point in time 700,000 years from repository closure coincides with an expected major glaciation and is considered hypothetical for repository excavation. One million years aligns with the time at which the erosion modelling calculated the probabilities of repository excavation (for excavation by glacial erosion and by non-glacial erosion, respectively). Finally, two and four million years approximately correspond to the estimated time needed for repository excavation based on the 5th and 50th percentiles of the erosion rate calculated for the NL siting region (Nagra 2024d). The same set of time points was used for glacial as well as non-glacial excavation scenarios. Together, these timesteps show how the results change over a long period of time, providing an insight into the sensitivity of the result to this parameter, and are appropriate given the requirements of this study.

The consequence analysis presented here aims to evaluate potential doses based on the assumption that the repository excavation scenarios will occur. The assessments aim to provide a realistic evaluation of potential consequences. However, several unavoidable and significant uncertainties relevant to the assessment remain, not least with regard to:

- the timescales for deep glacial erosion to reach repository depths or for the repository to become exposed in the side of the valley;
- the timescales and nature of the processes associated with the resulting excavation, transport, deposition, and subsequent reworking of repository and surrounding material; and
- uncertainties concerning the timescale before which it might be feasible for humans to return to the environment affected by the glacial erosion scenario.

Rather than assess all possible permutations and combinations of situations, the study aims to evaluate a reasonable bounding range of situations.

Consistent with this context, simplifications and assumptions are adopted in defining the inventory in the repository at the time of excavation:

- Shorter-lived radionuclides and contamination associated with L/ILW will have decayed to relatively insignificant levels over the timescale of hundreds of thousands of years relevant to the scenario. Therefore, the study focuses on potential consequences associated with the excavation of spent fuel (SF), which remains hazardous over such timescales.
- The study assumes that none of the radionuclides associated with the spent fuel will have been lost from the repository prior to excavation. Given that the facility is engineered to retain the radionuclides, this can be considered to be a minor pessimism.

As described in Section 1.1, the modelling assumptions draw on situations and processes observable in Northern Switzerland at the present day, albeit giving consideration to the context for the repository host rock and overlying Malm limestone.

The glacial erosion scenario is, therefore, made on the basis that the excavated material is distributed in the post-glacial landscape immediately after excavation of the repository. This avoids conjecture about timescales and detailed evolution between excavation and potential exposure. It also maximises the potential for eroded spent fuel to be deposited directly in the accessible near-surface environment. Potential implications of different distributions of eroded spent fuel between the repository and accessible near-surface region are reviewed in evaluating the results.

For the non-glacial erosion scenario, the presence of the remaining repository within the biosphere is explicitly considered. For hillside erosion, this includes transport of excavated material down the hillslope.

2.3 Evolution of repository system on excavation timescales

This section discusses the evolution of the repository system over the long timelines associated with repository excavation scenarios. The repository system is described in Section 2.3.1; its evolution is explored in Section 2.3.2. Finally, Section 2.3.3 discusses the availability of radionuclides during an excavation of the repository.

2.3.1 Overview of repository system and its environment

The proposed repository system consists of a combined deep geological repository in the Opalinus Clay with separate disposal areas for high-level waste (HLW) and for low- and intermediate-level waste (L/ILW) (Fig. 2-1). A detailed description of the repository system is provided in Nagra (2021).

The repository consists of a main repository for emplacement of the radioactive waste, a pilot repository and test areas. Both the HLW and L/ILW pilot repositories will be constructed in an area of the host rock that fulfils the safety requirements relating to the main repository and can ensure the long-term containment of the waste (i.e. act as a geological barrier).

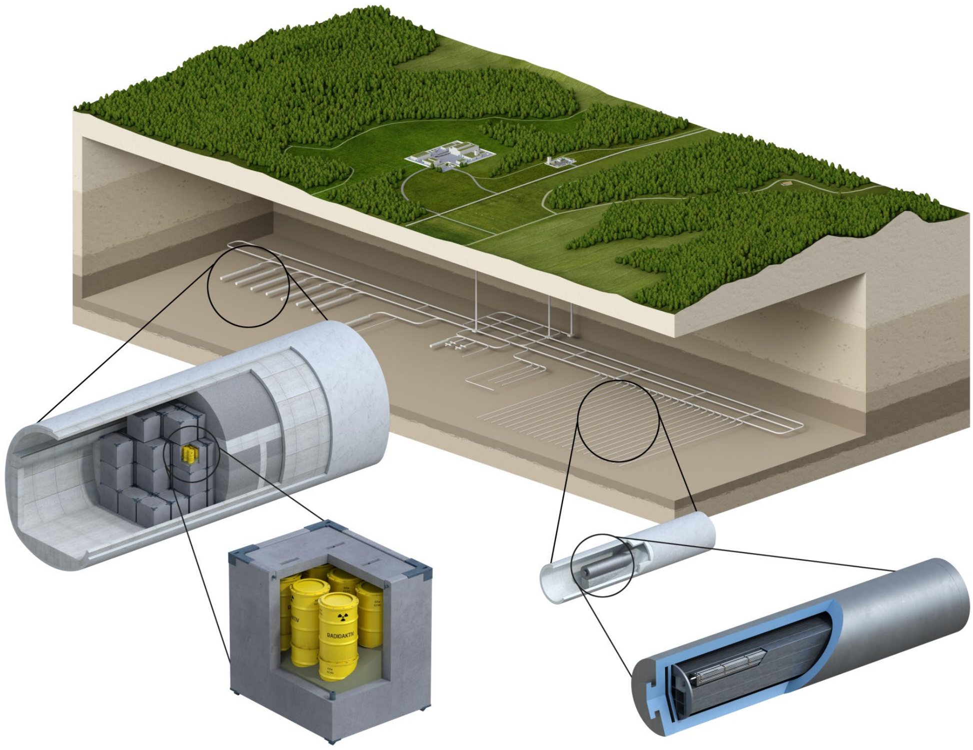

Fig. 2-1: Schematic illustration of the combined deep geological repository in the Opalinus Clay

Left: L/ILW repository section. Right: HLW repository section.

In the disposal concept for HLW (right in Fig. 2-1), spent fuel and vitrified HLW from reprocessing are packaged in steel canisters. The canisters are emplaced in drifts, which are backfilled with a compacted bentonite buffer and sealed. In the disposal concept for L/ILW (left in Fig. 2-1), L/ILW waste containers are emplaced in caverns and backfilled with cement-based mortar.

The HLW section of the repository includes drifts for emplacement of HLW disposal canisters as well as the associated disposal area accesses. It contains one or more disposal areas in which the emplacement drifts are arranged.

The L/ILW section of the repository includes caverns for emplacing L/ILW disposal containers as well as the associated disposal area accesses. It is arranged into one or more disposal areas.

The emplacement drifts and caverns are constructed in the Opalinus Clay host rock at a depth of over 800 m, with all underground openings and access structures closed following emplacement operations and a subsequent monitoring period by means of a system of seals and backfill.

The geological barrier is provided by the Opalinus Clay and its confining geological units (shown in Fig. 2-2), termed the containment-providing rock zone. The Opalinus Clay is characterised by a fine and homogeneous pore structure, extremely low hydraulic permeability, a homogeneous and high clay mineral content and the associated high sorption capacity for many radionuclides.

It provides an effective and stable barrier against radionuclide transport and a suitable physical and chemical environment for the engineered barriers.

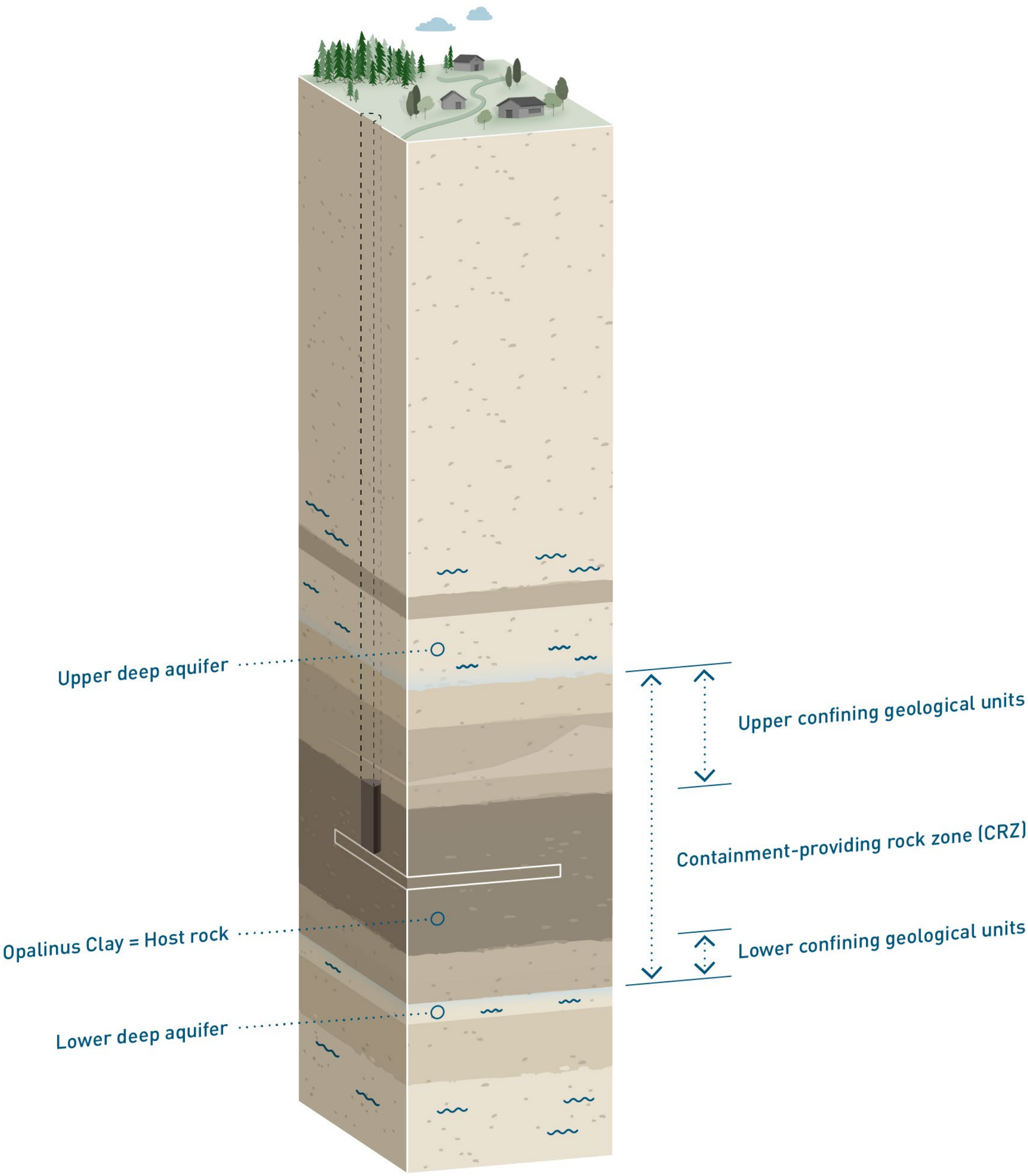

Fig. 2-2: Sketch of the location of the repository within the Opalinus Clay host rock, as well as the containment-providing rock zone (not to scale)

The containment-providing rock zone includes the Opalinus Clay and its confining geological units and is bounded above and below by deep aquifers.

2.3.2 Evolution of the repository over long timescales

Due to radioactive decay, the activity and radiotoxicity of the waste inventory decrease with time. After 100,000 years, the radiotoxicity of the L/ILW inventory falls below the radiotoxicity of the equivalent volume of granite (Nagra 2024a). The activity of the HLW stays high for much longer. For this reason, both the time period under consideration (for the site comparison) and the time period for assessment (for the safety case) are defined as one million years for HLW (Nagra 2024a). Given the timescales considered in this work (described in Section 2.2), only HLW (spent fuel (SF) and vitrified high-level waste from reprocessing (RP-HLW)) needs to be considered.

Assumptions about the state of the repository and SF/RP-HLW are needed for the timescales associated with the potential repository excavation scenarios. Disposal canisters will continue to contain the waste over very long timescales under repository conditions at depth. Similarly, engineered barriers and the bentonite buffer will protect the canisters and will also act to retard potential radionuclide releases. However, in the very long term, the canisters and the engineered barriers will evolve, with some degradation in performance, whereas the bentonite buffer and the Opalinus Clay, in particular, will continue to provide reliable containment.

As discussed in Section 2.2, extremely long timescales are needed before repository excavation scenarios could become plausible. Given uncertainty about the exact evolution of the repository systems on these timescales, assessment of potential consequences of repository excavation scenarios is undertaken on the basis that no reliance is placed on continued isolation within waste canisters. This means that consequence analysis does not need to consider the detail of the gradual evolution of repository conditions between emplacement and potential excavation. However, the potential distribution of radionuclides at the time that repository excavation scenarios become feasible does need consideration.

For excavation by deep glacial erosion, the repository will have been breached by glacial erosion processes at depth, resulting in the transport of material – including SF and/or RP-HLW – to the near-surface region. Prior to or during disruption, transport and deposition of eroded material, the containment function is assumed to have been lost for the purpose of consequence analysis. Eroded material is expected to be transported, deposited and reworked alongside other glacial materials and sediments.

For excavation by non-glacial processes, the repository itself needs to be present in the near-surface environment. In addition to the evolving repository conditions over long timescales, as it approaches the surface, the repository will enter zones of increased weathering and more oxidising environments. These conditions, coupled with physical disruption from deformation, landslides and erosion, again mean that canisters and repository engineering are taken to be significantly degraded by the time of excavation by non-glacial processes, so no reliance is placed on repository containment under these circumstances.

2.3.3 Radionuclide availability during excavation

Spent fuel is expected to be a durable waste form under repository conditions, in which the porewater chemistry is conditioned by the Opalinus Clay and bentonite, and conditions are reducing (Mäder & Wersin 2023). In safety assessments, the fractional release rate for spent fuel under repository conditions is typically assumed to be in the order of 10^{-7} a^{-1}, meaning that it takes a characteristic timescale of 10 million years for the spent fuel to dissolve and release the radionuclide inventory (Johnson et al. 2023). This fractional release rate is determined from consideration of parameters such as the dissolution rate, surface area, particle size and shape, and geochemical conditions.

Measured dissolution rates of spent fuel under oxidising conditions show that fuel will dissolve in the range of tens to hundreds of years.

The dissolution rate for vitrified high-level waste from the reprocessing of spent fuel in safety assessments is generally assumed to be such that the glass dissolves and the associated radioactivity is released on a timescale of approximately 10^5 years (Curti 2022). The dissolution rate of vitrified waste is expected to be faster under erosion scenarios, such that the glass would not be expected to remain present in the surface or near-surface environment after erosion and deposition.

For excavation by deep glacial erosion, it is therefore anticipated that, while radionuclides associated with disrupted material will be present and deposited in the near-surface and surface environment, the spent fuel particles and glass that the material is initially associated with at the time of excavation will have completely dissolved on the timescale relevant to assessing potential dose consequences.

For excavation by non-glacial processes, the radionuclides are taken to have been released from the degraded canisters, spent fuel and glass, and are distributed throughout the clay layer, representative of the Opalinus Clay host rock and remaining buffer.

The radionuclide source term for both repository excavation scenarios is, therefore, taken to be readily available for dissolution and sorption onto host material (e.g. clays and gravels).

On the basis of screening calculations (Nagra 2024i), the following 63 radionuclides are explicitly addressed in the post-closure safety assessments:

Ac-227, Ag-108m, Al-26, Am-241, Am-242m, Am-243, C-14, Ca-41, Cf-249, Cf-251, Cl-36, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Cs-135, Cs-137, Fe-60, Hg-194, Ho-166m, I-129, Mo-93, Nb-91, Nb-93m, Nb-94, Ni-59, Ni-63, Np-237, Pa-231, Pb 202, Pb-210, Pd-107, Po-209, Po-210, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Ra-226, Ra-228, Se-79, Si-32, Sm-151, Sn-121m, Sn-126, Sr-90, Tc-99, Th-228, Th 229, Th-230, Th-232, Ti-44, U-232, U-233, U-234, U-235, U-236, U-238, Zr-93.

The list of radionuclides considered for repository excavation scenarios is the same as that considered for all of Nagra's post-closure safety scenarios. The basis of the screening was reviewed to provide confidence that no radionuclides relevant to the long-term excavation context were omitted.

2.4 General basis for the assessment

This assessment is based on conservative and pessimistic[4], yet still plausible, assumptions, which are used to develop stylised safety scenarios applicable to all three siting regions. This assessment is thus not site-specific and, if excavation were to occur (at a particular point in time), the processes and assumptions are taken to be identical in each region. The only general difference between the sites is taken to be the expected time of occurrence (Nagra 2024d).

Observations from the present-day landscape in Northern Switzerland are used to define the geometries and sediments in which contaminated materials from an eroded repository could be found. This approach is used to ensure the assessed calculation cases are physically plausible although it is accepted that, particularly in the case of glacial erosion, there could be systematic differences

[4] The term "conservative" is used in this report to refer to simplifications, assumptions, or parameter values, which are confidently expected to lead to results that are less favourable than those anticipated under real conditions, taking uncertainty into account. Conservative parameter values can lie outside the range of what is physically possible (e.g. hypothetical assumptions). The term "pessimistic" is used in this report to refer to assumptions or parameter values which are possible but lead to results less favourable than the most likely outcome.

in the eroded rock types, which would affect sediment types and volumes and hence deposition environments. Given that there are no known examples of sedimentation following deep glacial erosion into the Opalinus Clay, the present-day analogues are used as the best available information, with the associated uncertainty explored by assessing different assumptions about the types of sediment that radionuclides are deposited within, as well as through sensitivity calculations.

The chosen points in time for radiological consequence assessment in this report (cf. Section 2.2) illustrate the generic evolution of radiological consequences of repository excavation over time. The probabilities of the repository excavation scenarios occurring at the different sites are not discussed in this report; they are addressed in the erosion report NAB 24-15 (Nagra 2024d). The assessment of these scenarios (based on the calculated consequences and probabilities) against the regulatory limits is performed in the post-closure safety report NTB 24-10 (Nagra 2024h). The impact of erosion processes on site comparison is discussed in NTB 24-03 ("*Bericht zur Begründung der Standortwahl*") (Nagra 2025a).

3 Excavation by deep glacial erosion

Section 3.1 describes glacial processes observed in present-day Northern Switzerland. These observations provide a basis for storyboards relating to deep glacial erosion in Section 3.2. Those storyboards are conceptualised in terms of potential for repository excavation in Section 3.3, with resulting calculation cases being described in Section 3.4. The mathematical models for the deep glacial erosion cases are described in Section 3.5, along with associated data in Section 3.6. Results of the dose assessment are presented in Section 3.7, along with conclusions from sensitivity calculations.

3.1 Glacial processes

Sections 3.1.1 and 3.1.2 set the stage for assessing repository excavation by deep glacial erosion. They provide a brief overview of the Quaternary glaciation history and associated landscape evolution in Northern Switzerland. This is followed by a summary of the general concepts on erosion, transport and deposition of sediments in a glacial system in Section 3.1.3. Section 3.1.4 reviews the processes of glacial sediment deposition on land as well as in water. Section 3.1.5 discusses the postglacial geology and hydrogeology in Northern Switzerland to indicate what glacial deposits arising from deep glacial erosion are expected to look like in the far future. Finally, Section 3.1.6 uses the information from observations in Northern Switzerland to define three plausible variant cases for consideration in the assessment of the excavation by deep glacial erosion scenario. The variant cases bound the range of exposure scenarios that can be plausibly expected.

3.1.1 Glaciation in Northern Switzerland

Glaciations play a significant role in landscape evolution at regional to continental scales. By sculpting the landscape (Valla et al. 2011, Ward et al. 2012) and transporting and depositing sediment (Hallet et al. 1996, Cowton et al. 2012), glaciers exert a strong influence on relief and landscape dynamics. Glacial processes not only result in an area-wide denudation and the erosion of deep and sometimes overdeepened basins, but also in an areal distribution of erosional debris (moraines) as well as glaciofluvial and glaciolacustrine infill of valleys.

The evolution of the Swiss landscape during the Quaternary over the past 2.6 million years was characterised by multiple glaciations and deglaciations with at least 15 ice advances that reached the foreland (Preusser et al. 2011, Ivy-Ochs et al. 2006, Schlüchter et al. 2020). The three main glaciations (Fig. 3-1) were, from young to old, the Last Glacial Maximum (LGM) that occurred during Marine Isotope Stage (MIS) 2 (Preusser et al. 2011) the Beringen glaciation, which probably occurred during MIS 6 (Preusser et al. 2011) and the Möhlin glaciation (or Most Extensive Glaciation (MEG)). The latter is not yet dated, and evidence for its extent is rare and might not even be synchronous. Evidence of smaller, less significant advances might have been erased by subsequent events. Of significance is that all the proposed siting regions (Nagra 2008a, Nagra 2014) are located within the ice extent during the MEG, the eastern two are within the extent of Beringen, and only one is fully located within that of the LGM (Fig. 3-1).

One of the relevant aspects with respect to foreland glaciations concerns the effects of "deep glacial erosion". This term refers to the origin of deeply incised troughs and overdeepened valleys (Jordan 2010, Pietsch & Jordan 2014, Nagra 2008c, Nagra 2014) beneath glaciers that extended from the Alps far into the Alpine Foreland and repeatedly covered the midland areas of Northern Switzerland (Swiss Plateau) with hundreds of metres of ice during the Quaternary (Schlüchter 1986, Preusser et al. 2011).

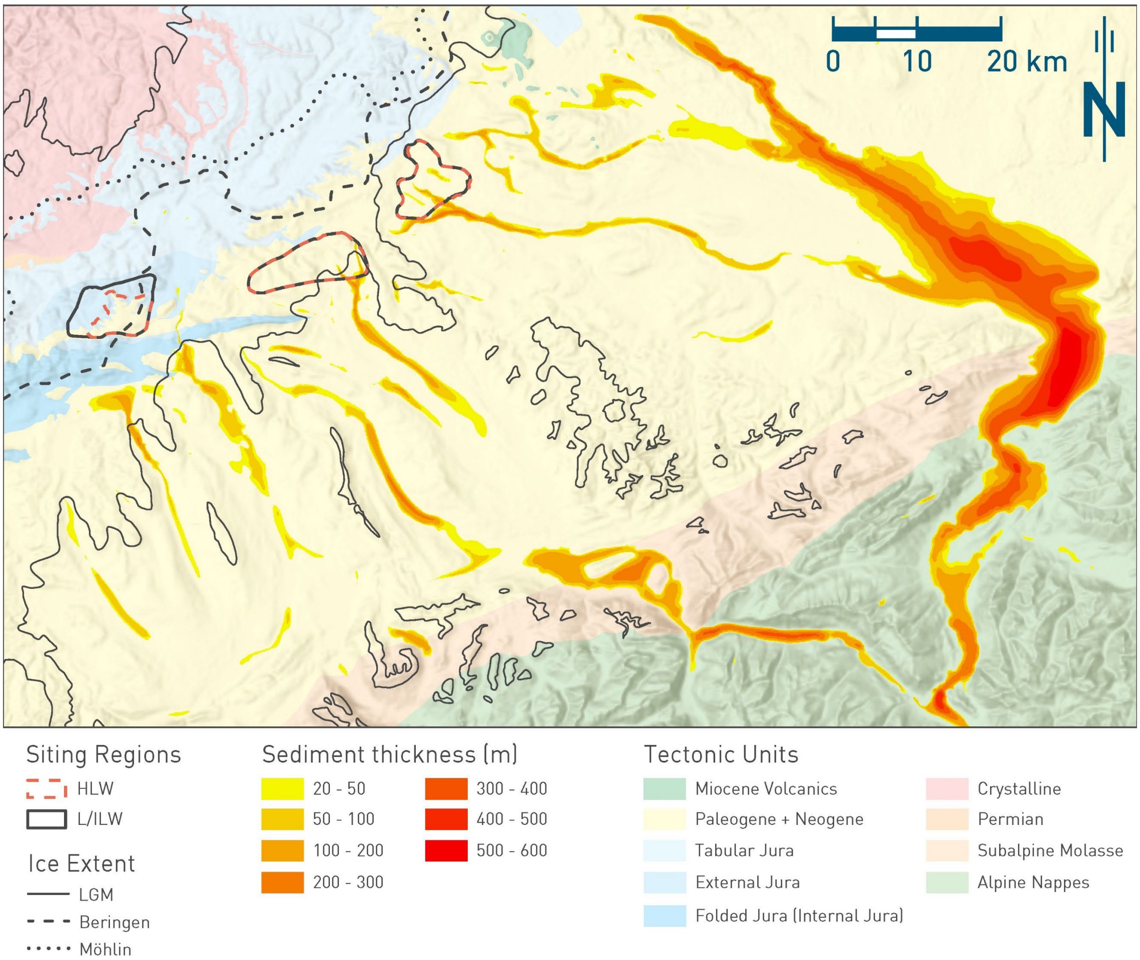

Fig. 3-1: Geological map of Northern Switzerland emphasising glacial overdeepenings

Black/red-dashed lines show the proposed deep geological repository siting regions. The thickness of the Quaternary sediments (below the local fluvial erosion base which corresponds to glacial overdeepening) indicates a system of deep, overdeepened, and buried valleys (Jordan 2010, Pietsch & Jordan 2014). Also shown is the ice extent at the Last Glacial Maximum (LGM) (Kelly et al. 2004, Bini et al. 2009), the Beringen glaciation (Preusser et al. 2011) and the Möhlin glaciation (Most Extensive Glaciation, MEG) (Preusser et al. 2011). Note that most of the overdeepenings were cut into the easily eroded Molasse sedimentary rocks (Paleogene and Neogene).

Most overdeepenings are observed within the LGM ice extent (Fig. 3-1). However, within many overdeepened valleys, pre-LGM sediments are also preserved (Dehnert et al. 2012, Buechi et al. 2018). No example of LGM-based bedrock erosion is known in the foreland of Northern Switzerland. Although not all glaciations were able to excavate the postglacial sediment infill and produce renewed overdeepening, progressive deepening over successive glacial cycles may take place because ice is likely steered away from hills and ridges into already existing troughs and valleys (Kessler et al. 2008). This topographic steering causes the thicker and faster-flowing ice to generate more basal melting that will further increase basal sliding and sediment evacuation and thus result in enhanced erosion.

The time of first ice advances far into the foreland of Northern Switzerland is debated, but might have occurred only after the glacial cycle switched from a predominantly 40 ka- to a 100 ka-cycle during the Mid-Pleistocene Transition (between 1.25 and 0.7 Ma BP) (Knudsen et al. 2020). The future climate in the time period of consideration (1 Ma) is expected to continue to oscillate between glacial and interglacial periods. However, because anthropogenic CO_2 input has significantly altered the climate evolution, the inception of the next glaciation could be delayed by several hundred thousand years (Fischer et al. 2021, Talento & Ganopolski 2021).

3.1.2 Ice conditions during glaciation

The LGM is the best understood glaciation to date. Conditions inferred for it are assumed to apply to the other glaciations. During the coldest time intervals, the frontal reaches of the glaciers spreading out over the Swiss Plateau (Fig. 3-1) were predominantly polythermal (Blatter & Haeberli 1984, Cohen et al. 2018, Seguinot et al. 2018), surrounded by up to 150-metre-thick continuous periglacial permafrost (Schindler et al. 1978, Frenzel et al. 1992, Vandenberghe & Pissart 1993, Deslisle et al., Lindgren et al. 2016), and characterised by low driving stresses and correspondingly low mass balance gradients, mass turnover and flow velocities (Haeberli & Penz 1985, Benz-Meier 2003). Glacier ice tended to be cold at high elevations, but warm-based (not frozen to the bed) over large areas in the Alpine valleys and the Alpine Foreland. In the piedmont lobes of the LGM Rhine glacier, basal sliding dictated main fluxes of ice (Cohen et al. 2018). The ice was channelled in between bedrock highs along troughs, some of which coincide with prior glacially eroded overdeepenings (Fig. 3-1). More humid conditions with higher flow velocities, increased mass turnover and meltwater effects must have prevailed during ice advance across the Swiss Plateau, and rapid downwasting or even collapse of the ice masses accompanied by violent outburst floods from temporarily ice-dammed lakes is likely to have taken place during the retreat phase into the Alpine valleys (Haeberli 2010).

3.1.3 Erosion, transport and deposition of sediment in a glacial system

The main processes of direct glacial erosion are abrasion and quarrying. Abrasion involves the wearing down of rock surfaces by the grinding effect of glacier ice charged with basal debris. Quarrying, or plucking, is the removal of well-jointed or loosened blocks of bedrock by the overriding glacier. For abrasion and quarrying to take place, there must be relative movement between the glacier sole and the bed, which requires the basal ice to be at the pressure-melting point and sliding. Abrasion and quarrying, therefore, depend on the temperature and velocity of the basal ice, debris concentrations, ice thickness and subglacial water pressure (Iverson 2002, Bennett & Glasser 2009, Burki 2009, Swift et al. 2015, Swift et al. 2021, Alley et al. 2019).

Significant wear to the glacier bed can also be caused by subglacial fluvial action. Erosion of bedrock in subglacial meltwater channels proceeds in a manner similar to the bedrock incision by subaerial streams and is dependent on water velocity, discharge and turbulence as well as the quantity of suspended sediment and bedload in traction (Drewry 1986, Burki 2009, Benn & Evans 2010, Swift et al. 2015, Swift et al. 2021, Alley et al. 2019). Of specific importance in subglacial environments is that high water velocities and discharges require strong pressure gradients in relatively large, hydraulically efficient and well-connected subglacial channels. The efficiency of subglacial drainage not only affects meltwater erosion but also likely plays a predominate role in evacuating sediments produced by erosion, thus keeping bed surfaces accessible for further erosion (Fischer & Haeberli 2010, Fischer & Haeberli 2012).

Glacial erosion occurs where ice is warm-based, which enables basal sliding and thus abrasion. Furthermore, where surface meltwater is produced and reaches the bed, this promotes rapid sliding, stimulates quarrying or can directly lead to subglacial meltwater erosion and sediment evacuation. Generally, the three processes can lead to erosion in all rock types, however, quarrying is particularly relevant in fractured rocks. Fluvial action of subglacially flowing meltwater is most effective in mechanically weak rocks. While areal denudation by glaciers and the overall glacially eroded volumes are primarily associated with the processes of abrasion and quarrying (Drewry 1986, Burki 2009), local maxima of erosion depth may more strongly be linked to the complex behaviour of subglacial meltwater drainage and erosion, which can be linearly concentrated in places (Fischer & Haeberli 2010, Fischer & Haeberli 2012, Beaud & Flowers 2015, Beaud et al. 2016, Beaud et al. 2018).

The formation of glacial overdeepenings is likely the result of the combined action of ice and basal water and depends on the extent to which processes and feedbacks are able to focus erosion and maintain the evacuation of water and sediment (Cook & Swift 2012). Overdeepening formation occurs time-transgressively during ice advance, when the steep surface slope of the ice margin provides the large hydraulic gradients necessary for a vigorous subglacial water flow and an efficient evacuation of erosion products from the ice-bed interface. It may also occur during the retreat phase by the outburst of subglacial meltwater dammed behind a cold-based ice margin or a marginal permafrost wedge (Fischer 2015, Fischer et al. 2015, Fischer et al. 2021).

Depending on the dynamic and thermodynamic conditions, different processes contribute to how the eroded material is entrained and transported by the glacier, modified during glacial transfer, deposited beneath or in front of the glacier, and subsequently reworked (Fig. 3-2). Because glaciers concentrate runoff, subglacial stream channels are exceptionally efficient in transporting sediment if abundant surface melt reaches the bed (Alley et al. 1997). Away from channels, subglacial bed deformation (glaciotectonic deformation of sediment at the bed of a glacier) is an important mechanism for sediment transport if unconsolidated sediment is available. Alternatively, sediment may be incorporated into the base of the glacier through regelation into subglacial sediment, conductive freeze-on, freeze-on by supercooling of rising subglacial waters, or thrusting and folding. In general, subglacial fluvial transport tends to be dominant beneath temperate glaciers whereas sediment transport within the ice is more important in polythermal and cold glaciers (Cook & Swift 2012). During transport, the sediment is subject to further abrasion, fracturing and crushing at the ice-bed interface (Alley et al. 1997, Hambrey & Glasser 2003). An important aspect is the evacuation of sediment out of an overdeepening, sometimes along steeply inclined adverse slopes. The grinding up of larger rock fragments produces finer particles that can be more easily transported upslope as suspended material.

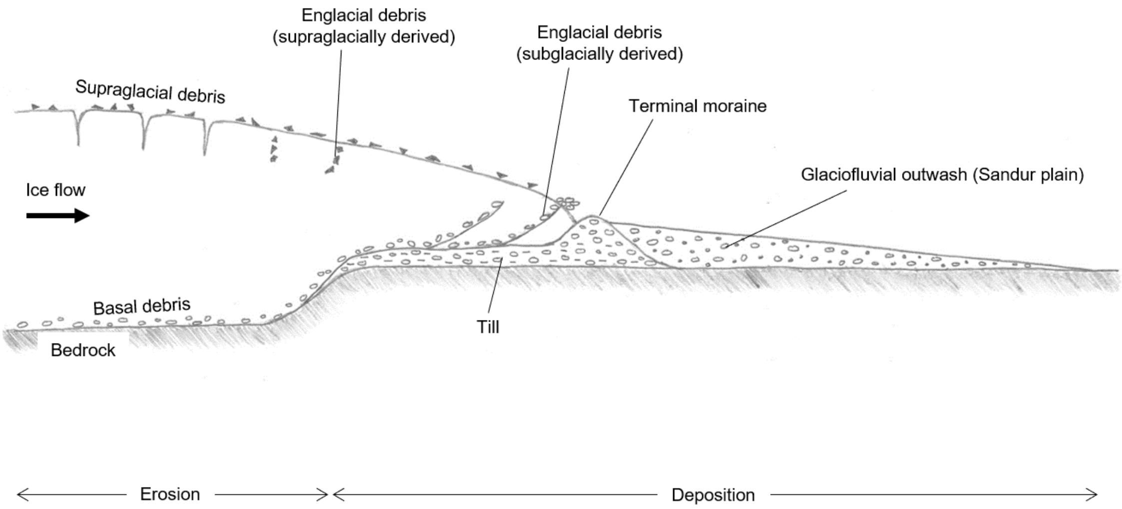

Fig. 3-2: Schematic diagram showing the processes and products of sediment entrainment, transport and deposition in a terrestrial glacial environment

Sediment is deposited directly beneath the glacier or at its margin, or it can be transported significant distances from the glacier itself by other agents such as proglacial meltwater streams. After release from the ice, numerous glacier-related processes, including reworking in streams and lakes, debris flows and aeolian activity, may further modify and transport the sediment. The extent to which each of these processes operates is largely controlled by the surrounding topography as well as meteorological and climatological conditions (Hambrey & Glasser 2003). As glacial meltwater emerges from the glacier, sediment is deposited at or beyond the ice margin forming outwash, or sandur, plains (Fig. 3-2). The ratio between the supply rates of water and sediment from the glacier and the transport capacity of the proglacial stream determines whether the stream aggrades and adjusts to a braiding pattern or degrades and incises into the proglacial outwash deposits (Fenn & Gurnell 1987).

