PROJECT 'PURCHASE OF STUDIES FOR THE PREPARATION OF A DESIGNATED SPATIAL PLAN AND THE ASSESSMENT OF IMPACT'

PROJECT PART: STUDIES NECESSARY FOR THE ESTABLISHMENT OF THE RADIOACTIVE WASTE REPOSITORY

ACTIVITY 2. Studies of the three repository locations

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REVISION SHEET

Revisions of this document are made by replacement of the complete document, including the title page with signatures. Replacement of individual pages is not permitted.

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Relevant definitions

'Disposal' means the emplacement of radioactive waste in a facility without the intention of retrieval.

'Disposal facility' means any facility or installation the primary purpose of which is radioactive waste disposal.

'Site characterization' means detailed surface and subsurface investigations and activities at a site to evaluate candidate disposal sites, to obtain information to determine the suitability of the site for a disposal facility and to evaluate the long term performance of a disposal facility at the site.

'Institutional control' means control of a radioactive waste site by an authority or institution designated under the law. This control may be **active** (monitoring, surveillance, remedial work) or **passive** (land use control) and may be a factor in the design of a facility.

'Operational period' of the disposal facility begins when waste is first received at the facility. From this time, radiation exposures may occur as a result of waste management activities, and these are subject to control in accordance with the requirements for protection and safety. In the operational period, construction activities may still take place at the same time as waste emplacement in and closure of other parts of the facility. This period may include activities for waste retrieval, if considered necessary, prior to closure, activities following the completion of waste emplacement and final closure, including backfilling and sealing of the facility.

'Pre-operational period' of the disposal facility includes concept definition, site evaluation, Safety Assessment and design studies. The pre-operational period also includes the development of programmes and procedures required in support of the application for a licence for construction and initial operation of a disposal facility. During this period, the monitoring and testing programmes that are needed to establish baseline conditions should be put in place.

'Decision to close' a disposal facility is also a decision to initiate a period of active institutional control, for a near surface disposal facility, or, for other disposal facilities, the post-closure period. Initiation of a period of active institutional control leads to decisions on further activities following the completion of waste emplacement (closure and sealing of the facility). At this time, the duration of period of active institutional period should be determined in accordance with the risks incurred by potential human intruders.

'Post-closure period' begins at the time when all the engineered containment and isolation features have been put in place, operational buildings and supporting services have been decommissioned, and the facility is in its final configuration. After closure, the safety of the disposal facility is provided for by means of passive features inherent in the characteristics of the site and the facility as well as of the waste packages. A monitoring and surveillance programme is aimed at confirming that the disposal system is performing as expected. Monitoring may also be carried out to enhance confidence in, and therefore acceptance of, the disposal process. For near surface disposal facilities, institutional controls are put in place to prevent intrusion into the facility.

Introduction

The ultimate goal of the project is to select the most suitable location of the establishment of the disposal facility for the radioactive waste accumulated Estonian. The siting is to be performed using a step wise approach. The main objective of a stage presented in the current report is to study suitability of the previously identified potential locations and to acquire the data necessary to make a decision principle on the disposal site, i.e. to provide a basis for the strategic assessment of environmental impact of the establishment of the disposal facility and the preparation a designated spatial plan.

As a result of Activity 1, "Determining the three most optimal locations for the repository," two possible sites, Altküla (ALT), and Pedase (PED) were selected for the future disposal facility. Paldiski (PAL) as the current location of the naval nuclear reactors and radioactive waste interim storage facility was pre-selected by the stakeholders as one potential repository site. The three candidate sites are relatively close to each other in the territory of Lääne-Harju local municipality (Figure 1). Therefore, many of general characteristics, such as the deep structure of the Earth crust, volcanism, seismicity, climate, are nearly identical or similar for all three investigated sites.

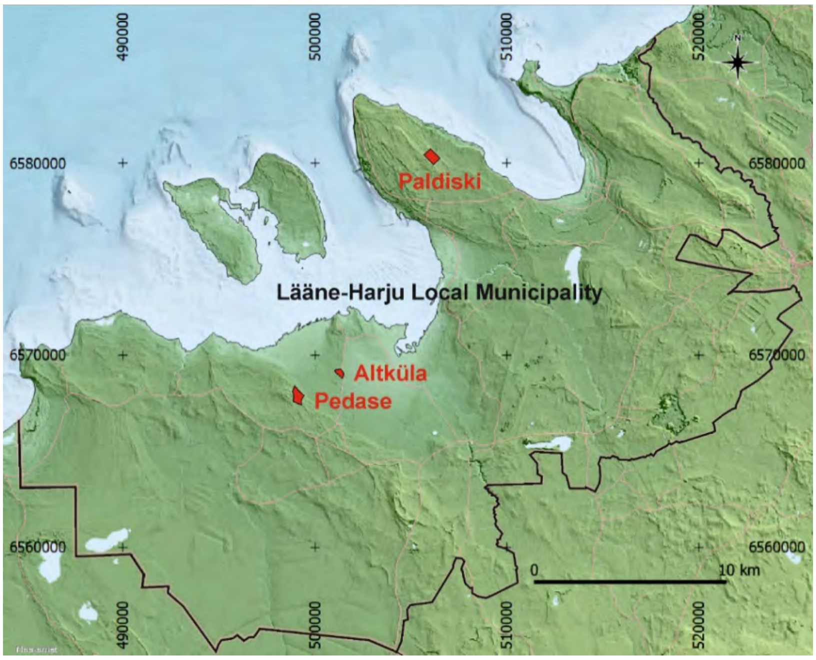

Figure 1. Location of three possible disposal facility locations in the area of Lääne-Harju local municipality. The base topographic data are by the Estonian Land Board.

According the IAEA guidance (IAEA Safety Standards Series No SSG-29 'Near Surface Disposal Facilities for Radioactive Waste') the site selection process is usually divided in to four main stages: the conceptual and planning stage, the area survey stage, the site investigation stage, the stage of detailed site characterization leading to site confirmation for construction of the disposal facility. Site characterization should contribute to a comprehensive description of the site that is sufficient to support development of the safety case and its supporting assessments.

The context of this recommendation studies presented in the current report represents finalization of the site investigation stage and initial phase of site characterisation. It will be followed by detailed site characterisation of the selected site in order to achieve a comprehensive knowledge that is sufficient to support development of the safety case and its supporting assessments and finally to get an authorization for construction.

However, already at the current stage, the potential sites should be characterized to an appropriate level of detail to provide the necessary information to ensure that the disposal facility can meet the safety requirements for disposal of the intended types of wastes. Site characterization is undertaken in order to understand the natural features, events and processes at a site (at the present time, in the past and potentially in the future) and to describe their spatial and temporal extent and variability. The site characterization should provide information on the effects the natural environment will have on the containment and isolation of radionuclides. Therefore, the potential effects of erosion, flooding, seismicity and other disruptive processes should be sufficiently understood. According the IAEA Specific Safety Requirements No SSR-5 'Disposal of Radioactive Waste' this shall include its present condition, its probable natural evolution, possible natural events, and also human plans and actions in the vicinity that may affect the safety of the facility over the period of interest. An important part of characterization of the site lies in understanding how the site will behave over the long term. Site characterization should contribute to a comprehensive description of the site relevant for obtaining licencing documents for establishment of the disposal facility.

An account should be taken of the likelihood of future disturbances and radiation protection of people who could be affected by the release of radionuclides from the disposal facility. The disposal facilities should comply with the requirements for protection of the environment. The site should be located so that the environment will be adequately protected for the entire lifetime of the facility and so that potential adverse impacts can be mitigated to an acceptable degree, technical, economic, social and environmental factors being taken into account.

1. Sub-activity 2.1: Mapping specific tectonic features

The purpose of sub-activity 2.1 has been to provide information on the geological history of the area, the structural geological conditions, neotectonic processes, and the nearest volcanic activity for the three possible candidate sites (PAL, ALT and PED) of the future disposal facility in the territory of Lääne-Harju local municipality (LHLM). The detailed results are presented in an Appendix 1. The study includes analysis of available information, such as the geological base map, geological/geophysical reports, and literature. The work was performed by Jüri Plado, Argo Jõeleht and reviewed by Marko Kohv (Tartu University, Department of Geology).

1.1. Geological structure

1.1.1. Crystalline basement

Estonia is situated in the East European Platform, where the Precambrian crystalline basement is overlaid by a layer of Paleozoic sedimentary rocks and Quaternary sediments, ranging in thickness from 100 to 780 meters. All three sites are positioned within the West-Estonian structural zone, which is part of the Svecofennian-aged (1.9-1.77 Ga) and rapakivirifting and intrusion related (1.65-1.54 Ga) crystalline basement. As indicated by the geological map (Figure 1.1) of the crystalline basement, the crystalline basement beneath the three sites consists of amphibole gneisses and amphibolites. The boundary between the crystalline basement and the overlying sedimentary sequence can be found at an approximate depth of 160 meters below sea level (PAL) and around 190 meters below sea level (PED and ALT).

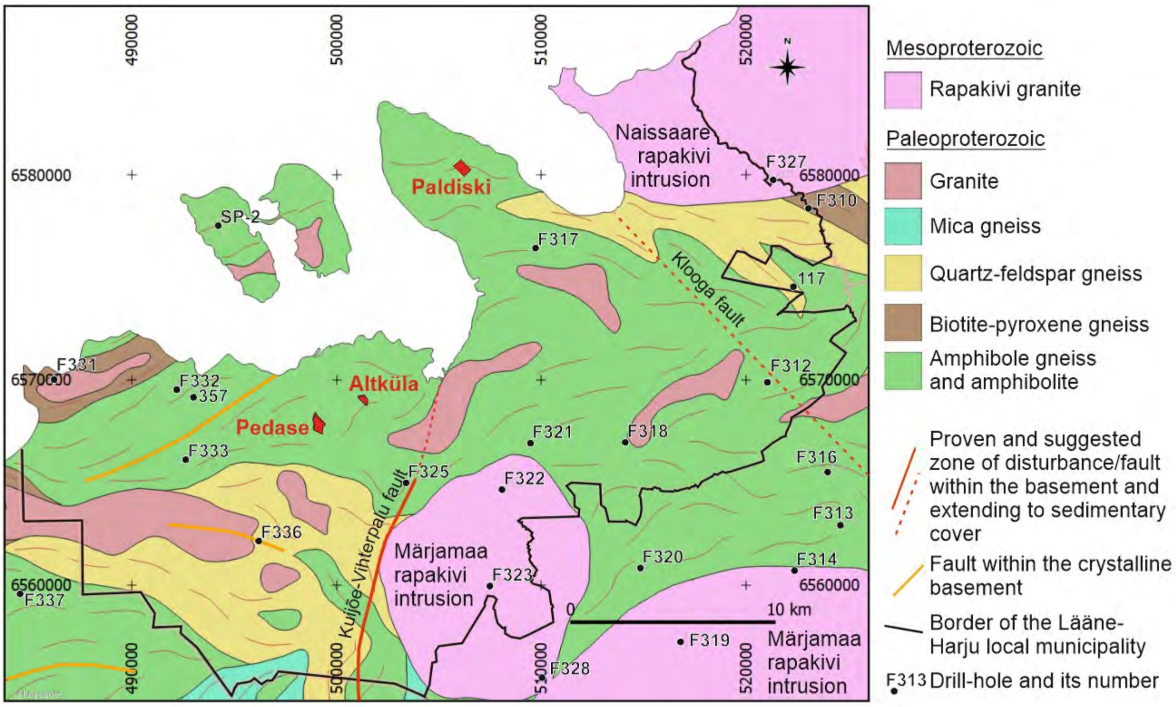

Figure 1.1. Geological map of the crystalline basement in the area of Lääne-Harju local municipality.