3.1.4 Processes of glacial sediment deposition

Sediment deposited directly by glacier ice (glacial till) is poorly sorted and contains a wide range of particle sizes (boulders to clay) (Fig. 3-3). In contrast, sediment deposited by meltwater is typically sorted and stratified. The pattern of sedimentation is controlled by the ability of the proglacial stream to transport sediment in suspension or as bedload. The particle size of the deposited sediment is primarily a function of the water flow velocity and rapidly falls away with distance from the ice margin, which reflects the decline in stream power (Ehlers 1994). Hence, close to the glacier portal, the sediments are coarse (boulders and gravels) (Fig. 3-3), whereas the finer sediments are transported further and may eventually settle from suspension to form finely laminated silt units (Fig. 3-3). Especially in cold arid environments, silts and clays can be further distributed over great distances by wind, resulting in regionally extensive and thick accumulations of loess (Hambrey & Glasser 2003, Bennett & Glasser 2009).

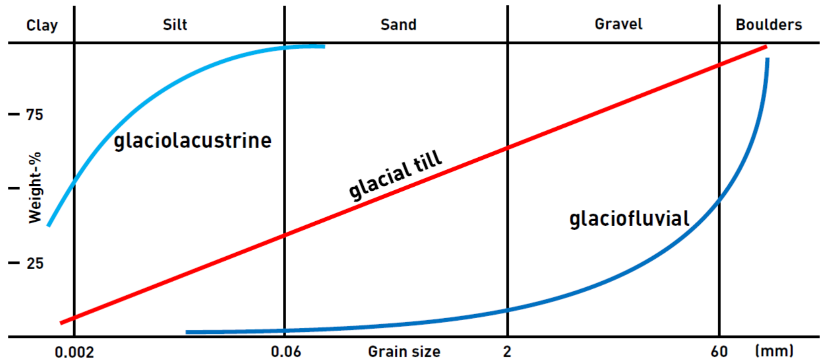

Fig. 3-3: Schematic diagram of the grain-size distribution of a glacial till (red), glaciofluvial deposit (dark blue) and glaciolacustrine deposit (light blue)

From (Kündig et al. 1997).

Glacial sediment deposition on land

Glaciers that terminate on land deposit sediment either directly by the ice or via meltwater. Direct glacier deposition is restricted to the immediate vicinity of the glacier while meltwater can carry sediment beyond the glacier.

Ice-marginal moraines are produced directly by the action of glacier ice and formed by a combination of processes which include the pushing, dumping and melt-out of glacial debris (Fig. 3-4a). Debris deposited directly by a glacier is known as till. Till is a diamicton, which is a non-genetic term for a poorly sorted unconsolidated sediment that contains a wide range of particle sizes (Fig. 3-3). It normally consists of large pebbles, cobbles or boulders, referred to generally as clasts, set within a fine-grained matrix of sand, silt and clay (Bennett & Glasser 2009). Grain-size distribution characteristics of till depend on whether it is basally or supraglacially derived (Hambrey 1994). The till particles in transport along the bed of a glacier experience considerable modification through the processes of crushing and abrasion (comminution) and are thus typically subrounded. A significant proportion of these particles are silt- and clay-sized (Haldorsen 1981). In contrast, debris that is transported within or on the surface of a glacier retains its primary characteristics and is unaltered by glacial transport. Consequently, it is typically angular, coarser-grained and contains little fine material.

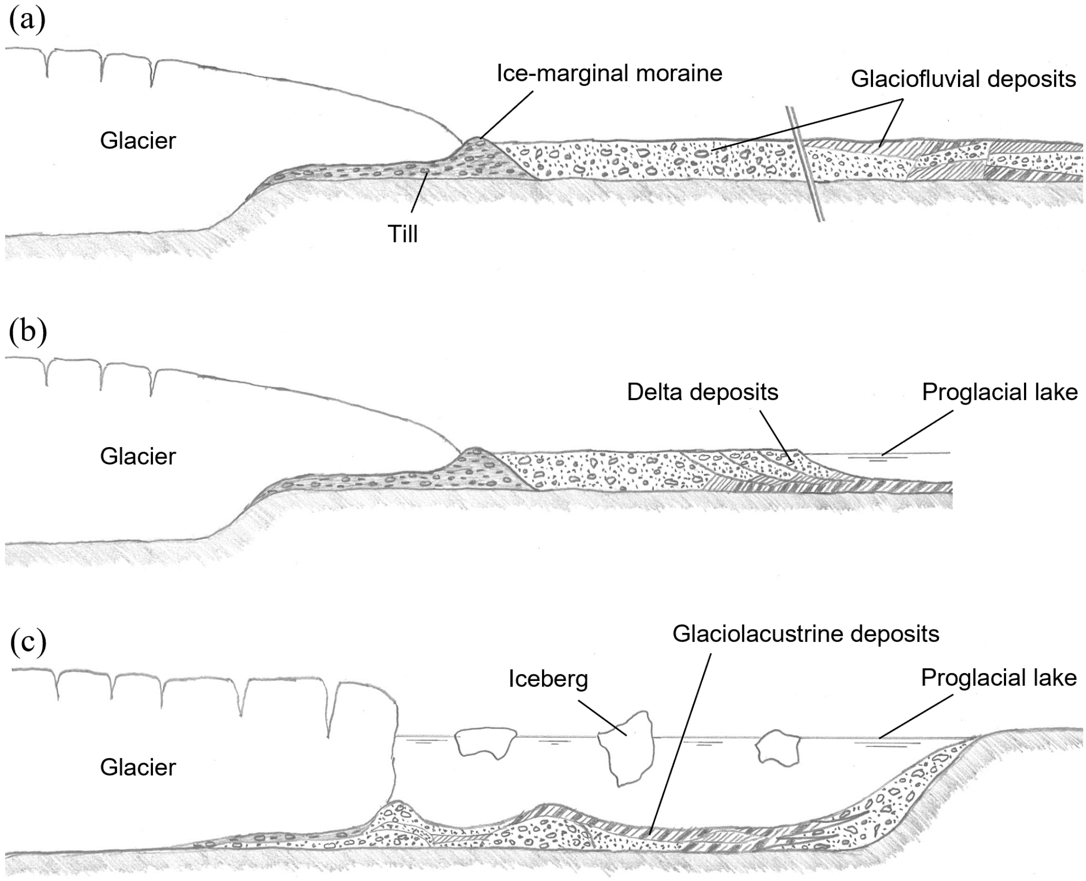

Fig. 3-4: Schematic diagrams of glacial deposits

(a) Till deposition in a glacial moraine and glaciofluvial deposition in a proglacial outwash plain. (b) Delta deposition in a shallow proglacial lake. (c) Glaciolacustrine deposition in a deep proglacial lake.

Not to scale. Vertically exaggerated for clarity. Inspired by figures in Schindler (1968).

As glacial meltwater emerges from the glacier, the pressure gradient, which drives the meltwater from beneath the glacier, drops, and its velocity, and hence transport capacity, falls. Consequently, rapid sedimentation occurs in front of the glacier to form an outwash, or sandur, plain, with coarse material being deposited relatively close to the glacier portal, while the finer fraction is transported further (Fig. 3-4a). Away from the ice margin, a braided stream pattern develops, in which ephemeral bars and channels dominate. The sediments resulting from the braided stream system range from boulders to sands. The sedimentary structures within these sediments reflect the processes of formation of bars, erosion (scour) and fill of channels and deposition of finer sediments during low flows (Bennett & Glasser 2009). Grain-size distributions for glaciofluvial deposits are clearly different from those of tills (Fig. 3-3) as most of the particles in sand and gravel sequences are rock fragments, while the silt- and clay-sized particles characteristic of till have been largely flushed out (Sugden & John 1976).

Glacial sediment deposition in water

Glaciers that terminate in water produce a different assemblage of sediments than those deposited on land. The glacier acts as a source of debris, and deposition is controlled not by the glacier ice directly but through processes of sedimentation within the water body.

Proglacial lakes can form behind sediment (e.g. moraines, debris deposits) or ice barriers in front or at the margins of glaciers or in depressions created by the melting out of stagnant ice buried beneath the proglacial surface (Carrivick & Tweed 2013). By trapping potentially large volumes of sediment leaving the glacier, the lakes usually constitute important sedimentation basins that regulate the fluvial transfer of sediment through the proglacial area (Bogen et al. 2015). The delivery of debris into the lake leads to the formation of deltas by a combination of fluvial aggradation above water level, and progradation on the delta front, where bedload is rapidly deposited when the incoming sediment-laden meltwater stream decelerates upon contact with standing water (Fig. 3-4b). The deposition of delta fronts generally takes the form of avalanching and slumping of coarse material, while fine-grained suspended sediment is carried beyond the delta by turbidity currents to be deposited in the deeper parts of the lake (Church & Gilbert 1975, Benn & Evans 2010). The general fall-off in flow competence away from the point of water inflow within the lake results in a broad size grading with sand and gravel deposits occurring near the lake shore and evenly bedded, laminated fine silt and clay being dominant in the lake centre (Hambrey 1994).

As glaciers retreat, overdeepened basins can host large proglacial lakes (Fig. 3-4c). Steep, often near-vertical, calving ice cliffs are characteristic of glaciers that terminate in lakes (Hambrey 1994). Such lakes act as important sediment traps where thick sequences can be preserved (Benn & Evans 2010). The coarse fraction of the sediments released from subglacial streams emanating below water level drops quickly to the lake bottom, whereas the fine fraction becomes dispersed within the main body of the lake before gradually settling to form thin layers of mud and clay which drape other sediments (Schindler 1968). This type of sedimentation dominates over much of the lake floor. Material may also simply be dumped into the water body from the glacier front, resulting in irregular-shaped deposits of diamicton. Another source of sedimentation is the rain-out from icebergs. Calving icebergs can float debris out into the lake where it can be released as the iceberg melts (Fig. 3-4c). Low concentrations of debris and icebergs result in the deposition of occasional dropstones, anomalously large clasts set in fine-grained sediments, while high concentrations result in thick, laterally extensive deposits of diamicton. If the overall ice-rafted debris component is small, then rhythmic fine-grained sediments produced by settling of material out of suspension dominate. This settling process gives rise to fine laminations of silt and clay (Fig. 3-3). In contrast, if the component of ice-rafted debris is large, sedimentation is dominated by coarse debris melting from icebergs. In this case, the deposition of diamictons and resedimentation by subaqueous gravity flows from the lake margin will dominate (Bennett & Glasser 2009).

3.1.5 Postglacial geology and hydrogeology in Northern Switzerland

The main processes during the Quaternary that have shaped the present-day landscape of Northern Switzerland are the combined action of rivers and especially the drainage evolution of the Aare-Rhine river system, as well as erosion and sedimentation by repeated large foreland glaciations. Four main morphostratigraphic units of mostly glaciofluvial gravels have been differentiated in the Swiss foreland and are interpreted to reflect the stepwise incision and sedimentation since the Early to Mid-Pleistocene, when glaciers first advanced into the foreland (from top to bottom): Höhere Deckenschotter ("Upper Cover Gravel"), Tiefere Deckenschotter ("Lower Cover Gravel"), Hochterrasse ("High Terrace") and Niederterrasse ("Low Terrace") (Graf & Burkhalter 2016, Preusser et al. 2011) (Fig. 3-5). In general, because of progressive incision, older terraces are at higher elevation while younger terraces are inset at lower elevation. Today, large parts of Northern Switzerland are characterised by a low-relief landscape where comparatively wide fluvial valleys and extended terrace systems define the postglacial terrain. While both Höhere Deckenschotter and Tiefere Deckenschotter deposits are preserved as remnants in the shape of flat-topped hills (hence called Deckenschotter, "cover gravels"), the Hochterrasse and Niederterrasse deposits follow a continuous and traceable fluvial network (Fig. 3-5b). Fig. 3-6 details the hydrogeology of three typical postglacial landscape types imprinted in Northern Switzerland today.

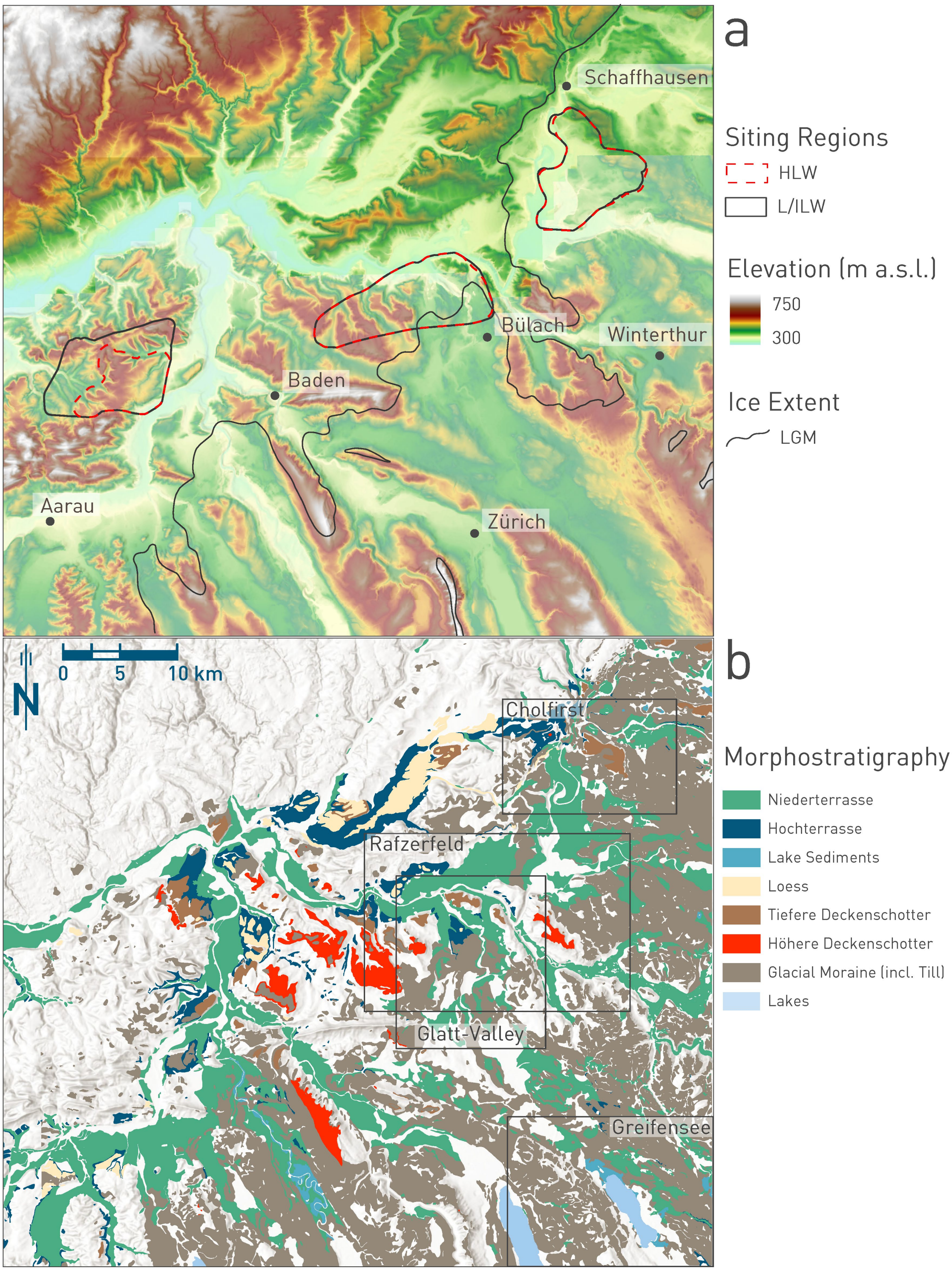

Fig. 3-5: Geomorphology and Quaternary sediments around the siting regions

(a) Digital elevation model with outlines of siting regions and main geomorphic features. Also shown is the LGM ice extent. (b) Simplified map of Quaternary deposits showing the same area as (a). Note that most glacial moraine deposits are located (as expected) within the LGM ice extent. Loess occurrences are rare. Lake sediments represent progressive infilling of proglacial lakes, but are expected to be more abundant within the overdeepenings. Boxes labelled "Cholfirst", "Rafzerfeld" and "Greifensee" refer to Fig. 3-6. The "Glatt Valley" box shows the outline of Fig. 3-7.

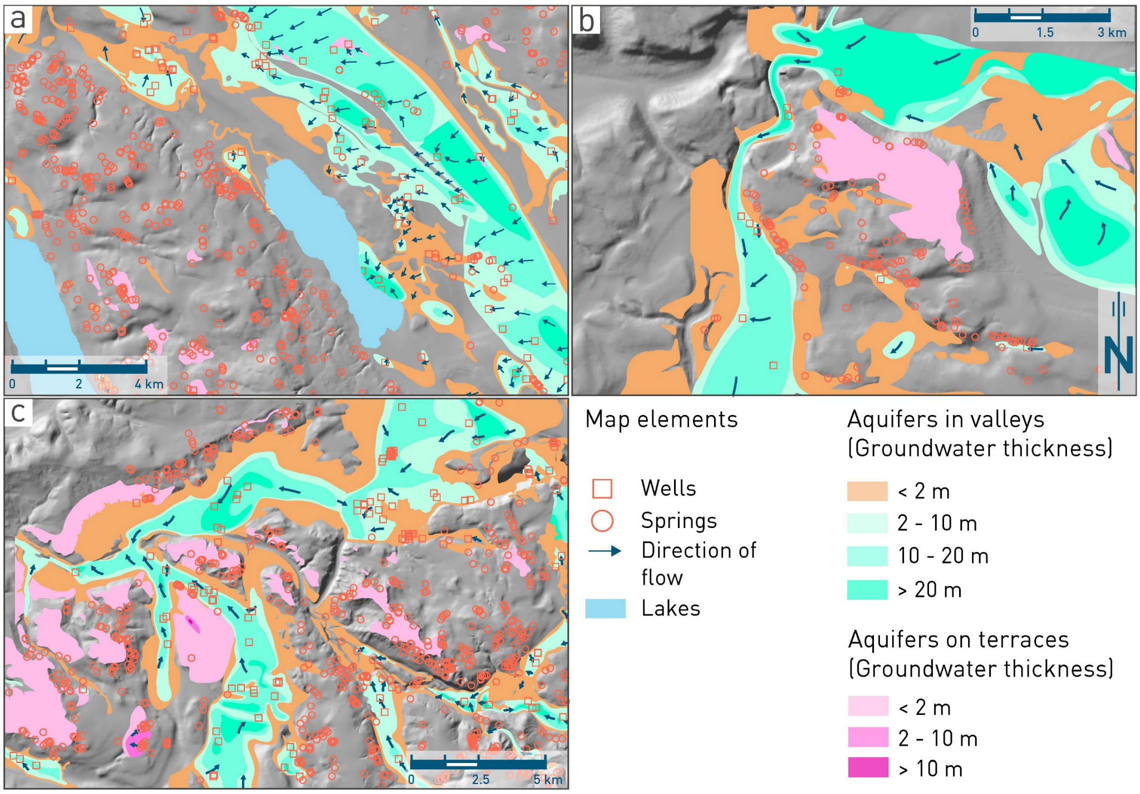

Fig. 3-6: Hydrogeology of postglacial/proglacial landscapes in Northern Switzerland

(a) Greifensee, (b) Cholfirst and (c) Rafzerfeld (see Fig. 3-5b for locations). The spatial coincidence of typical glacial and glaciofluvial deposits (Fig. 3-5b), their condition and their intersection with the geomorphology define typical hydraulic conditions. These example landscapes form the basis for the biosphere variants (Section 3.1.6). Background is a hillshade model.

Examples from sedimentary facies observed in the surface deposits in the Glatt Valley (Buechi et al. 2018) show terminal moraine complexes and extensive gravel outwash plains that partly interfinger (Fig. 3-7). Drill cores from overdeepened troughs in the same area (simplified here) reveal densely packed, gravel-rich diamicton as deepest infill, interpreted as subglacial till. These deposits are overlain by stratified and massive sands (glacio-deltaic origin) fining into laminated silt and clay (settling in proglacial lakes) (Fig. 3-8). Such sequences can be repeated by a multiphase erosional and depositional evolution (Buechi et al. 2018).

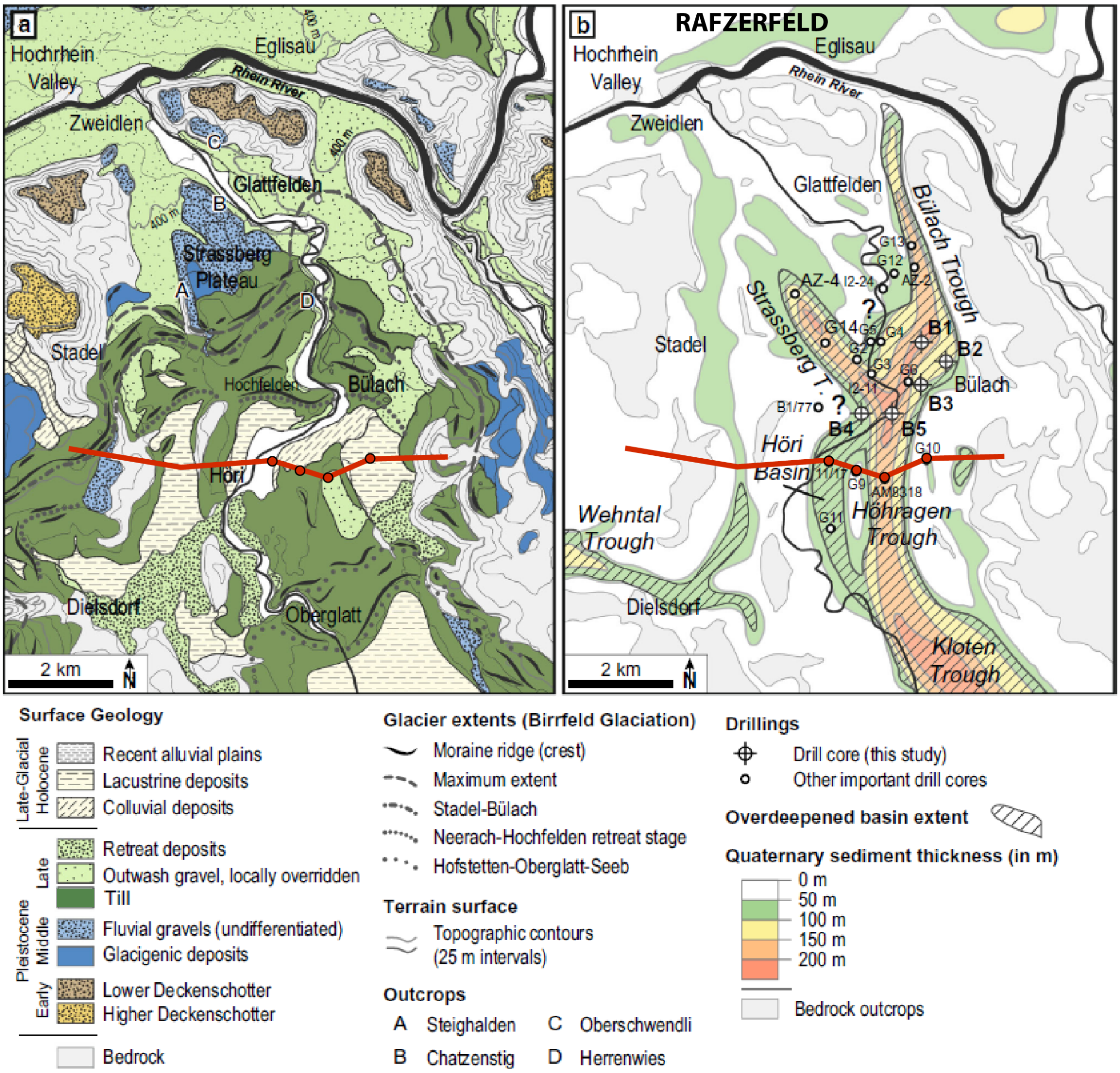

Fig. 3-7: Surface deposits in the Lower Glatt Valley

(a) Geological map. (b) Quaternary sediments (up to 200 m thick) infilled into distinct overdeepened bedrock troughs (Buechi et al. 2018).

The red line indicates the location of the profile shown in Fig. 3-8. Note the spatial coincidence of Late-Pleistocene glacial deposits (e.g. till and outwash gravel) and late-glacial Holocene deposits, including lacustrine sediments in (a). See Fig. 3-5b for location in a regional context.

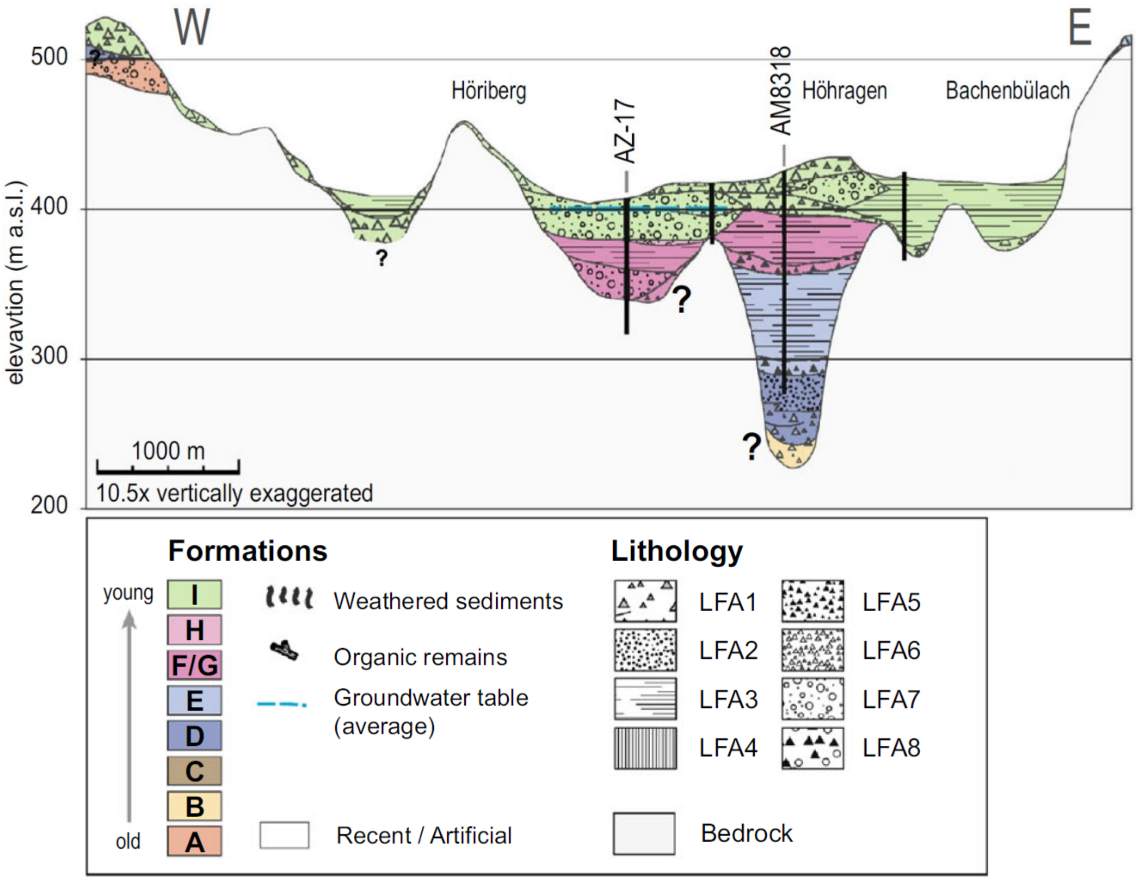

Fig. 3-8: Schematic profile across the Lower Glatt Valley

Formation names are indicated with colours and letters A–I (oldest to youngest). Lithofacies are LFA1, LFA5, LFA6 – subglacial till; LFA2 – stratified and massive sands; LFA3 – laminated silt and clay; LFA7, LFA8 – gravels (Buechi et al. 2018). Location of the profile is shown in Fig. 3-7.

Fig. 3-9 shows a schematic profile section through the northern Swiss Plateau. The sequence of gravel terraces (Deckenschotter, Hochterrasse, Niederterrasse), with the younger terraces lying increasingly at lower elevation, reflects the stepwise process of valley incision and infilling during successive glacial-interglacial cycles during the Quaternary (Nagra 2008c, Nagra 2014). Potential locations of glacial deposits within the accessible near-surface environment in today's landscape are shown. The nomenclature is given to material types that will be used throughout the remainder of this chapter: G – gravels derived from proglacial outwash plains; D – delta deposits corresponding to deposition in shallow proglacial lakes; C – clay derived from deposition in deep proglacial lakes; and T – till deposited in glacial moraines.

From here on, a distinction is drawn between material deposited in the near-surface environment (this includes surface sediments) and the fill remaining within the overdeepening, which is not accessible.

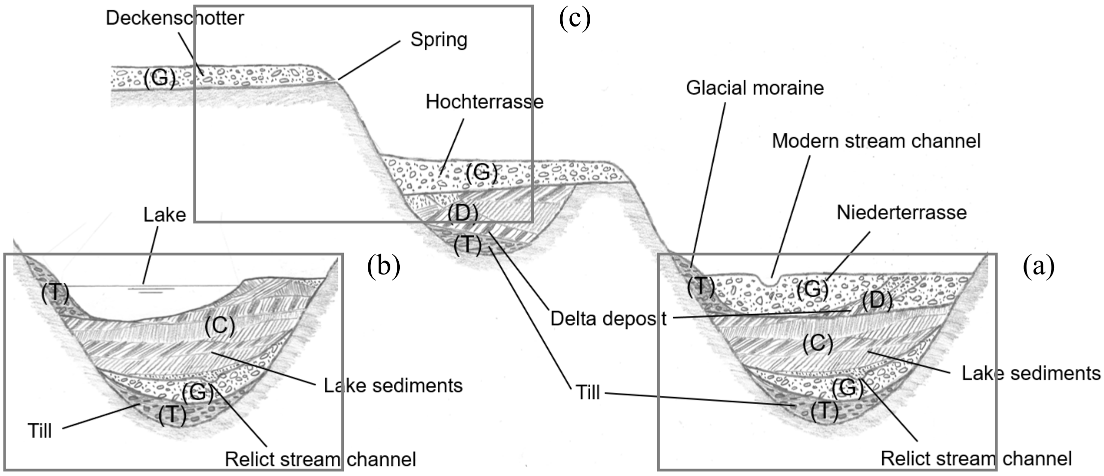

Fig. 3-9: Schematic morphostratigraphic diagram and lithostratigraphic units of accessible near-surface Quaternary deposits in the northern Swiss Plateau

Inspired by figures in Graf & Müller (1998), Müller et al. (2002) and Buechi et al. (2018).

The schematic profile shows a typical sequence of glaciofluvial and glaciolacustrine deposits in Northern Switzerland. Generally, the higher terraces are older than those at lower elevation (Nagra 2008c, Nagra 2014). (G), (D), (C) and (T) mark potential locations of glacial deposits presented in Fig. 3-4.

Boxes indicate the three distinct variants considered for post-glacial configurations that provide a basis for the consequence analysis: (a) river, (b) lake and (c) spring.

3.1.6 Landscape elements incorporating glacial deposits

Based on the distribution and profiles of glacial sediment deposits and accounting for different surface water features and hydrogeological conditions (Fig. 3-5 to Fig. 3-9), three representative biosphere variants (hereafter called variants) were defined (illustrated with boxes in Fig. 3-9). These represent near-surface environments from landscapes known to exist in Switzerland and can include material deposited after erosion and transport through an overdeepening (Fig. 3-9):

a) River incised into a glaciofluvially deposited outwash plain (Fig. 3-9a). This situation represents a typical river valley in the northern Swiss Plateau and largely corresponds to the Rafzerfeld example (Fig. 3-6c), downstream of buried overdeepenings in the Thur Valley. The extensive Niederterrasse gravel deposits constitute a thick aquifer.

b) Lake in an overdeepened basin (Fig. 3-9b). This situation corresponds to the postglacial lakes in the foreland of Northern Switzerland that occupy overdeepenings that have not (yet) been completely infilled. Examples are Zürichsee and Greifensee (Fig. 3-6a). The infilled example of the Marthalen Trough within the Thur Valley (Fig. 3-1) testifies to similar conditions during earlier, larger glaciations within the siting regions.

c) Spring that drains glaciofluvial terrace deposits (Fig. 3-9c). An example for this situation is Cholfirst (Fig. 3-6b), a flat-topped hill in the northern Swiss Plateau covered with Tiefere Deckenschotter gravels that directly overlie Mesozoic bedrock. Groundwater in the terrace deposit discharges through springs that develop along the hill flanks at the interface to the underlying bedrock.

These three variants characterise the sources of water used for irrigation, human consumption and agriculture (farmland). They are not an exhaustive list of landscapes, nor are they end-members, but they capture known landscape types associated with glacial processes in Northern Switzerland.

3.2 Storyboard for deep glacial erosion

Drawing on the understanding and synthesis presented in Section 3.1, the potential behaviour of excavated material and the evolution of the landscape, hydrology and biosphere is now considered for the case that the repository is directly impacted by deep glacial erosion. This section presents timelines for the way in which the system may evolve from repository erosion through to potential exposure situations. Specifically, this section describes potential evolution scenarios of the glacial system leading to the three variants identified in Section 3.1.6. The purpose is to create some plausible illustrations of how a landscape could evolve from the time of repository closure to the time of human exposure to radionuclides in the environment and to use these illustrations to understand how sediment and contaminated material could be transported by glacial (Section 3.2.1) and post-glacial processes (Section 3.2.2). These illustrations are hypothetical and are not designed to precisely replicate what could happen in a particular location; instead, they highlight important processes that could influence the spatial distribution and concentration of contaminants eroded from the repository.