The basement geologic map of the basemen reveals four faults in the territory of LHLM. Among these, two faults, identified through geophysical data, are associated with Svecofennian or rapakivi-time deformation and do not affect the sedimentary cover. The magnitude of these faults is still undetermined. However, the prominent N-S-trending Kuijõe-Vihterpalu fault, located near Kuijõe village (south of LHLM), exhibits a maximum amplitude of 40 meters and is linked to a flexure within the sedimentary cover. This fault is accompanied by extensive fracturing of both crystalline and sedimentary rocks within a 1-kilometer-wide zone. Moving north of drill-core F325 (see Figure 1.1), the fault diminishes and is identified as a potential disturbance zone. In the eastern part of the municipality, a NW-SE-trending Klooga fault has been proposed based on the discovery of fracturing within the sedimentary cover (core F312; Figure 1.1). The estimated length of this potential disturbance is approximately 20 kilometers, but its vertical amplitude and presence within the crystalline basement remain unknown. The Klooga fault coincides with the regional Paldiski-Pskov Tectonic Zone.

1.1.2. Sedimentary cover

Within the LHLM territory, the drill holes reveal a total thickness of Ediacaran and Paleozoic sediments ranging from 172.7 to 223.7 meters. Generally, the thickness is lower in the northern part and higher in the southern part of the municipality. However, local undulations in the topography of the crystalline basement's top surface lead to variations in this overall trend. One such variation occurs atop the Märjamaa rapakivi intrusion, where the sedimentary cover thickness is comparatively lower compared to adjacent areas at the same latitude. Additionally, the local Ordovician sequence exhibits a southward tilt (with a dip direction of 160-188° and a dip rate of 2-5 meters per kilometer).

The deepest sediments consist of weakly cemented fine-grained clastic rocks, including argillites, siltstones, and sandstones, belonging to the **Ediacaran System's** Kotlin Formation. Within the LHLM territory, the thickness of this formation ranges from 36.8 to 50.7 meters. The formation tends to increase in thickness towards the northeast direction.

The **Cambrian System** within the LHLM territory comprises clays, siltstones, and sandstones belonging to the Terreneuvian and Series 2 series. This system is regionally divided into four formations: Lontova, Sõru, Lükati, and Tiskre. The rocks of the Cambrian System are found at the greatest depth in the southernmost part of the municipality, where they are also the thickest, measuring 109.2 meters. In the drill hole F317, which is the closest to the PAL site and located in the northernmost area (refer to Figure 1.1), the thickness of the Cambrian System lithologies is 96 meters. Furthermore, in comparison to the southern areas, these lithologies are situated at a higher elevation.

The *Lontova Formation*, which is **a potential host for the shaft-type Intermediate Depth Disposal Facility**, primarily comprises almost unlithified greenish-blue clay. Based on data from the nearest drill holes (F317 and F325; see Figure 1.1), the thickness of the Lontova Formation exceeds 60 meters in all three possible disposal facility host locations. However, it is important to note that the area under consideration is situated at the western boundary of this well-known low permeability clay unit. Moving westwards, the coeval Voosi Formation, consisting of higher permeability sandy sediments, replaces the Lontova clays, as observed in drill hole F336 (refer to Figure 1.1). The *Sõru Formation*, which overlies the Lontova Formation in a transgressive manner, has only been identified in drill core F336. It mainly consists of sandstone with thin interbeds and films of clay. The *Lükati Formation* transgressively overlies either the Sõru or Lontova Formation. This lithologically homogeneous formation is composed of interbedded greenish-grey argillaceous rocks and very fine-grained sandstones. It commonly contains pyrite and glauconite. According to the data from drill holes F325 and F317, which are closest to the three potential sites, the thickness of the Lükati Formation is 8.6 and 12.0 meters, respectively. The *Tiskre Formation*, approximately 20-25 meters thick, primarily consists of light-colored massive and thick-bedded sandstones with occasional thin interbeds of greenish-grey argillaceous rocks.

The *Kallavere Formation* serves as a boundary between the Cambrian and Ordovician periods. This formation is characterized by a thin bed, which increases in thickness towards the east. It primarily consists of quartzose sandstone with interbeds of dark argillite. The Lower Ordovician *Türisalu Formation* is predominantly composed of dark-brown horizontally thinly laminated graptolite argillite, also known as black shale or Dictyonema shale. The black shales of the Türisalu Formation exhibit relatively high radioactivity, with levels reaching up to 1.84 µSv/h. The *Varangu Formation*, ranging from 0.6 to 1.5 meters in thickness, consists of light grey to beige compact silty clay. The *Leetse Formation* has a similar thickness and is composed of poorly lithified glauconitiferous terrigenous sediments, siltstones, and sandstones. The upper part of the Leetse Formation is calciferous and slightly more lithified.

Within the Middle Ordovician sequence, which is approximately 10 meters thick, the formations consist exclusively of carbonate rocks. In the discussed area, five distinct formations have been identified, arranged from bottom to top: Toila, Loobu, Kandle, Väo, and Kõrgekalda. The *Toila Formation* is characterized by glauconitic limestones. The rocks of this formation contain greenish grains of glauconite within the limestone matrix. The *Loobu Formation* primarily consists of grey limestone with slight clay content. Occasional dolomitization can also be observed within this formation. The *Kandle Formation* has a similar composition to the Loobu Formation, but it is distinguished by the presence of small iron ooids, which are approximately 1 mm in diameter. The *Väo Formation* is the thickest within the Middle Ordovician sequence, measuring 6 to 7 meters in thickness. It is characterized by whitish-grey limestone composed of detrital grains, ranging from small to microcrystals. Finally, the topmost formation of the Middle Ordovician is the *Kõrgekalda Formation*, with a thickness of 2 to 3 meters. It is composed of light to greenish-grey slightly clayey limestone.

The Upper Ordovician sequence is characterized by four formations: Viivikonna, Tatruse, Kahula, and Vasalemma. The *Viivikonna Formation* has a thickness ranging from 6.9 to 10.2 meters. This formation consists of argillaceous bioclastic limestones. A layer of approximately 3 meters in thickness is formed by a combination of argillaceous limestones with intercalations of marls from the lower *Tatruse Formation*, along with thin inclusions of K-bentonites in the upper Vasavere sub-formation (lowest part of the Kahula Formation). The remaining part of the *Kahula Formation* is composed of clayey limestones and detrital marl. In core F325 (refer to Figure 2), the *Vasalemma Formation* is represented by argillaceous bioclastic limestones.

None of the three selected sites for the future disposal facility are located on buried valleys identified through geological mapping. The PAL and PED sites are situated in areas with a relatively thin cover of Quaternary sediments. However, the ALT site is positioned on top of an old and extensive incision that was occupied by a proglacial lake and sea for an extended period after deglaciation.

1.2. Neotectonics

The formation of the bedrock topography commenced in the late Devonian. Alongside long-term crustal movements and various continental denudational processes, the final shaping of the topography was influenced by glacial erosion during the Pleistocene epoch. The recent uplift of the crust in northwestern Estonia provides evidence of glacioisostatic relaxation. Alongside vertical movements, minor horizontal deformations of the crust occur, specifically in the form of intraplate horizontal displacement towards the southeast at a rate of approximately 1.15 mm/year in northwestern Estonia. Most of the horizontal movements are attributed to plate tectonics. The combined sum of plate and intraplate shifts amounts to approximately 23-24 mm/year, resulting in a northeastern shift of the territory.

The rate of uplift, as well as horizontal movements, is currently estimated through the analysis of Global Navigation Satellite System (GNSS) observatory data. The nearest continuously operating reference station to the selected sites are Suurupi and Dirhami. Suurupi is situated approximately 22 km east-northeast from site PAL and 32-34 km northeast from sites ALT and PED sites. In Dirhami, located around 28-30 km west-southwest from PED and ALT, and roughly 39 km southwest from PAL. The GNSS campaign measurements were conducted in 1997, 2008, and 2017. According to the analysis of the time series, the horizontal speed at Suurupi is 23.45 mm/year with an azimuth of 57.5°, while in Dirhami, it is 23.89 mm/year with an azimuth of 56.8° (Figure 1.2). The estimated horizontal speed ranges from 23.31 to 23.58 mm/year in Suurupi and from 23.78 to 24.01 mm/year in Dirhami. Therefore, the differences in speed and movement direction between the two measurements are negligible.

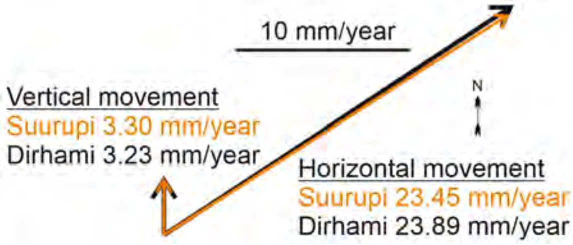

Figure 1.2. Horizontal and vertical velocities of the Suurupi station and Dirhami point. Horizontal movement is given regarding cardinal direction (north is up); vertical movement is in the upward direction.

1.3. Nearest volcanic activity

Estonia is situated in an intraplate position, with the closest active plate boundaries located more than 2000 km away in northern Italy (Alp Mountains) and the Atlantic Ocean (Iceland). As a result, there has been no volcanic activity within the country since the formation of the crystalline basement.

1.4. Conclusions

1. The three sites are relatively close to each other, with a distance of approximately 14 km between PAL and PED, and only 2.5 km separating ALT and PED. Therefore, the deep structure of the Earth crust is nearly identical for all three sites.

2. The following features of the three sites are favourable for waste disposal:

- There are no known active faults in the vicinity of the sites. The speed and movement direction are almost identical, producing no tectonic stresses.
- The nearest modern volcanic activity in Iceland is located about 2100 km apart.
- The sedimentary cover is uniform and predictable.

2. Sub-activity 2.2. Seismic analysis

The purpose of sub-activity 2.2 was to provide an overview of known seismicity in the region surrounding the three possible candidate sites, Paldiski (PAL), Altküla (ALT), and Pedase (PED) of the future disposal facility in the territory of Lääne-Harju local municipality. It outlined the background for assessment of seismic hazard. Also, possible seismic phenomena related to man-made activities were discussed. Detailed results are presented in Appendix 2. The study includes analysis of available information, such as the catalogue of historical and instrumentally recorded earthquakes and different seismic hazard studies. The work was performed by Heidi Soosalu (Geological Survey of Estonia).

2.1. Seismic dataset of Estonia

Due to its geological setting at the East-European sedimentary platform on the flank of the stable Fennoscandian shield, Estonia is a region of modest seismicity. This is valid also for the surroundings of the three candidate sites.

Known seismic history of Estonia spans approximately 200 years and about forty earthquakes. For historical earthquakes only macroseismic notions are available, i.e., descriptions of effects of an earthquake to people, buildings, and landscape reflecting its intensity. Instrumental observations by local seismic stations are available for the latest few decades. Earthquakes of Estonia until 2012 are listed in FENCAT, the catalogue of earthquakes in Northern Europe. Later data until 2022 has also been included in this study.

2.2. Seismicity in the region of the candidate sites

Past seismicity was examined within an area spanning not more than 50 km distance from any of the three candidate sites (Figure 2.1, Table 1 in Appendix 2). This includes 16 earthquakes with magnitudes from 0.9 to 4.5. Events forming a series of a main shock with fore- and/or aftershocks are considered dependent. Accordingly, 10 independent events have been observed.