At the time of closure, the repository is situated several hundred metres below the ground surface in a low-relief landscape (northern Swiss Plateau) that has some small undulations but no significant (alpine scale) mountains. The repository is located in the foreland north of the Alps, so any glacial advance is expected to come from a southeasterly direction. This situation is shown in Fig. 3-1.

For the purposes of this work, it is assumed that glaciations for which a disruption of the repository is assessed occur at 700 ka, 1 Ma, 2 Ma and 4 Ma after repository closure (Section 2.2). The duration of the glaciation is likely to be a few thousand years, with an agricultural landscape developing after glaciation on a timescale of a few thousands of years.

3.2.1 Erosion, transport and deposition during glaciation

At the onset of glaciation, climate conditions change from temperate interglacial to cold glacial. In the intervening time between repository closure and onset of glaciation, surface processes and rock uplift are expected to have decreased the depth of the repository beneath the ground surface. Previous glaciations may have occurred, eroding and depositing material, and uplift and associated river incision could have removed some of the overburden.

During glacial advance, the ice will thicken and start to erode into the subsurface. The rates and style of erosion are likely to depend on the rock type of the subsurface and the temperature at the base of the glacier. In regions of cold-based ice, the eroded material can be entrained in the ice. As the ice advances over the location of the repository, bedrock is eroded down to the repository level and material from the repository entrained within the ice is transported forward and upward by the movement of the ice. Whilst trapped in the ice, material from the repository will undergo minimal abrasion or chemical degradation, so will remain of similar grain size as in the repository.

In regions of warm-based ice, subglacial erosion and transport are dominated by fluvial action. As described in Section 3.1.3, subglacial meltwater erosion requires a high energy water flow that carries away much of the sediment from the base of the glacier. There is significant deposition of sediment as the water loses energy at the toe of the glacier. In such a high-energy, oxygen-rich environment, it is likely that any material from the repository would be subject to abrasion and chemical denudation (e.g. dissolution) as it is transported from the repository to the near-surface region in the subglacial water.

How the repository is eroded and how the excavated material is transported up an adverse slope and away from the repository will affect where it is deposited as well as the particle size of the eroded material and the degree to which dissolution might have occurred.

Where excavated material is entrained in the ice, the material will be deposited as glacial tills, initially without significant further transport, so the distribution of excavated material in the tills could look quite similar to that within the ice.

Where excavated material is predominantly transported by subglacial water, deposition will occur as the water loses energy as it rises from deep beneath the glacier, undergoing water-mediated sorting, resulting in coarse gravels closer to the ice margin and fine sediments at distal positions.

3.2.2 Post-glacial landscape evolution

Once deposited in the near-surface environment, either by retreat of the glacier or by water rising from the base of the glacier, eroded material will be subject to further transport and sorting in a braided river system that carries meltwater away from the glacier. Eroded material deposited in the accessible near-surface region could be transported and sorted by these processes (see also Section 3.1.4). In the case of a cold-based glacier, there would be limited sorting and the eroded material could include a wide range of grain sizes. For a temperate wet-based glacier, eroded material will have been sorted and the finer sediments will have been transported further.

After glaciation, the amount of sediment input into the river system will decrease, and the braided river system could coalesce into a single river channel. There could be contaminated material in the sediments on either side of the river and beneath it (within the accessible near-surface region) as well as within the overdeepening, extending back to the depth of the repository. The timescale for a change from a cold climate during glacial times to a temperate one during interglacial times in which agriculture is prevalent is uncertain. Here, an illustrative time of 5 ka is assumed between peak glaciation and agriculture being prevalent. In this agricultural landscape, contaminated material could be close to the surface over a wide area in the valley, while an individual farm could occupy only a small proportion of the area (see Fig. 3-9a, cf. Fig. 3-6c).

An alternative evolution of the system as the ice retreats could be the formation of a proglacial lake, which would form a sediment trap for contaminated material from the repository (see also Section 3.1.4). Depending on how erosion occurred at the base of the glacier, contaminated material could enter the lake as dissolved or suspended particles in water or could be released directly into the lake from melting ice. Depending on the particle size, sediment including contaminated material could be deposited relatively quickly near the ice or be suspended in the water and deposited broadly across the whole lake. Once interglacial climate conditions return, humans could start agriculture on the lake shore and make use of lake water (see Fig. 3-9b, cf. Fig. 3-6a).

A third possible configuration of glacial sediments observed in the landscape in Northern Switzerland is gravel accumulation in terrace deposits. After glaciation, incision could occur, either by a river or by a subsequent glaciation. Assuming that a river incises the sediment, this could occur within a few thousand years of glaciation. If another glacier erodes the valley, this could be at the next glaciation, i.e. roughly 100 ka later, considering the present 100 ka-cycle. When interglacial climate conditions return, a line of springs could form along the terrace edge and the water could be collected and used by humans living and farming in the valley below (see Fig. 3-9c, cf. Fig. 3-6b).

3.2.3 Distribution of excavated repository material in the post-glacial environment

The potential distribution of excavated material in the post-glacial near-surface environment depends on the processes responsible for their transport and the characteristics of the material.

The northern Swiss Alpine Foreland comprises glacial overdeepenings that necessitate the transport of eroded material from below the local erosional base up an adverse slope. A morphometric study based on the deepest erosion in overdeepenings in Northern Switzerland (Magrani et al. 2020) suggests that adverse slopes are generally low (median of a skewed distribution being 1.1°) but still potentially large enough to significantly restrict up-slope sediment transport. An estimation of the potential for subglacial fluvial sediment transport along adverse slopes of overdeepenings can be obtained by relating the basal shear stress necessary for the initiation of bed-load movement of a sediment grain to the velocity of the water flowing in the subglacial stream channel system. For realistic subglacial hydraulic conditions (e.g. typical subglacial water-flow velocities and cross-sectional area of subglacial drainage channels), the transport of material with a grain-size diameter > 0.05 – 0.10 m along adverse slopes becomes increasingly unlikely. This size is further reduced for material with a higher density, as might e.g. be appropriate for spent fuel. It can be concluded that material eroded from a repository could probably be transported as part of the sediment mass along the adverse slopes expected under glaciers in the northern Swiss Alpine Foreland.

When the adverse slope of overdeepenings lies within the range of glacio-hydraulic supercooling, the export of sediment becomes dependent on glacial transport (e.g. entrainment of sediment into the ice, glacio-tectonic deformation). This process could also transport material excavated from the repository and result in slower degradation/dissolution of the material because it would not be subject to flowing water while entrained in the ice.

Material eroded from the repository could be transported out of an overdeepened valley that intersects the repository and into the downstream glacial sedimentary sequence. However, this material would be expected to dissolve relatively rapidly under the geochemical conditions expected in the glacial environment (see also Section 2.3.3). The general implication is that the grain size of the material that reaches the near-surface environment is likely to be small and, as a result, could be more likely to be associated with finer-grained deposits.

SF and RP-HLW will release their inventory as they dissolve. After dissolution, mobile radionuclides could be transported through the system relatively quickly and be dispersed beyond the region of interest before habitation of the biosphere. Less mobile radionuclides are likely to sorb to the glacial sediments once released and potentially accumulate in sedimentary layers with high sorption such as clays. The extent of radionuclide dispersal through the system will depend on the characteristics of the glacial/post-glacial environment (sediment types, configuration, water flow rates and geochemistry), which determine how far the contamination can be transported before it becomes sorbed (i.e. reaches the biosphere or is transported beyond the biosphere).

It is assumed for the storyboards that some material eroded from the repository is present (i) in the glacial sediments between the repository and the near-surface environment, and (ii) directly in the near-surface environment at the start of the consequence analyses. The material eroded from the repository could initially be deposited in any of the sediments identified above (Fig. 3-9), namely, glacial tills (T), glaciofluvial gravels (G), delta deposits (D) and lake sediments (C).

3.3 Conceptualisation of repository excavation by glacial processes

Consideration of glacial processes (Section 3.1) and storyboards for repository excavation by deep glacial erosion, transport, deposition and reworking of excavated materials (Section 3.2) provide a basis for identifying features, events and processes (FEPs) relevant to radionuclide transport and potential exposure under this scenario. Identifying and conceptualising these FEPs provides the basis for subsequent development of mathematical models to support the quantitative assessment.

Firstly, consideration is given to processes occurring at depth and in the pathway between the remaining repository and near-surface region (Section 3.3.1). Secondly, consideration is given to biosphere processes for the river, lake and spring configurations (Section 3.3.2). These are then drawn together in a conceptual model for radionuclide behaviour and potential exposure (Section 3.3.3).

3.3.1 Repository excavation and pathway to the near-surface

For the purpose of assessing potential dose consequences, it is assumed that some fraction of the repository is directly affected by deep glacial erosion, such that a proportion of the disposed material is transported by glacial processes and is deposited both (i) in the pathway from depth to the near-surface region, and (ii) directly in the near-surface/biosphere itself (see Fig. 3-10 and Fig. 3-11). These two components are directly assessed.

For the consequence analysis, neither the excavation event itself nor the transport and deposition of excavated material due to glacial processes are explicitly represented. The modelling starts with the material that has been deposited and is present in the post-glacial landscape, after which humans could return and potential exposures might arise. The potential for radionuclides to have left the repository prior to excavation is ignored; this is pessimistic because there would be a greater degree of dispersion as a result of these processes.

In addition to radionuclide release arising from the material excavated from the repository, there is also potential for radionuclides to be released from material left at depth within the remaining repository (see also Fig. 3-10). Radionuclides associated with the excavated material itself will be more readily available for release compared to material within the remaining repository at depth (e.g. isolated within the emplacement drifts). Consequences associated with excavated material are, therefore, taken to dominate and the material in the remaining repository is not considered further.

Consideration is given to the potential for excavated repository material to be initially deposited along with granular material (e.g. in fragments that would be expected to release contamination relatively quickly, as discussed in Section 2.3.3) and within low-permeability, finer sediments (including clays).

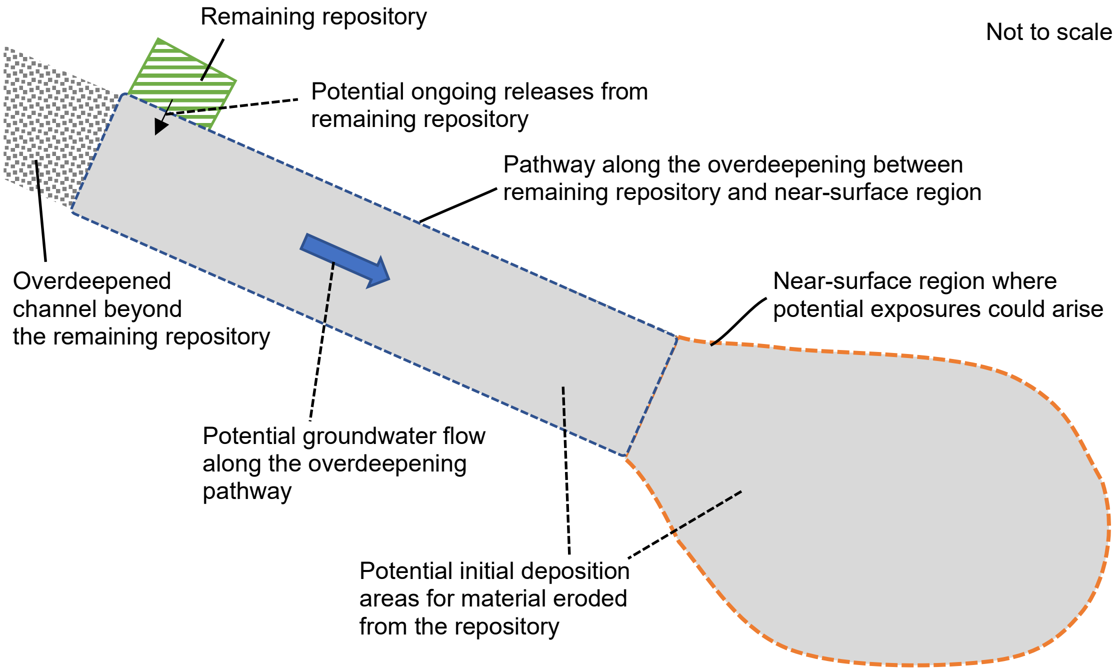

Fig. 3-10: Plan view providing a schematic illustration of overdeepening cutting through the remaining repository and a deposition zone in the accessible near-surface region

A zone within the overdeepening that can both include excavated material and act as a pathway along which groundwater can flow to the more easily accessible near-surface zone is shown by a blue dashed line. A shallower, more accessible near-surface zone beyond the overdeepening, which can also include excavated material, is indicated with an orange dashed line (this is discussed further in Section 3.3.2).

The pathway from the repository to the near-surface region is conceived as a channel of sediments with a constant width and height/thickness. The channel is taken to include permeable layers (cf. Fig. 3-8). The location of discharge from the groundwater pathway to the near-surface region is a key consideration in specifying the calculation cases (see Section 3.4). The processes relevant to the pathway are indicated in Fig. 3-11.

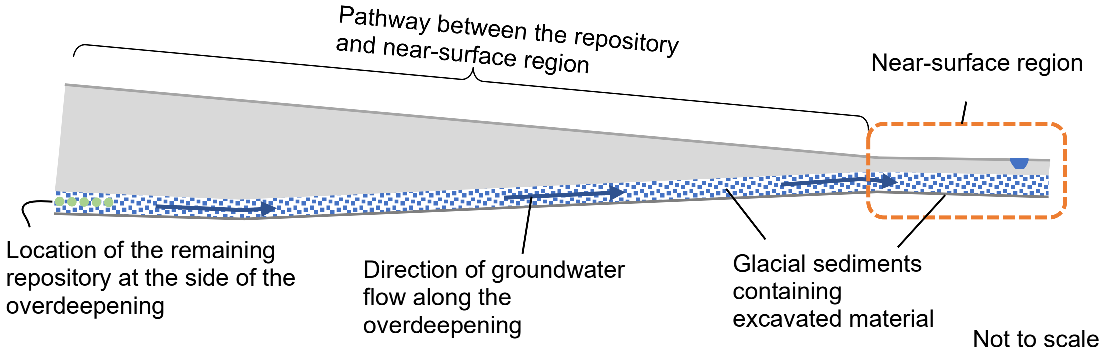

Fig. 3-11: Conceptual model (downstream cross-section) for the pathway between the repository and the near-surface region

Green indicates the remaining repository zone and blue the groundwater flow through sediments that can include excavated material. There is potential for groundwater flow from depth towards the near-surface region along the pathway due to water pressure at depth exceeding hydrostatic pressure (e.g. due to confinement). The near-surface region is discussed further in Section 3.3.2.

Tab. 3-1 lists the FEPs considered in evaluating radionuclide transport in the pathway from the repository to the near-surface region in the post-glacial period[5]. Material deposited directly within the near-surface region, as well as radionuclide transport and potential exposure in that region are considered in Section 3.3.2.

Radionuclide transport in the pathway within the overdeepening is taken to be dominated by groundwater advection, such that diffusion need not be explicitly considered.

Tab. 3-1: Features, events and processes (FEPs) between depth and near-surface to be considered following excavation of the repository by deep glacial erosion, transport by glacial processes and associated deposition

Category	Items
Features	• The fill material deposited by glacial processes within the potential pathway between the remaining repository and near-surface region, including material eroded from the repository.
Events and processes	• Degradation/dissolution of the material eroded from the repository. • Groundwater flow. • Advection/dispersion. • Dilution. • Sorption onto the solid phase within the pathway.

5 Nagra's general FEP database (Nagra 2024f) does not specifically consider the effects of the repository excavation scenarios on the FEPs. Nonetheless, the list of FEPs considered here (and in Section 3.3.3 and 4) has been reviewed against the general FEP list to ensure consistency.

3.3.2 Description of near-surface processes

Three potential landscapes that could contain material eroded from a repository are identified in Section 3.1.6. The river, lake and spring variants (Fig. 3-9) were chosen to envelope the range of configurations that could arise and, between them, are considered to bound potential consequences. The FEPs relevant to the movement of mass and water within the landscapes are listed in Tab. 3-2; these are relevant because they are the primary mechanisms for radionuclide transport in the near-surface region following deposition. The FEPs draw on Nagra's established biosphere modelling approach (Nagra 2024g).

The resulting conceptualisations are discussed and illustrated in Fig. 3-12 to Fig. 3-14. the corresponding radionuclide transport is then considered in Section 3.3.3.

Tab. 3-2: Features, events and processes (FEPs) for mass and water flows within the near-surface region following excavation and deposition

Note that the focus on mass and water flows means that other processes relevant to radio-nuclide transport, including sorption and diffusion, are not listed here, although they are explicitly considered in the subsequent conceptual model (Section 3.3.3). There are no "events" in this context.

The letters assigned to the Processes refer to Fig. 3-12, Fig. 3-13 and Fig. 3-14.

Category	Items
Features	• Aquifer (water-bearing, high-permeable subsurface layer). • Aquitard (bed of low permeability along an aquifer or solid, impermeable area underlying or overlying an aquifer. If the impermeable area overlies the aquifer, pressure could cause it to become a confined aquifer). • Saturated zone (including aquifer and aquitard, see above). • Unsaturated zone. • Sedimentary units (glacial deposits). • Surface water (river, lake or spring). • Sediments beneath surface water (river or lake sediments). • Soil. • Plants (crops and natural vegetation). • Animals (livestock, fish and other animals). • Atmosphere. • Humans.
Processes	a) Precipitation. b) Evapotranspiration. c) Overland flow and erosion. d) Infiltration and bioturbation. e) Bioturbation and capillary flow. f) Near-surface interflow. g) Surface water flow. h) Sedimentation. i) Resuspension. j) Groundwater recharge from surface water (not present in lake variant). k) Groundwater recharge from soils. l) Groundwater flow. m) Irrigation from the river or groundwater. n) Deposition of bed sediments on river/lake bank. o) Groundwater discharge to surface water (only present in connected river system). p) Interflow (uncontaminated shallow groundwater flow, only present in the spring variant). q) Discharge in springs.

Fig. 3-12 shows a conceptual model for the river variant. The depth to the water table (indicated by the blue triangle) means that the shallow groundwater is directly connected to the river, which reflects the Rafzerfeld system, where the river is incised into the gravels. In this context, ground-water can discharge to the river, and it is possible for the river to recharge into the groundwater. This is called a connected river system. In situations where the water table is disconnected from the surface water, there can only be recharge from the river to the groundwater. For the purpose of consequence analysis here, the assessment is based on a connected river system. This situation is pessimistic compared to a disconnected river, because the groundwater, which can interact directly with material eroded from the repository, discharges to the surface water, from where potential exposure can occur.

Material eroded from the repository could initially be deposited in the sediments beneath the river, and water contaminated with radionuclides deposited in the pathway from the repository to the near-surface region could enter the shallow aquifer. When humans return to the environment in the subsequent interglacial period, potential doses will be derived from occupying and farming the land adjacent to the river.

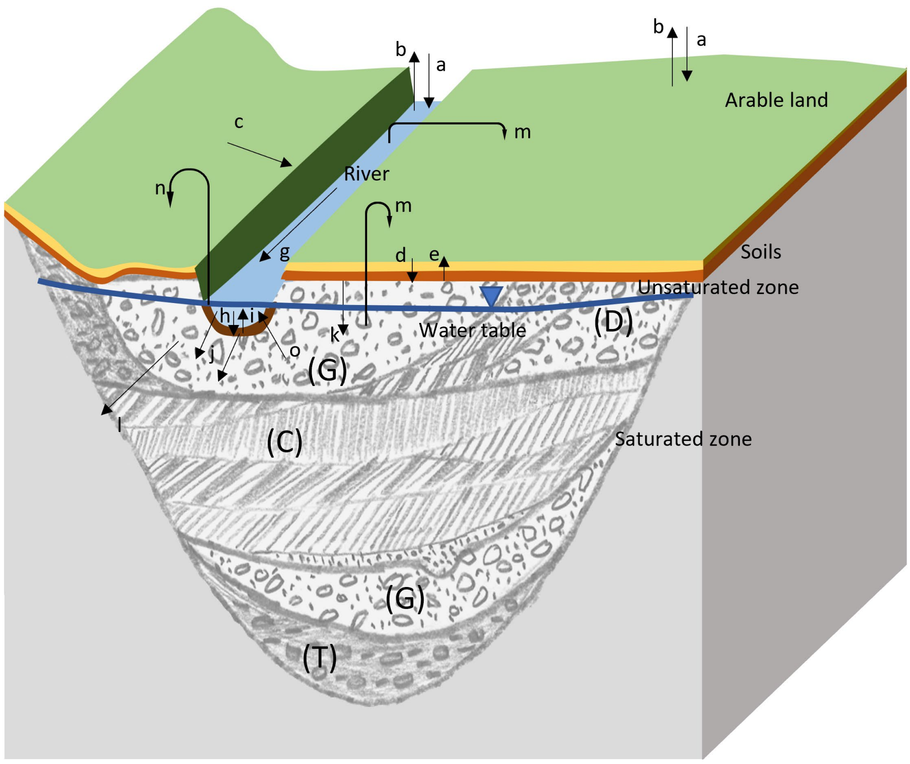

Fig. 3-12: Illustration of the near-surface environment associated with the river variant, showing the main features and processes relevant to mass and water transport

The depth to the water table means that the groundwater is directly connected to the river (i.e. a connected river system). Lowercase letters represent the transport processes of both water and sediments (defined in Tab. 3-2). Uppercase letters represent the sedimentary units (explained in Section 3.1.5 and Fig. 3-9). Note that the clay layer (C) represents an aquitard separating two more permeable layers.

For the lake variant, once humans return to the local environment, eroded material ending up in post-glacial deposits beneath a lake and contaminated water from material deposited in the pathway from depth discharging to the lake could result in exposure. The processes considered in this conceptual model are shown in Fig. 3-13. There is no connection between the surface water in the lake and the groundwater below the thick, impermeable lake sediments ("C" in Fig. 3-13).

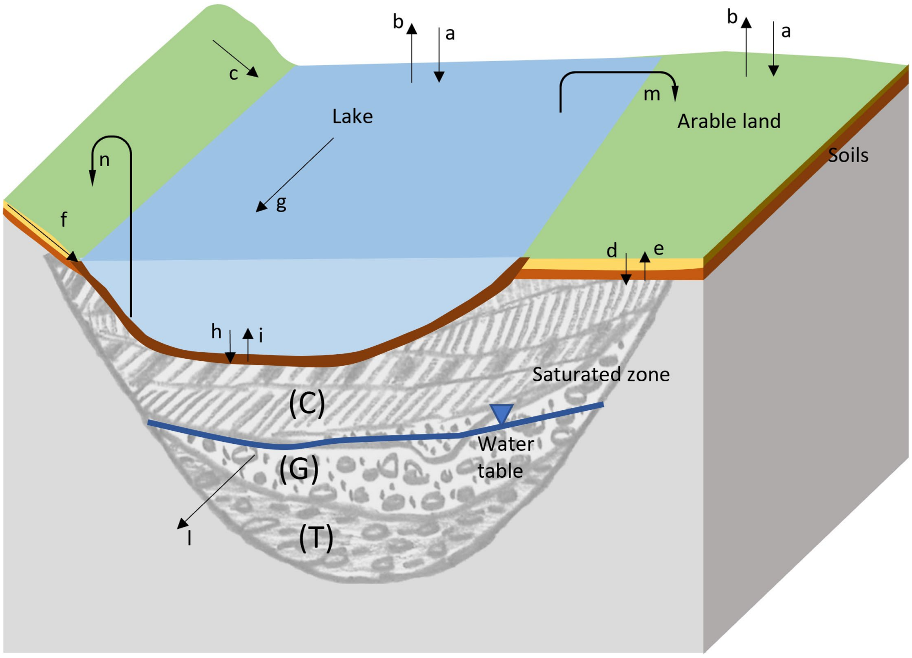

Fig. 3-13: Illustration of the near-surface environment associated with the lake variant, showing the main features and processes relevant to mass and water transport

Lowercase letters represent the transport processes of both water and sediments that could move radionuclides from the deposition site to a location that could cause radiological exposure (defined in Tab. 3-2). Uppercase letters represent the sedimentary units (explained in Section 3.1.5 and Fig. 3-9). The clay layer (C) isolates the lake from the permeable sediments below.

If material excavated from the repository at depth were deposited within near-surface sediments that end up as terrace deposit by progressive incision during successive glacial-interglacial cycles, exposure could occur through contaminated spring discharges. Due to the hilltop location of the post-glacial sediments, no groundwater connection between the remaining repository and the springs is expected. A conceptual model for this situation is shown in Fig. 3-14. Water infiltrating at the top of the hill hits a low-permeability aquitard and moves laterally to discharge in springs along the hill flanks.

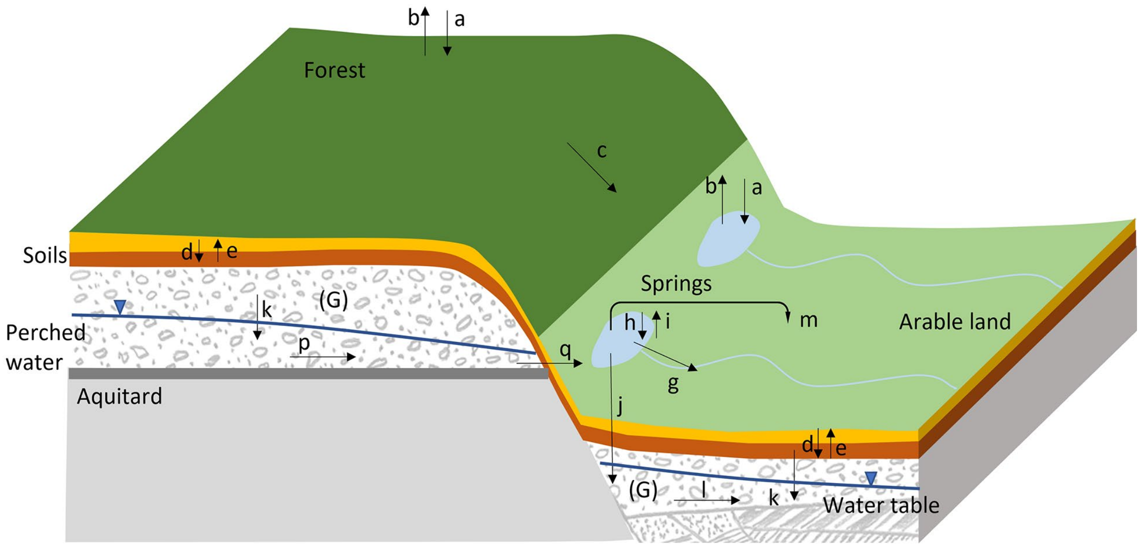

Fig. 3-14: Illustration of the near-surface environment associated with the spring variant, showing the main features and processes relevant to mass and water transport

Lowercase letters represent the transport processes of both water and sediments that could move radionuclides from the deposition site to a location that can cause radiological exposure (defined in Tab. 3-2). Uppercase letters represent the sedimentary units (explained in Section 3.1.5 and Fig. 3-9).

Flooding directly onto land from the springs is considered unlikely, so deposition of sediment from the springs onto the surrounding land (process n) is not included. Groundwater recharge to the surface water (o) is assumed not to occur because the springs are well above the regional groundwater.

3.3.3 Conceptual model for radionuclide transport and potential exposure

Consideration of the excavated material and the processes occurring in the river, lake and spring variants in Section 3.3.2 provides a basis for (i) understanding the behaviour of radionuclides within those systems following excavation by deep glacial erosion, and (ii) potential exposure pathways. These are described below using compartment model schemes[6].

Conceptual model for radionuclide transport

The conceptual model for radionuclide transport in the near-surface region is built around a generic compartment model structure and is capable of representing radionuclide transport leading to exposure in the landscape variants being considered. Although this features a simplified representtation of the landscapes, the modelling approach represents the key features, events and processes that have been identified, suitable for implementation in a generic numerical model.

[6] This approach represents features within which radionuclide retention needs to be evaluated as discrete 'compartments', with events and processes that can move radionuclides between compartments being explicitly represented as transfers. By defining the characteristics of the system and by defining the processes and events in terms of rates of transfer, the conceptualisation can be translated into a mathematical representation allowing quantitative evaluation – see also Nagra (2024g).

The structure and processes that are included in the conceptualisation are very similar to the structure of Nagra's established biosphere modelling approach that is represented in the Swiss Biosphere Assessment Code (SwiBAC) (Nagra 2024g) and are illustrated in Fig. 3-15. There is additional refinement in the subsurface layers, compared to SwiBAC, to reflect greater focus on the structure of sediments deposited following glacial excavation; in place of the variably saturated zone and aquifer compartments in SwiBAC, a sequence of sediments is represented to correspond to the schematic sedimentary columns illustrated in Fig. 3-12 to Fig. 3-14.

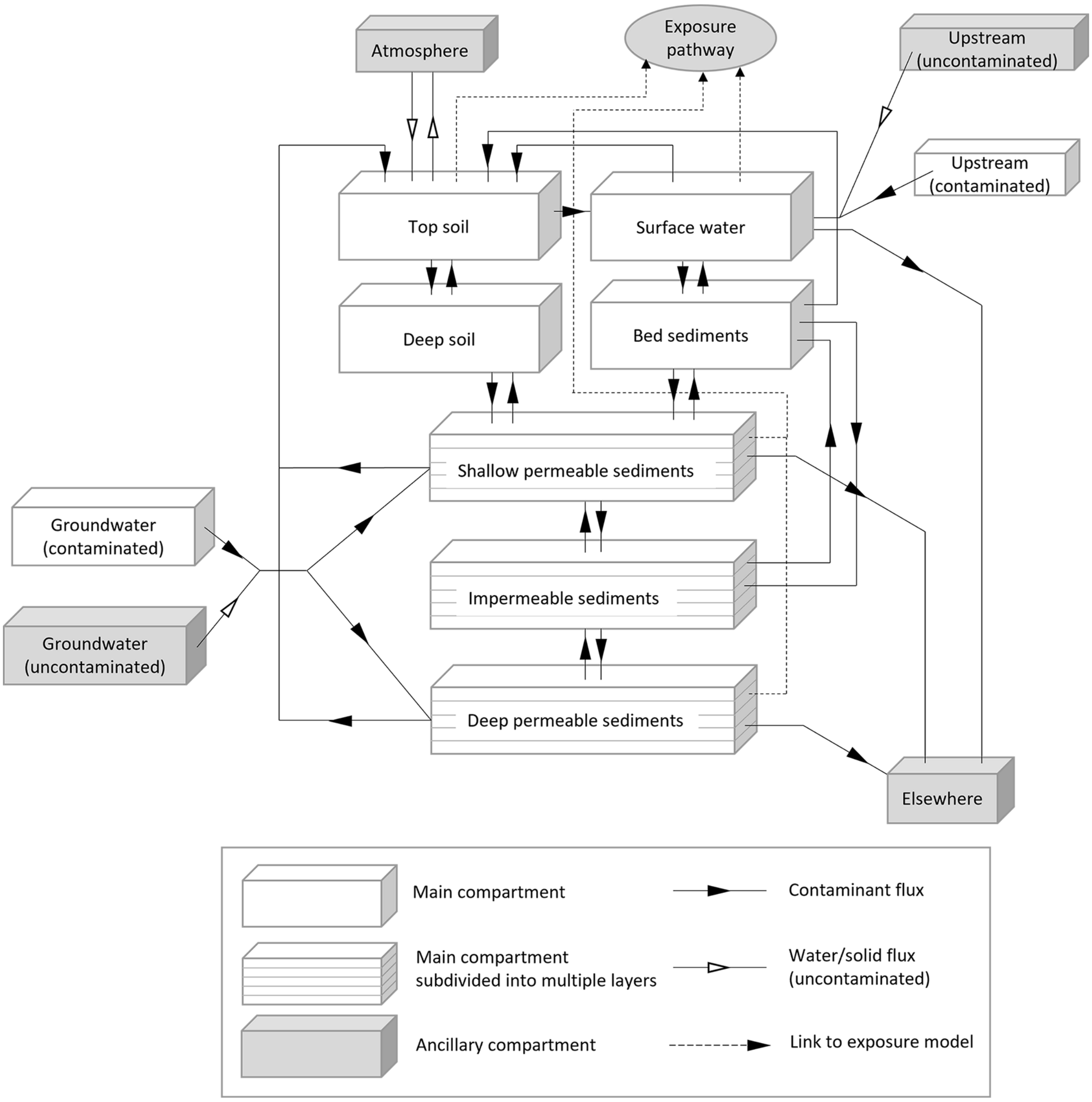

Fig. 3-15: Conceptual model of transfers (water or solid) that contain radionuclides (solid arrows) or uncontaminated material (open arrows)

Note that the structure is very similar to that used in Nagra's general biosphere modelling, as represented in SwiBAC (Nagra 2024g), with greater resolution in terms of layers beneath the deep soil and bed sediments to reflect greater interest in post-glacial sediments in the context of excavation by deep glacial erosion.

In all variants, contaminated material could, in principle, accumulate in any of the deposits (C, G, D, T, see Fig. 3-12 to Fig. 3-14). There is no groundwater flow through the sedimentary unit C (clay) due to its low permeability, although radionuclides could migrate from and through the unit via diffusion. Any radionuclides deposited in shallow permeable sediments above the low-permeability unit (C) will interact with the shallow groundwater system (deep soil, surface water and bed sediments). Radionuclides deposited in deep-permeable sediments below the low-permeability unit (C) will only interact with the shallow groundwater system via diffusion across the clay; this situation would result in lower potential doses and is thus not considered further.

The conceptual model allows for any of the sedimentary units to be unsaturated or saturated, as required for each specific case. By using different thicknesses of the sedimentary units, including or excluding certain transfers, and by adapting parameterisation, the model is capable of representing the three landscape variants described above. The processes listed in Tab. 3-2 are either explicitly included in the conceptual transport model (they map directly onto contaminant transfers), implicitly included (they influence other contaminant transfers), or excluded (e.g. if they are not relevant for contaminant transport for a specific variant).

The river variant (Fig. 3-12) makes use of all compartments and transfers except those connecting the bed sediments to the impermeable sediments. It is assumed that the bed sediments will always sit on top of the shallow permeable sediments (glaciofluvial gravel (G) and delta deposits (D)). In the near-surface region, material eroded from the repository is taken to be deposited in a layer at the base of the shallow permeable sediments, maximising the degree of interaction between the initially contaminated material and groundwater that might be used for drinking water. An alternative situation is also considered, in which the excavated material is fine-grained and sits at the top of the clay layer immediately beneath the local aquifer. Like Rafzerfeld, the river is cut into the unsaturated zone, i.e. there is a direct connection between the river and the aquifer.

The lake variant (Fig. 3-13) is similar to the river variant, with the main differences being the relative compartment sizes. The lake sits above low-permeability sediments (C), so there is a direct transfer between the bed sediments and the clay. Material eroded from the repository is taken to be deposited at the top of the low-permeability sediments beneath the lake. For agriculture and exposure, soils are assumed to be present along the sides of the lake, overlying the impermeable sediments. Use of groundwater from deep permeable sediments beneath a large lake is implausible, so the potential for groundwater discharge below the impermeable sediments need not be assessed.

In the spring variant (Fig. 3-14), the deeper parts of the glacial sediments are not relevant. It is assumed that material excavated from the repository is deposited in permeable glaciofluvial gravels that are perched as a terrace on a hilltop; the permeable layer will be saturated at the bottom and unsaturated higher up. It is pessimistically assumed that material excavated from the repository is deposited within the saturated layer at the base of the shallow permeable sediments, maximising the degree of interaction with groundwater emerging at the springs. The surface water fed by the springs could be used to irrigate agricultural land. The presence of springs means that it is unlikely that water would be taken from a well in the permeable terrace deposit. If the flow rate of contaminated water from the springs is insufficient to satisfy the water demand (which is high because of the irrigation demand), it can be supplemented with additional uncontaminated water (e.g. from other nearby springs). Transfers representing irrigation from groundwater and flooding are not required.

The near-surface river and lake systems shown in Fig. 3-12 and Fig. 3-13 could remain in contact with the overdeepening. In both cases, it is pessimistically assumed that deposition between the repository and the near-surface region occurs within a permeable gravel fill, such that a groundwater pathway exists that connects the remaining repository at depth and excavated material that is deposited within the overdeepening to the near-surface (illustrated in Fig. 3-11).

For the river variant, this pathway represents the "groundwater (contaminated)" source shown in Fig. 3-15. For the lake variant, this pathway represents the "upstream (contaminated)" source shown in Fig. 3-15 and either represents direct groundwater discharge to surface water, or discharge to an upstream river that feeds into the lake.

The deposition of sediment in a terrace necessary for the spring variant means that a potential connection with the original overdeepening will have been lost, such that there is no longer any pathway from depth in that variant.

Conceptual model for potential exposures

The variants seek to evaluate potential dose consequences once humans have returned to the landscapes following excavation by deep glacial erosion. The climate is taken to be temperate, consistent with the present day, because this supports a wide range of potential exposure pathways, including agricultural production. Nagra's reference biosphere modelling, as represented in SwiBAC (Nagra 2024g), includes the same climate conditions and range of potential exposure pathways as are relevant for the evaluation of the repository excavation scenario. Therefore, conceptualisation of potential exposure pathways and associated FEPs can draw upon the same approach as adopted in Nagra's established biosphere modelling (Nagra 2024g). The potential exposure pathways are illustrated in Fig. 3-16.

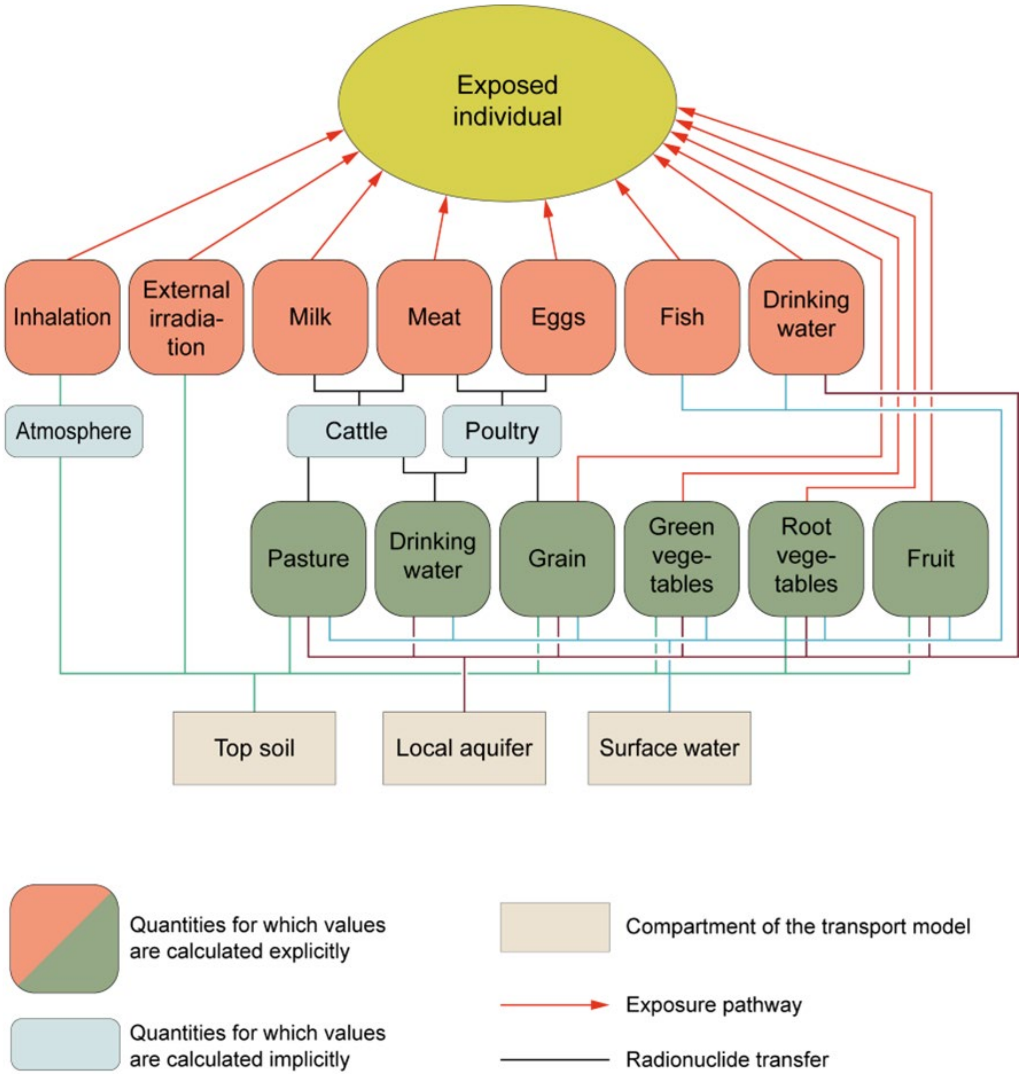

Fig. 3-16: Potential exposure pathways represented

These pathways are fully consistent with (Nagra 2024g).

The consequence analysis is made on the basis that the configurations being considered exist at the time that potential exposures could occur, such that the processes involved in deep glacial erosion, transport and deposition need not be explicitly represented. In practice, a substantial amount of time will be needed before exposures could potentially occur, allowing for the correspondingly required transport, deposition, reworking of sediments, climate changes, soil development, etc. Based on consideration of timescales for climate change and for human habitation of the Alps following the last glaciation, a minimum timescale of 5,000 years between excavation and potential exposure has been adopted for the river and lake variants.

Once potential exposures become feasible, groundwater within the shallow permeable sediments is taken to provide the principal source of water for domestic and agricultural purposes in the river variant (consistent with assumptions in Nagra's established biosphere modelling approach (Nagra 2024g)); this groundwater interacts directly with material deposited after being excavated from the repository. For the lake variant, the lake water itself is taken to provide the principal source of water used by humans.

The deposition of eroded material as glaciofluvial gravels in a terrace perched on a hilltop necessary for the spring variant requires erosion and sedimentation by repeated foreland glaciations. Such erosion could occur as a consequence of a subsequent glacial episode, which would require a full interglacial and glacial cycle to occur after repository erosion, such that potential exposures from this configuration would only be able to occur around 100,000 years after initial erosion. It is pessimistically assumed that none of the contamination initially deposited in the near-surface environment is lost as a result of the progressive incision during successive glacial-interglacial cycles. Also, in the absence of a viable pathway from the remaining repository, all of the originally eroded material is pessimistically taken to be deposited within the near-surface region.

3.4 Calculation cases associated with excavation by deep glacial erosion

The river, lake and spring variants provide the basis for three situations that envelope a plausible range of post-glacial conditions following excavation by deep glacial erosion. Given the diversity of near-surface conditions encompassed by the variants, a single calculation case is considered sufficient to explore the range of potential dose consequences for each of the lake and spring variants. However, due to the greater complexity in near-surface sediments for the river variant, two cases are used to explore different assumptions about where material excavated from the repository may have initially been deposited.

In addition to the type of near-surface system, calculations need to explore the range of potential timescales for excavation by deep glacial erosion. These are discussed in Section 2.2, which identifies timescales of 700 ka, 1 Ma, 2 Ma and 4 Ma after repository closure.

The resulting calculation cases are summarised in Tab. 3-3. In addition to these cases, sensitivity calculations are used to identify important processes and parameters. These are described in Section 3.6.2.

Tab. 3-3: Calculation cases for assessment of excavation by deep glacial erosion for excavation times of 700 ka, 1 Ma, 2 Ma and 4 Ma after repository closure

For the river and lake variants, deposition within the deep permeable sediments (below the impermeable layer in Fig. 3-12 and Fig. 3-13) need not be considered because of the greater potential dose consequences of deposition within the shallow permeable sediments.

Variant	Case	Summary
Ra	Base river case	River variant with excavated material initially deposited in the shallow permeable sediments (upper G and D in Fig. 3-12); groundwater connected to the river. Water for drinking, animal husbandry and irrigation drawn from the shallow aquifer.
Rb	Alternative river case	River variant with excavated material initially deposited in the impermeable layer below the shallow permeable sediments (lower G and T in Fig. 3-12); groundwater connected to the river. Water for drinking, animal husbandry and irrigation drawn from the shallow aquifer.
L	Lake case	Lake variant with excavated material initially deposited in the impermeable sediments below the lake (Fig. 3-13). Water for drinking, animal husbandry and irrigation drawn from the lake.
S	Spring case	Spring variant with excavated material initially deposited in the permeable sediments on the hilltop (Fig. 3-14). Water for drinking, animal husbandry and irrigation drawn from the spring.

3.5 Model for calculating doses due to repository excavation by glacial processes

FEPs associated with radionuclide transport and potential exposure following excavation by deep glacial erosion overlap considerably with those in the SwiBAC code (Nagra 2024g). Radionuclide transport and retention within SwiBAC are based on a flexible approach using the AMBER generic compartment-modelling code (Quintessa 2023a).

Given the degree of commonality in FEPs and the flexibility of the underlying AMBER code, the SwiBAC compartment-modelling approach is used as a basis for modelling potential consequences of excavation by deep glacial erosion. The SwiBAC models are established and, importantly, include water and mass balance as a fundamental prerequisite. Much of the SwiBAC modelling approach is retained, including radioactive decay and ingrowth, the requirement for water and mass balance, the compartment-modelling concept, models for moving radionuclides by water and mass transfers, including sorption, and evaluation of potential exposures. Description of the mathematical modelling approach in this report can, therefore, focus on the adaptations/extensions required to represent the excavation context.

3.5.1 Pathway between the repository and near-surface

A specified fraction of the radionuclide inventory within the repository at the time of excavation by deep glacial erosion is deposited (i) directly in the near-surface environment, and (ii) in the pathway in the overdeepening between the repository and near-surface, where it exists. The distribution of the excavated radionuclide inventory between these two regions represents an area-weighted average.

Radionuclides are taken to become available for leaching and advection in groundwater from the deposited material at a constant rate that depends on a represented lifetime of eroded material within the pathway and the near-surface region. While relatively stable under repository conditions, eroded material is expected to last only tens to hundreds of years in the active and oxidising conditions following excavation.

Once released from the eroded material, radionuclides could migrate along the pathway towards the near-surface region with groundwater and suspended sediment. A Darcy model is used to determine the groundwater flow rate, which is characterised by the hydraulic conductivity, hydraulic gradient and cross-sectional area perpendicular to the flow.

The pathway from the repository depth to the near-surface is discretised into five compartments; this ensures a suitable degree of time-dependency in the release rate to the near-surface, taking numerical dispersion and physical dispersion into account (see Appendix B to Quintessa 2023b).

Radionuclide transport along the overdeepening is then determined based on SwiBAC's representation of transfers via water flow, including sorption/desorption and suspended solids.

3.5.2 Near-surface environment

The entire area within which material excavated from the repository could be deposited in the near-surface environment is explicitly represented. The reference biosphere model that forms the basis of SwiBAC includes a single compartment for the local aquifer and a single compartment for the variably saturated zone above the local aquifer and below the deep soil (Nagra 2024g). The storyboards presented in Section 3.2 and the associated conceptualisation in Section 3.3 have a greater degree of complexity in vertical structure compared to the base SwiBAC implementation. Additional vertical discretisation is, therefore, required in the near-surface system to:

- enable explicit representation of sedimentary units of different post-glacial sediments, as shown in Fig. 3-15, using:
  - five compartments to represent diffusion across low-permeability clay units (sedimentary unit C) where diffusion is dominant;
  - four compartments to represent the shallow permeable sediments above the impermeable layer; and
  - another four compartments to represent the deep permeable sediments below the impermeable layer;
- enable a layer of post-glacial sediments containing the material eroded from the repository to be explicitly represented at different depths.

Where vertically adjacent compartments are both fully saturated, a degree of vertical dispersion is explicitly represented in advective transfers.

For the lake variant, the surface water and bed sediment sit directly above the impermeable layer, so the shallow permeable sediments need not be represented. In the spring variant, the impermeable and deep permeable compartments are not used, and there are advective transfers from the shallow permeable sediments directly into the surface water.

While the full deposition area is modelled for post-glacial sediments (25 km^2 – see Tab. 3-4), only a smaller area of soils (2.275 km^2) situated atop those sediments is explicitly modelled in support of the dose calculations to ensure consistency with SwiBAC assumptions, especially in the evaluation of potential exposures. For the river variant, the soil compartments effectively sit on top of the shallow permeable sediments. For the lake variant, they are adjacent to the surface water, and for the spring variant, they are effectively down-slope from the contaminated hilltop sediments/springs.

The flow along the pathway from the remaining repository (see Section 3.5.1) could feed into any of the saturated permeable sediment compartments in the near-surface region, or into the surface water body. Where the flow from the remaining repository is less than the assumed flow through the near-surface sediments (or surface water), the remainder of the supplied groundwater (or surface water) is assumed to be uncontaminated water.

Water for irrigation and drinking could be drawn from the surface water or from a groundwater well. This groundwater well could draw water from any of the saturated permeable sediment compartments. Water is assumed to be drawn from the bottom 10 m of the sedimentary unit in which the well is located; the contaminant concentration in the well water is calculated by averaging the concentration across the compartment heights that are intersected by this 10 m region. The water required for drinking is not subtracted from the water balance as it is a small volume compared to the total volume of groundwater and to the water required for irrigation.

As in the reference SwiBAC model, infiltration through the topsoil passes down through the deep soil into the shallow permeable sediments in the river variant. For the lake and spring variants, infiltrating water is directed back to the surface water.

In the reference SwiBAC model, solid material is transported from the topsoil to the surface water as a result of erosion. There is no flux of solid material from bed sediments to topsoil due to dredging and no deposition of uncontaminated solid material onto the topsoil that could compensate the mass loss due to erosion. The mass balance is therefore maintained by solid material transfer from the deep soil to the topsoil, and then from the permeable sediments to the deep soil (i.e. weathering and pedogenesis). Although the non-irrigated soil area is not explicitly represented as a compartment in the model, the erosion of that soil area is included in the mass transport balance. The overall long-term mass balance means that compartment volumes are not to be affected by net erosion.

3.5.3 Potential exposures

The FEPs described above result in a time-dependent distribution of radionuclides in the compartments representing the near-surface region after excavation (including surface soils, surface water and bed sediments). As in the reference biosphere modelling in SwiBAC, the resulting concentrations in soils, surface water and groundwater provide a basis from which potential dose consequences can be evaluated.

The equations used to calculate (i) concentrations in the compartments and in features that are taken to be in equilibrium with those compartments (like the atmosphere, crops and animal produce), and (ii) potential exposure rates and dose consequences, are the same as those used in reference biosphere modelling in SwiBAC and are not reproduced here (Nagra 2024g).

Potential exposures can only arise once humans return to the landscape after excavation by deep glacial erosion. As discussed in Section 3.2, this is taken to be 5,000 years after excavation for the river and lake variants, and roughly 100 ka after excavation for the spring variant.

3.6 Data for dose calculations due to repository excavation by deep glacial erosion

The basis for modelling radionuclide transport and potential exposures following excavation by deep glacial erosion is described in the sections above. The resulting mathematical model is supported by data that are summarised in the following subsections. The parameter values themselves, including supporting arguments, are described in Section 3.6.1. Assumptions and uncertainties are discussed in Section 3.6.2, which describes the approach adopted to identify important processes and parameters via sensitivity calculations.

3.6.1 Data for consequence analyses

Where available, parameter values used for assessment of potential dose consequences following excavation by deep glacial erosion are drawn from the reference biosphere modelling (Nagra 2024g). Adaptation and extension of the reference biosphere model to represent the additional FEPs associated with modelling radionuclides deposited in the pathway from depth and within the near-surface region means that additional data are needed. Where practicable, those data are based on consideration of analogous systems available in present-day Northern Switzerland.

The assessment adopts a deterministic approach. Plausible assumptions are used, erring on the side of being pessimistic (i.e. overestimating potential dose consequences). Parameter values generally represent best estimates, and a balance is struck in assuming that humans could be present and make maximum use of local, potentially contaminated, materials, consistent with Nagra's reference biosphere modelling. Sensitivity calculations are subsequently used to vary parameters over plausible ranges to help identify the important processes and assumptions (these are discussed in Section 3.6.2).

Parameters consistent across all three variants are presented in Tab. 3-4 and those specific to the river, lake and spring variants are then presented in Tab. 3-5, Tab. 3-6 and Tab. 3-7, respectively.

Tab. 3-4: Generic parameters for assessment of excavation by deep glacial erosion

Parameter values consistent with reference biosphere modelling (Nagra 2024g) are not reproduced here. Sensitivity to parameter assumptions is discussed in Section 3.6.2.

Parameter	Value	Notes
Canister inventory and number of canisters	See Notes column	Based on the radionuclide inventory for the general licence applications (RBG) (Nagra 2023)
Fraction of repository eroded	0.1	Varied in sensitivity calculations
Lifetime of eroded material following excavation (radionuclides are released at a constant rate over this period)	100 a	Based on review of potential particle sizes for eroded material and dissolution rates for spent fuel (representing the majority of the relevant inventory) under oxidising conditions
Length and width of the pathway from depth	10 km × 1 km	Based on general review of the nature of existing overdeepenings in Northern Switzerland
Thickness of saturated layer within the pathway from depth	10 m	Taken to be the same as the thickness of the saturated zone in the near-surface region for the river variant
Hydraulic gradient in the pathway from depth	0.75‰	Taken to be half the hydraulic gradient in the near-surface due to the adverse slope
Surface area of the near-surface deposition area	25 km^2	Based on gravel area mapped in the Rafzerfeld
Hydraulic gradient in the near-surface region	1.5‰	Based on groundwater gradients in 15 different regions in Northern Switzerland (Haldimann & Schatzmann 2014)
Total porosity of sediments	See Notes column	Based on sedimentary material described in Carsel & Parrish (1988) and Domenico & Schwartz (1998)
Element-dependent solid:liquid equilibrium sorption coefficients (K_d)	See Notes column	Based on review and update in preparation for the RBG (Metcalfe et al. 2023); the gravels adopt sorption values for coarse aquifer material and the lake deposits adopt values for fine, low-organic-content material
Hydraulic conductivity of gravels	$1 \times 10^{-2.5}$ m s^{-1}	Based on pumping tests from 15 different regions in Northern Switzerland in Haldimann & Schatzmann (2014) and relatively young unconsolidated fluvio-glacial and fluvial sediments in the Rhine basin in Bayer et al. (2011)

Tab. 3-5: River variant parameters for assessment of excavation by deep glacial erosion

<table>
<tr><th colspan="2">Parameter</th><th colspan="2">Value</th><th>Notes</th></tr>
<tr><td colspan="2">Length and width of surface water</td><td colspan="2">15 km long by
80 m wide</td><td>Typical length of a river section in Northern Switzerland extracted from Gmünder et al. (2014); width based on consideration of larger rivers in Northern Switzerland</td></tr>
<tr><td rowspan="4">Vertical thickness of sedimentary units</td><td colspan="2">Shallow permeable gravel</td><td>40 m</td><td rowspan="4">Based on consideration of Rafzerfeld and similar valley cross-sections</td></tr>
<tr><td colspan="2">Impermeable clay</td><td>100 m</td></tr>
<tr><td colspan="2">Deep permeable gravel</td><td>40 m</td></tr>
<tr><td colspan="2">Deep permeable till</td><td>10 m</td></tr>
<tr><td colspan="2">Depth-to-water table</td><td colspan="2">30 m</td><td>Based on consideration of Rafzerfeld, where the river is cut into the unsaturated zone, and data in Fan et al. (2013) and Haldimann & Schatzmann (2014)</td></tr>
<tr><td colspan="2">Location of material eroded from repository deposited in the near-surface region</td><td colspan="2">1 m thick layer at the base of the shallow permeable gravels</td><td>Pessimistic assumption, because this maximises the degree of interaction between the eroded material and the groundwater; the thickness is based on consideration of placer deposits (e.g. LeBarge (1995))</td></tr>
<tr><td colspan="2">Uncontaminated water flow into surface water</td><td colspan="2">1.25×10^7 m^3 a^{-1}</td><td>Based on consideration of the Rhine in BWG (2001) and Schädler & Weingartner (1992) and smaller rivers of Northern Switzerland from the MQ-GWN-CH dataset (BAFU 2013); the value is smaller than for reference biosphere modelling in (Nagra 2024g) given post-glacial valley context</td></tr>
<tr><td colspan="2">Fraction of net flow from shallow permeable sediments to surface water</td><td colspan="2">0.55</td><td rowspan="2">Based on consideration of connected river systems in Brunner et al. (2009) and data in Zektser & Loaiciga (1993) and Winter et al. (1998)</td></tr>
<tr><td colspan="2">Fraction of net flow from surface water directed to shallow permeable sediments</td><td colspan="2">0.15</td></tr>
</table>

Tab. 3-6: Lake variant parameters for assessment of excavation by deep glacial erosion

Parameter	Value	Notes
Length, width and depth of surface water	8.33 km long by 1.15 km wide 20 m deep	Based on typical dimensions for lakes in Northern Switzerland
Vertical thickness of sedimentary units: Impermeable clay	100 m	Consistent with the structure of sediments in the river variant minus the shallow permeable sediments
Vertical thickness of sedimentary units: Deep permeable gravel	40 m	
Vertical thickness of sedimentary units: Deep permeable till	10 m	
Location of material eroded from repository deposited in the near-surface region	1 m thick layer at the top of the impermeable clay beneath the lake	Pessimistic assumption, because this maximises the degree of interaction between the eroded material and the lake; the thickness is consistent with the river variant
Uncontaminated water flow into surface water	1.64×10^8 m^3 a^{-1}	Based on analogue lakes in Northern Switzerland

Tab. 3-7: Spring variant parameters for assessment of excavation by deep glacial erosion

Parameter	Value	Notes
Vertical thickness of shallow permeable gravel (on the hill)	40 m	Consistent with the structure of sediments in the river variant minus the shallow permeable sediments
Depth to water table (on the hill)	30 m	Thickness of the unsaturated zone above the saturated gravels perched on the hilltop; the value is consistent with assumptions for the river variant
Location of material eroded from repository deposited in the near-surface region	1 m thick layer at the base of the shallow permeable gravels	Pessimistic assumption, because this maximises the degree of interaction between the eroded material and the groundwater; the thickness is consistent with the river variant
Width of terrace	3 km	Width of deposition perpendicular to flow and width of terrace from which springs emerge
Groundwater discharge to springs	1×10^6 m^3 a^{-1}	Based on data for analogous springs obtained from the Federal office for the Environment (FOEN); this represents about 10% of the groundwater flow rate through the hilltop sediments – the remainder flows subsurface to elsewhere (see e.g. Fig. 3-15)
Uncontaminated water flow into surface water	0 m^3 a^{-1}	Springs only fed by groundwater discharge from terrace

3.6.2 Assumptions and uncertainties

Uncertainties are unavoidable in modelling the post-closure safety for deep geological repositories for radioactive waste; this is especially true given the extraordinarily long timescales associated with assessing potential consequences of repository excavation scenarios. For excavation by deep glacial erosion, consideration of glacial processes and their relationship with material deposited at depth in this study has identified a range of variant post-glacial landscape configurations that bound the range of potential situations that could arise. Our conceptualisation and modelling err on the side of conservative assumptions, such that the consequence analyses aim to provide a generally pessimistic assessment of the potential radiological consequences.

A deterministic approach has been adopted for the consequence analyses. It provides an internally consistent and coherent basis for the assessment. There is uncertainty associated with each of the parameter values. Sensitivity calculations help identify important processes, parameters and associated assumptions.

Reference assumptions are based on evidence from examples of deep glacial erosion in Northern Switzerland, to help ensure plausibility and internal consistency across the range of necessary assumptions. These examples do not reflect overdeepenings cutting through the Malm and into the Opalinus Clay (as would be necessary for the repository excavation scenario), for which no direct analogue exists. The potential for erosion through the Malm to result in differences is taken into account in ranges used when exploring the sensitivity of the model to these assumptions. This includes ranges for the dimensions of the overdeepening (e.g. it could be narrower through the harder cover rock above the Opalinus Clay) and dimensions of the near-surface deposition areas.

For the sensitivity calculations, plausible ranges have been used around the parameter values presented in Section 3.6.1. Each parameter has been varied with discrete deterministic calculations using the minimum and maximum values across a plausible range to reveal the importance of associated uncertainty to the key metric for the assessment, which is the maximum calculated effective dose.

A list of the parameters varied for each of the landscape variants is provided in Tab. 3-8. These focus on parameters and assumptions specific to assessment of doses due to excavation by deep glacial erosion. Parameters and conceptualisation based on Nagra's reference biosphere modelling are not varied here because they are explored in Nagra (2024g).

Tab. 3-8: Parameters varied over plausible ranges to explore sensitivities in assessing excavation by deep glacial erosion

See Tab. 3-4 to Tab. 3-7 for reference values.

Variant	Parameters varied for sensitivity analyses
River	Fraction of the repository eroded, dissolution timescale for material eroded from the repository, area of deposition in the near-surface, river flow rate and dimensions, porosity and density of materials, hydraulic conductivity, hydraulic gradient, hydrologically effective rainfall, fraction of shallow groundwater discharging to river, degree of saturation within unsaturated compartments, diffusivity, soil erosion rate, sorption coefficients (K_d)
Lake	Fraction of the repository eroded, dissolution timescale for material eroded from the repository, area of deposition in the near-surface, lake flow rate, dimensions of the lake, porosity and density of materials, hydraulic conductivity, hydraulic gradient, hydrologically effective rainfall, degree of saturation within unsaturated compartments, diffusivity, soil erosion rate, sorption coefficients (K_d)
Spring	Fraction of the repository eroded, dissolution timescale for material eroded from the repository, deposition area, porosity and density of materials, hydraulic conductivity, hydraulic gradient, hydrologically effective rainfall, fraction of groundwater discharging via springs, degree of saturation within unsaturated compartments, diffusivity, soil erosion rate, sorption coefficients (K_d)

3.7 Calculated doses due to excavation by glacial processes

Results for the calculation cases summarised in Section 3.4 are presented in this section, with the time history of potential doses for the variants, peak values and times presented in Section 3.7.1, and results of the sensitivity calculations being discussed in Section 3.7.2.

3.7.1 Calculation case results

Results for the river, lake and spring variants for the range of excavation times considered are shown in Fig. 3-17. The peak calculated doses for the sixteen cases are summarised in Tab. 3-9.

The calculated effective doses for excavation by deep glacial erosion are shown to be within the low-end or below the range of natural radiation exposure rates within Switzerland (taken from BAG (2023)) for the range of calculation cases explored.

Hypothetical excavation 700 ka after closure results in the highest calculated effective doses. Results for excavation after 1 Ma, 2 Ma and 4 Ma are all progressively lower. The long-lived nature of some of the decay chains, including U-238 (which has a half-life of 4.5×10^9 years) and Np-237 (which has a half-life of 2.1×10^6 years) means that the maximum calculated effective doses only decline by about a factor of three between excavation after 700 ka and 4 Ma.

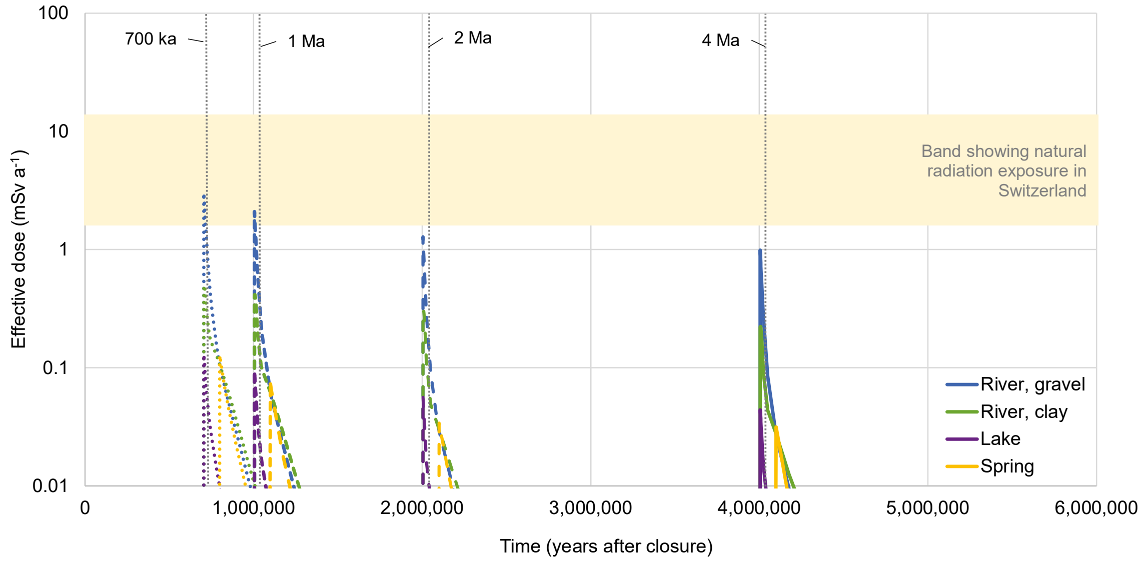

Fig. 3-17: Total effective dose following excavation by deep glacial erosion, exploring different landscape variants and times of excavation

Results are shown for the river variant with material excavated from the repository being deposited in the shallow permeable gravel (Ra) and impermeable clay (Rb), as well as for the lake variant (L) and the spring variant (S). Tab. 3-3 provides a definition for the calculation cases.

Tab. 3-9: Peak calculated effective doses (mSv a^{-1}) and associated time (years after closure) for excavation by deep glacial erosion

Calculation cases are summarised in Tab. 3-3. The main contribution to the delay between the time of excavation and peak calculated doses is the period required for humans to return to the landscape following glacial conditions (for the river and lake variants) and the period required for the configuration of post-glacial sediments to occur (for the spring variant).

Variant/case	**Time of excavation (years after closure)**			
	700 ka	1 Ma	2 Ma	4 Ma
River; eroded material in gravel (Ra)	3.0 (705 ka)	2.1 (1.005 Ma)	1.3 (2.005 Ma)	1.0 (4.005 Ma)
River; eroded material in clay (Rb)	0.5 (708 ka)	0.4 (1.007 Ma)	0.3 (2.006 Ma)	0.2 (4.007 Ma)
Lake (L)	0.1 (705 ka)	0.09 (1.005 Ma)	0.06 (2.005 Ma)	0.04 (4.005 Ma)
Spring (S)	0.1 (800 ka)	0.07 (1.1 Ma)	0.03 (2.1 Ma)	0.03 (4.1 Ma)

For the river variant, the case where the eroded material is deposited at the base of the shallow permeable sediments (Ra case) results in a higher peak dose compared to the case where the material is deposited at the top of the impermeable clay (Rb case). This indicates that the greater degree of interaction between the eroded material and the groundwater is more important in determining potential dose consequences compared to the potential for a longer diffusive source were the eroded material to be deposited within a clay layer (e.g. at the base of a pro-glacial lake).

Po-210 contributes most to the calculated effective doses and is ingrown via the extremely long-lived U-238 from Am-242m, Cm-246 and Cm-242 in the disposed waste.

Ingestion of crops irrigated with groundwater contributes most to the calculated effective doses, followed by ingestion of animal produce (animals are taken to drink water from groundwater wells) and by humans drinking water obtained from groundwater wells.

For the river variant, about 30% of the material that is eroded from the repository is taken to be deposited in the pathway remaining within the overdeepening between the repository location and near-surface region, with the remaining 70% being deposited directly in the near-surface region (see Fig. 3-10). The excavated material deposited within the pathway from depth contributes about 20% to the peak calculated effective dose for the river case where eroded material is deposited in the shallow permeable sediments (i.e. the case resulting in the highest calculated effective doses). This indicates that material deposited within the pathway from depth is an important contributor to peak doses in this case, but that the excavated material that is deposited directly in the near-surface region dominates in terms of the highest potential radiological consequences.

Calculated effective doses for the river variant are higher than for either the lake or the spring variants. The peak calculated effective doses mostly arise close to when humans return to the landscape after the initial excavation event, which occurs under glacial conditions. The spring variant can only occur after incision by a subsequent foreland glaciation such that the initial glacial deposits end up as a terrace; the ca. 100 ka period is evident in the dose curves (yellow lines in Fig. 3-17) and in the time of peak doses summarised in Tab. 3-9.

In practice, glacial-interglacial cycling means that the post-glacial landscape will be reworked by further glaciations some period after the initial excavation/deposition. A time frame with a periodicity of ca. 100 ka might be expected for such glacial-interglacial cycling, during which the deposited material would be further eroded, mixed, transported and dispersed. However, during subsequent glacial episodes, more material could be excavated from the repository. Except for the spring variant, the modelling does not explicitly represent subsequent glacial episodes, such that results for each variant can be discounted about 100 ka after the initial peaks. This does not affect analysis of the results for this safety scenario because the peak calculated effective doses occur close to the time of initial excavation and deposition.