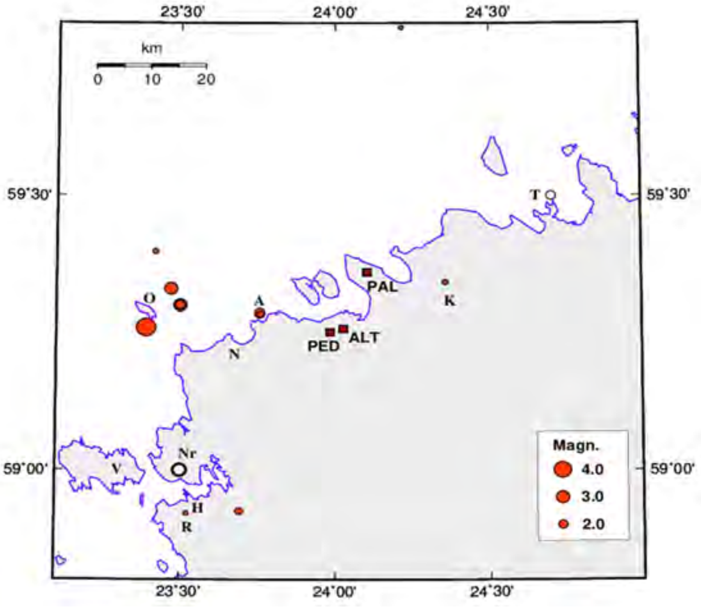

Figure 2.1. Known historical and instrumentally recorded earthquakes at distances of 50 km or less from any of the chosen locations, ALT, PAL, or PED (brown squares). Black circles are historical, macroseismically determined locations and red dots are instrumentally recorded events, scaled by their magnitude. Locations: A – Alliklepa Bay, H – Haapsalu town, K – Keila, Nr – Noarootsi, N – Nõva, O – Osmussaar island, R – Ridala, T – Tallinn Bay, V – Vormsi.

Magnitude, a dimensionless physical parameter reflecting the release of seismic energy is estimated for historical earthquakes using macroseismic intensity observations and the area of perceptibility. Magnitudes of instrumentally recorded events are calculated from seismograms.

Throughout the years, regions around the Osmussaar island and Haapsalu town stand out as loci of recurring seismicity. The first entry in the dataset is a magnitude-3.4 earthquake with the epicentre in Noarootsi in 1827. The latest entries are two earthquakes with magnitudes 2.3 and 1.4 under Alliklepa Bay offshore NW Estonia in June 2022. These two earthquakes have also been the closest ones to the disposal facility candidate sites, with the epicentral distances of 13 km to PED, 16 km to ALT and 21 km to PAL.

The most remarkable event has been the magnitude-4.5 Osmussaar earthquake on 25 October 1976. It was followed by four aftershocks. The epicentre of the Osmussaar earthquake lies at the distance 34 km from PED, 36 km from ALT and 42 km from PAL. Macroseismic observations point to maximum intensity of 6–7, or strong to very strong.

Hypocentre estimates of the instrumentally recorded earthquakes of the latest decade are very uniform, being in the upper crust, within the crystalline basement at approximately 4 km depth. The depths agree with the remark that crystalline basement is more prone for occurrence of earthquakes than sedimentary bedrock.

2.3. Focal mechanisms

Focal mechanisms have been calculated for five Estonian earthquakes. Within the study area, these include the Osmussaar event, a magnitude-1.2 earthquake in Keila in 2017 and a magnitude-1.7 earthquake in Haapsalu in 2018. They all can be associated with left-lateral movement in crystalline basement faults directed NNW-SSE, in accordance with the general stress pattern and plate tectonic context of northern Europe.

2.4. Earthquake statistics

Incompleteness of earthquake catalogues is a problem in moderately seismic areas such as Estonia. There is lack of information on earthquakes during the pre-instrumental era, until the turn of the 20th and 21st centuries. Other natural phenomena may also have been misidentified as earthquakes.

Figure 2.2 shows a graph of cumulative number of earthquakes with up to 50 km distance from any of the candidate sites ALT, PAL or PED. Data gaps are obvious until the beginning of the 21st century and lowering of the detection threshold through time can be noted. Minor earthquakes (magnitude < 2) can tentatively be expected to occur every few years. It is more difficult to estimate occurrence of middle-sized (2 < M < 4) earthquakes, as only one such event has taken place during the last two decades of local instrumental observations. This is too short a time window for return period remarks. It can be quite confidently stated that no magnitude > 4 event other than the 1976 Osmussaar earthquake has taken place within the study area during a few hundred years.

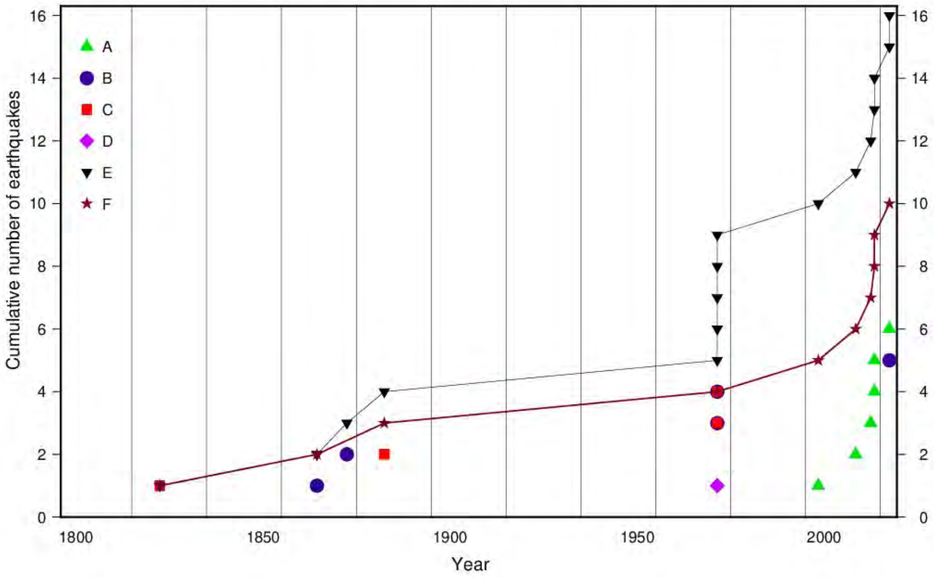

Figure 2.2. Cumulative number of earthquakes within the region with maximum distance of 50 km from any of the selected sites. Magnitude classes are marked as letters, A: M < 2, B: 2 ≤ M < 3, C: 3 ≤ M < 4, D: 4 ≤ M, E: all events, connected with a black line. F: all events after declustering, connected with a brown line.

2.5. Seismic hazard assessment

Seismic hazard is a natural phenomenon generated by an earthquake (e.g., ground shaking, fault rupture, soil liquefaction). Seismic risk is an interaction between seismic hazard and vulnerability of people or built environment. It is a product of local occurrence of earthquakes (magnitude, distance, probability), site-specific ground response to the earthquakes, and exposure and vulnerability of infrastructure near the site.

Vague historical earthquake data hampers estimation of seismic risk. This is especially a problem for areas of low seismicity, such as Estonia, where a seismic dataset complete for assessment of seismic risk should cover several centuries. Occurrence of earthquakes large enough to cause damage to sensitive structures cannot be ruled out. However, they have long return periods – several hundreds of years or more.

Probabilistic seismic hazard assessment and hazard maps in European level show that Estonia and surrounding regions experience low-level seismicity. Two approaches for assessing regional seismic hazard can be applied: the seismic source area method and identification of active seismic belts.

Division of a region into seismic source areas is useful for assessing probabilities of earthquakes in regions where seismicity is low and diffuse and earthquake catalogues incomplete. Seismic, geological, and geophysical datasets are used for a synthesis. Resulting seismic source areas are proxies for unidentified seismogenic structures.

The active seismic belt study is applicable for examining seismicity in the study area. It belongs to an area characterized by the NW-SE lineated seismic zone extending from the

Åland archipelago through Paldiski all the way to Pskov. As an upper limit assessment, it can be anticipated that the frequency of earthquakes of $M \geq 3.0$ would be one event in ~140 years and frequency of earthquakes of $M \geq 4.0$ would be one event in ~710 years, respectively.

2.6. Seismicity related to human activities

Together with natural earthquakes, seismicity of man-made origin needs to be considered when designing sensitive objects such as a radioactive waste repository. Even if purposeful (blasting) or other seismicity induced by human activities would not pose a threat as such, its occurrence may affect risk perception of residents and influence social acceptability of establishing sensitive objects.

Elimination of old sea mines in the Paldiski Bay region and blasting related to construction work in Paldiski area are detected as man-made seismic events and occasionally felt as shaking. Sources of man-made seismic events must be identified and not confused with natural earthquakes to not bias seismic hazard assessment.

Industrial activities that influence the stress field of the Earth's crust, e.g., establishment of underground cavities may produce induced seismicity by reactivating pre-existing faults or triggering earthquakes that were almost ready to occur. This is relevant for the location of the becoming radioactive waste disposal facility, as an underground energy storage facility or the Pumped-Hydro Energy Storage (PHES) is being planned in Paldiski.

Ground vibration and possible induced seismicity related to construction and use of PHES require attention particularly in regard with PAL, because of its planned location at approximately 2 km distance. The distance to other candidate sites is ~10 km to ALT and ~12 km to PED, and they are less likely to be affected.

Environmental assessment of construction-related vibration of PHES has been carried out. Potential induced seismicity and measures for its prevention and mitigation have been studied separately. Possible issues can be anticipated and prevented or mitigated with careful planning and use of the underground PHES system.

2.7. Conclusions

The catalogue of seismicity in the study area, within the radius of 50 km from any of the radioactive waste disposal facility candidate sites, PAL, ALT and PED, spans almost 200 years. However, the first ~180 years of the earthquake list have considerable data gaps. Detection of all events down to magnitude ~1 has been reality only during the latest two decades. Statistical analysis of known seismic activity contains large margins of error.

The study area experiences modest seismicity. Sporadic occurrences of minor earthquakes (magnitude < 3) can be expected. The magnitude-4.5 Osmussaar event shows that occurrence of earthquakes large enough to cause damage to sensitive structures cannot be ruled out. However, their return periods are likely to be long: several hundreds of years for an earthquake of magnitude 4.0 or larger. The existing dataset does not allow making more precise predictions regarding future seismicity.

Circumstances regarding seismicity are similar for all the three candidate sites and the risk level due to earthquake activity is small. Accordingly, seismicity is not the decisive factor in the choice of the final location. Distance to the epicentre of the Osmussaar earthquake is more than 30 km to all of them. Historical earthquakes with magnitudes ≥ 3 have taken place at distances of ~40 km away or more, furthest away from PAL.

Failure in Earth’s brittle crust is likely to occur as reactivation of old zones of weakness. None of the three candidate sites are located near known major faults. This decreases the possibility for sizeable earthquakes in their vicinity, for either natural or man-made causes, including induced/triggered earthquakes. Low natural seismicity is possibly a useful indicator for low tendency for felt or damaging induced events. Accordingly, if earthquakes (either natural or induced) occur near these locations, they are likely to be small in magnitude, not causing structural damage.

3. Sub-activity 2.3. Analysis of the geological-lithological composition of the Earth's crust

The sub-activity aims to specify the geological structure of the three sites proposed for a disposal facility of radioactive waste in the following aspects:

- analysing the lithology, mineral and geochemical composition, and natural gamma intensity variation of the sedimentary rocks exposed in drillcores,
- testing the mineral solubility of the characteristic lithologies,
- mapping the locations of potential clay layers, and
- assessing the nature, quantity, and location of possible mineral resources at the potential locations.

The performed works also included studying the three possible sites for the disposal facility by surficial geophysical methods, drilling of boreholes and taking samples for laboratory investigations. The results of the performed investigations are detailed in an Appendix 3.

The study was performed by Kalle Kirsimäe and Jüri Plado (University of Tartu, Department of Geology), Hardi Aosaar (Engineering Bureau Steiger LLC). It was reviewed by Argo Jõeleht (University of Tartu, Department of Geology).

3.1. Geophysical structure

3.1.1. PAL site

The thickness of the Quaternary sediments is generally low and is estimated to be about 1.5 m, while appearing to decrease towards the western corner of the cadastral unit. No large fracture zones were indicated in the electric resistivity tomography (ERT) profiles.

3.1.2. ALT site

The ground-penetrating radar study revealed 3 radar facies (RF). RF1 with a thickness of 1.5 m comprises of topsoil, peat in a swampy area, sandy/gravelly material, and rare boulders. Additionally, it hosts a water table. Below RF1, the marine sediments (RF2) include reflections from boulders that were distributed by storms and ice and are most abundant in the lower part of the approximately 1.5 m thick RF2. Below (RF3), the material has a small grain size (silt/clay-rich sediments). The boundary between RF2 and RF3 is located at 2.0-3.0 m a.s.l. The resistivity profiles reveal no lateral electrical anomalies that could correspond to fracture zones.