3.7.2 Sensitivity calculations

Sensitivity calculations allow us to explore the relative roles of important processes and parameter assumptions. Calculations were undertaken for the river, lake and spring cases within which many of the parameters described in Section 3.6 were varied one at a time over plausible ranges. The sensitivity calculations centred on excavation 700 ka after closure (the highest calculated effective doses). Similarly, only the river variant with excavated material being deposited in the shallow permeable sediments was explored.

The sensitivity of each of the river, lake and spring variant results has each been explored through 24 sets of calculations varying each parameter, or small subsets of parameters, independently over plausible ranges. The results of the sensitivity calculations are summarised in Tab. 3-10 and discussed below, with a focus on the river variant, which gives the highest calculated doses.

Tab. 3-10: Relative importance of parameters identified as affecting the peak calculated effective doses for excavation by deep glacial erosion

The parameters are listed in order of importance; ">" indicating more important, ">>" indicating much more important, and the lack of a symbol indicating that parameters were of equivalent importance. Calculation cases are summarised in Tab. 3-3.

Variant	Relative sensitivity of important parameters
River (Ra)	River flow rate > aquifer K_d, fraction of repository eroded
Lake (L)	Fraction of repository eroded, clay layer K_d > lake flow rate > hydraulic conductivity and porosity in the pathway from depth
Spring (S)	Aquifer K_d >> fraction of repository eroded > hydrologically effective rainfall, fraction of groundwater discharging to springs, soil erosion rate

The sorption coefficient (K_d) is shown to be important across all of the variants, with sorption on the coarse aquifer material being important for the river and spring variants, and sorption onto the impermeable clay beneath the lake being important for the lake variant. The degree of radionuclide retention on the modelled sediments determines their relative mobility and longevity. As a result, assumptions concerning the degree of retention and sorption are typically important to long-term consequence analyses (see also Nagra (2024g)). The known importance to assessment modelling means that the reference sorption assumptions have been subject to review in preparation for the RBG assessments (Metcalfe et al. 2023). The modelling described here draws upon that review.

The fraction of the repository that is assumed to have been excavated is shown to be important in all cases. The relationship is linear. The results in Section 3.7.1 are based on excavation and deposition of 10% of the inventory remaining within the repository, such that results can be a factor of ten higher if 100% of the material is excavated and deposited within the same region. There will be a degree of correlation between the fraction eroded, and other characteristics, including the dimensions of the overdeepening and the area within which the material is deposited.

The river flow rate is shown to be important for the river variant; this reflects both a large range in the flow rates explored[7] and recharge from the river to the local aquifer (i.e. the river flow is a factor in determining the flow rate through the local aquifer). The flow rate will reflect catchment and valley characteristics of the river that flows through the sediments deposited from the overdeepening (see Fig. 3-11).

For the lake variant, the flow rate through the lake itself is shown to be important in that variant, however, the flow rate would be strongly correlated with the size of the lake, which was not varied at the same time. In practice, the overall turnover rate of water within the lake would, therefore, be expected to vary less than the range explored in the sensitivity calculations.

The importance of hydraulic conductivity and porosity of the pathway from depth to the lake indicates that the repository material deposited within that pathway is more important compared to the river cases. The material deposited beneath the lake sits atop the impermeable clay, from where release to the lake water occurs relatively slowly via diffusion. In this case, therefore, groundwater advection through the smaller proportion of repository material deposited in the overdeepening is the dominant source of radionuclide concentrations in the lake water.

[7] The range in river flow rates spanned 5×10^5 m^3 a^{-1} to 3×10^{10} m^3 a^{-1}, based on analysis of gauged rivers in Northern Switzerland; see also Tab. 3-5, which gives the reference value of 1.25×10^7 m^3 a^{-1}.

For the spring variant, parameters affecting the volume and flow rate of groundwater through the hilltop sediments and springs are shown to be important.

The models are shown to be relatively insensitive to a range of other parameters that were explored. The lifetime of eroded material (varied over a range from about 10 years to about 300 years, based on side calculations for dissolution of excavated material) after excavation is shown to be unimportant in all cases. For the river variant, the results were also insensitive to characteristics of the sediments (density, porosity, hydraulic conductivity) and were insensitive to effective rainfall and groundwater discharge/recharge fractions. For the lake variant, the results were insensitive to effective diffusivity and tortuosity, which supports the observation that diffusion from material deposited in sediments beneath the lake was relatively unimportant. For the spring variant, the results were insensitive to characteristics of the terrace sediments themselves.

4 Excavation by non-glacial erosion processes

Section 4.1 describes non-glacial erosion processes observed in present-day Northern Switzerland. These observations are used to describe a storyboard for variant cases in Section 4.2. Section 4.3 discusses the features, events and processes to form a conceptual model, and the calculations cases to be considered are presented in Section 4.4. The mathematical models and data are described in Section 4.5 and Section 4.6, respectively, and results of the dose assessment are given in Section 4.7.

4.1 Non-glacial erosion processes

In addition to glacial processes (Chapter 3), the main erosional processes in Northern Switzerland are fluvial incision by main and tributary rivers and the associated hillslope response, here summarised as "non-glacial processes". Key elements and geomorphic processes of non-glacial valley evolution in general are depicted in Fig. 4-1.

The first two subsections review the main topics of fluvial processes (Section 4.1.1) and hillslope processes (Section 4.1.2). In addition, a separate section (4.1.3) is dedicated to the (rapid) formation of new main valleys by so-called breakthrough channels (cf. Section 2.1) and a short introduction of the related analogue of the Wutach Valley in Southern Germany.

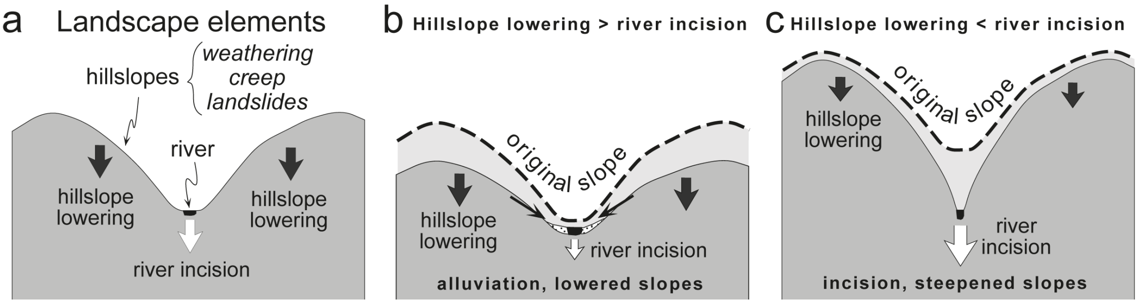

Fig. 4-1: Key geomorphic elements and processes of non-glacial landscape evolution

From (Burbank 2002).

These general illustrations and concepts can be applied to the past and potentially future landscape evolution of Northern Switzerland. They indicate the relevant hillslope processes (a) as well as the links between (river) erosion rate and adjacent hillslope relief, where less pronounced river incision produces lower hillslopes (b) and vice versa (c). See text for further explanation.

4.1.1 Fluvial processes

This section summarises the general processes of river incision and valley floor aggradation (alluviation), as indicated in Fig. 4-1. Within a non-glacial landscape, the main river system importantly sets the level of the lowest topographic elevations. This level (or more precisely: the lowest bedrock elevations reached by the main rivers) is also referred to as the local erosion base (LEB). Lowering of the local erosion base relative to the lithostratigraphic stack by fluvial incision propagates through the landscape via tributary rivers and adjacent hillslopes (cf. Section 4.1.2).

As indicated in Section 2.1, long-term rock uplift rates can be considered a good first-order approximation of average fluvial incision rates. They can be additionally influenced by factors such as changes in climate or drainage area (and therefore runoff), e.g. by large-scale drainage reorganisations (Nagra 2024d). In phases, this can lead to both positive and negative deviations of the fluvial erosion rate as compared to the average uplift rate. Moreover, the complex interplay of these factors, in combination with variable erodibility of different lithological substrates, usually produces temporally and spatially variable patterns of erosion rates. As a consequence, natural landscapes such as that of Northern Switzerland are in a transient state, with periods and regions of faster and slower fluvial incision, rather than reflecting an equilibrated landscape of steady-state erosion rates. The transient effects, however, tend to be averaged out over long timescales.

At times, sediment supply from adjacent hillslopes, but even more from upstream fluvial reaches, can outpace the erosional efficiency of the river. In this case, aggradation can fill the base of the valley with unconsolidated sediments such as fluvioglacial gravels, forming a flat and sometimes wide valley floor. Repeated phases of aggradation and incision, especially in association with glacial-interglacial cycles, can produce stepped terrace systems that reflect the different phases of aggradation. As a result of such dynamics during the Quaternary, extensive alluvial valley floors and terraces are also found along most of the main river reaches in present-day Northern Switzerland. Considering the more recent levels of deposition (i.e. the "Niederterrasse"), valley floor widths of up to ~ 2 – 3 km are measured along the main rivers, e.g. in the lower Aare Valley. In response to the main valleys, many of the tributary rivers also show aggraded flat-valley bottoms, especially in their lower reaches. Consistent with the smaller valley size, the dimensions of the valley infill and therefore the valley floor width tend to become smaller. For instance, valley floor widths of ~ 500 m are observed for the lower reaches of the Sissle River near Frick, considered as an example of a medium-sized tributary valley. Despite their smaller sizes, the deposits can be permeable enough to develop a usable shallow aquifer (e.g. for groundwater pumping at the location of Frick, cf. Hoehn (1979)), as is the case for the main valleys.

4.1.2 Hillslope processes

The effects of fluvial incision and variation in its rates on adjacent hillslopes are illustrated in Fig. 4-1. As indicated, hillslope response to fluvial incision mainly occurs by:

i.) weathering and production of transportable material,

ii.) near-surface diffusive hillslope processes ("creep" in Fig. 4-1), and,

iii.) (bedrock) landsliding.

These processes are largely driven by the hillslope gradient, which in turn depends on the erosion rate as set by the river incision. In general, low river-erosion rates are accompanied by correspondingly low hillslope-erosion rates[8], thicker soils, and more shallow hillslope angles, that are (mostly) subject to diffusive hillslope processes. The latter combine a variety of possible mechanisms (Burbank 2002, Gabet & Mudd 2010), including creep, rainsplash erosion or biosphere-related processes, such as tree throw. The opposite effects, i.e. high hillslope-erosion rates, thinner soils or bedrock exposure, and steeper hillslope angles, can be expected for high river-erosion rates. Such steep hillslopes will favour (bedrock) landsliding, acting as an efficient process of hillslope erosion (see more detailed discussion of landslide processes further below in this section).

[8] Even though hillslope lowering can occasionally still be larger than the concurrent river incision, as indicated in Fig. 4-1. This is then indicative of a retarded transient response of the hillslope to attenuation of the river-incision rate.

For soil-mantled landscapes, a nonlinear transition as a function of hillslope gradient from creep-dominated to shallow landslide-dominated conditions has been inferred, e.g. based on experimental studies (Roering et al. 2001). That is, hillslope material flux (and thus hillslope erosion rate) scales roughly linearly along low-angle, creep-dominated hillslopes. However, an exponential increase is observed towards higher hillslope angles, which are then characterised by increasing landslide activity. In theory, this increase in hillslope material flux rises to infinity at the so-called "critical slope" angle. In practice (and applied to bedrock landscapes), the term "threshold slope" is additionally employed for the steepest possible hillslopes observed in the field (e.g. Wolff et al. 2018), dominated by bedrock landsliding.

The landslide process itself can be represented by many different landslide types. These can be distinguished based on properties such as the style of failure (e.g. sliding, toppling), material involved (solid bedrock, soils), depth of failure surface, process rates, etc. A systematic classification of different landslide types is provided by Hungr et al. (2014), which includes further influencing factors such as topography, weathering or rock type. Weak sediments such as the Opalinus Clay are typically prone to landsliding by various processes (Jordan 1993, Ludwig 2018). In particular, following the taxonomy by Hungr et al. 2014 and including the terminology for landslide velocities, these include:

- Deep-seated and typically slow to extremely slow "rock-slope deformation", an example of which has been described for the location of Frickberg near the Jura Ost siting region (Ludwig 2018; Fig. 4-2).
- More shallow "earthflows", with the potential to occur rapidly as "surges" (e.g. following periods of increased rainfall) and to reach comparably long travel distances (e.g. Baltzer (1876); Fig. 4-3).

Comparable landslide phenomena are also observed and described for hillslopes of the Opalinus Clay and similar lithology in the Wutach region in Southern Germany (Jordan 1993; cf. Section 4.1.3).

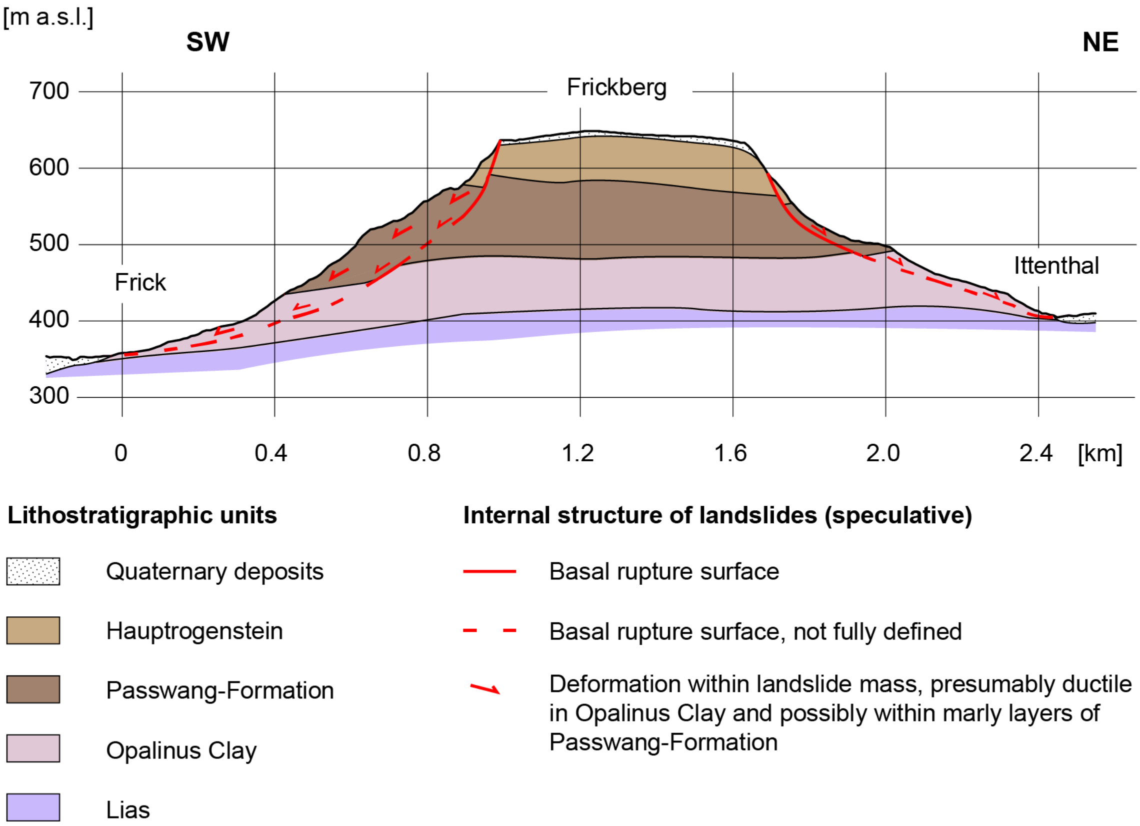

Fig. 4-2: Simplified geological cross-section of deep-seated landsliding within the Opalinus Clay and overlying lithostratigraphic units at Frickberg

From Ludwig (2018).

The landslide type has been interpreted as a "rock-slope deformation", following the definition in Hungr et al. (2014). See text for further explanation. Location is nearby the Jura Ost siting region. Note that the vertical axis is scaled by a factor of 2.

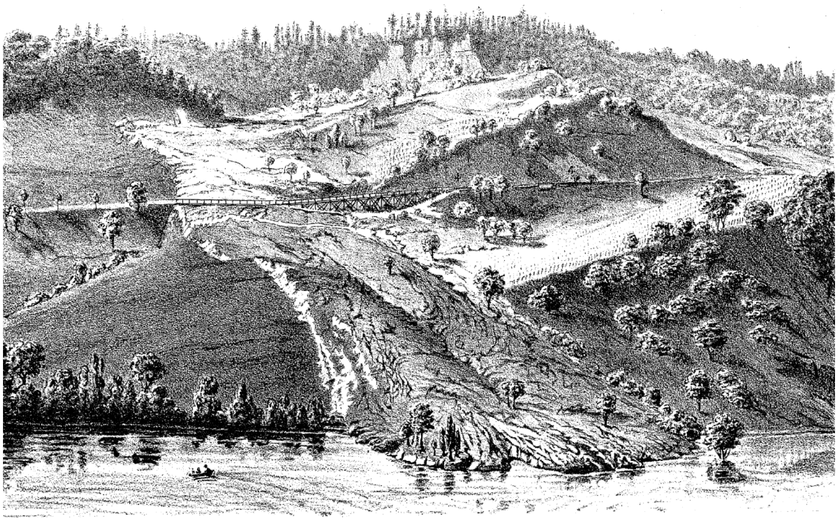

Fig. 4-3: Opalinus Clay earthflow reaching the Aare River near Böttstein in March 1876
From Baltzer (1876).
Location is nearby the Jura Ost siting region.

Similar to the fluvial incision described above, the process rates associated with these landslide types can be temporally variable. For instance, the slow to extremely slow "rock-slope deformation" can, in certain cases, evolve into an intermittent faster "rock-compound slide" (Hungr et al. 2014), reflecting an increase in landslide velocity from ~ mm/a to ~ metres per hour. Similarly, while recent earthflows attract attention if occurring as rapid and discrete events (with landslide velocity ~ metres per hour), they also show prolonged phases of dormancy and slower displacement rates (see examples below).

While landsliding in general is favoured by steep terrain, as caused by high river-erosion rates (see above), Hungr et al. (2014) notes that earthflows are usually associated with shallow hillslopes of < 12°, with rapid surges typically attributed to rising porewater pressure. The latter control is also partly supported by the historically documented Opalinus Clay earthflow at Böttstein (Fig. 4-3) nearby the Jura Ost siting region, that is reported to have occurred during a period of increased precipitation in spring 1876 (Baltzer 1876). Similarly, acceleration related to increased rainfall is reported from other earthflows (e.g. Mackey et al. 2009).

While the Böttstein earthflow spatially coincides with the location of a present-day clay pit, a morphologically well-preserved earthflow is observed in very close proximity at the location of Nassberg (Ludwig 2018). In contrast to the Opalinus Clay earthflow at Böttstein, the Nassberg earthflow is associated with the predominantly marly layers of the overlying Passwang Formation (cf. outcrop descriptions in Wohlwend et al. (2019)). At this location, the stratigraphic layers show a steeper dip than found on average within the siting regions, due to its proximity to a regional thrust fault. Nevertheless, it suggests similar landslide processes occur in these directly overlying units as within the Opalinus Clay itself. The Nassberg earthflow, sitting on a larger deep-seated landslide complex, shows an (eroded) width of ~ 200 m. The upper end of the release zone is at the hilltop at 525 m a.s.l., the toe extends to the edge of the Aare Valley bottom at 345 m a.s.l., thus affecting the entire hillslope in this example. The resulting relief of 180 m in combination with a total length of 1,000 m yields an average hillslope gradient of ~ 10°, which fits the general conclusions by Hungr et al. (2014) above. Steeper earthflows within similar rock types can be observed on the lower parts of the 350 m high and 1,000 m long western flank of the Buchberg in the Wutach Valley (cf. Section 4.1.3, as well as Fig. 4-4 for location of the Buchberg). There, Jordan (1993) investigated an individual earthflow initiating within the Opalinus Clay at ~ 120 m above the valley floor, with the toe of the earthflow reaching down to the Wutach River. At a length of the earthflow of nearly 500 m, the average mean hillslope gradient here corresponds to ~ 14°.

Importantly, more shallow landslides such as "earthflows" and deep-seated landslides such as "rock-slope deformation" can often occur as superimposed processes (as mentioned for the example of Nassberg above). Moreover, even for the single processes (e.g. within an individual earthflow; Hungr et al. 2014) there can be multiple sliding surfaces. If averaged over sufficiently long timescales and combined with the rates of near-surface diffusive hillslope processes (see above), this will typically produce a depth-dependent function of material flux, with the highest rates at the hillslope surface, and a decrease towards zero material flux at the basal sliding surface.

4.1.3 Breakthrough channels and the Wutach analogue

This section gives a short summary of the specific aspect of so-called "breakthrough channels", as briefly introduced in Section 2.1. These features provide evidence of rapid formation of new main valleys and have been previously identified as an important phenomenon for the evolution of local topography in Northern Switzerland during the Quaternary (e.g. Schnellmann et al. (2014)). This is of interest for the deep geological repository due to the potentially high associated rates of fluvial incision and adjacent hillslope processes.

The formation of breakthrough channels can be attributed to a variety of causes, e.g. aggradation as described in Section 4.1.1 can cause main river courses to be shifted laterally. This can be a gradual process (also in alternation with lateral erosion), where the river course remains located within the original main valley. However, if there is sufficient aggradation to raise the valley floor up to the level of a nearby topographic depression, overspill of the main drainage to a neighbouring (and possibly backward eroding) tributary valley can occur. Subsequent incision can then initiate the formation of the new main river valley as the so-called breakthrough channel. The associated rates of fluvial incision can be relatively high, especially if the downstream local base level is significantly lower than the initial elevation at the overspill location. Similarly, the overspill leading to the formation of a breakthrough channel can be generated by the processes listed in Section 2.1, i.e. by glacial impoundment of a present drainage, or by ice-marginal drainage.

The situation of main river aggradation leading to overspill into a backward-eroding tributary river and subsequent fluvial incision at (very) high erosion rates is particularly well documented by the example of the Wutach catchment in Southern Germany (Einsele & Ricken 1995). Following a drainage reorganisation event at ~ 18 ka, when the former "Donau-Wutach" was deflected towards the Rhine at the location of Achdorf (Fig. 4-4). This led to incision of up to 170 m within 7 ka, yielding a mean erosion rate of 25 mm/a for the corresponding period, which is two orders of magnitude higher than the expected long-term uplift rates according to Section 2.1. The analogue is of additional interest, as it reflects a high erosion event into the Opalinus Clay and its confining geological units, similar to the relevant lithostratigraphic sequence in Northern Switzerland. It also provides useful insights into the response of hillslopes to such rapid fluvial incision and their dependence on rock type, as evidenced by widespread landslide processes in the present-day landscape. Selected examples for this include the deep-seated Opalinus Clay landslide in Fig. 4-4 , or the earthflow processes described by Jordan (1993) (cf. Section 4.1.2).

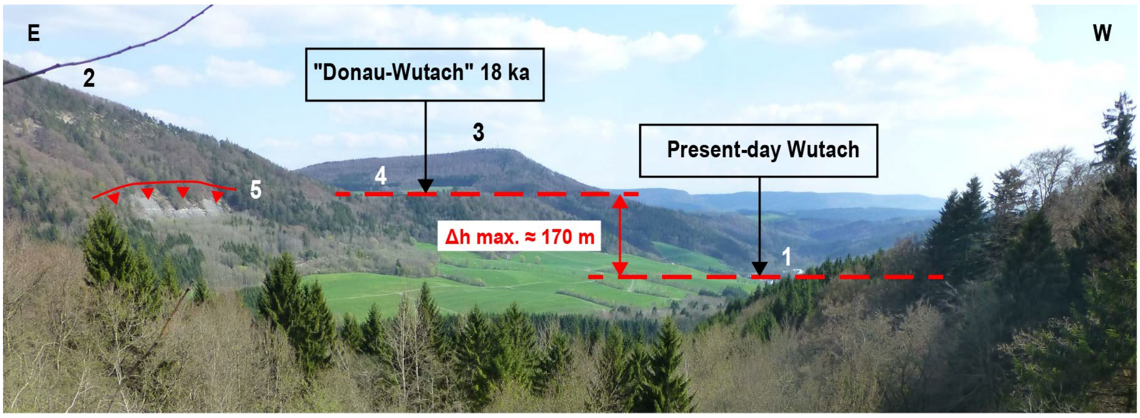

Fig. 4-4: Wutach catchment as an analogue of high erosion rates by non-glacial processes

The photograph shows the location of the Wutach deflection at 18 ka near the village of Achdorf (1), as seen from a northern tributary valley. The wind gap between the hilltops of Eichberg (2) and Buchberg (3) marks the entrance to the abandoned Aitrach Relict Valley (4). The latter represents the eastward-directed flowpath of the Donau-Wutach prior to drainage reorganisation. The present-day Wutach turns southward at Achdorf and has incised up to ~ 170 m below the level of the former Donau-Wutach in the first ~ 7 ka after stream deflection (Einsele & Ricken 1995). Location (5) marks the head scarp of a deep-seated Opalinus Clay landslide, indicating an attenuated but still ongoing hillslope response to the former incision pulse.

4.2 Storyboard for excavation by non-glacial processes

Over long timescales, the processes described in Section 4.1, driven by relative lowering of the local erosion base in response to rock uplift, are expected to gradually reduce the rock overburden above the repository (Fig. 4-5). Direct glacial erosion can, at times, additionally contribute to this reduction. However, as outlined in Section 1.4, this is treated separately in Chapter 3, such that the storyboard presented here can focus on the non-glacial processes of Section 4.1.

While the repository is more than 200 m below the terrain surface, the surrounding Opalinus Clay will be fully intact, characterised by its very low hydraulic conductivity and a regime of diffusive solute transport in porewater. With reduction to less than 200 m below the terrain surface, the Opalinus Clay could begin to lose its self-sealing capacity in case of larger fractures, such that advective flow could be locally enabled, while solute transport would generally still be diffusion-dominated. The relevant minimum overburden for the non-glacial excavation scenarios is set by the depth of the near-surface weathering zone, where advective flow starts to dominate over diffusive transport. Mazurek et al. (2023) and Hekel (1994) found effects of weathering within the Opalinus Clay reaching down to a depth of ~ 25 m below the surface, while deviations can occur, e.g. due to topographic influences (cf. Section 4.2.2). The base of the weathered zone thus largely follows the shape of the terrain surface at relatively shallow depth.

This section first describes the possible main trajectories for the repository during excavation in a non-glacial valley such as in Northern Switzerland (Section 4.2.1). A hillside and a valley-floor setting are identified as the two main variants. A specific section (4.2.2) is then dedicated to the characteristics of the near-surface weathering zone within the Opalinus Clay. More detailed considerations for the hillside variant are provided in Section 4.2.3. The valley-floor variant is then addressed in Section 4.3.2.

4.2.1 Main excavation trajectories in a non-glacial valley

With respect to the terrain surface, roughly V-shaped valley flanks separated by a flat (aggraded) valley bottom can be expected for non-glacial landscape evolution in Northern Switzerland (cf. Section 4.1, e.g. Fig. 4-1). Importantly, the relative topographic position of where the repository first enters the weathered zone can differ, depending on the initial distance of the repository to the river and the exact valley geometry. As illustrated by the corresponding trajectories in Fig. 4-5, this is either somewhere along the hillside (a), or at the valley floor (b).

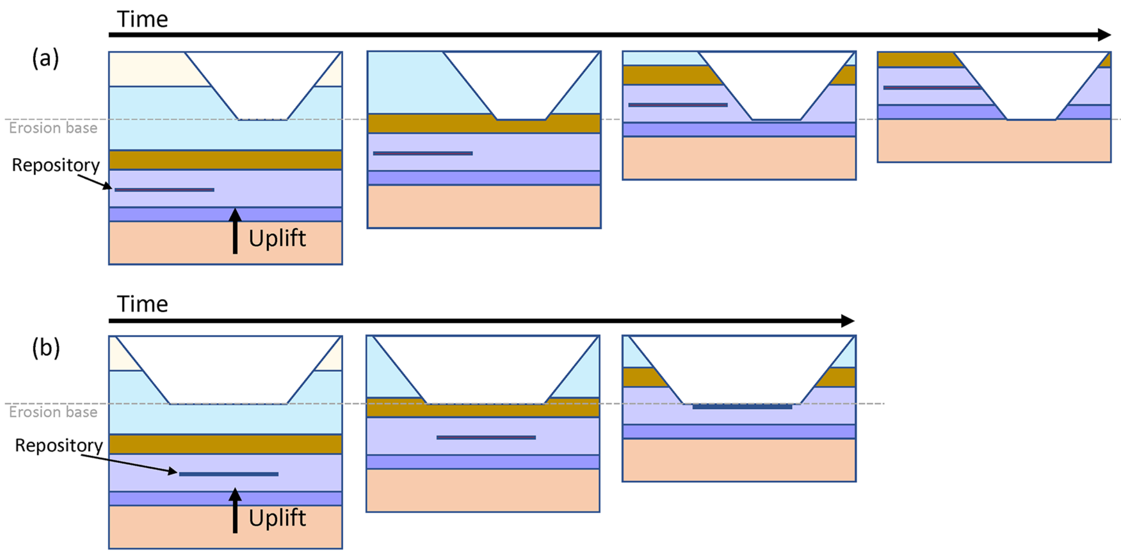

Fig. 4-5: Possible trajectories of the repository during excavation in a non-glacial valley

Sequences indicate how the repository (thin bar) is gradually brought to terrain surface from depth by the interplay of tectonic uplift and fluvial incision over very long timescales. The simplified illustration shows an abstraction of the layered stratigraphy and the typical valley geometry expected for non-glacial valleys in Northern Switzerland, i.e. (roughly) V--shaped valley flanks separated by a flat (aggraded) valley bottom. Depending on the initial distance of the repository to the river and the valley geometry, the repository will first reach the surface either (a) somewhere on the hillside or (b) at the valley floor. See text for further explanation.

For the hillside variant (and assuming a continuing erosion rate), the repository will be lifted up towards the valley floor and will eventually pass the weathered zone until finally emerging at the terrain surface. This uplift process relative to the valley bottom then continues, with the repository getting laterally eroded by hillslope processes. Obviously (and as indicated in Fig. 4-5), the lithostratigraphic layers are lifted up synchronously with the repository. Provided a sufficiently high relief, less erodible carbonate formations further above the Opalinus Clay could act as a cap rock, forming prominent plateaus at the hilltop. Such cap rocks will be laterally eroded by hill-slope processes, particularly as they become destabilised by deep-seated landsliding within weaker underlying units (see Hauptrogenstein in Fig. 4-2, as an example).[9]

While the lithostratigraphic layers (and thus the repository) are uplifted, a plateau held up by resistant carbonates narrows and finally disappears. In contrast to carbonate formations, weaker sedimentary units such as the Opalinus Clay do not develop prominent flat plateaus on the hilltop,

[9] To a lesser degree, carbonate cap rocks will also erode vertically by chemical weathering.

but instead form curved hilltops, with curvature depending on the erosion rate. Sharper crests are expected at high erosion rates, while hilltop curvature is reduced with lower erosion rates. Therefore, if the Opalinus Clay containing the repository reaches the hilltop, there will not be a flat plateau enabling exposure of the whole repository. Instead, only a limited plan area of the repository will be exposed due to the curvature of the hilltop before the repository is completely eroded.

For the valley floor variant, a repository could be situated beneath an alluvial valley floor for a considerable time period (at least long enough to be inhabited by a human population), as seen for example in present-day Northern Switzerland. With on-going erosion in a valley floor setting, the repository itself would be eroded either in the valley bottom (cf. Fig. 4-5a) or, depending on the position of the repository in relation to the valley, a remaining part of the repository could be exposed in the hillside (cf. Fig. 4-5b). Direct erosion within a valley floor setting is, therefore, not dissimilar to erosion in a hillside setting, so is not assessed separately.

Whilst on timescales of millions of years it is useful to define long term average erosion rates and hillslope angles, on shorter timescales, there is likely to be variation in erosion rate and hillslope angle. Periods of higher erosion rate may result in steeper hillslope angles. On very short timescales, erosion rate could be very high during discrete landslide events. These high energy events can result in material travelling a relatively long distance, based on the description of earthflows in Section 4.1.2.

4.2.2 Near-surface weathering zone and present geochemical conditions

The importance of the near-surface weathering zone to non-glacial excavation was pointed out in the introduction to Section 4.2. The key aspect is the transition from diffusion-dominated solute transport in porewater within the intact bedrock at greater depth to a (more effective) advection-dominated flow regime above the base of the weathered zone. This transition is controlled by a corresponding increase in porosity and hydraulic conductivity within the weathered zone towards the terrain surface, as compared to the intact bedrock below. In turn, this increase can be attributed to the disintegration of formerly intact bedrock due to combined effects of mechanical decompaction and chemical alteration, as the rock is exhumed close enough towards the terrain surface.

For the Opalinus Clay, these effects have been thoroughly studied, e.g. at the Lausen borehole in Northern Switzerland (Vogt et al. 2017, Mazurek et al. 2023), which is located at the margin of an aggraded valley floor belonging to a tributary of the Rhine. Mazurek et al. (2023) identified the following vertical depth profile for "weathered" Opalinus Clay, below a 6 m thick Quaternary clay:

- 6 – 12 m: strongly altered Opalinus Clay
- 12 – 16 m: moderately altered Opalinus Clay
- 16 – 24 m: decompacted Opalinus Clay

The exponential increase of both hydraulic conductivity and porosity within this weathered zone is quantitatively demonstrated within the mentioned studies (Vogt et al. 2017, Mazurek et al. 2023, respectively). Corresponding values can be found in Tab. 4-5.

The observed weathering depth of ~ 25 m is in good agreement with depths identified by Hekel (1994) for the Opalinus Clay in boreholes in similar (flat) topographic positions. This latter study, encompassing a larger set of Opalinus Clay boreholes in Southern Germany, provides useful indications of the topographic controls on the near-surface weathering zone and associated hydrogeologic conditions within the Opalinus Clay (Fig. 4-6). In general, and also in line with geomorphic concepts about the relation between weathering depth and erosion rates, thicker weathering zones (~ 25 m) are identified by Hekel (1994) for areas with a flat topography, such as within the valley bottom or on (curved) ridgetops. In contrast, thinner weathering zones are inferred for the steeper parts of the landscape, as representative of more active erosion.

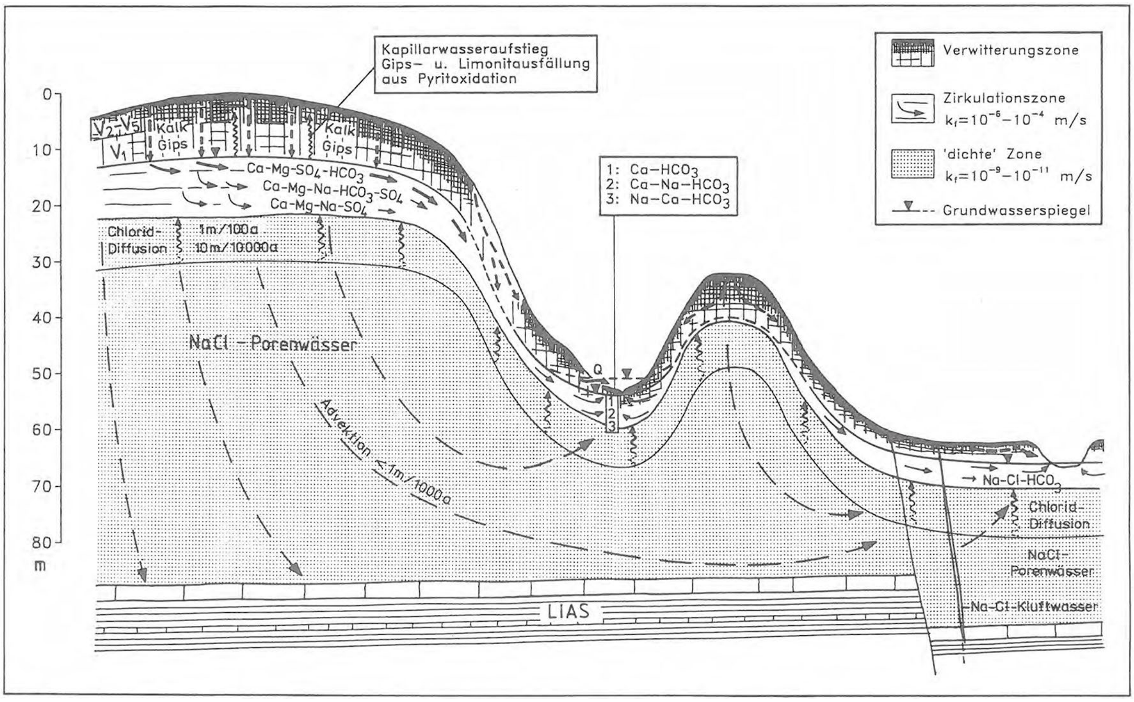

Fig. 4-6: Conceptual model of near-surface weathering and associated hydrogeological conditions within the Opalinus Clay, and its relation to topography

From Hekel (1994).

Note that the qualitative concepts, showing the transition from diffusion-dominated solute transport in porewater within the intact bedrock at greater depth to a (more effective) advection-dominated flow regime above the base of the weathered zone, are consistent with more recent studies by Vogt et al. (2017) and Mazurek et al. (2023). However, the latter studies are thought to provide more precise values of hydraulic conductivity, mainly for the intact Opalinus Clay ("dichte Zone"), given the technical progress concerning borehole measurements over the decades.

None of the boreholes mentioned by Hekel (1994) penetrated a central region of a deep-seated Opalinus Clay landslide. Therefore, and also due to the lack of other evidence found in the literature, it remains elusive whether internal deformation within deep-seated landslides could still increase hydraulic permeability towards depth, even at steeper hillslopes. Given this uncertainty, a general reference thickness of 25 m is suggested for the weathering zone in the assessment of the hillside variant, irrespective of the hillslope gradient.

Moreover, the findings from the studies at the Lausen borehole and by Hekel (1994) allow us to structure the near-surface weathering zone on the hillside into the following vertical subunits (cf. Section 4.3.1 and 4.6.1):

- Top and deep soil
- Shallow, weathered unsaturated zone
- Shallow, weathered saturated zone
- Deep, weathered (saturated) zone

4.2.3 Further considerations for the hillside variant

If averaged over sufficiently long observation times, it can be assumed that material flux on hillsides built up by the Opalinus Clay and its confining geological units will erode by the superposition of the main hillslope processes as identified in Section 4.1.2, i.e. (i) deep-seated landsliding, typically by slow to extremely slow "rock slope deformation", (ii) more shallow and temporarily rapid landsliding, as reflected by the presented earthflows examples, and (iii) near-surface diffusive hillslope processes, such as creep. This combination generally favours a depth-dependent material flux, with the lowest rates expected at the basal sliding surface and an increase towards the highest rates at the terrain surface. The precise shape of this depth dependency is not known. However, as previously indicated by the diverging landslide velocities for the deep-seated and shallower landslide types in Section 4.1.2, and taking into account their superposition, a significant exponential increase in downslope soil velocities from depth to surface can be expected.

Processes described in Section 4.1.2, as well as the internal deformation and sometimes chaotic surface expression on landslide bodies (as indicated for instance on the tongue of the Böttstein earthflow in Fig. 4-3) imply a certain degree of vertical mixing of material within the weathered zone of the hillside. Similar to the depth-dependent material flux rates addressed above, it is assumed that this vertical mixing will be more pronounced closer to the terrain surface. Considerations for the latter include, (i) vertical mixing as part of diffusive hillslope processes within top and deep soil, e.g. by biological activity, or (possibly) also freeze-thaw cycles, (ii) higher energy involved with potentially higher landslide velocities of more shallow landslides, such as the earthflow examples described in Section 4.1.2, (iii) more degrees of freedom for internal deformation given the more advanced disintegration of the former bedrock substrate closer to the surface (cf. Section 4.2.2), (iv) generally high degrees of freedom for internal deformation at the terrain surface itself, given the absence of an overlying layer. For the deeper layers, the described processes of deep-seated landsliding within the Opalinus Clay and its confining geological units (Section 4.1.2, Fig. 4-2) do not suggest a pronounced vertical mixing (as would e.g. be expected for a rock avalanche of more brittle rock, cf. Hungr et al. (2014)). Instead, increasing overburden and integrity of the former bedrock substrate should reduce the potential for vertical mixing towards depth.

As already indicated in the previous paragraph, certain correlations can be drawn between the different soil and weathering layers, as distinguished in Section 4.2.2, and the depths of the relevant hillslope processes in Section 4.1.2. This correlation is not straightforward (or based on a full scientific concept). However, it is roughly supported by borehole observations (e.g. Vogt et al. (2017) and Mazurek et al. (2023)) and interpreted depth profiles of deep-seated landslides within the Opalinus Clay and its confining geological units. Referring to the differentiation in

Section 4.2.2, the following allocation of hillslope processes is then made, which allows for direct transferability into the mathematical implementation described in Section 4.5 (via parameters for depth-dependent material flux and vertical mixing in Section 4.6):

- Diffusive hillslope processes affect the top and deep soil;
- Shallow and medium-depth landsliding, including earthflows, affect depths down to the base of the shallow weathered zone; and
- Deep-seated landsliding extends to the deep weathered zone.

Section 4.2.1 has indicated the relevance of the valley geometry during non-glacial excavation. For the hillside, the main geometric parameters are the hillside height and hillside width (that is, if looked at in a valley cross-section). In combination, these define the average hillslope gradient – and vice versa, the choice of the average hillslope gradient can be used to infer these parameters. The hillside angle will determine the extent of the intersecting domain of the repository with both the terrain surface and the near-surface weathering zone. Thus, the combined effects of erosion rate and hillslope gradient control non-glacial excavation in the hillside. This shall be addressed by considering three different cases of hillside geometry and associated hillside-erosion rates:

- Case A: shallow valley with low hillslope angle (and hillside height) and low erosion rate.
- Case B: average valley with average hillslope angle (and hillside height) and average erosion rate.
- Case C: steep valley with high hillslope angle (and hillside height) and high erosion rate.

Section 4.1.2 highlights the non-linearity between erosion rate and hillslope gradient, with a (theoretical) increase towards infinite hillslope material flux towards the so-called "critical slope" angle. This is reflected by a moderate increase of the erosion rate from hillside Case A to Case B, followed by a sharp increase in Case C. Moreover, the concept of threshold slope (cf. Section 4.1.2) is important as it sets the upper limit of steepness for the valley geometry. The exact pairing of erosion rates and associated hillslope gradients cannot be known. However, constraints can be derived from indications of past erosion rates, expectations of future erosion rates (Nagra 2024d) and morphometric observations in the present-day landscape. The very high rate of 25 mm/a inferred for the Wutach is considered a sufficiently high upper limit to be used for Case C. Present-day local relief near the former location of stream deflection at Achdorf reaches up to 350 m on the western flanks of the Eichberg and Buchberg (cf. Fig. 4-4 for location). This is paired with a hillside width (in the valley cross-section) of 1,000 m, yielding an average hillslope angle of nearly 20°. However, it can be assumed that the hillslope gradients were even steeper, i.e. from 18 to 11 ka at the threshold slope during the period of highest incision (cf. Section 4.1.3). Moreover, it cannot be ruled out that future local relief could exceed that of the present-day landscape. To account for this, a hillside height of 500 m (hillslope gradient of 26.5°) for Case C is chosen. Hillside heights for Case A and Case B were set to 50 m (hillslope gradient of 3°) and 250 m (hillslope gradient of 14°), respectively. This is primarily based on characteristic values of hillside relief within a search radius of 500 m applied to the digital elevation model of Northern Switzerland and should also allow consideration of a sufficiently broad range of hillside relief or hillslope gradients. The 500 m radius corresponds to an assumed hillside width of 1,000 m, identified as a reasonable reference width, as for instance found at the Buchberg (see above), the Frickberg (Fig. 4-2) and many other places. Following the consideration of non-linear erosion rates, and based on expected future erosion rates (Nagra 2024d), values of 0.08 mm/a and 0.2 mm/a are assigned as the low and average erosion rates to Case A and Case B, respectively. A summary of the three cases is shown in Tab. 4-1, including a calculation of the time during which the repository could reside within the hillside.

Tab. 4-1: Summary of hillside heights, erosion rates and duration of transit of the repository within the hillside

Case	Hillside Height (m)	Erosion rate (mm/a)	Duration of repository transit from valley bottom to hilltop
Case A	50	0.08	625 ka
Cases B/D	250	0.2	125 ka
Case C	500	25	20 ka

The same assumptions on depth-dependent hillside material fluxes and vertical mixing (see above) are then applied to all three hillside cases. The relative proportions within the different near-surface layers are thus kept constant between the cases. The absolute rates of depth-dependent material flux, however, scale according to the different erosion rates. For the vertical mixing, it is acknowledged that this could be more pronounced on the steeper cases, given the potentially higher energy involved with (faster) landsliding processes. Nevertheless, the same assumption is chosen for the shallow angle case to account for the typical association of earthflow processes with rather low hillslope gradients.

Finally, an additional hillside case, Case D is added to explicitly explore potential hydrological effects of more permeable (a few metres thin) limestones beds below the Opalinus Clay. The first such stratigraphic unit to occur below the Opalinus Clay is represented by the so-called Beggingen Member, at a vertical distance of ~ 70 m below the repository. These limestone layers are assumed to have the potential to intercept the near-surface hillside drainage from the upslope sections and to direct it to springs emerging from the hillsides. Springs emerging from the Beggingen Member are reported from various locations across Northern Switzerland. However, they are described as being of rather low discharge. Quantitative measurements are reported from the Frick region (Hoehn 1979), indicating average discharge rates in the order of 10 l/min for individual springs.

4.3 Conceptualisation of repository excavation by non-glacial processes

Consideration of non-glacial erosive processes in river valleys (Section 4.1) and storyboards for repository excavation due to non-glacial processes (Section 4.2) provide a basis for identifying processes relevant to radionuclide transport and potential exposure under this scenario. The previous sections identify hillside settings and valley-floor settings as variants for consideration.

Consideration is given to hillside processes that transport radionuclides, focusing on movement of solid mass and water into valleys (Section 4.3.1). This includes long-term erosion, the effect of a potential high-permeability limestone layer on the hillside, and discrete landslide events. Consideration is then given to processes occurring in the valley-floor setting (Section 4.3.2). These processes form the basis for two variants with distinct conceptual models for radionuclide behaviour and potential exposure (Section 4.3.3).

4.3.1 Description of the hillside variant

The FEPs involved in moving solid mass and water downslope in a hillside setting are listed in Tab. 4-2. Assessment-level conceptualisations are then discussed and illustrated in Fig. 4-5 to Fig. 4-7, including how the solid mass and water from the hillside are deposited in the valley.

Tab. 4-2: Features, events and processes (FEPs) associated with excavation by non-glacial processes within a hillside setting

Italicised FEPs are those that may or may not be present in a hillside setting.

Category	Items
Features	• Repository with associated radionuclides. • Unweathered Opalinus Clay. • Weathered Opalinus Clay (degree of weathering decreases with depth). • Soils. • Surface water. • Suspended sediment. • Groundwater. • Saturated zone. • Unsaturated zone. • Plants (crops and natural vegetation). • Animals (livestock, fish and other animals). • Atmosphere. • Humans. • *High-permeability layer (limestone).*
Events	• *Discrete landslides.*
Processes	a) Precipitation. b) Evapotranspiration. c) Overland flow. d) Infiltration (water movement into the subsurface). e) Interflow (flow in the unsaturated zone). f) Recharge (flow into the saturated zone from the unsaturated zone). g) Groundwater flow (flow in the saturated zone). h) Capillary flow. i) Uplift. j) Depth-dependent mass movement (long-term average). k) Internal deformation of the hillside. l) Bioturbation. *m) Discharge in springs.*

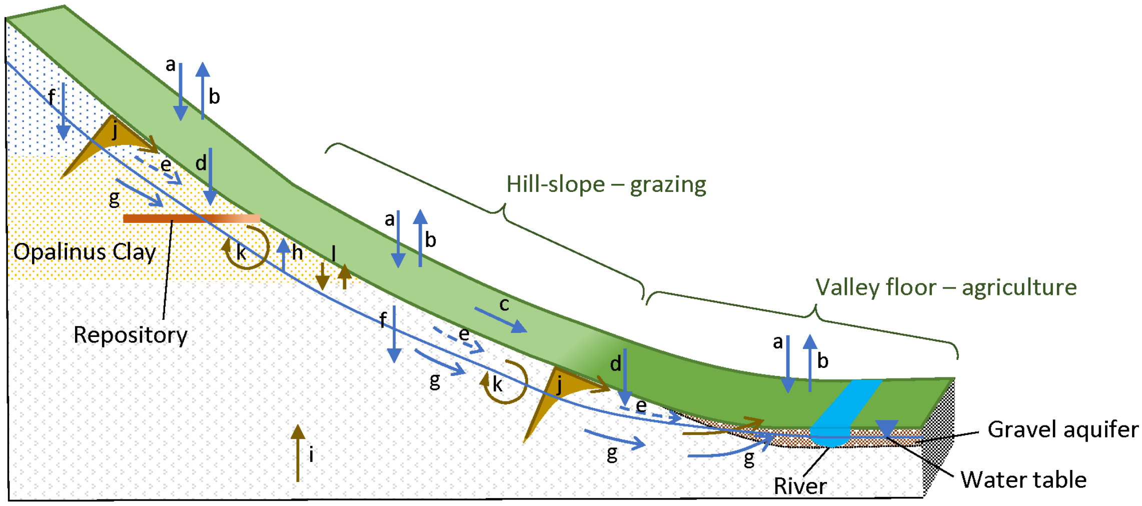

Fig. 4-7: Illustration of the hillside setting for Cases A-C showing the main features and processes relevant to mass and water transport

The wedge shapes labelled "j" represent depth dependent mass transfer with greater rate of transfer close to the ground surface.

The geometry of the hillside is assumed to be constant through time (Fig. 4-5), with regional uplift balanced by a downcutting river and hillslope-erosion processes. This means the hillside is taken to have the same length (top to bottom) and hillslope angle through time. A weathered zone with a constant (in time and space) thickness overlies the intact Opalinus Clay. The weathered zone consists of a deeper, less weathered layer and a shallower, more weathered layer, which is then overlain by soils.

In the intact Opalinus Clay, groundwater flow is negligible due to the low permeability. Water flows become significant in the weathered zone. The deep weathered zone is assumed to be permanently saturated, and the shallow weathered zone is assumed to have a lower, saturated layer and an upper, unsaturated layer. Within both the saturated and unsaturated zones, water flows have components that are (i) vertically downwards and (ii) down-slope, parallel to the hillside, towards the base of the hillside and river. At the base of the hillside, water flows into corresponding layers in the valley floor. In the valley floor, water moves downwards through the soils and variably saturated zone into the saturated zone, which forms an aquifer in the valley. There is an upwards component of flow through the gravel aquifer to the river as well as flow along the valley. Water from the aquifer is used for irrigation alongside drinking water for humans and animals.

Uplift and erosion bring intact Opalinus Clay into the weathered zone where it undergoes weathering, which increases porosity and permeability. A portion of this Opalinus Clay continues to move vertically upwards and undergo increased weathering until it forms a soil. Another portion moves down-slope parallel to the hillside through a range of gravity-driven processes (e.g. landslides). Some of these processes act slowly, resulting in a long-term transfer of mass down the hillside towards the valley bottom. Rapid processes are discussed below. The downslope sliding of mass will cause deformation within the hillside, leading to mixing of mass over depth. All the mass transported down the hillside is deposited in the topsoil at the bottom of the slope; it then moves towards the river due to soil erosion and is carried out of the valley as suspended sediment and/or is subject to sedimentation/resuspension.

Where a limestone layer exists on the hillside below the remaining repository (see Fig. 4-8), the high-permeability limestone collects all the groundwater from higher up the slope and diverts it to springs on the hillside. The spring water runs down the hillside into the valley. Below the limestone layer, infiltration and flows within the weathered zone continue.

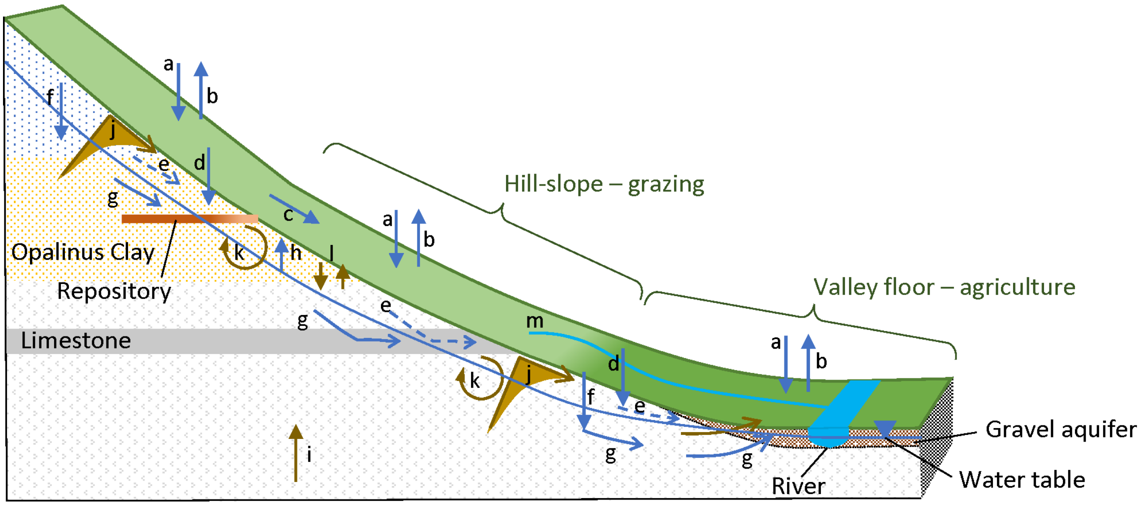

Fig. 4-8: Illustration of the hillside setting for Case D with a limestone layer showing the main features and processes relevant to mass and water transport

The presence of the limestone layer is the principal difference compared to Fig. 4-7 as this layer intercepts subsurface water flow down the hillside, such that it emerges at hillside springs instead.

Discrete landslide events can occur on the hillside in any of the three geometries (Case A – C), which rapidly transfer all mass in the landslide from the hillside onto the valley floor (see Fig. 4-9). Complete mixing of all materials in the landslide is assumed, and the resultant mass is deposited on the valley floor. Agriculture on the valley floor is taken to resume quickly after the landslide.

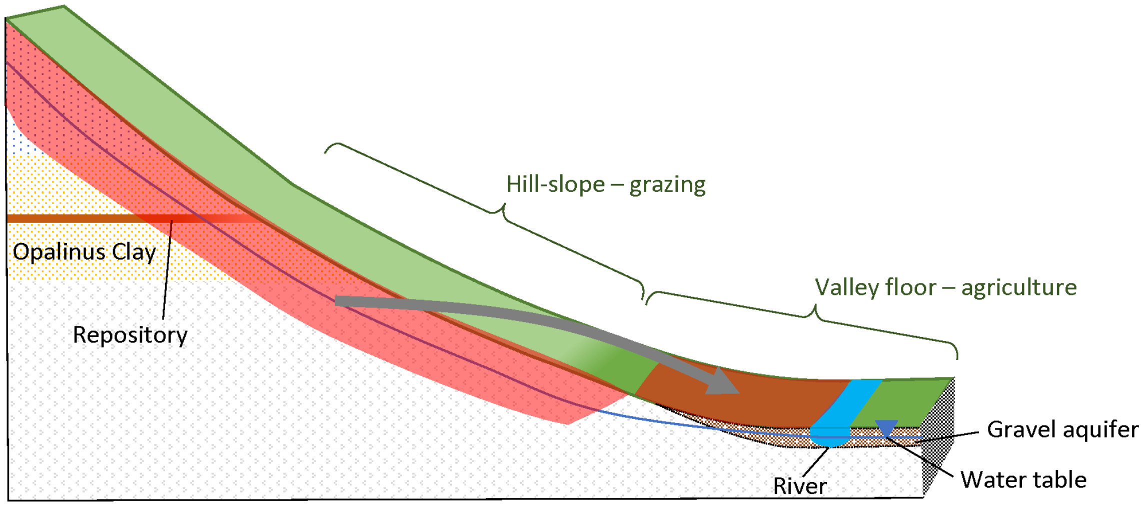

Fig. 4-9: Illustration of the hillside setting showing the main features and processes relevant to mass transport for an individual discrete landslide event

Complete mixing of all materials in the landslide (shown in red) is assumed, and the resultant mass is deposited on the valley floor.

4.3.2 Description of valley-floor variant

The features and processes involved in moving solid mass and water in the valley-floor variant are shown in Tab. 4-3. An assessment-level conceptualisation is then discussed and illustrated in Fig. 4-10. The valley-floor variant represents the special case in which the repository is coincidentally located directly below the valley floor, so does not transit the hillslope. The repository is situated within weathered Opalinus Clay immediately below a local aquifer.

Tab. 4-3: Features, events and processes (FEPs) associated with excavation by non-glacial processes within a valley-floor setting

Note that there are no "Events" associated with this variant.

Category	Items
Features	• Repository with associated radionuclides. • Unweathered Opalinus Clay. • Weathered Opalinus Clay (degree of weathering decreases with depth). • Soils. • Surface water. • Suspended sediment. • Groundwater. • Saturated zone. • Unsaturated zone. • Plants (crops and natural vegetation). • Animals (livestock, fish and other animals). • Atmosphere. • Humans.
Processes	a) Precipitation. b) Evapotranspiration. c) Overland flow. d) Infiltration (water movement into the subsurface). e) Groundwater flow (flow in the saturated zone). f) Erosion.

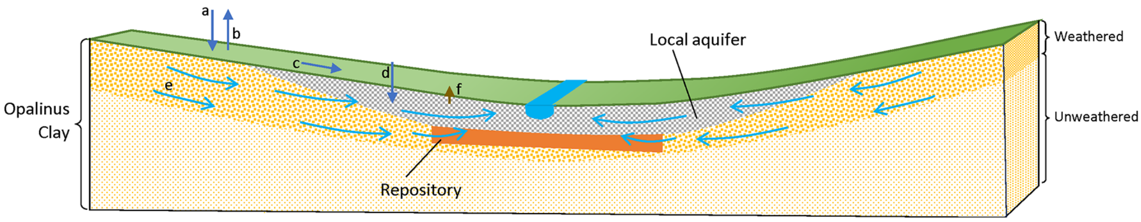

Fig. 4-10: Illustration of the valley-floor setting showing the main features and processes relevant to mass and water transport

The geometry of the valley-floor setting is assumed to stay constant with time and is very similar to Nagra's established biosphere modelling approach (Nagra 2024g), with the addition of weathered Opalinus Clay containing the repository directly below the local aquifer.

Water flows through the weathered Opalinus Clay are driven by the head gradient from recharge on the valley sides, creating an upwards flow through the weathered Opalinus Clay and local aquifer in the valley floor. Consistent with Nagra's reference biosphere (Nagra 2024g), groundwater within the local aquifer is assumed to be well mixed.

There is a very low erosion rate in the valley bottom, which moves mass from the soil to the river, and compensating movement of mass from the local aquifer into the soils.

4.3.3 Radionuclide transport and exposure

As discussed in Section 2.3.3, over the very long timescales considered in this assessment, radionuclides are assumed to be available for transport when the repository reaches the weathered zone of the Opalinus Clay. It is also assumed that no significant loss of radionuclides will have occurred before this time. The extremely long timescales considered mean that no reliance is given to further containment within the engineered barriers of the repository and/or the HLW disposal canisters during excavation, so the radionuclides are taken to be distributed in the porewater and sorbed to the mineral grains within a given volume of material that has the general characteristics of the Opalinus Clay, which is the dominant material.

Radionuclide transport for the hillside variant

In a hillside setting, only a small proportion of the repository will be within the weathered zone at any given time (see Fig. 4-7), with the remainder of the repository either having already been eroded or still located within intact Opalinus Clay. Within the weathered zone, the repository material is affected by leaching and movement of solid material parallel to the hillside (Fig. 4-11). The radionuclides sorb onto the solid material to different extents, with some radionuclides predominantly moving with water (e.g. Ra-226), while others predominantly move with solids. Most radionuclides move with both to varying degrees.

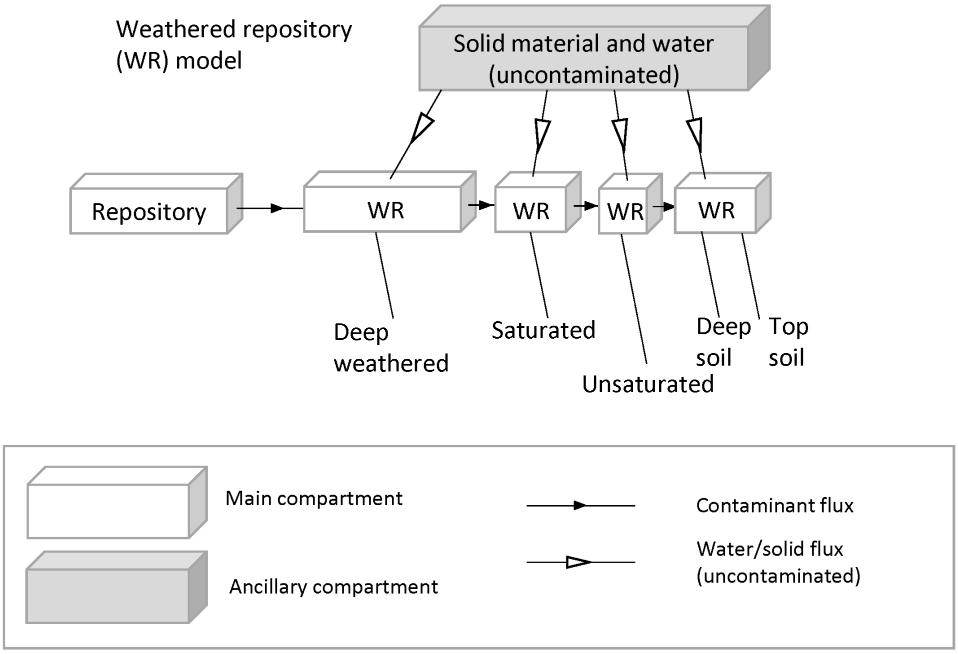

Fig. 4-11: Conceptual model of transfers (water or solid) that contain radionuclides (solid arrows) or uncontaminated material (open arrows) from the repository within intact Opalinus Clay to compartments that represent the repository within the weathered zone (WR)

Note that the structure of the weathered repository zone is related to the layers within the weathered zone.

The mass flux and water-flow processes within the hillside weathered zone move radionuclides downslope and from deeper parts of the weathered zone to shallower parts, including the hillside soils (Fig. 4-12). Radionuclides that remain in the repository material will eventually reach the ground surface and move downslope in the hillside soils. This leads to potential exposures when using the hillside for grazing and dwellings. Radionuclides that reach the base of the hillside result in contamination of both the soils and the aquifer, where potential exposure can occur through use of contaminated water from the aquifer or through agriculture.

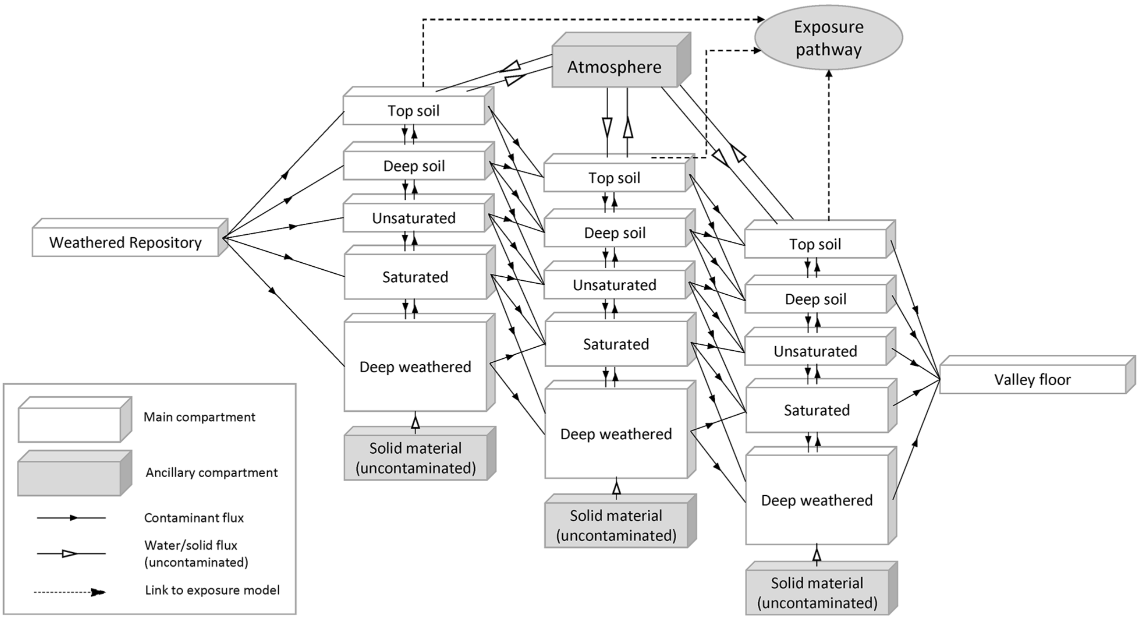

Fig. 4-12: Conceptual model of transfers (water or solid) that contain radionuclides (solid arrows) or uncontaminated material (open arrows) from the weathered repository through the hillside compartments to the valley floor

Note that the structure of the valley floor is taken from Nagra's reference biosphere model and is not repeated here. The hillside is discretised into eight columns in the model with only three columns shown here to simplify this figure.

For the limestone layer case, it is assumed that all dissolved radionuclides in groundwater entering the limestone layer from upslope are intercepted and discharge to springs. From the springs, the water travels to the river in the valley bottom. However, the radionuclides moving with solid phases are taken to pass over the limestone layer and continue to move downslope.

In a discrete landslide event, the radionuclides associated with the material on the hillside are assumed to have completely mixed throughout the mass of the landslide and to have been deposited over the valley floor.

Radionuclide transport for the valley-floor variant

With the remaining repository beneath the valley floor, radionuclides have the potential to migrate out of the weathered Opalinus Clay/repository material and into the local aquifer through leaching (with upwards-flowing groundwater) and diffusion. Mixing within the local aquifer means that radionuclide concentrations are relatively constant in that part of the system, which is consistent with Nagra's reference biosphere modelling in Nagra (2024g).

Potential exposure pathways for the hillside and valley-floor variants

Given the similarity in structure (i.e. agriculture in a valley-floor context with a local aquifer), potential exposure pathways for both the hillside and valley-floor settings are consistent with Nagra's reference biosphere modelling (Nagra 2024g), shown in Fig. 3-16. For the hillside setting, potential use of the hillside is restricted to grazing livestock and dwellings.

For the hillside settings, the total area of potentially contaminated soils is smaller than that of Nagra's reference biosphere, so a proportion of the exposure group's food and water is taken to be obtained from elsewhere and a proportion of their occupancy time is spent elsewhere. For the valley-floor setting, the area of potentially contaminated soils is taken to be equal to that of Nagra's reference biosphere. These assumptions both maintain consistency between Nagra's established reference biosphere modelling and the assessment presented here.

4.4 Calculation cases associated with excavation by non-glacial erosion

The hillside and valley-floor variants provide the basis for calculation cases that envelope a plausible range of post-glacial conditions following excavation by non-glacial erosion.

For the hillside setting, a range of hillslope angles are feasible (see Section 4.2.3). This uncertainty is managed by explicitly representing three different hillslope angles and erosion rates, based on analogues in Northern Switzerland and Southern Germany. These encompass shallow valleys with lower erosion rates through to steeper valleys with higher erosion rates. Hillslopes are treated as planar surfaces in the model. This is a simplification as compared to the more irregular and variable morphology of certain hillslopes within natural landscapes. However, potential effects of more irregular hillslope surfaces (e.g., on the intersection area of the hillslope surface and the repository) are also indirectly addressed through the consideration of the three different hillslope angles.

A fourth calculation case for the hillside setting explores the potential for a limestone layer in the hillside below the repository level, as discussed in Section 4.3.1. To help constrain the overall number of calculation cases, the limestone-layer variant adopts the average slope angle and mid-range erosion rate.

For the hillside settings, consideration is given both to long-term nuclide flux and exposures, as well as to potential exposures that could occur over relatively short timescales as a result of individual discrete landslide events.

Finally, calculations are also needed to reflect the valley-floor variant.

In addition to the type of near-surface system, the model should explore the range of potential timescales for excavation by non-glacial erosion. These are discussed in Section 2.2, which identifies timescales of 700 ka, 1 Ma, 2 Ma and 4 Ma after repository closure. For the hillside settings, the times are taken to reflect when the repository reaches the base of the weathered zone. For the valley-floor setting, the times are taken to represent the start of radionuclide releases from what remains of the repository into the overlying local aquifer.