3.1.3. PED site

In Pedase, two radar facies (RF1 and RF2) were identified based on their patterns. RF1 corresponds to Quaternary sediments and includes pebbles of marine origin and basal till. In some locations, a water table appears as seen by a reflection that runs through the RF1. Thickness of these facies varies between 1 and 2 m. RF2 includes long subhorizontal reflections originating from the layered Upper Ordovician limestones and marl of the Kahula Member. Occasionally, shallow surficial karst features develop along the layer boundaries, but no karst related caves have been developed. No fracture zones or vertical shifts were identified within the layered Ordovician rocks.

3.2. Lithology

3.2.1. PAL site

The succession (Figure 3.1) starts with a 1.3 m thick **Quaternary** basal till layer composed of brownish-beige diamictite with angular to subangular limestone clasts. Below, the succession is described from top to bottom.

The **Ordovician** limestones/dolostone sequence starts with Viivikonna Formation (Kukruse Regional Stage) between 1.3 to 10.05 m depth. Kõrgekalda Formation clayey micrcritic grey limestones of the Uhaku Regional Stage occur at depths 10.05 to 11.37 m and are followed by Väo Formation (Lasnamäe Regional Stage). A thin bed of clayey micritic limestones with Fe-ooiids of the Kandle Formation (Aseri Regional Stage) is intersected at 18.35 to 18.65 m depth. Grey to light brownish grey sandy limestones of the Pakri Formation (Kunda Regional Stage) are at 18.65 to 19.74 m depth. The Ordovician carbonate succession is followed by glauconite limestones and sandy glauconitic limestones of the Toila Formation (Volkhov and Hunneberg Regional Stages) between 19.74 – 20.92 m depth.

Terrigenous sediments start at 21.08 m depth with glauconite sandstones of the Leetse Formation and 0.5 m thick grey siltstone – fine-grained sandstone bed of the Varangu Formation. Tremadocian black shales (graptolite argillite) of the Türisalu Formation (Pakerort Regional Stage) are at 24.52 to 29.50 m depth, followed by **Ordovician/Cambrian** Kallavere Formation sandstone between 29.50 – 33.90 m depth. Fine-grained quartz arenite sandstones of the Tiskre Formation are at 33.90 – 56.75 m depth, and glauconitic claystone, siltstone to fine-grained sandstone alteration of the Lükati Formation follow to the depth of 70.65 m. Alternating greenish-grey to violet claystone-siltstone succession of the Lontova Formation lies between 70.65 to 132.7 m depths. The lower part of the Lontova Formation (defined as Sämi Member) is composed of alternating greenish-grey claystone and sandstone between 98.1 – 126.2 m.

The lowermost part of the succession is represented by **Ediacaran** Kroodi Group (Kotlin Regional Stage) sandstones with thin greenish-grey siltstone interbeds at 126.2 – 132.7 m.

3.2.2. ALT site

In the ALT-402 drill core (Figure 3.1), the thickness of the **Quaternary** deposits reaches 24.5 m, and the sediments are represented by greyish-beige to brown till with numerous limestone and crystalline rock boulders.

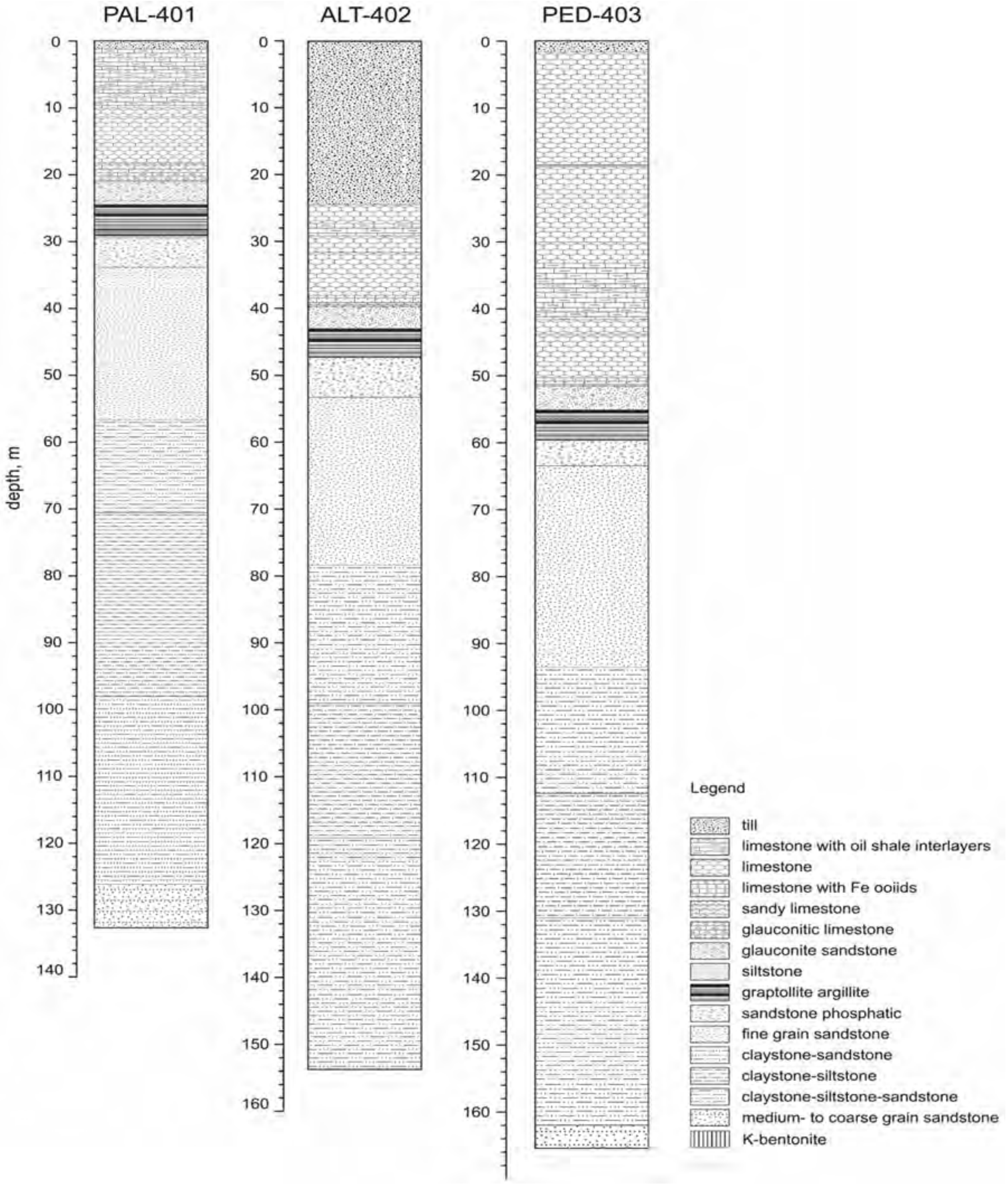

Figure 3.1. Lithological columns of PAL (PAL-401), ALT (ALT-402), and PED (PED-403) drill cores.

The **Ordovician** limestones sequence in the ALT-402 drill core starts with Tatruse Formation (Haljala Regional Stage) limestones at 24.5 to 27.34 m depth. Viivikonna Formation (Kukruse Regional Stage) occur between 27.34 to 29.20 m depth. Kõrgekalda Formation occurs at depths 29.20 – 31.65 m. Väo Formation (Lasnamäe Regional Stage) is between 31.65 and 38.05 m, and Kandle Formation (Aseri Regional Stage) is 38.05 to 38.47 m of depth. Grey to light brownish grey sandy limestones of Pakri Formation (Kunda Regional Stage) are intersected at 38.47 to 39.48 m depth. The lowermost beds of the Ordovician carbonates are represented in the Toila Formation (Volkhov and Hunneberg Regional Stages) between 39.48 to 39.75 m depth.

Like the PAL-401 drill core succession, the terrigenous deposits start in the Leetse Formation at 39.75 to 42.95 m depth and only 5 cm thick Varangu Formation. The thickness of the of the Türisalu Formation (Pakerort Regional Stage) reaches 4.38 m. **Ordovician/Cambrian** Kallavere Formation sandstone occurs at 47.38 – 53.30 m depth.

Fine-grained quartz arenite sandstones with clayey bluish-grey interbeds/lenses of the Tiskre Formation are at 53.30 – 78.40 m depth. Fine-grained sandstone of the Lükati Formation follows to the depth of 99.0 m. The Lontova Formation lies between 99.0 and 119.15 m, and the Sämi Member of the Lontova Formation is at 119.15 – 151.73 m depth.

3.2.3. PED site

In the PED-403 drill core (Figure 3.1), the thickness of the **Quaternary** greyish-brown till with limestone clasts reaches 1.7 m. The uppermost part of the **Ordovician** sequence of the Kahula Formation (Keila Regional Stage) at 1.7 to 18.54 m depth. At 18.54 to 18.82 m depth, a partly silicified beige-grey K-bentonite bed occurs, followed down-core by grey micritic to clayey limestones of the Kahula Formation belonging to the Haljala Regional Stage at the 30.1 m depth. Tatruse Formation (Haljala Regional Stage) limestones are between 30.1 and 33.25 m, and micritic grey limestone) of the Viivikonna/Pihla Formation (Kukruse Regional Stage) are at 33.25 – 41.65 m depth. Kõrgekalda Formation clayey micritic grey limestones of the Uhaku Regional Stage occur at depths 41.65 to 43.85 m. Väo Formation (Lasnamäe Regional Stage) micritic limestone is between 43.85 and 50.35 m. Clayey micritic limestone of the Kandle Formation (Aseri Regional Stage) occurs at the depth of 38.05 to 38.47 m. Sandy limestones of the Pakri Formation (Kunda Regional Stage) are between 50.85 and 51.35 m. The glauconite limestone bed of the Toila Formation (Volkhov and Hunneberg Regional Stages) is intersected at 51.35-51.60 m depth.

Green glauconite sandstone of the Leetse Formation (Hunneberg regional Stage) is at 51.60-55.10 m depth.The Varangu Formation is missing in the PED-403 drill core section. The Türisalu Formation black shale (graptolite argillite) reaches 4.65 m thickness. It lies on cross-bedded sandstone of the Kallavere Formation between 59.75-63.50 m depth.

Lower **Cambrian** (Terreneuvian) sandstones with clayey interbeds/lenses of the Tiskre Formation are at 63.50 – 93.60 m depth and are followed down-section by claystone, siltstone to fine-grained sandstone of the Lükati Formation at 93.60 to 112.45 m. Lontova/Voosi Formation alternating claystone-siltstone and sandstone are at 112.45 to 162.00 m depth.

The lowermost part of the drill core is represented by sandstones with a few siltstone interbeds of the **Ediacaran** Kroodi Group down to 165.40 m depth.

3.3. Leaching

Leaching tests show low solubility of the studied bedrock lithologies' mineral matrix, except for the Türisalu Formation black shale (graptolite argillite). In black shale, the oxidation of abundantly present pyrite lowers the leachate pH and increases, particularly, sulfate concentration in dissolved solids that combined with low pH can be aggressive towards surrounding rocks and construction elements made of steel and concrete.

3.4. Location and characteristics of the clay-rich beds in studied drill core successions

Based lithological descriptions, mineralogical and geochemical analyses as well as core gamma logging (Figure 3.2), the main clayey (shale) lithological complexes occur in lowermost Ordovician beds represented by black shales of the Türisalu Formation and in the Lower Cambrian (Terreneuvian) Lükati Formation and in the upper-middle and the lowermost part of the Lontova Formation (Kestla and Mahu Members, and lower part of the Sämi Member). Also, the lower part of the Leetse Formation glauconite sandstone is more clayey in its lower part, but the clay-rich beds in this formation are thin, patchy, and do not form laterally continuous beds.

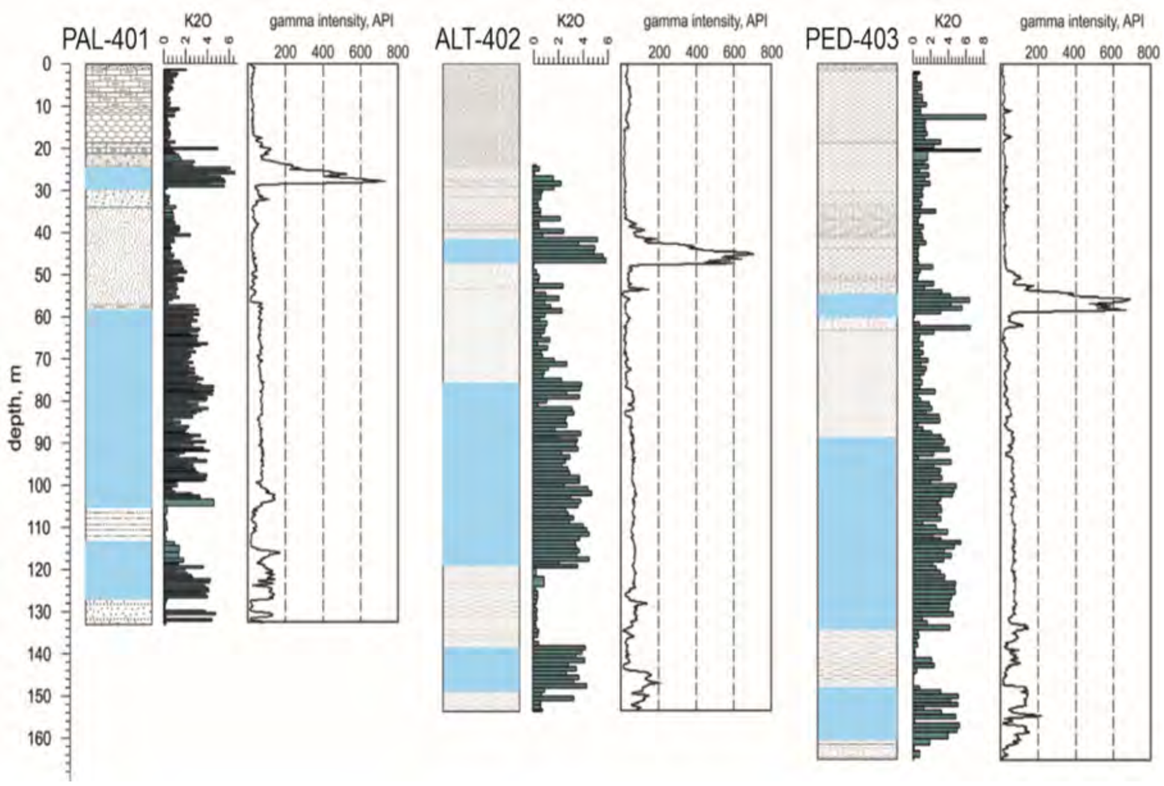

Figure 3.2. The location of the clayey sediment layers (marked with blue) in studied drill cores as based on natural radioactivity gamma intensity logging and K concentration variation according to hand-held XRF scanning.

The Kestla and Mahu formations of the Lontova Formation contain greenish-grey to violet-reddish silty clays that represent the most massive and extensive clay unit **that is most suitable for the IDDF** if compared with other clay-rich lithologies (Türisalu Formation and Leetse formation). The total thickness of these units ranges from 18 m in PED-403 to 20 m in ALT-402, and 27.5 m in the PAL-401 drill core. In the clay-rich beds, illite and illitic illite-smectite constitute 50 to 60 wt.% of the mineral composition (25-40 wt.% in silty lithologies), while chlorite and kaolinite vary from 5 to 8 wt.% and 3 to 9 wt.%, respectively. The homogenous clay-rich beds make up ~60% of the total thickness of the Kestla and Mahu Members in Paldiski and Altküla sites but ~50% in in Pedase site. Additionally, the clay mineral content is significantly high (up to 40-45 wt.%) in the clayey interbeds of clayey sandstones in the lowermost part of the Sämi Member. However, it is important to note that the Sämi Member primarily consists of coarse-grained sandstones.

3.5. Potential mineral resources

The studied locations do not contain valuable mineral resources that are being actively mined, nor have they been registered as proved or probable reserves, nor explored as potentially useful resources. However, future projections suggest that the limestones of the Kõrgekalda and Väo formations in the PAL core site could be considered as potential reserves for building limestone and aggregate production. Furthermore, at all three studied sites, there are 4-5 meter-thick Türisalu Formation black shales, which are rich in U, Mo, and V, occurring at depths between 25 to 60 meters below the ground surface. These black shales are not currently explored but represent a potential metal resource in the future.

3.6. Conclusions

1. The vicinities of the site do not currently contain valuable mineral resources that are being currently mined, nor explored as potentially useful resources. However, future projections suggest that the limestones from the PAL site could be considered as potential reserves for building limestone. In future projections extending to hundreds of years is cannot be hypothetically excluded that given a shortage of the high-quality limestone resources in northern Estonia that mining of the limestones becomes profitable at the depths exceeding 10 m as at the PAL site and this area could be considered as containing future limestone reserves.

2. Furthermore, at all three studied sites, there are 4-5 meter-thick layer of black shales, which are rich in U, Mo, and V, occurring at depths between 25 to 60 meters below the ground surface. These black shales are not currently explored but represent a potential metal resource in the future.

3. Due to the regional geological structure of the Estonian bedrock, there are differences in the depth of geological units between three sites. The most substantial and thickest clay-rich interval, known as the Lontova Formation, which is the most suitable for the IDDF, occurs at depths of 57-98 m, 78-119 m, and 93-131 m at PAL, ALT, and PED sites, respectively. In the PAL site, the transition from sandstone-dominated formation to clay-rich one is sharp, and the overall thickness of the unit is the same as in the PED and ALT sites.

4. In addition, there are clay rich intervals at all three sites:

- 4-5 m thick organic rich shales in upper part of the successions at the depths between 25 to 60 m in different studied drill cores;
- 40-45 m thick clayey interval composed of 14-12 m thick unit of alternating claystone and siltstone to fine-grained sandstone; and a succeeding 18 to 27.5 m thick claystone at the depths between 60 to 100 m;
- about 20 m thick unit of clayey sandstones at the depths between 104 to 160 m in different studied drill cores.

They create aquitards that protect against the vertical flow of water.

5. At the most preferred PAL site the thickest clay-rich unit is at the shallowest depth and the clay-rich interval is the most homogenous, and with well-defined lithological boundaries. The least preferred ALT and the PED sites are similar in terms of overall lithology and both show

a gradual transition from sandstone dominated lithology to the claystone in the thickets clay-rich interval that also occur at a greater depth compared with the PAL site.

4. Sub-activity 2.4: Analysis and geodetic surveys of surface terrain

The objective of the surface topography analysis was to study surface features relevant for safety of waste disposal facility. Surface inclination, and presence of kettle holes were identified using LIDAR data digital elevation models. Dangers of potential rising of the Sea level was considered in addition. Additionally, the risk of potential sea level rise was considered.

The study followed the IAEA guidance for site investigation and characterisation by providing a detailed overview of the terrain of the three potential disposal sites:

- the nature and properties of the geological structure of the location, including folding, faults, bedding plane, fissures, etc. and
- a topographic overview of the region. Distinction of natural and man-made terrain changes.

The results of the performed investigations are detailed in Appendix 4. The study was performed by Marko Kohv and reviewed by Jüri Plado (University of Tartu, Department of Geology).

4.1. PAL site

The PAL potential repository area is located near the top of the Pakri peninsula, with an elevation between 19-25 m above sea level (a.s.l.). The Pakri peninsula is well-known for its active coastal cliff, reaching a maximum height of approximately 22 m at the tip of the peninsula. The active sections are found at the peninsula's tip and NW side, approximately 3.5 km away from the potential repository area. The closest section of the cliff to the potential repository area, which is currently unaffected by the Baltic Sea, has a relative height of around 8 m and is situated about 1 km NEE from the site (Figure 4.1).

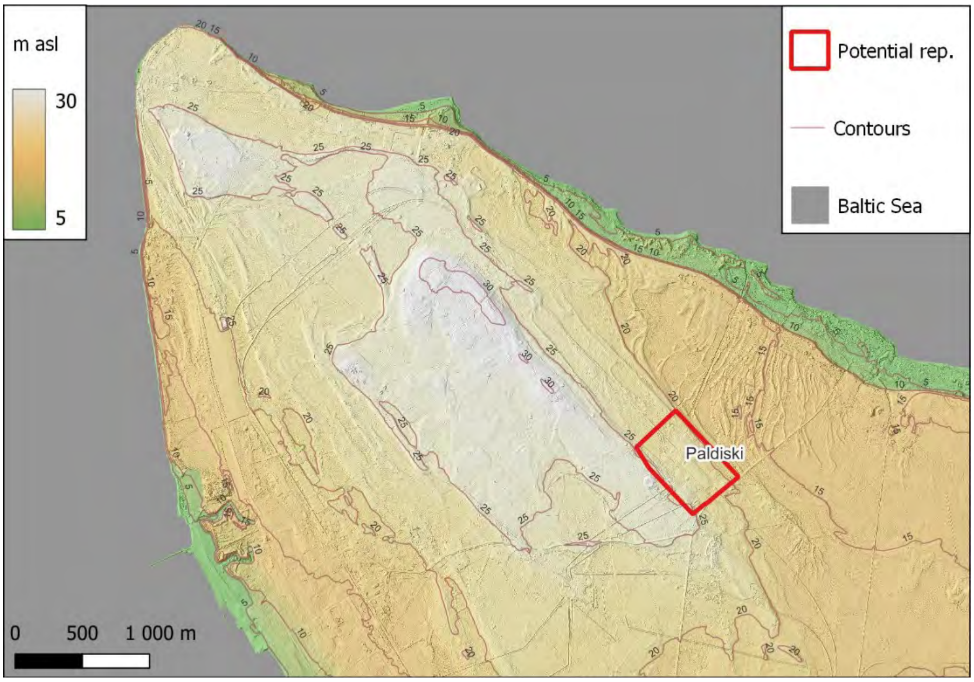

Figure 4.1. Location of the PAL site and Pakri peninsula. The base digital elevation map with contours is by the Estonian Land Board.

The area has an average altitude of 22.1 m a.s.l., ranging from 18.0 to 26.7 m. The altitude range significantly exceeds even the worst-case projections for sea-level rise, which predict an increase of 15 meters by 2500. The site is heavily influenced by human activity, lacking natural landforms. It occupies one of the relatively flat levels on the peninsula, ranging from 22 to 25 m a.s.l. The flat area is bordered by steeper terrain on the SW and NE sides. The site itself has predominantly gentle slopes, averaging around 3° (ranging from 0 to 43°). The steepest slopes are associated with artificial landforms such as drainage ditches, trenches, or filled areas. The surrounding region is also relatively flat, with an average slope of ~3°. However, its NE border extends to the cliff section, where slope angles reach approximately 70°.

The high-pass filtered relief shown in Figure 4.2 reveals the presence of two prominent scarps that dominate the PAL site, serving as natural boundaries and generally aligned in a NE-SW direction. The rims of these scarps are slightly elevated, indicating that their formation and height are influenced by the underlying limestone. Over time, the slopes have been shaped and smoothed by hillslope and coastal processes, which involve erosion and deposition. The area between these scarps is predominantly flat and may have been artificially leveled and filled.

Towards the SW, just outside the site border, there is a relatively higher landform that is likely an artificial soil or crushed limestone dump. Moving in that direction, there is a relative depression, currently occupied by a wetland, located at the top of the highest plateau. This wetland is likely somewhat artificial, as the natural water flow towards the SE is obstructed by a road embankment. The top plateau exhibits several other relative depressions, characterized by sharp and jagged borders, suggesting that they are incised into the underlying limestone layers. These depressions likely serve as significant infiltration areas for groundwater.