The resulting twenty calculation cases are summarised in Tab. 4-4. In addition to these cases, sensitivity calculations are used to identify important processes and parameters; these are discussed further in Section 4.6.2.

Tab. 4-4: Calculation cases for assessment of excavation by non-glacial erosion

All variants and cases are calculated at 700 ka, 1 Ma, 2 Ma and 4 Ma.

Variant/Case		**Summary**
Hillside	Case A	Shallow valley with 50 m high hillside, low erosion rate 0.08 mm a^{-1}, considering long-term exposures and discrete landslide events.
	Case B	Average valley with 250 m high hillside, average erosion rate 0.2 mm a^{-1}, considering long-term exposures and discrete landslide events.
	Case C	Steep valley with 500 m high hillside, high erosion rate 25 mm a^{-1}, considering long-term exposures and discrete landslide events.
	Case D	Average valley with high-permeability limestone layer creating springs on the hillside below the repository.
Valley floor		Release from weathered repository below the local aquifer in a valley-floor setting, with a soil erosion rate of 0.1 mm a^{-1}.

4.5 Model for calculating doses due to repository excavation by non-glacial processes

The modelling approaches used for the hillside and valley-floor variants are described below. As with excavation by deep glacial erosion (see Section 3.5), there is a notable degree of consistency with Nagra's reference biosphere modelling approach, as encoded in SwiBAC (Nagra 2024g). Radionuclides are moved through the compartment model either sorbed onto solid mass or dissolved in water, with solid mass and water fluxes calculated by the model using the same methodology encoded in SwiBAC (Nagra 2024g).

4.5.1 Hillside variant

As discussed in Section 4.3.3, it is pessimistically assumed that no radionuclides will have been lost from the repository before the start time of the assessment, other than due to decay. The excavation time is considered to represent the time when the repository reaches the weathered zone on the hillside. From this time onwards, ongoing erosion means that the repository gradually moves closer to the ground surface along the hillside. The repository within the intact Opalinus Clay is represented by a single compartment with a time-dependent volume that becomes smaller as the repository moves into the weathered zone. Within the weathered zone, the repository is represented by four compartments (Fig. 4-11) to correspond to the layered structure of the weathered zone (soils, unsaturated zone, shallow and deep weathered zones). Transfers of radionuclides between the five repository compartments are calculated based on the erosion rate and apply to the volume of each compartment (solids and liquids). Transfers between repository compartments only become active once the repository reaches the depth of the recipient compartment.

The compartment structure for the hillside is determined by the height of the repository above the river at the time that the repository first reaches the ground surface. The hillside at this time is divided into five equally sized columns of compartments that remain constant in size and are adjacent to the weathered repository compartments. A further three columns of compartments are located between the five hillside compartment columns and the valley bottom. These three compartment columns initially have a very small length but grow with time, as ongoing erosion means that the position of the repository moves further up hill. Each column is split vertically into five compartments (Fig. 4-12) representing topsoil, deep soil, unsaturated shallow weathered zone, saturated shallow weathered zone and saturated deep weathered zone. The compartment structure for the valley floor is based on the SwiBAC reference biosphere model (Nagra 2024g).

Radionuclides move through the compartments due to a combination of mass and water transport. The movement of mass and water through the hillside are calculated separately, with both mass and water-balance checks implemented in the model to ensure internal consistency. The partitioning of radionuclides between the mass and water is given by the sorption coefficient.

Uncontaminated mass enters the hillside compartments from depth due to ongoing uplift/erosion and from upslope of the repository as the hillside above the repository erodes. Given the assumption that the valley shape stays constant as the position of the repository moves up the hillside, the "clean" area above the repository decreases, so the amount of uncontaminated material feeding into the model from upslope decreases with time. At the base of the hillside, all the mass moving in the hillside is transferred to the soil in the valley floor, from where erosion transfers the mass to the river.

Uncontaminated water enters the hillside compartments via infiltration and also as subsurface flow from upslope of the repository. The amount of rainfall that can infiltrate is calculated assuming saturated Darcy flow on the hillside, with a plausibility check that the amount of water remains less than the effective rainfall. The Darcy calculation assumes the hydraulic head gradient to be equal to the hillside gradient. As with the mass input from above the repository, the clean water input from upslope is reduced over time with the decreasing area upslope from the repository. At the base of the hillside, the water moving in the hillside is transferred into corresponding layers in the valley floor.

Within the hillside, mass transport is partitioned between the layers using a transport scaling factor, with most of the mass moving downslope in the soil layers and decreasing amounts of mass moving in the shallow and deep weathered zones. The mass of solids moving downslope increases with proximity to the base of the hillside due to the increasing volume of material that is generated by erosion with distance down the hillside. Mass mixing between the layers is also represented with a high degree of mixing in the soils (due to mass mixing and bioturbation) and decreasing amounts of mixing in the shallow and deep weathered zones. The movement and mixing of mass down the hillside represent a combination of processes, including surface erosion, subsurface deformation, subsurface sliding and the long-term effects of landslides.

Water flow within the hillside is partitioned between the layers based on transmissivity (hydraulic conductivity × thickness), with total infiltration limited to the total transmissivity of the weathered zone. As with the mass transport, the amount of water flowing through the hillside increases with proximity to the valley floor due to infiltration over the increasing upslope distance. Dispersion, in terms of water mixing between adjacent layers, is represented.

In the valley, the transfer of mass and water is based on the SwiBAC reference biosphere model.

The equations used to calculate (i) concentrations in the compartments and in features that are taken to be in equilibrium with those compartments (such as the atmosphere, crops and animal produce), and (ii) potential exposure rates and dose consequences, are identical to those used in the SwiBAC reference biosphere modelling (Nagra 2024g).

Assumptions for exposure pathways from the base of the hillside to the river (valley floor) are consistent with Nagra's reference biosphere modelling. Humans are taken to spend some time on the hillside, and agriculture on the hillslope is taken to be limited to grazing. The total area of contaminated soil (valley floor plus hillside) is lower than the reference biosphere area, so a local fraction approach is used to account for the additional area required for consistency with Nagra's reference biosphere assumptions.

To evaluate potential dose consequences from discrete landslide events, an additional exposure calculation is included. A separate concentration is calculated for soils contaminated as a result of a landslide; this is based on the total amount of radionuclides in all the hillside compartments divided by the total volume of the hillside weathered zone, including the clean part of the hillside above the repository. Potential exposures arising from use of soils contaminated by the discrete landslide are then calculated in the same way as the reference biosphere, including taking account of a typical width of a landslide using the local fraction approach, as above. The evaluation is pessimistic in assuming that the landslide soils could be used immediately for agriculture.

For the addition of a limestone layer, all the water flows out of the fifth column of compartments are diverted from continuing down the hillside and are instead connected directly to the river. This is representative of groundwater being intercepted by the limestone layer and diverted to springs. In this context, the hillside springs are taken to be too small for direct use and instead discharge to the local river.

4.5.2 Valley-floor variant

The valley-floor model is based on the SwiBAC reference biosphere model, with additional compartments used to represent the repository below the local aquifer.

As discussed in Section 4.3.3, it is pessimistically assumed that no radionuclides have been lost from the repository before the start time of the assessment, other than due to decay. This ignores potential losses – for example, due to erosion before the aquifer material is laid down (downcut and backfill). Over these long timescales, no reliance is given to further containment of the radionuclides within repository engineering, so the radionuclides are taken to be distributed within a volume of weathered Opalinus Clay (see Section 2.3.3). It is assumed that the radionuclides are initially evenly distributed over a total thickness equivalent to that of the local aquifer, and this assumption is then explored in sensitivity calculations.

The valley-floor area is taken to be equal to Nagra's reference biosphere area, which is 2.275 km^2 (Nagra 2024g). The repository footprint can be expected to be smaller than this, however, as the radionuclides will have become dispersed to some extent before this configuration could arise. Exposure modelling adopts the same assumptions as Nagra's reference biosphere modelling, so the resource use area will be the same. In modelling the valley-floor variant, the decision has been made to represent the whole biosphere area rather than introduce a local contaminated fraction in the exposure calculations.

Radionuclides are transported from the repository material to the local aquifer by advection and diffusion. To ensure that the time-dependency of the diffusive transport is represented appropriately, both the weathered Opalinus Clay and local aquifer are discretised vertically with five compartments (see Appendix B in Quintessa 2023b). The relative sizes of the compartments are parameterised such that the compartments increase in size away from the interface between the weathered Opalinus Clay and the local aquifer; having small, equal-sized compartments close to this interface ensures that diffusion between the two materials is well represented (see also Appendix B in Quintessa 2023b). The relative compartment size is varied in sensitivity calculations. Consistent with Nagra's reference biosphere modelling, the local aquifer is taken to be well mixed, and dispersive transfers between the local aquifer compartments are used to achieve this.

Recharge from the hills on both sides of the valley flows into the valley floor. The amount of recharge is calculated from the thickness and permeability of the hillside-saturated zone and the head gradient of the hillslope. This cannot exceed the maximum amount of recharge onto the hillsides, calculated as the total effective rainfall onto the slopes flanking the valley. The inflow is apportioned between the weathered Opalinus Clay and local aquifer compartments according to the relative transmissivity of each layer (the permeability of the compartment multiplied by its vertical thickness). Consistent with Nagra's reference biosphere modelling, there is additional uncontaminated groundwater flow into the local aquifer, and precipitation and irrigation water onto the topsoil in the valley bottom infiltrates through the deep soil and variably saturated zone into the local aquifer.

Consistent with Nagra's reference biosphere modelling, all flow through the shallow local aquifer discharges into the surface water via the bed sediments. Water for irrigation and drinking by humans and animals is drawn from a well in the local aquifer (as in Nagra's reference biosphere modelling (Nagra 2024g)).

Erosion transports mass from the topsoil to the surface water, with a compensating movement of mass from the local aquifer through the soils topsoil. For the purpose of the assessment, the overall configuration illustrated in Fig. 4-10 is taken to be maintained (i.e. the aquifer thickness does not reduce over time).

The equations used to calculate (i) concentrations in the compartments and in features that are taken to be in equilibrium with those compartments (such as the atmosphere, crops and animal produce), and (ii) potential exposure rates and dose consequences are identical to those used in Nagra's reference biosphere modelling (Nagra 2024g).

4.6 Data for excavation by non-glacial erosion

The data used for consequence analyses are described in Section 4.6.1. Assumptions and uncertainties are discussed in Section 4.6.2, which describes the approach adopted to identify important processes and parameters via sensitivity calculations.

4.6.1 Data for consequence analyses

Where available, parameter values used for assessment of potential dose consequences following excavation by non-glacial processes are drawn from the reference biosphere modelling (Nagra 2024g). Adaptation and extension of the reference biosphere model to represent the additional FEPs associated with modelling radionuclides in the non-glacial excavation contexts means that additional data are needed. So far as is practicable, these data are based on consideration of analogous systems available in present-day Northern Switzerland.

The same approach is adopted with regard to deterministic assessment and erring on the side of being pessimistic, as has been used for assessment of excavation by deep glacial erosion (see Section 3.6.1). Sensitivity calculations are subsequently used to vary parameters over plausible ranges to help identify the important processes and assumptions (these are discussed in Section 4.6.2).

Tab. 4-5: Parameters for excavation by non-glacial erosion

Parameter values consistent with reference biosphere modelling (Nagra 2024g) are not reproduced here. Sensitivity to parameter assumptions is discussed in Section 4.6.2. Where is it difficult to justify parameters values, but the model has been found to be insensitive to the parameter, this is noted here as part of the reasoning around the parameter value.

Parameter		Value	Notes
Canister inventory and number of canisters		See Notes column	Based on the radionuclide inventory for RBG (Nagra 2023)
Length and width of repository		1 km × 1 km	
Repository thickness hillside case		5 m	Assumption tested in sensitivity cases and found to be insignificant
Repository thickness valley-floor case		20 m	Assumed to be equivalent to the thickness of the local aquifer, and explored in sensitivity calculations
Hillside width, perpendicular to the river		1 km	Based on analogous present-day valleys (e.g. at Frick)
Hillside height	Hillside case A	50 m	Based on analogous present-day valleys (e.g. at Frick), also allowing for a steeper and higher hillside than observed in the present-day landscape (case C)
	Hillside case B	250 m	
	Hillside case C	500 m	
Valley-floor width, perpendicular to the river		500 m	Based on analogous present-day valleys (e.g. at Frick)
Horizontal distance between repository and river		300 m	Assumption tested in sensitivity cases and found to be insignificant.
Width of river		10 m	Assumption tested in sensitivity cases and found to be insignificant.
Thickness of weathered zone on hillside		25 m	Based on Vogt et al. (2017) Lower 50% "deep weathered", upper 50% "shallow weathered" plus soils
Thickness of unsaturated zone on hillside		5 m	Assumption tested in sensitivity cases and found to be insignificant.
Thickness of topsoil on hillside		0.1 m	Thinner than the reference biosphere topsoil thickness (which is 0.25 m) due to being on a hillside
Thickness of deep soil on hillside		2 m	Consistent with the reference biosphere
Erosion rate	Hillside case A	0.08 mm a^{-1}	Based on constraints of past erosion rates (e.g. Einsele & Ricken 1995) and expectations of future erosion rates (Nagra 2024d).
	Hillside case B	0.2 mm a^{-1}	
	Hillside case C	25 mm a^{-1}	
Porosity of weathered Opalinus Clay	Shallow	0.3	Based on Mazurek et al. (2023)
	Deep	0.2	

Parameter		**Value**	**Notes**
Hydraulic conductivity of weathered Opalinus Clay on hillside	Shallow	10^{-6} m s^{-1}	Based on Vogt et al. (2017). Permeability in the shallow weathered zone is between 10^{-5} and 10^{6} m s^{1}. A value of 10^{-6} m s^{-1} was chosen, representing the lower parts of the zone as this is where flow will occur in transient periods of higher water level on the hillside.
	Deep	10^{-8} m s^{-1}	See discussion in text
Hydraulic conductivity of weathered Opalinus Clay in valley floor	0–10 m depth	3×10^{-5} m s^{-1}	Based on Vogt et al. (2017). In this case, flow is expected through the whole of the weathered Opalinus Clay. A pessimistic assumption of high hydraulic conductivity is used to maximise the mobilisation of radionuclides.
	10–20 m depth	5.4×10^{-6} m s^{-1}	See discussion in text
Saturation (topsoil, deep soil and weathered Opalinus Clay on the hillside)		0.75	Calculated to give saturation consistent with the reference biosphere in the valley bottom.
Element-dependent sorption coefficient (K_d) for weathered Opalinus Clay		See Notes column	K_d values for most elements are taken directly from Bradbury & Baeyens (2003) using values for pH 7.24, and are not repeated here. A small number of elements are not considered in Bradbury & Baeyens (2003) and justification for their K_ds are presented below: Al: 1 m^3/kg (Metcalfe et al. 2023), low value chosen due to Opalinus Clay being weathered. Cf: used Am as analogue Fe: 0 m^3/kg (Metcalfe et al. 2023) chosen values representative of oxidising conditions Si: 0.2 m^3/kg (Metcalfe et al. 2023) consistent with reference assumptions.
Transverse dispersion		0.01	Assumption tested in sensitivity cases and found to be insignificant.
Groundwater flow in valley		1.89×10^{7} m^3 a^{-1}	Calculated considering Darcy Law and mean properties of valleys in Northern Switzerland
Transport scaling factor for mass moving downslope in different layers	Topsoil	1	Assumptions based on expert judgement; see considerations on (non-linear) depth-dependency of hillside material flux in Section 4.2.3. The mass flux in each layer is determined by the produce of the transport scaling factor and the thickness of the layer.
	Deep soil	0.75	
	Shallow weathered	0.25	
	Deep weathered	0.025	

Parameter		Value	Notes
Solid mixing between layers	Topsoil / deep soil	0.8	Assumptions based on expert judgement; see considerations on (non-linear) depth-dependency of vertical hillside material mixing in Section 4.2.3.
	Deep soil / shallow weathered	0.25	
	Shallow weathered / deep weathered	0.025	
Occupancy of hillside		0.05	Assumption tested in sensitivity cases and found to be insignificant.

4.6.2 Assumptions and uncertainties

Uncertainties are unavoidable in modelling post-closure safety for deep geological repositories for radioactive waste; this is especially true given the extraordinarily long timescales associated with assessing potential consequences of repository excavation by erosive processes. For excavation by non-glacial erosion, it is necessary to make assumptions about the valley geometry and how it changes with time, in particular, how it affects the input of clean (uncontaminated) mass and water from above the repository. Assumptions must also be made around the parameterisation of depth-dependent mass transport and mixing processes in the hillside. The calculation cases explore a range of hillslope angles and erosion rates, and sensitivity calculations have been used to help identify important processes and parameter assumptions.

For the sensitivity calculations, plausible ranges have been used around the parameter values presented in Section 3.6.1. Each parameter has been varied independently using the minimum, reference and maximum values to provide three model runs per parameter that indicate the importance of associated uncertainty to the key metric for the assessment, which is the maximum calculated effective dose.

A list of the parameters varied for each of the landscape variants is provided in Tab. 4-6. These focus on parameters and assumptions specific to assessment of excavation by non-glacial erosion. Parameters and conceptualisation based on Nagra's reference biosphere modelling are not varied here because they are explored in Nagra (2024g).

Tab. 4-6: Parameters varied over plausible ranges to explore sensitivities in assessing excavation by non-glacial erosion

Variant	Parameters varied for sensitivity analyses
Hillside	Suspended sediment concentrations in groundwater and surface water, porosity of the weathered Opalinus Clay, hydraulic conductivity of the weathered Opalinus Clay, K_d, erosion rate, dispersion, length and height of the hillside, distance between repository and river when repository first reaches ground surface, width of river, width of valley floor, thickness of weathered zone, thickness of unsaturated zone, thickness of repository compartments, depth-dependent mass transport, depth-dependent mixing, saturation, occupancy of hillside
Valley floor	Suspended sediment concentrations in groundwater and surface water, porosity of the weathered Opalinus Clay, hydraulic conductivity of the weathered Opalinus Clay, K_d, depth range over which the radionuclide inventory is initially distributed within the weathered Opalinus Clay, relative compartment sizes in the aquifer and weathered Opalinus Clay, groundwater recharge from the valley sides, tortuosity of the weathered Opalinus Clay

4.7 Calculated doses due to repository excavation by non-glacial processes

Results for the calculation cases summarised in Section 4.4 are presented and discussed in Section 4.7.1. Results of the sensitivity calculations are discussed in Section 4.7.2.

4.7.1 Calculation case results

Results for the hillside variant are presented first, followed by results for the valley-floor setting; both sets of results are then summarised at the end of this subsection.

Results for the hillside variant

Results for the hillside variant cases that explore different hillslope angles and erosion rates are shown in Fig. 4-13.

The calculated effective doses for the valley-floor variant are shown to fall within the range of natural radiation exposure rates in Switzerland (taken from BAG (2023)). The hypothetical case of excavation 700 ka after closure results in the highest calculated effective doses. Effective doses arising from the same exposure model but with excavation after 1 Ma, 2 Ma and 4 Ma are all progressively lower. The long-lived nature of some of the decay chains, including U-238 (which has a half-life of 4.5×10^9 years) and Np-237 (which has a half-life of 2.1×10^6 years) means that the maximum calculated effective doses only decline by about a factor of three between excavation after 700 ka and 4 Ma.

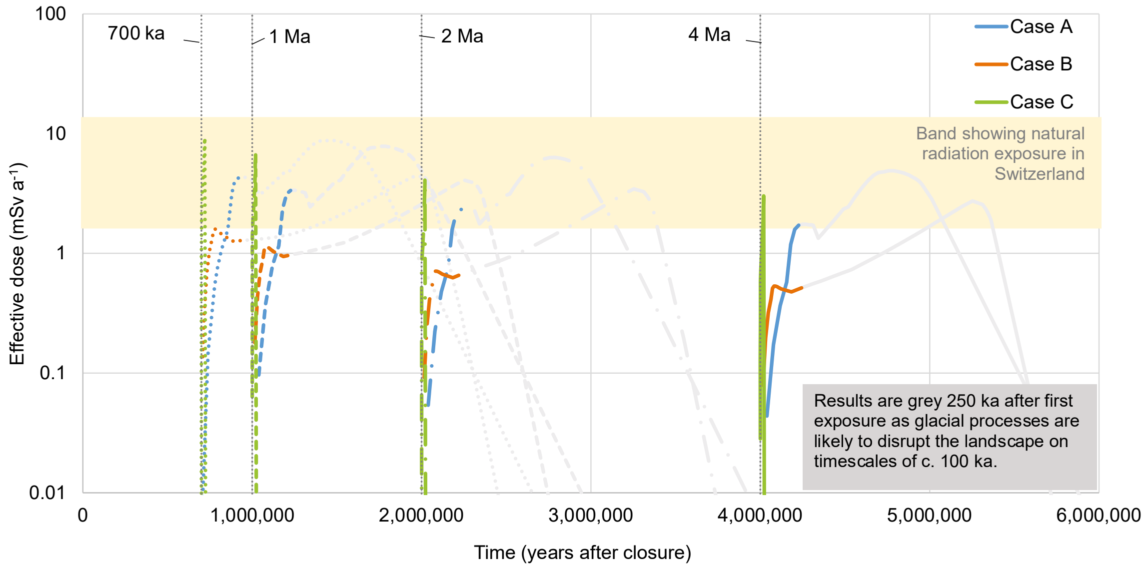

Fig. 4-13: Total effective dose following excavation by non-glacial erosion for different hill-slope angles and erosion rates for the hillside variant at different excavation times

Tab. 4-4 provides a definition for the calculation cases. Case A represents a lower hillslope angle and erosion rate, Case B represents a mid-range hillslope angle and erosion rate, and Case C represents a steeper hillslope angle and a higher erosion rate. Note that Case D is discussed below and is not presented here.

The dominant pathway for dose is consumption of milk. The dose results show an initial peak when the repository material moves into the weathered zone with radionuclides being transported within the weathered zone to pasture soils in the valley floor. At longer time periods, the repository material reaches pasture soils on the hillside, and concentrations increase as the repository moves uphill and the influx of clean eroded material from above the hillside decreases.

For the hillside variant, the effective dose rate is dominated by consumption of milk with Po-210 and Th-229 being the dominant radionuclides. There is grazing land in both the valley bottom and on the hillside, with the initial dose being dominated by grazing in the valley. At later times, the effective dose is dominated by grazing on the hillside, as the concentration in the hillside increases due to the reduction in clean mass and water input from above the repository, coupled with the contaminated area getting larger as the repository moves higher up the hillside.

The relative contributions of Po-210 and Th-229 to the total dose changes across the cases, depending on the relative important of radionuclide transport by water and solid mass. The decay chain ending at Po-210 involves Ra-226, which has a relatively low degree of sorption and is therefore transported to the biosphere relatively quickly by water. The decay chain ending at Th-229 only involves radionuclides that sorb on solid mass, so Th-229 will reach the biosphere predominantly with solid materials.

For Cases A to C, which assess different valley geometries and corresponding erosion rates, the timing of the maximum effective dose is affected by the erosion rate, with a higher erosion rate resulting in an earlier peak dose. The erosion rate in Case C (steeper valley with higher erosion rate) results in the repository reaching the top of the hillside 20 ka after it reaches the weathered zone, so radionuclides are present within the valley for a much shorter period of time compared to Cases A and B, which take 900 ka and 1.3 Ma, respectively, before the remaining repository location reaches the top of the hillside. Over such long timescales, it is unlikely that the valley configuration would remain the same when multiple glaciations may occur; effective dose rates are shown in grey from 250 ka after the repository reaches the weathered zone to illustrate model behaviour rather than as projections that might occur. Potential impacts during initial excavation are taken to be more significant than those that might occur during excavations extending over multiple glacial/interglacial cycles.

There are many processes leading to potential exposure and the effective dose rates shown in Fig. 4-13, and there is no simple linear trend between erosion rate and hillside height/steepness with dose. Higher erosion rates move contaminated material into the biosphere more quickly, whereas flatter valleys have more of the repository in the weathered zone at any given time, potentially allowing higher concentrations in the biosphere.

For the limestone-layer variant (Case D, based on the hillside geometry of Case B), where water is diverted to springs on the hillside, the effective dose is reduced compared to Case B, as mobile radionuclides are effectively diverted to the river, bypassing the lower slope and local aquifer. The difference is a reduction in effective dose of about a third when the repository reaches the weathered zone on the hillside about 700 ka after closure, and the difference is further reduced at later times of emergence.

All presented calculations assume a constant erosion rate through time. Cases with a range of hillslope angles and transient high erosion rates for 10 ka when the repository reaches the weathered zone have been investigated. Some of these cases include the whole repository being eroded during the transient period and show that doses can be increased by a factor of up to three compared with Case C.

A discrete landslide event directly affecting the repository could, in principle, occur at any time in these cases. The short-term maximum effective dose rate associated with agriculture on soils derived from such landslides is less than a factor of two higher than the long-term average (the latter combining erosion, deformation, subsurface slips and the long-term effects of landslides in mixing material over the hillside and valley floor).

Results for the valley-floor variant

The total effective doses calculated for the valley-floor variant at different timescales are shown in Fig. 4-14. The relatively static nature of this system (e.g. erosive removal of the remaining repository is not represented in this case) means that the consequences become a function of the radioactivity remaining in the repository. Results for the different timescales for this variant, therefore, are shown to sit on a consistent curve in Fig. 4-14.

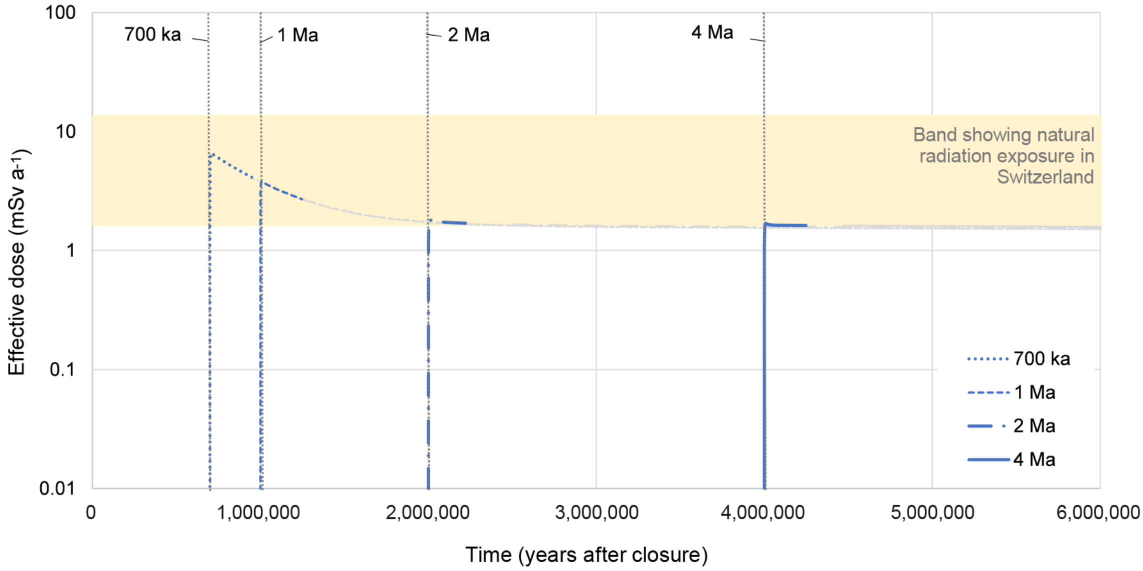

Fig. 4-14: Total effective dose following excavation by non-glacial erosion for the valley-floor variant

Tab. 4-4 provides a definition for the calculation cases. The results for each case are shown in grey ca. 250 ka after the start of each case to emphasise that the valley system would not remain the same over long timescales because it would be subject to significant reworking through glacial-interglacial cycles.

The calculated effective doses for the valley-floor variant are shown to fall within the range of natural radiation exposure rates in Switzerland. As with the other repository excavation scenarios and calculation cases, Po-210 dominates the calculated effective doses. In this variant, ingestion of crops is the leading exposure pathway, followed by ingestion of animal produce and then drinking water from the aquifer.

Summary of results for excavation by non-glacial erosion

The maximum calculated effective doses for all of the calculation cases exploring potential consequences of excavation by non-glacial erosion are shown in Tab. 4-7. The results are shown to be within the range of natural radiation exposure rates within Switzerland for the explored range of calculation cases.

Tab. 4-7: Peak calculated effective doses (mSv a^{-1}) and associated time of peak dose (years after closure) for excavation by non-glacial erosion

The time lag between excavation and peak dose is due to the time taken to move radionuclides from the base of the weathered zone into the biosphere. A discrete landslide directly affecting the repository could, in principle, occur at any time within the configurations represented in Cases A to C; this would result in short-term maximum effective dose rates that are less than a factor of two higher than those presented here.

Tab. 4-4 provides a definition for the calculation cases.

Variant/Case		**Time of excavation (years after closure)**			
		700 ka	1 Ma	2 Ma	4 Ma
Hillside	Case A	4.3 (927 ka)	3.4 (1.23 Ma)	2.3 (2.24 Ma)	1.7 (4.23 Ma)
	Case B	1.6 (781 ka)	1.1 (1.08 Ma)	0.7 (2.08 Ma)	0.5 (4.08 Ma)
	Case C	9.2 (720 ka)	6.8 (1.02 Ma)	4.3 (2.02 Ma)	3.0 (4.02 Ma)
	Case D	1.0 (791 ka)	0.8 (1.09 Ma)	0.5 (2.24 Ma)	0.4 (4.24 Ma)
Valley floor		6.6 (700 ka)	3.8 (1 Ma)	1.8 (2 Ma)	1.7 (4 Ma)

The calculation with the remaining repository emerging on the valley side, with a combination of a steeper slope and faster erosion rates results in the highest calculated effective doses across the non-glacial erosion cases. However, the variant with the remaining repository situated beneath the valley floor is second in terms of relative importance.

4.7.2 Sensitivity calculations

Sensitivity calculations have been used to identify important processes and parameter assumptions. Calculations were undertaken for the hillside Case B and for the valley-floor variant, for the hypothetical case of repository emergence in the weathered zone 700 ka after closure. The parameters outlined in Section 4.6.2 were varied over plausible ranges.

The results of the sensitivity calculations are summarised in Tab. 4-8.

Tab. 4-8: Relative importance of parameters identified as affecting the peak calculated effective doses for the non-glacial erosion variants

The parameters are listed in order of importance; ">" indicating more important, ">>" indicating much more important, and the lack of a symbol indicating that parameters were of equivalent importance.

Variant	**Relative sensitivity of important parameters**
Hillside	Erosion rate >> hill depth > valley floor width > K_d > upslope dilution
Flat	K_d >> hydraulic conductivity of the weathered clay > initial thickness of contamination, porosity of clay

For the hillside variant, the erosion rate is shown to be the most important parameter. Variation in erosion rates is explored via the different calculation cases for this variant and coupled with different valley geometries.

For the valley-floor variant, radionuclide sorption is shown to be most important. This is because it determines the degree of radionuclide retention on the weathered Opalinus Clay. The greater the degree of sorption, the lower the mobility of radionuclides and the fewer radionuclides are able to migrate from the clay to the overlying aquifer via groundwater flow and diffusion.

After K_d, hydraulic conductivity of the weathered clay is shown to be the second-most important parameter in the valley-floor variant, which indicates that the small degree of groundwater flow through the weathered clay driven by recharge from the valley sides dominates over diffusion as a transport mechanism towards the local aquifer.

5 Discussion and conclusion

In the very long term (10^6 – 10^7 years), uplift and erosion by both glacial and non-glacial processes will bring the deep geological repository closer to the surface. In the distant future, there is potential for repository material to be excavated as a result of glacial and non-glacial processes. For example, channels of deep glacial erosion are evident in the landscape of Northern Switzerland today, extending to depths of a few hundred metres. Such overdeepened channels can intersect the repository once it is moved closer to the surface. The host rock bearing the repository could potentially emerge at a valley or hillside setting as a result of rock uplift and erosion. In its guidelines related to deep geological disposal in Switzerland, ENSI requires assessment of potential dose consequences of repository excavation scenarios in the very long term.

It is expected that more than one million years are needed before excavation of a deep geological repository by glacial or non-glacial processes becomes feasible. Over such timescales, the global climate will undergo several glacial-interglacial cycles. Uplift and erosion by both glacial and non-glacial processes over these timescales mean that the surface environment above a deep geological repository in Northern Switzerland will evolve from the present day, as it has over previous glacial cycles.

Given the uncertainties inherent in making projections over extremely long timescales, assessment of potential dose consequences from repository excavation scenarios must necessarily be stylised in nature. The present-day landscape form in Northern Switzerland is used as an analogue of the situation at the time of potential excavation, with valleys carved by glacial and non-glacial processes. Confidence in the plausibility and internal consistency of the assessment is drawn by considering the landscape setting and processes operating at the present day. It is appreciated that the situation in the distant future will not be identical to that of the present day, and this is explored through sensitivity analyses.

Assessment calculations have been undertaken to explore potential dose consequences of repository excavation scenarios. These have separately considered excavation by deep glacial erosion and non-glacial erosion.

- Assessment of deep glacial erosion considers an overdeepening directly impacting the repository and transporting excavated material from the repository up an adverse slope to the near-surface region, with a range of post-glacial landscape settings.
- Assessment of non-glacial erosion considers emergence of what remains of a repository below a valley or in a hillside setting, with a range of erosion rates and valley geometries.

A compartment-modelling approach is used to represent the distribution of material excavated from the repository, subsequent radionuclide release, transport and potential exposures. The exposure assessment assumes that humans are present in the area local to the excavated material and make maximum use of that environment. The exposure-modelling approach is based on Nagra's established reference biosphere assessment modelling; this helps ensure assessments for different scenarios are made on a reasonably consistent basis.

A range of potential excavation contexts has, therefore, been studied, with 36 calculation cases accompanied by further sensitivity calculations to help identify important processes, parameters and assumptions. The assessment explores potential consequences of excavation over timescales ranging from 700,000 years to four million years after repository closure. These timescales span early hypothetical timescales through to more plausible timescales for repository excavation.

The range in the maximum calculated effective doses is illustrated over the full set of calculation cases in Fig. 5-1.