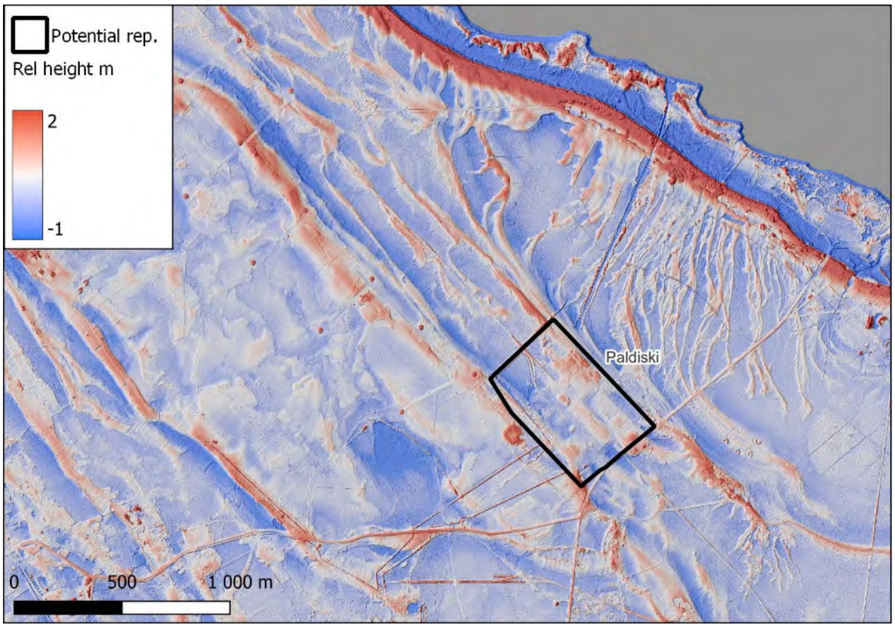

Figure 4.2. High-pass filtered relief map of the PAL site.

To the NE of the site, there is a lower plateau characterized by numerous relatively narrow, long, and roughly parallel ridges with a relative height ranging from 1 to 3 m. These landforms are indicative of the former coastal environment, resulting from the formation of bars and spits during episodes of sea level regression. The main composition of these landforms is likely to be well-rounded cobbles, gravel, and sand. The depressions between the ridges are prone to peat formation, as the drainage towards the sea is hindered by the presence of positive landforms. The lower parts, or talus, of the scarps commonly exhibit groundwater seepage and springs. A significant straight drainage channel, originating just north of the site, was likely constructed primarily for the purpose of draining such areas. Roughly 500 m SE of the site, there is a drained mire that has already transitioned into the bog stage. This is indicated by its smooth dome shape intersected by straight drainage ditches. Bogs typically have deeper peat layers (>1 m) compared to the shallow fens found between the coastal landforms.

The PAL site is located at the watershed, and its drainage is artificially controlled by a ditch along the northwest border, which directs water flow towards the northern coast. Generally, the site benefits from good drainage due to the natural slope of the border and the presence of artificial drainage systems. In the surrounding area, there are some notably wetter regions with a higher wetness index, located approximately 200 m NW and in the NEE direction.

Nearly all observable changes in the terrain near the potential repository site are the result of human activities. The most significant surface height alteration occurred at the wetland situated about 300 m SW of the PAL site between 2016 and 2020. During this period, the surface level dropped by approximately 0.6-1 m. This drop is likely attributed to the construction or renovation of a culvert through the road embankment, which facilitated the drainage of the waterbody behind it. Furthermore, to the northwest of the potential site, there are construction areas and foundations of wind turbines that were erected in 2013.

4.2. ALT site

The ALT area, as shown in Figure 4.3, has an average altitude of 5.1 m a.s.l. Consequently, the site exhibits a remarkably flat topography, situated at the summit of a low-profile tombolo. The tombolo is encompassed by a uniformly even and flat plain, characterized by an average slope of less than 2°. The steepest slopes within the area are associated with artificial landforms such as road embankments and ditches.

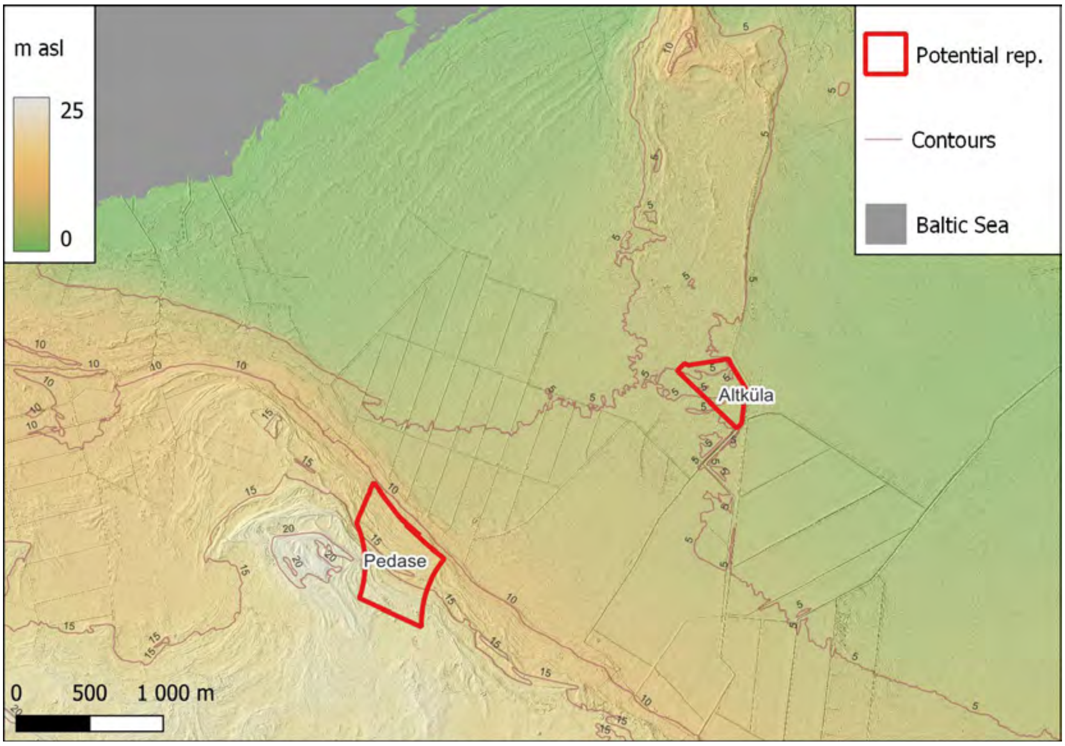

Figure 4.3. Digital elevation model of the ALT and PED sites and surrounding area.

No clear preferred slope direction is evident in the area. However, a notable landform near the site is a ridge of the former tombolo, which is further accentuated in the digital terrain model by a man-made road embankment that aligns with the natural ridge (Figure 4.4). Additionally, a sinuous and branching channel system is observed, eroded into an otherwise gradual slope of the former tombolo. This channel system is likely the result of storm-induced overflow at a previous time when sea levels were higher, occurring at the lowest point along the tombolo ridge.

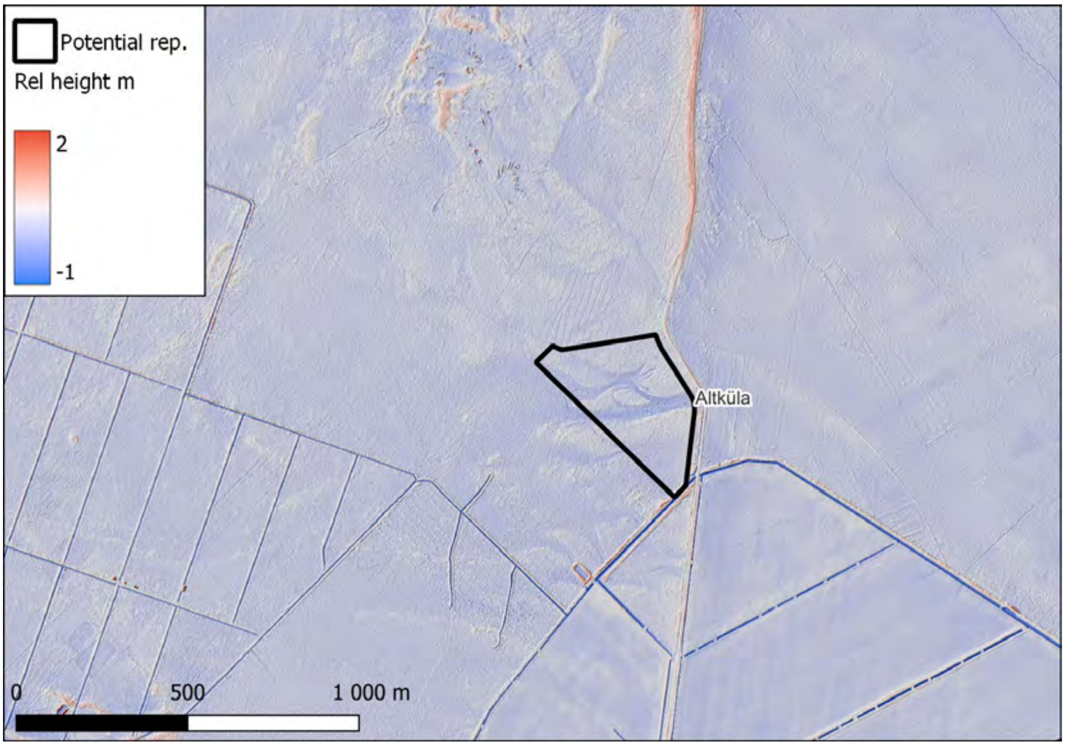

Figure 4.4. High-pass filtered relief map for ALT site and surrounding area.

The analysis conducted for the regional harbor in Haapsalu bay reveals that, on average, a storm event with a return period of once in a thousand years could cause the sea level to rise by 2.69 m above the mean level. Additionally, climate change is expected to increase the likelihood of extreme storm events. The combination of these two trends leaves very little margin between the sea and the potential repository, even within the relatively near timeframe of 2100.

Long-term predictions regarding future sea level rise carry greater uncertainties. However, in the worst-case scenario, the sea level could rise by up to 15 m by 2500. Such a significant rise would result in the complete submergence of the ALT (and PED) potential sites. Nevertheless, it is important to note that North Estonia experiences substantial isostatic land uplift, which counteracts the global sea level rise.

This land uplift is projected to reduce the anticipated 1-m global sea level rise by approximately 25 cm by 2100. However, despite this uplift, it will not be sufficient to fully offset the long-term effects of sea level rise.

The site demonstrates relatively good drainage, with a general flow direction towards NNE. There is an agricultural underground drainage system in close proximity to the site. However, the drainage situation carries inherent risks as the site is situated in the midst of an expansive and flat plain. The drainage system relies on an artificial network of ditches. Nonetheless, due to its low altitude, the system can only provide minimal slope for effective drainage. Any obstruction, such as a beaver dam or similar barrier, between the Baltic Sea and the site would have a significant impact on the drainage. It is important to note that if the artificial drainage network were to be closed, it would not lead to the inundation of the site, as its elevation is higher than the surrounding plain.

Between 2009 and 2020, the changes in terrain altitude primarily comprise man-made alterations. One notable example is the renovation of the drainage systems located southeast and southwest from the site. These renovations are evident through consistent elevation of berms, the presence of new ditch sections, and the formation of ponds.

4.3. PED site

Compared to ALT, the PED site is situated on higher ground (Figure 4.5). It has an average altitude of 15.1 m a.s.l. The site exhibits a slight tilt, with a mean slope of approximately 3° (ranging from 0 to 24.6°). The steepest slopes can be attributed to probable karst sinkholes located in the southern part of the site, as well as former coastal berms that traverse the site in a NW-SE direction.

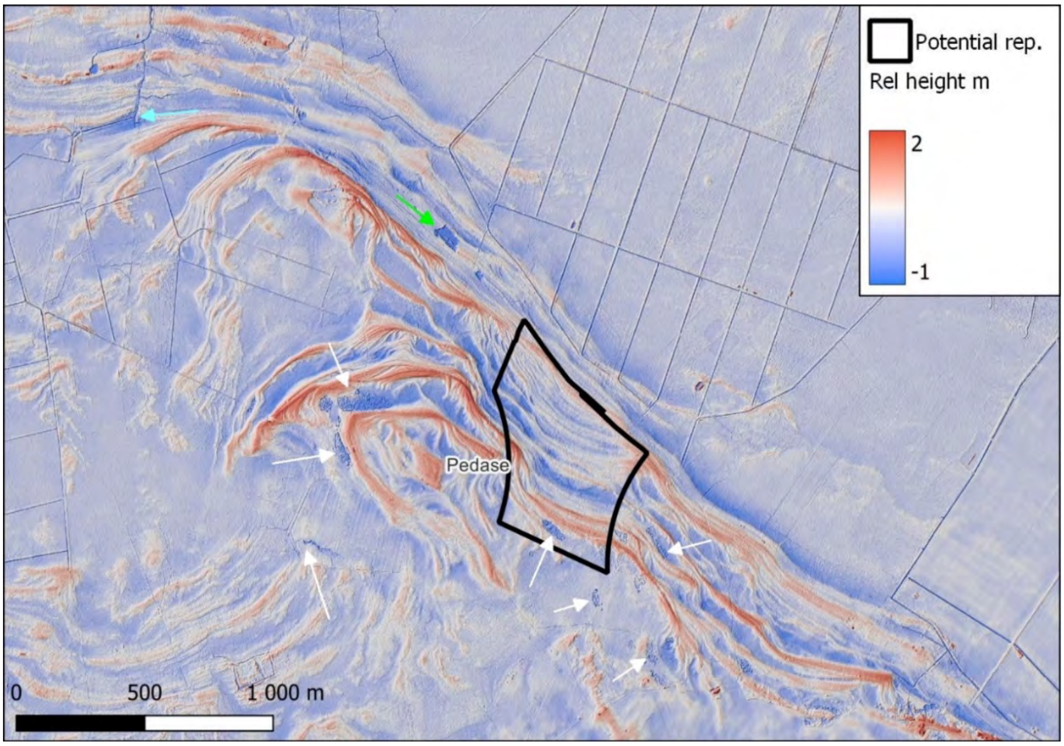

Figure 4.5. High-pass filtered relief map of PED site and surrounding area.

The PED site displays distinct parallel ridges that delineate former shorelines and are likely composed of sand and gravel. In the vicinity of the site, numerous well-defined rugged depressions can be observed (indicated by white arrows in Figure 4.5), suggesting the presence of karst sinkholes where surface water infiltrates. The probable outflow area for this water is located just NE of the site, where drainage networks are present. Notably, a prominent spring and stream system can be found 1.7 km NE of the site (indicated by a blue arrow in Figure 4.5). Additionally, the map reveals the presence of small, local sand/gravel quarries, with the largest one indicated by a green arrow. No significant changes in terrain altitude have occurred from 2009 to 2020.

4.4. Linear features

The most prominent regional linear features exhibit a general NW-SE direction, as depicted by the blue lines in Figure 4.6. These features are likely influenced by geological characteristics within the pre-Quaternary sedimentary rocks. During the latest ice age, approximately 22,000 to 13,500 years ago, the main direction of movement was NW-SE, resulting in predominantly erosional features. The PAL site is bordered by such linear NW-SE-striking topographic features on two sides. Additionally, a similar relatively long and straight slope can be observed on the NE side of the PED site.

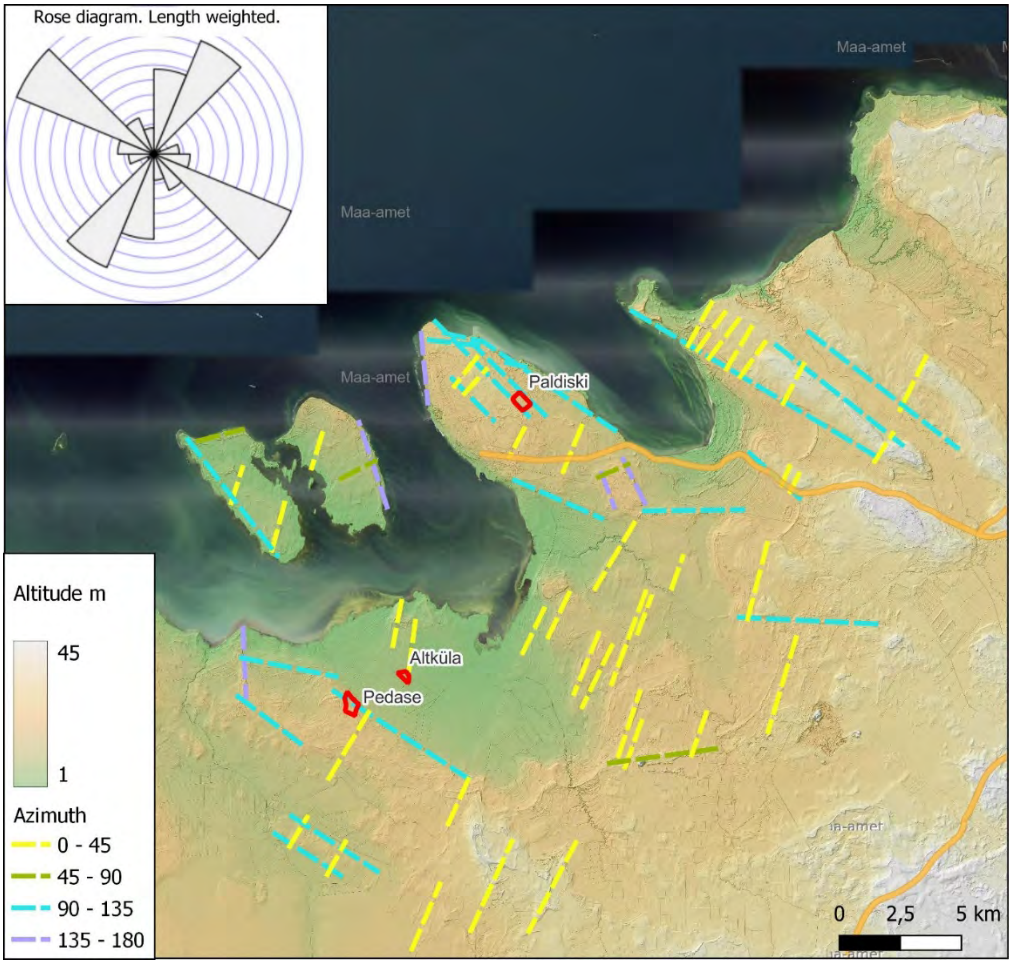

Figure 4.6. Linear features and length weighted azimuth rose diagram.

The second larger group of linear features, represented by yellow lines in Figure 6, exhibits a roughly NNE to SSW direction. These features are associated with marine and glacial sediments, likely formed during earlier stages of the ice cap. Compared to the NW-SE-directed features, these lines tend to be shorter in length.

4.5. Summary

The topographic survey confirmed that the surface is smooth with a minor inclination of a few degrees. As a result, there is no risk of landslides in all sites.

Topographical analysis reveals a significant concern regarding the ALT site. Its proximity to the current sea level, combined with the anticipated rise in sea levels and more severe storm events, poses a growing threat to the site within the next century. However, it's important to note that North Estonia experiences considerable isostatic land uplift, with a rate of 3.2-3.3 mm/year in the region, which helps counteract the global sea level rise. This land uplift is estimated to reduce the predicted 1 m global sea level rise by 2100 by approximately 25 cm. Nevertheless, in the long term, it may not be sufficient to mitigate the risks fully.

The PED site, although situated at a higher elevation, remains vulnerable in the long term if the current worst-case predictions for global sea level rise (+15 m by 2500) come to fruition. The site is located on a regional slope and contains numerous karst sinkholes within and around its borders. This abundance of karst features, coupled with the significant difference in height, is expected to result in intensive groundwater flow, which is a negative characteristic for the disposal site.

On the other hand, the PAL site is located at a higher elevation, making it safe even under the predicted worst-case scenario for sea level rise. The topographic analysis did not reveal any significant negative aspects associated with this site.

In terms of drainage, the ALT site presents the most complex and risky situation. Being situated in the middle of an extensive flat plane, the site relies on an artificial ditch network for drainage. However, due to its low altitude, the slope of the drainage system is minimal, and any obstructions such as beaver dams between the Baltic Sea and the site would have a significant adverse effect. Conversely, the PED and PAL sites, being located on slopes or in close proximity to them, are generally well-drained or require only minimal artificial drainage.

The impact of terrain on the local climate is relatively insignificant, as the landforms in the area are relatively small. However, the PED site is slightly more exposed to prevailing westerly winds due to its elevated location and aspects within the potential site.

4.6. Conclusions

1. There is no risk of landslides in all three sites.

2. Potential sea level rise over the next century, combined with severe storms, poses a growing threat to the NSDF if built on the ALT site. The PED site is situated at a higher elevation, remains potentially vulnerable in the long term if the current worst-case climate change predictions.

3. Abundance of karst features, coupled with the significant height difference leading to intensive groundwater flow, results significant threat to the stability of NSDF if it is built on the PED site.

4. The topographic analysis did not reveal any significant negative aspects associated with the PAL site. It is located at a higher elevation, making it safe even under the predicted worst-case scenario for sea level rise.

5. Sub-activity 2.5. Analysis of specific geomorphological features

The objective of the study is a detailed overview of the landforms at the three potential disposal facility locations and overall ranking of candidate sites in terms of specific geomorphological features.

The work includes an overview of landforms and sediments at the three candidate sites and an assessment of geohazards as well as comparison of the sites terms of specific geomorphological features. The results of the performed investigations are detailed in Appendix 5.

The work was performed at the Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu by Tiit Hang and Alar Rosentau.

5.1. Methodology

For terrain analyses, we used LiDAR-based digital elevation models (DEM) with resolutions of 1 × 1 m. Data on the geology and corresponding genesis of landforms are predominantly derived from large-scale geological mapping data, which are available from the ELB server and the Geological Archive of the Estonian Geological Survey. For the eastern part of LHLM, which also holds two of the selected sites PAL and ALT, geological mapping data on a scale of 1 : 50 000 is available digitally. For the western part of the municipality, where the PED site is located, both 1 : 200 000 and 1 : 50 000 geological mapping data are available on paper reports in Geological Archive and also digitally generalised in scale 1 : 400 000. A digital soil map on a scale of 1 : 10 000 has also been used for more precise tracing of local landforms. Data from scientific surveys and data from coastal monitoring and Global Navigation Satellite System observatory have also been used. Fieldworks to map and describe the landforms at the candidate sites were carried out in spring early summer 2022. In each candidate disposal facility site, the stratigraphy and lithology of sediments were described in three boreholes (ALT) or three trenches (PAL and PED).

5.2. Outlines of geomorphology and Quaternary sediments

The modern topography of the area has developed over a long geological period, and therefore, the main elements of the relief are of different ages. The forms of the ancient or pre-Quaternary relief have formed in the bedrock and have significantly influenced the later movement of glaciers and the formation of glacial topography. The topography has been shaped by the period of ice recession. The glacier has also indirectly affected the post-glacial development of the area through the relative sea-level (RSL) change caused by the total effect of glacial isostatic adjustment (GIA) and sea-level change. Thus, in the late- and post-glacial period, the entire territory of the municipality was flooded by glacial lakes and the waters of the Holocene Baltic Sea. Therefore, in many places, the previous glacial topography has been levelled by younger sediments. Due to following RSL change induced coastline regression wave activity has been significant with corresponding accumulative and erosional coastal landforms, especially abundant along the coastal area at lower altitudes.

Wetlands prevail among post-glacial terrestrial landforms, especially in the municipality's western part. Other terrestrial landforms, e.g. aeolian and alluvial, are of local importance. The karst phenomenon on Lääne-Harju Local Municipaly (LHLM) territory has not been described earlier, but clear surface karst landforms at the PED candidate site have been mapped. Artificial landforms are also of limited distribution, represented as negative landforms like quarries, peat cuts and drainage ditches and positive landforms like mining spoil hills in the Rummu limestone mining area or road constructions.