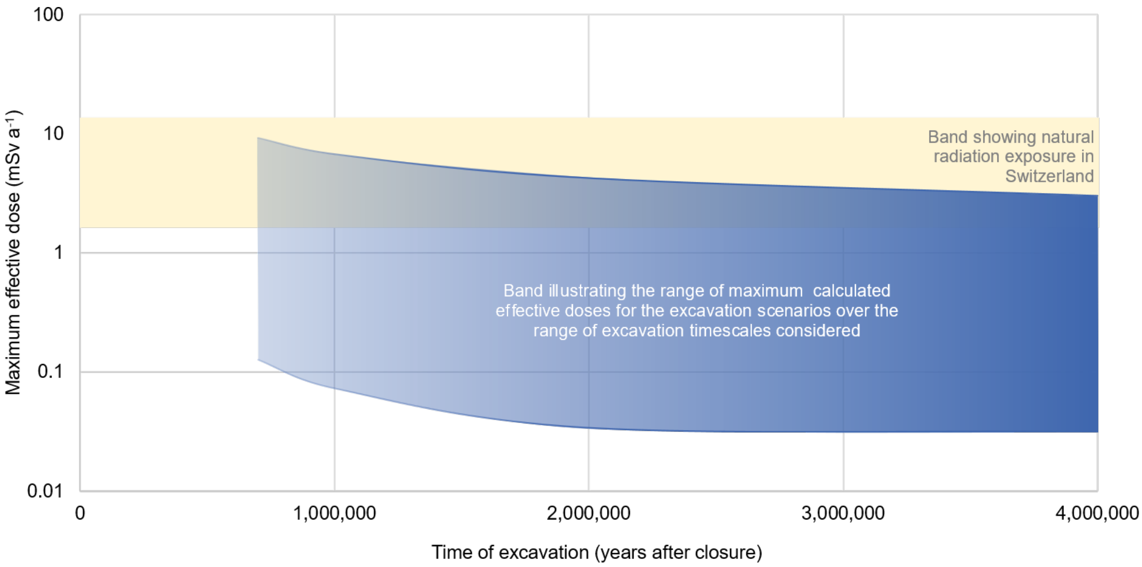

Fig. 5-1: Illustration of the range in calculated effective doses for the range of repository excavation scenarios and associated calculation cases considered

Based on the range of maximum calculated effective dose consequences across the full range of cases assessed for excavation after 700 ka, 1 Ma, 2 Ma and 4 Ma. Transparency is used in the figure to indicate the increasing likelihood over time, with repository excavation not expected within 1 Ma.

The assessment demonstrates that both excavation by deep glacial erosion and by non-glacial erosion results in potential maximum dose consequences comparable with natural, present-day radiation exposures in Switzerland, with the majority of cases leading to much lower doses. The disposed inventory includes decay chains that have some very long-lived radionuclides, including U-238 (which has a half-life of 4.5×10^9 years) and Np-237 (which has a half-life of 2.1×10^6 years). The assessment results are dominated by radionuclides within these decay chains, including Po-210 (ingrown from the U-238 decay chain) and Th-229 (ingrown from the Np-237 decay chain).

For excavation by deep glacial erosion, where eroded material is taken to be deposited in a shallow aquifer within a valley, irrigation of crops using water taken from that aquifer[10] is the dominant exposure pathway. For non-glacial erosion in a hillside setting, where eroded material will mix with soils and sediments down the hillside and onto the base of the hillside (valley floor), the ingestion of produce from animals grazing on the hillside and valley is shown to be dominant. These exposure pathways arise because the assessment adopts pessimistic assumptions about humans spending all of their time in the local area and making maximum use of the local resources.

The range of cases studied, along with sensitivity calculations, help to identify important processes, parameters and associated assumptions. For excavation by deep glacial erosion, the variants demonstrate the importance of where the excavated material is deposited, with deposition directly within the material, which then forms a local shallow aquifer, resulting in higher calculated doses compared to deposition beneath a lake, or within sediments that end up on a hillside with groundwater feeding springs. The flow rate through a river associated with the local shallow aquifer is shown to be important, with a range of characteristics being explored based on present-

[10] This is a pessimistic assumption that is included for the sake of consistency with Nagra's reference biosphere modelling (Nagra 2024g).

day gauged rivers in Northern Switzerland. The degree of sorption on the aquifer sediment is also important, and Nagra's biosphere sorption database was correspondingly subject to a recent review and update. The fraction of the repository that is excavated is also influential, although there will be a degree of correlation between the extent of the excavation and the area over which the material is distributed.

Assessment of excavation by non-glacial erosion within a hillside setting reveals a non-linear relationship between erosion rates/hillslope angles (which are correlated) and potential dose consequences. Steeper hillslopes with higher erosion rates result in the highest doses because the material is excavated over a shorter timeframe. However, low erosion rates/hillslope angles resulted in higher, albeit later, potential doses compared to an intermediate position, as the low hillslope angle means that more of the remaining repository intersects the hillside, and the low erosion rates mean that excavated material remains within the local area for longer. This extends to the potential for the remaining repository to be situated below a valley floor with a low topographic relief, which results in potential doses comparable with those of a steeper hillside setting.

For the hillside setting, the erosion rate is the dominant parameter and is explored through a range of variant geometries. For the valley-floor setting, the degree of groundwater flow through the weathered Opalinus Clay containing the remaining repository material is an important assumption.

Given the uncertainties involved, the assessment has been made on a generally pessimistic basis, so the results bound what could reasonably be expected. Notable pessimisms include:

- that an overdeepening directly intersects the remaining repository, given that the majority of the areas in the considered siting regions are not directly affected by deep glacial erosion;
- that excavation by non-glacial erosion could hypothetically occur on timescales before a million years after repository closure, given that repository depths and rates of uplift/erosion mean that longer timescales will be needed;
- that excavated repository material is directly deposited in the local area, given that some material would be dispersed more widely before deposition, or some would be lost as the deposited material is reworked through subsequent erosive processes prior to the potential exposures that are assessed;
- that excavated material remains accessible in the near-surface environment; such that configurations where the material could be buried more deeply are not explicitly assessed; and
- that humans are present, spend their time in the local area, draw groundwater for domestic and agricultural purposes directly affected by the excavated material, where feasible, and make maximum use of local crops and animal produce.

Overall, the assessment effectively demonstrates similar potential dose consequences across different repository excavation scenarios and ranges of associated calculation cases. These remain very low, with the maxima being comparable with the range of natural radiation exposure levels in Switzerland.

6 References

Alley, R.B., Cuffey, K.M., Evenson, E.B., Strasser, J.C., Lawson, D.E. & Larson, G.J. (1997): How glaciers entrain and transport basal sediment: Physical constraints. Quaternary Science Reviews 16/9, 1017-1038. DOI: 10.1016/S0277-3791(97)00034-6.

Alley, R.B., Cuffey, K.M. & Zoet, L.K. (2019): Glacial erosion: status and outlook. Annals of Glaciology 60/80, 1-13. DOI: 10.1017/aog.2019.38.

BAFU (2013): Datensatz MQ-GWN-CH, modellierte mittlere natürliche Abflüsse für das Gewässernetz der Schweiz. Bundesamt für Umwelt BAFU, available online at https://www.bafu.admin.ch/bafu/de/home/themen/wasser/zustand/karten/geodaten/mittlerer-monatlicher-und-jaehrlicher-abfluss/mittlere-abfluesse-und-abflussregimetyp-fuer-das-gewaessernetz-d.html, status as of January 4, 2024.

BAG (2023): Strahlenschutz und Überwachung der Radioaktivität in der Schweiz: Ergebnisse 2022. Bundesamt für Gesundheit (BAG), Bern.

Baltzer, A. (1876): Der Erdschlipf von Böttstein. Vierteljahresschrift der Naturforschenden 21/3, 285-290.

Bayer, P., Huggenberger, P., Renard, P. & Comunian, A. (2011): Three-dimensional high resolution fluvio-glacial aquifer analog: Part 1: Field study. Journal of Hydrology 405/1-2, 1-9. DOI: 10.1016/j.jhydrol.2011.03.038.

Beaud, F. & Flowers, G.E. (2015): Implementation of glaciofluvial erosion and sediment transport in models of subglacial hydrology. Nagra Arbeitsbericht NAB 15-19.

Beaud, F., Flowers, G.E. & Venditti, J.G. (2016): Efficacy of bedrock erosion by subglacial water flow. Earth Surface Dynamics 4/1, 125-145. DOI: 10.5194/esurf-4-125-2016.

Beaud, F., Flowers, G.E. & Venditti, J.G. (2018): Modeling Sediment Transport in Ice-Walled Subglacial Channels and Its Implications for Esker Formation and Proglacial Sediment Yields. Journal of Geophysical Research: Earth Surface 123/12, 3206-3227. DOI: 10.1029/2018JF004779.

Benn, D. & Evans, D.J.A. (2010): Glaciers and Glaciation, 2nd edition. Routledge, London.

Bennett, M.R. & Glasser, N.F. (2009): Glacial Geology. Ice Sheets and Landforms, 2nd edition. John Wiley & Sons Ltd., Chichester.

Benz-Meier, C. (2003): Der würmeiszeitliche Rheingletscher – Maximalstand, Digitale Rekonstruktion, Modellierung und Analyse mit einem Geographischen Informationssystem. Ph.D. thesis. Mathematisch-naturwissenschaftliche Fakultät der Universität Zürich.

Berger, A. & Loutre, M.F. (1991): Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10/4, 297-317. DOI: 10.1016/0277-3791(91)90033-Q.

BFE (2008): Sachplan Geologische Tiefenlager: Konzeptteil. BFE 2. April 2008 (Revision vom 30. November 2011). Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK, Bern.

Bini, A., Buonchristiani, J.F., Couterand, S., Ellwanger, D., Felber, M., Florineth, D., Graf, H.R., Keller, O., Kelly, M., Schlüchter, C. & Schoeneich, P. (2009): Switzerland during the Last Glacial Maximum (LGM). Swiss Federal Office of Topography, swisstopo, available online at https://map.geo.admin.ch/?layers=ch.swisstopo.geologie-eiszeit-lgm-raster, Stand am 17. June 2024.

Blatter, H. & Haeberli, W. (1984): Modelling Temperature Distribution in Alpine Glaciers. Annals of Glaciology 5, 18-22. DOI: 10.3189/1984AoG5-1-18-22.

Bogen, J., Xu, M. & Kennie, P. (2015): The impact of pro-glacial lakes on downstream sediment delivery in Norway. Earth Surface Processes and Landforms 40/7, 942-952. DOI: 10.1002/esp.3669.

Bradbury, M. & Baeyens, B. (2003): Far Field Sorption Data Bases for Performance Assessment of a High-Level Radioactive Waste Repository in an Undisturbed Opalinus Clay Host Rock. Nagra Technical Report NTB 02-19.

Brunner, P., Cook, P.G. & Simmons, C.T. (2009): Hydrogeologic controls on disconnection between surface water and groundwater. Water Resources Research 45/1, 2008WR006953. DOI: 10.1029/2008WR006953.

Buechi, M.W., Graf, H.R., Haldimann, P., Lowick, S.E. & Anselmetti, F.S. (2018): Multiple Quaternary erosion and infill cycles in overdeepened basins of the northern Alpine foreland. Swiss Journal of Geosciences 111/1-2, 133-167. DOI: 10.1007/s00015-017-0289-9.

Burbank, D.W. (2002): Rates of erosion and their implications for exhumation. Mineralogical Magazine 66/1, 25-52. DOI: 10.1180/0026461026610014.

Burki, V. (2009): Glaziale Erosion: Prozesse und ihre Kapazitäten. Nagra Arbeitsbericht NAB 09-06.

BWG (2001): Hydrologisches Jahrbuch der Schweiz 2000. Bundesamt für Wasser und Geologie BWG, Bern.

Carrivick, J.L. & Tweed, F.S. (2013): Proglacial lakes: character, behaviour and geological importance. Quaternary Science Reviews 78, 34-52. DOI: 10.1016/j.quascirev.2013.07.028.

Carsel, R.F. & Parrish, R.S. (1988): Developing joint probability distributions of soil water retention characteristics. Water Resources Research 24/5, 755-769. DOI: 10.1029/WR024i005p00755.

Church, M. & Gilbert, R. (1975): Proglacial fluvial and lacustrine environments. *In:* Jopling, A.V. & McDonald, B.C. (eds.): Glaciofluvial and Glaciolacustrine Sedimentation. SEPM Society for Sedimentary Geology, 22-100.

Cohen, D., Gillet-Chaulet, F., Haeberli, W., Machguth, H. & Fischer, U.H. (2018): Numerical reconstructions of the flow and basal conditions of the Rhine Glacier, European Central Alps, at the Last Glacial Maximum. The Cryosphere 12/8, 2515-2544. DOI: 10.5194/tc-12-2515-2018.

Cook, S.J. & Swift, D.A. (2012): Subglacial basins: their origin and importance in glacial systems and landscapes. Earth-Science Reviews 115/4, 332-372. DOI: 10.1016/j.earscirev.2012.09.009.

Cowton, T., Nienow, P., Bartholomew, I., Sole, A. & Mair, D. (2012): Rapid erosion beneath the Greenland ice sheet. Geology 40/4, 343-346. DOI: 10.1130/G32687.1.

Curti, E. (2022): Aqueous Corrosion of Vitrified Nuclear Waste: Current Process Understanding, Literature Review and Recommended Rates. Nagra Arbeitsbericht NAB 23-09.

Dehnert, A., Lowick, S.E., Preusser, F., Anselmetti, F.S., Drescher-Schneider, R., Graf, H.R., Heller, F., Horstmeyer, H., Kemna, H.A., Nowaczyk, N.R., Züger, A. & Furrer, H. (2012): Evolution of an overdeepened trough in the northern Alpine Foreland at Niederweningen, Switzerland. Quaternary Science Reviews 34, 127-145. DOI: 10.1016/j.quascirev.2011.12.015.

Deslisle, G., Caspers, G. & Freund, H.: Permafrost in north-central Europe during the Weischselian: how deep? *In:* Haeberli, W. & Brandovà, D. (eds.): ICOP 2003 Permafrost. Extended Abstracts Reporting Current Research and New Information. 8th International Conference on Permafrost Zurich, Switzerland, 20-25 July 2003, 187-191.

Domenico, P.A. & Schwartz, F.W. (1998): Physical and chemical hydrogeology. 2nd ed. Wiley, New York.

Drewry, D. (1986): Glacial Geologic Processes. Edward Arnold, London.

Ehlers, J. (1994): Allgemeine und historische Quartärgeologie. F. Enke, Stuttgart.

Einsele, G. & Ricken, W. (1995): The Wutach gorge in SW Germany: late Würmian (periglacial) downcutting versus Holocene processes. Zeitschrift für Geomorphologie, Neue Folge Suppl. Bd. 100, 65-87.

ENSI (2018): Präzisierungen der sicherheitstechnischen Vorgaben für Etappe 3 des Sachplans geologische Tiefenlager. Sachplan geologische Tiefenlager, Etappe 3. ENSI 33/649. Eidgenössisches Nuklearsicherheitsinspektorat ENSI, Brugg.

ENSI (2020): Geologische Tiefenlager. Erläuterungsbericht zur Richtlinie ENSI-G03/d. Eidgenössisches Nuklearsicherheitsinspektorat ENSI, Brugg.

ENSI (2023): Geologische Tiefenlager. Ausgabe Dezember 2020 (Änderung vom 1. November 2023). Richtlinie für die schweizerischen Kernanlagen ENSI-G03/d. Eidgenössisches Nuklearsicherheitsinspektorat ENSI, Brugg.

Fan, Y., Li, H. & Miguez-Macho, G. (2013): Global patterns of groundwater table depth. Science 339/6122, 940-943. DOI: 10.1126/science.1229881.

Fenn, C.R. & Gurnell, A.M. (1987): Proglacial channel processes. *In:* Gurnell, A.M. & Clark, M.J. (eds.): Glaciofluvial sediment transfer: an alpine perspective. Wiley, Chichester, UK, 423-472.

Fischer, U.H. (2015): Prozessverständnis der glazialen Tiefenerosion: Zusammenfassung. Nagra Arbeitsbericht NAB 15-05.

Fischer, U.H., Bebiolka, A., Brandefelt, J., Cohen, D., Harper, J., Hirschhorn, S., Jensen, M., Kennell, L., Liakka, J., Näslund, J.-O., Normani, S., Stück, H. & Weitkamp, A. (2021): Radioactive waste under conditions of future ice ages. *In:* Haeberli, W. & Whiteman, C. (eds.): Snow and Ice-Related Hazards, Risks and Disasters. Updated 2nd edition. Elsevier, Amsterdam, 323-375.

Fischer, U.H., Bebiolka, A., Brandefelt, J., Follin, S., Hirschhorn, S., Jensen, M., Keller, S., Kennell, L., Näslund, J.-O. & Vidstrand, P. (2015): Radioactive waste under conditions of future ice ages. *In:* Haeberli, W. & Whiteman, C. (eds.): Snow and Ice-Related Hazards, Risks and Disasters. Elsevier, Amsterdam, 345-393.

Fischer, U.H. & Haeberli, W. (2010): Glacial Erosion Modelling: Results of a workshop held in Unterageri, Switzerland, 29 April-1 May 2010. Nagra Arbeitsbericht NAB 10-34.

Fischer, U.H. & Haeberli, W. (2012): Glacial Overdeepening: Results of a workshop held in Zürich, Switzerland, 20 – 21 April 2012. Nagra Arbeitsbericht NAB 12-48.

Frenzel, B., Pécsi, M. & Velichko, A.A. (1992): Atlas of paleoclimates and paleoenvironments of the northern hemisphere – late Pleistocene/Holocene. (153). Hungarian Academy of Sciences and Gustav Fischer Verlag, Budapest and Stuttgart.

Gabet, E.J. & Mudd, S.M. (2010): Bedrock erosion by root fracture and tree throw: A coupled biogeomorphic model to explore the humped soil production function and the persistence of hillslope soils. Journal of Geophysical Research: Earth Surface 115/F4. DOI: 10.1029/2009JF001526.

Gmünder, C., Malaguerra, F., Nusch, S. & Traber, D. (2014): Regional Hydrogeological Model of Northern Switzerland. Nagra Arbeitsbericht NAB 13-23.

Graf, H.R. & Burkhalter, R. (2016): Quaternary deposits: concept for a stratigraphic classification and nomenclature—an example from northern Switzerland. Swiss Journal of Geosciences 109/2, 137-147. DOI: 10.1007/s00015-016-0222-7.

Graf, H.R. & Müller, B.U. (1998): Das Quartär: Die Epoche der Eiszeiten. *In:* Bolliger, T. (ed.): Geologie des Kantons Zürich. Ott Verlag, Thun, 71-95.

Haeberli, W. & Penz, U. (1985): An attempt to reconstruct glaciological and climatological characteristics of 18 ka BP ice age glaciers in and around the Swiss Alps. Zeitschrift für Gletscherkunde und Glazialgeologie 21, 351-361.

Haldimann, P. & Schatzmann, P. (2014): Charakterisierung der Lockergesteinsaquifere für die Modellierung der Biosphäre. Nagra Arbeitsbericht NAB 13-75.

Haldorsen, S. (1981): Grain-size distribution of subglacial till and its realtion [sic] to glacial scrushing [sic] and abrasion. Boreas 10/1, 91-105. DOI: 10.1111/j.1502-3885.1981.tb00472.x.

Hallet, B., Hunter, L. & Bogen, J. (1996): Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. Global and Planetary Change 12/1-4, 213-235. DOI: 10.1016/0921-8181(95)00021-6.

Hambrey, M.J. (1994): Glacial environments. UCL Press, London.

Hambrey, M.J. & Glasser, N.F. (2003): Glacial sediments: processes, environments and facies. *In:* Middleton, G.V. (ed.): Encyclopedia of sediments and sedimentary rocks. Kluver, Dordrecht, 316-331.

Hekel, U. (1994): Hydrogeologische Erkundung toniger Festgesteine am Beispiel des Opalinustons (Unteres Aalenium). Tübinger Geowissenschaftliche Arbeiten (TGA). (Reihe C: Hydro-, Ingenieur- und Umweltgeologie, 18). Institut für Geologie und Paläontologie, Tübingen.

Hoehn, E. (1979): Hydrogeologische Untersuchungen im Gebiet westlich von Frick (Aargauer Tafeljura). Beiträge zur Geologie - Hydrologie 26. Geographischer Verlag Kümmerly + Frey, Bern.

Hungr, O., Leroueil, S. & Picarelli, L. (2014): The Varnes classification of landslide types, an update. Landslides 11/2, 167-194. DOI: 10.1007/s10346-013-0436-y.

Iverson, N.R. (2002): Processes of glacial erosion. *In:* Menzies, J. (ed.): Modern and Past Glacial Environments, revised student edition. Butterworth-Heinemann, Oxford, 131-146.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Maisch, M., Sailer, R., Schaefer, J., Kubik, P.W., Synal, H.-A. & Schlüchter, C. (2006): The timing of glacier advances in the northern European Alps based on surface exposure dating with cosmogenic ^{10}Be, ^{26}Al, ^{36}Cl, and ^{21}Ne. DOI: 10.1130/2006.2415(04).

Johnson, L.H., Curti, E. & Spahiu, K. (2023): A Radionuclide Release Model for Spent UO2 and MOX Fuel for Safety Assessment with Application to Waste to be Disposed of in a Deep Geological Repository in Switzerland. Nagra Arbeitsbericht NAB 23-10.

Jordan, P. (2010): Analysis of overdeepened valleys using the digital elevation model of the bedrock surface of Northern Switzerland. Swiss Journal of Geosciences 103/3, 375-384. DOI: 10.1007/s00015-010-0043-z.

Jordan, U. (1993): Die holozänen Massenverlagerungen des Wutachgebiets (Südschwarzwald). Tübinger Geowissenschaftliche Arbeiten (TGA). (Reihe C: Hydro-, Ingenieur- und Umweltgeologie, 16). Institut für Geologie und Paläontologie, Tübingen.

KEG (2003): Kernenergiegesetz (KEG) vom 21. March 2003, Stand am 1. January 2024. Systematische Sammlung des Bundesrechts SR 732.1, Schweiz.

Kelly, M.A., Buoncristiani, J.-F. & Schlüchter, C. (2004): A reconstruction of the last glacial maximum (LGM) ice-surface geometry in the western Swiss Alps and contiguous Alpine regions in Italy and France. Eclogae Geologicae Helvetiae 97/1, 57-75. DOI: 10.1007/s00015-004-1109-6.

Kessler, M.A., Anderson, R.S. & Briner, J.P. (2008): Fjord insertion into continental margins driven by topographic steering of ice. Nature Geoscience 1, 365-369.

KEV (2004): Kernenergieverordnung (KEV) vom 10. Dezember 2004, Stand am 1. Januar 2024. Systematische Sammlung des Bundesrechts SR 732.11, Schweiz.

Knudsen, M.F., Nørgaard, J., Grischott, R., Kober, F., Egholm, D.L., Hansen, T.M. & Jansen, J.D. (2020): New cosmogenic nuclide burial-dating model indicates onset of major glaciations in the Alps during Middle Pleistocene Transition. Earth and Planetary Science Letters 549, 116491. DOI: 10.1016/j.epsl.2020.116491.

Kündig, E., Mumenthaler, T., Eckardt, P., Keusen, H.R., Schindler, C., Hofmann, F., Vogler, R. & Guntli, P. (1997): Die mineralischen Rohstoffe der Schweiz. Schweizerische Geotechnische Kommission SGTK, Zürich.

LeBarge, W.P. (1995): Sedimentology of placer gravels near Mt. Nansen, central Yukon Territory. Indian and Northern Affairs Canada, Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Bulletin 4.

Lindgren, A., Hugelius, G., Kuhry, P., Christensen, T.R. & Vandenberghe, J. (2016): GIS-based maps and area estimates of northern hemisphere permafrost extent during the Last Glacial Maximum. Permafrost and Periglacial Processes 27, 6-16. DOI: 10.1002/ppp.1851.

Ludwig, A. (2018): Local topography and hillslope processes in the Jura Ost siting region (and surrounding area). Nagra Arbeitsbericht NAB 17-42.

Mackey, B.H., Roering, J.J. & McKean, J.A. (2009): Long-term kinematics and sediment flux of an active earthflow, Eel River, California. Geology 37/9, 803-806. DOI: 10.1130/G30136A.1.

Mäder, U. & Wersin, P. (2023): Reference porewaters for SGT Stage 3 of the Opalinus Clay for the siting regions Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO). Nagra Arbeitsbericht NAB 22-47.

Magrani, F., Valla, P.G., Gribenski, N. & Serra, E. (2020): Glacial overdeepenings in the Swiss Alps and foreland: Spatial distribution and morphometrics. Quaternary Science Reviews 243, 106483. DOI: 10.1016/j.quascirev.2020.106483.

Mazurek, M., Wersin, P., Hadi, J., Grenèche, J.-M., Prinpreecha, N. & Traber, D. (2023): Geochemistry and palaeo-hydrogeology of the weathered zone in the Opalinus Clay. Applied Clay Science 232, 106793. DOI: 10.1016/j.clay.2022.106793.

Metcalfe, R., Wilson, J.C., Walke, R.C. & Möck, C. (2023): An Updated Sorption Database for Use in the Swiss Biosphere Modelling. Nagra Arbeitsbericht NAB 23-14.

Müller, W.H., Naef, H. & Graf, H.R. (2002): Geologische Entwicklung der Nordschweiz, Neotektonik und Langzeitszenarien Zürcher Weinland [mit Korrigendum]. Nagra Technischer Bericht NTB 99-08.

Nagra (1985): Project Gewähr 1985: Nuclear Waste Management in Switzerland: Feasibility Studies and Safety Analyses. Nagra Project Report NGB 85-09.

Nagra (2002): Project Opalinus Clay: Safety report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05.

Nagra (2008a): Vorschlag geologischer Standortgebiete für das SMA- und das HAA-Lager: Darlegung der Anforderungen, des Vorgehens und der Ergebnisse. Nagra Technischer Bericht NTB 08-03.

Nagra (2008b): Vorschlag geologischer Standortgebiete für ein SMA- und ein HAA-Lager: Begründung der Abfallzuteilung, der Barrierensysteme und der Anforderungen an die Geologie (Bericht zur Sicherheit und Machbarkeit). Nagra Technischer Bericht NTB 08-05.

Nagra (2008c): Vorschlag geologischer Standortgebiete für ein SMA- und ein HAA-Lager: Geologische Grundlagen (Bericht zur Geologie). Text. Nagra Technischer Bericht NTB 08-04.

Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage: Geologische Grundlagen Dossier III Geologische Langzeitentwicklung. Nagra Technischer Bericht NTB 14-02 Dossier III.

Nagra (2016): Zusammenfassende Darstellung der Zusatzdokumentation (Hauptbericht): ENSI-Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in SGT Etappe 2. Nagra Arbeitsbericht NAB 16-41.

Nagra (2021): Waste Management Programme 2021 of the Waste Producers. Nagra Technical Report NTB 21-01E.

Nagra (2023): Modellhaftes Inventar radioaktiver Materialien MIRAM-RBG. Nagra Technical Report NTB 22-05.

Nagra (2024a): Abfallzuteilung und Betrachtungszeiträume. Nagra Arbeitsbericht NAB 24-05.

Nagra (2024b): Development of Safety Scenarios. Nagra Technical Report NTB 24-21.

Nagra (2024c): Geological long-term evolution: Climate and Iceflow. Nagra Arbeitsbericht NAB 24-14.

Nagra (2024d): Geological long-term evolution: Erosion. Nagra Arbeitsbericht NAB 24-15.

Nagra (2024e): Geosynthesis of Northern Switzerland. Nagra Technischer Bericht NTB 24-17.

Nagra (2024f): Phenomenological Description of the Evolution of a Combined Geological Repository for Radioactive Waste in Opalinus Clay: Handling of FEPs in the Safety Assessment. Nagra Arbeitsbericht NAB 24-20 Suppl. Vol.

Nagra (2024g): Post-Closure Biosphere Assessment. Nagra Arbeitsbericht NAB 24-06.

Nagra (2024h): Post-closure safety report. Nagra Technical Report NTB 24-10.

Nagra (2024i): Safety Assessment Methodology. Nagra Technical Report NTB 24-19.

Nagra (2025a): Rahmenbewilligungsgesuch für das geologische Tiefenlager – Begründung der Standortwahl. Nagra Technischer Bericht NTB 24-03.

Nagra (2025b): Rahmenbewilligungsgesuch für das geologisches Tiefenlager – Sicherheitsbericht. Nagra Technischer Bericht NTB 24-01.

Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2014 und ausgewählte Auswertungen. Nagra Arbeitsbericht NAB 14-02.

Preusser, F., Graf, H.R., Keller, O., Krayss, E. & Schlüchter, C. (2011): Quaternary glaciation history of northern Switzerland. Glaciations and periglacial features in Central Europe: Eiszeitalter und Gegenwart / Quaternary Science Journal: Special issue for the XVIII INQUA congress in Bern, Switzerland 60/43892, 282-305.

Quintessa (2023a): AMBER 6.7 Reference Manual. QPUB-AMBER-1, Version 6.7. Quintessa Limited, Henley-on-Thames, UK, available online at www.quintessa.org/amber, status as of June 4, 2024.

Quintessa (2023b): AMBER 6.7 User Guide. QPUB-AMBER-2, Version 6.7. Quintessa Limited, Henley-on-Thames, UK, available online at www.quintessa.org/amber.

Roering, J.J., Kirchner, J.W., Sklar, L.S. & Dietrich, W.E. (2001): Hillslope evolution by nonlinear creep and landsliding: An experimental study. Geology 29/2, 143. DOI: 10.1130/0091-7613(2001)029<0143:HEBNCA>2.0.CO;2.

Schädler, B. & Weingartner, R. (1992): Natürliche Abflüsse 1961-1980. Tafel 5.4. *In:* Hydrologischer Atlas der Schweiz. Landeshydrologie und -geologie, Bern.

Schindler, C. (1968): Zur Quartärgeologie zwischen dem untersten Zürichsee und Baden. Eclogae Geologicae Helvetiae 61/2. DOI: 10.5169/seals-163594.

Schindler, C., Röthlisberger, H. & Gyger, M. (1978): Glaziale Stauchungen in den Niederterrassen-Schottern des Aadorfer Feldes und ihre Deutung. Eclogae Geologicae Helvetiae 71/1, 159-174. DOI: 10.5169/seals-164722.

Schlüchter, C. (1986): The Quaternary glaciations of Switzerland, with special reference to the Northern Alpine Foreland. Quaternary Science Reviews 5, 413-419. DOI: 10.1016/0277-3791(86)90206-4.

Schlüchter, C., Akçar, N. & Ivy-Ochs, S. (2020): The Quaternary Period in Switzerland. *In:* Reynard, E. (ed.): Landscapes and Landforms of Switzerland. (World Geomorphological Landscapes). Springer, Cham, 47-69.

Schnellmann, M., Fischer, U.H., Heuberger, S. & Kober, F. (2014): Erosion und Landschaftsentwicklung Nordschweiz: Zusammenfassung der Grundlagen im Hinblick auf die Beurteilung der Langzeitstabilität eines geologischen Tiefenlagers (SGT Etappe 2). Nagra Arbeitsbericht NAB 14-25.

Seguinot, J., Ivy-Ochs, S., Jouvet, G., Huss, M., Funk, M. & Preusser, F. (2018): Modelling last glacial cycle ice dynamics in the Alps. The Cryosphere 12/10, 3265-3285. DOI: 10.5194/tc-12-3265-2018.

Sugden, D.E. & John, B. (1976): Glaciers and landscape. A geomorphological approach. Edward Arnold, London.

Swift, D.A., Cook, S., Heckmann, T., Gärtner-Roer, I., Korup, O. & Moore, J. (2021): Ice and snow as land-forming agents. *In:* Haeberli, W. & Whiteman, C. (eds.): Snow and Ice-Related Hazards, Risks and Disasters. Updated 2nd edition. Elsevier, Amsterdam, 165-198.

Swift, D.A., Cook, S., Heckmann, T., Moore, J., Gärther-Roer & I., Korup, O. (2015): Ice and snow as land-forming agents. *In:* Haeberli, W. & Whiteman, C. (eds.): Snow and Ice-Related Hazards, Risks and Disasters. Elsevier, Amsterdam, 167-199.

Talento, S. & Ganopolski, A. (2021): Evolution of the climate in the next million years: A reduced-complexity model for glacial cycles and impact of anthropogenic CO_2 emissions. Earth System Dynamics Discussions. DOI: 10.5194/esd-2021-2.

Valla, P.G., Shuster, D.L. & van der Beek, P.A. (2011): Significant increase in relief of the European Alps during mid-Pleistocene glaciations. Nature Geoscience 4/10, 688-692. DOI: 10.1038/NGEO1242.

Vandenberghe, J. & Pissart, A. (1993): Permafrost changes in Europe during the last glacial. Permafrost and Periglacial Processes 4/2, 121-135. DOI: 10.1002/ppp.3430040205.

Vogt, T., Hekel, U., Ebert, A., Becker, J.K., Traber, D., Giger, S., Brod, M. & Häring, C. (2017): Hydrogeologische Untersuchungen im oberflächennahen Opalinuston (Bohrloch Lausen, Schweiz). Grundwasser 22/3, 209-220. DOI: 10.1007/s00767-017-0363-2.

Ward, D.J., Anderson, R.S. & Haeussler, P.J. (2012): Scaling the Teflon Peaks: Rock type and the generation of extreme relief in the glaciated western Alaska Range. Journal of Geophysical Research: Earth Surface 117/F1. DOI: 10.1029/2011JF002068.

Winter, T.C., Harvey, J.W., Franke, O.L. & Alley, W.M. (1998): Ground water and surface water: A single resource. (Circular, 1139), U.S. Department of the Interior, U.S. Geological Survey, Denver, Colorado.

Wohlwend, S., Bläsi, H.R., Feist-Burkhardt, S., Hostettler, B., Menkveld-Gfeller, U., Dietze, V. & Deplazes, G. (2019): Die Passwang-Formation im östlichen Falten- und Tafeljura: Fasiswald (SO) – Unt. Hauenstein (SO) – Wasserflue (AG) – Thalheim (AG) – Frickberg (AG) – Cheisacher (AG) – Böttstein (AG) – Tegerfelden (AG) – Acheberg (AG). Nagra Arbeitsbericht NAB 18-11.

Wolff, R., Hetzel, R. & Strobl, M. (2018): Quantifying river incision into low-relief surfaces using local and catchment-wide 10 Be denudation rates. Earth Surface Processes and Landforms 43/11, 2327-2341. DOI: 10.1002/esp.4394.

Zektser, I.S. & Loaiciga, H.A. (1993): Groundwater fluxes in the global hydrologic cycle: past, present and future. Journal of Hydrology 144/1-4, 405-427. DOI: 10.1016/0022-1694(93)90182-9.