The most remarkable bedrock landform on the LHLM territory is the up to 22 m high bedrock cliff, the North Estonian klint, best exposed on Pakri Peninsula. The Pleistocene glaciers repeatedly designed the klint, widened the klint bays and shaped the klint peninsulas until it reached its present appearance after the last deglaciation. Two of the candidate disposal sites PAL and PED are located at higher altitude on top of the klint peninsulas, while ALT site is located at lower altitude at the klint bay filled with thick Quaternary sediments.

The further post-glacial development of the area and the formation of landforms have been influenced by the relative sea-level (RSL) change of the Baltic Sea basin and corresponding shore displacement and wave activity. The LHLM is located in the periphery of the Fennoscandian uplift area, which has experienced significant transgressive and regressive shoreline changes owing to the melting of the continental ice sheet, the damming and drainage of the basins, and post-glacial isostatic land uplift.

5.3. Main landforms and their genesis at the three candidate disposal facility sites

While two candidate sites, PAL and PED, are located in only slightly different geomorphological conditions, the ALT site' geological setting, topography and development are noticeably different. The PAL and PED sites are located at an elevated area (mean altitude 22.1 m and 15.1 m, respectively) on top of bedrock heights with very thin Quaternary sediment cover (1.5 m and 1.8 m, respectively). The ALT site is located at a low altitude (5.1 m) coastal lowland with thick (23.9 m) sedimentary cover. The location at different altitudes has also influenced the formation and age of the landforms, but in all areas, coastal processes have been the dominant designer of the topography. Since the candidate sites have a relatively small size, the surrounding terrain has also been inevitably discussed when describing the relief forms and their genesis. The description of the chronological background is based on the regional knowledge of deglaciation and development of the Baltic Sea, land uplift and RSL models.

5.3.1. PAL site

The PAL site is located in the central part of the Pakri Peninsula on slightly NE-inclined terrain at an altitude of 26.7 – 18.0 m. The Pakri Peninsula is a klint headland surrounded by an up to 22 m high locally actively abraded cliff in Palaeozoic sedimentary rocks. The highest central plateau of the peninsula with rather even topography is located at an altitude of 25 – 30 m. The plateau is covered by only a few tens of cm thick topsoil. A slightly inclined terrace surrounds the central plateau at an altitude of 20 – 25 m with random NW-SE oriented coastal ridges and spits with a relative height of up to 2 m. PAL site is located at this terrace. In the altitude range of 10 – 20 m, there are numerous low (1 – 2 m) and narrow beach ridges and spits of different orientations. NE of the PAL site is a spit system where the swales between the roughly parallel ridges are paludified and covered with a thin layer of fen peat because the water drainage towards the sea is blocked. Spits consist of gravel, pebbles and poorly rounded shingle. The up to 22 m high cliff in sedimentary rocks is a major landform in the surroundings of the PAL site. It is actively abraded on top of the peninsula ~3.5 km from the PAL site. The closest section of the cliff, which is currently not actively influenced by the waves, is ~1 km NE from the PAL site, with a relative height of around 8 m.

There are no naturally preserved landforms on the territory of the PAL site, as humans have intensively used the site. From LiDAR DEM and sediment description, it could be assumed that there are former coastal ridges of gravel and shingle crossing the NE part of the site. Artificial landforms are the drainage ditches along the NW and western border, and one starting at the NNE corner of the site. In the western part of the PAL site, there is an artificial trench filled with water; in the NW part there is a low road embankment.

As no natural landforms are preserved at the site, the topography development could only be presented for the whole of the Pakri Peninsula. A very thin till cover (20 – 40 cm) proves that the area was a glacial scouring area during the last Weichsel glaciation. Till accumulated during the area's deglaciation between 13 – 12 ka BP. After deglaciation, the area was flooded by the BIL and Early Holocene Baltic Sea. The central plateau of the peninsula, at an altitude of ~30 m, started to emerge after Ancylus Lake transgression ~10.2 – 10 ka BP. During and after the Litorina Sea transgression (~7.3 – 6 cal ka BP), beach ridges and spits were formed around the central plateau at an altitude of 24 – 21 m. The territory of the PAL site also emerged at that time and was likely covered by coastal ridges. Since then, the initial small islet started to grow due to isostatic rebound and corresponding RSL decline. The regressive coastline left behind numerous coastal spits and spit systems. The initial Pakri islet joined the mainland and turned into a peninsula when the water level dropped to 13 – 10 m a.s.l. at about 4 ka BP. Around this time, also paludification started in the depressions and swales around the PAL site due to poor drainage conditions.

5.3.2. ALT site

The ALT site is located in the middle of a large low-lying coastal plain with a sediment thickness of up to 30 m. The mean altitude at the site is 5.1 m (ranging from 4.5 to 6.1 m) with a mean slope of <2°. The site is located on S-N trending narrow slightly (0.5 – 1 m) higher ground which connects a small bedrock cored height (up to 10 m a.s.l.) to the north and the western slope of the bedrock incision, the Kurkse Klint Bay, to the south and west. Following the geological mapping data, there is no difference in the geological setting of the latter spit-like formation and the rest of the coastal lowland where the mainly fine-grained sand or locally silty sand is outcropping. The thick (23.9 m) sedimentary cover at the ALT site consists of Late Weichselian till (up to 10 m thick), an interval of proglacial varved clay (up to 7.4 m thick) which is covered by 8.6 m thick bluish-grey sandy silt or silt also of proglacial origin. Within the overlying layer, 1 – 3 m of beige-coloured massive fine sand, mollusc detritus is present, indicating a marine/lacustrine origin of these sediments.

The area has been occupied by a proglacial lake and the Holocene Baltic Sea for a prolonged period after deglaciation (after 12 – 13 ka BP). Proglacial fines and later sandy marine/lacustrine sediments have levelled the initial glacial topography. The final design of the coastal plain was given by the wave erosion/accumulation when the RSL declined during the Post-Litorina Sea (<4.5 ka BP). During the low water level period in the shadow of a bedrock cored height, which at that time served as a near-shore islet north to the ALT site, a tombolo-like coastal spit was formed. The ALT site and the surrounding coastal plain started to gradually emerge around 2.5 – 2 ka BP and were finally terrestrialised around 1.3 ka BP.

5.3.3. PED site

There are similar features in the development and relief of the PED site compared to the PAL, as it is also located on top of the bedrock height with a very thin sedimentary cover (max 2 m). However, there is a well-preserved NW-SE oriented natural coastal spit system on the PED site. Compared to the PAL site, the PED site is located at a lower altitude (19.3 – 11.2 m), although it is still 6 – 15 m higher than the surrounding plains. The elevation holding the PED site represents an NW-SE oriented bedrock remnant that separates the higher (16 – 18 m a.s.l.) plateau in SW from the much lower terrain (3 – 5 m a.s.l.) NE from the site. The PED site is located on the NE slope of this bedrock height, having a mean sloping of ~3° degrees (0 – 24.6°) with larger gradients at the slopes of the coastal ridges. Thin (1.5 – 2 m) sedimentary cover on top of the bedrock height consists of till, covered by coastal gravel, pebbles and shingle. These sediments form a coastal spit system of NW-SE veining 1 – 2 m high ridges and swales in between, developed due to longshore transport at gradually lower altitudes in conditions of the regressive coastline. The drainage conditions at the site are rather good, partly connected to the karst phenomenon. Namely, there are several up to 2.5 m deep karst sinkholes and ditches on top of the bedrock height, with a few smaller ones also located in the central and southern part of the PED candidate site. Usually, the sinkholes are some tens of meters in diameter, but the largest ones reach 100 – 200 m. Likely, there are swallow holes in the bottom, which could be concluded from the fact that after spring melting, the depressions are filled by water which drains rather rapidly in late spring.

The geological development of the PED site relief is also broadly similar to the PAL site. Bedrock height was polished and shaped during the last Weichselian glaciation. During the deglaciation (13 – 12 ka BP) a very thin cover (<50 cm at the PED site) of till was left on top of the bedrock remnant, which stayed under the BIL, the Yoldia Sea, and the Ancylus Lake water until the highest part of the bedrock height emerged during the Litorina Sea regression at ~4 ka BP. Intensive coastal processes occurred around the initial tiny islet, and the coastal spit system started accumulating. Following the RSL data, the lowest ridges at ~11 m a.s.l. were formed ~4 ka BP in the Post-Litorina Sea regressive coastline conditions. Since then, karstic landforms have been developed.

5.4. Characteristics and genesis of the Quaternary sediments at the three candidate disposal sites

5.4.1. PAL site

The PAL potential disposal facility site is located on top of the bedrock height of the Pakri klint headland at an altitude of about 22 m (18.0 – 26.7 m). Bedrock surface in the surroundings of the site is covered by 0 – 2 m thick Quaternary sediments, the thickness of which at the disposal facility site is 1.4 – 1.7 m. Three trenches were excavated at the PAL site down to the bedrock surface. In all sections, the upper 0.4 – 1 m thick interval is strongly influenced by human activity. In all sites, a thin (25 – 40 cm) layer of till covers the bedrock, while in trenches Q1 and Q2, it is greyish-coloured loamy till abundant with shingle, and in Q3, yellowish-brown sandy diamicton with fragments of local limestone. The gravelly coastal shingle is covering till in a thickness of about 1 m.

No direct age determinations have been made from the sediments of the Pakri Peninsula. Since the bedrock height has been a glacial scouring area, the till has been preserved only in places and as a thin layer, and it dates from the Palivere stage (<13 ka) of the retreat of the last Late Weichselian glacier. After the recession of the glacier edge, the Pakri bedrock height remained flooded by the BIL and the Yoldia Sea until the emergence of the central plateau about 10 ka BP during the Ancylus Lake regression. During the Ancylus Lake regression the central plateau started to grow as a small islet surrounded by the beach ridge system at an altitude of 24 – 22 m. Coastal shingle with gravel at an altitude of 21 – 22 m in the PAL site tended to accumulate a few thousand years later after the Litorina Sea transgression ~7 – 6.5 ka BP.

5.4.2. ALT site

The ALT site is located on top of a wide incision, Kurkse Klint Bay, cut into a sedimentary bedrock surface with a relative depth of ~30 m. This depression has been occupied by a proglacial lake and the Holocene Baltic Sea for a prolonged period after deglaciation. It is why the thickness of soft and porous Quaternary sediments of glacial (till and proglacial varved clay) and marine/lake origin is about 20 m in the surroundings of the ALT site, being 23.9 m at the site. In the ALT site, coring and description of Quaternary sediments were performed in 3 localities. In comparable depth intervals, all sites displayed a very similar sediment stratigraphy. ALT's bedrock surface lies at a depth of 23.9 m at an altitude of -18.8 m. A bluish-grey loamy till containing a poorly rounded shingle with a maximum thickness of 10.2 m lies directly on the bedrock. On top of the till horizon is an interval of proglacial varved clay in thickness of 4.7 – 7.4 m. Up to 8.6 m thick bluish-grey sandy silt or silt rests on top of the clay. It is probably the sediment settled at the end of the glacial lake's existence with a decreasing water level. In the upper interval of silty sand and within the overlying (1 – 3 m) layer of beige-coloured massive fine sand, mollusc detritus is present, indicating a marine/lacustrine origin of these sediments.

No direct sediment age estimates are available from the site. The till laying on top of bedrock is younger than 13 ka when the ice margin of the last Scandinavian Ice Sheet retreated to the Gulf of Finland. BIL developed in front of the retreating ice margin where the proglacial varved clay accumulated in thickness of up to 7.4 m. Sandy silt and silt covering the varved clay likely accumulated during the BIL water-level lowering. The ALT site remained flooded by the Holocene Baltic Sea until 1.3 ka BP. Before emergence, up to 3 m of fine- to silty sand covering the site and the surrounding areas was deposited.

5.4.3. PED site

The PED site is located on the NE slope of a bedrock height with thin sedimentary cover at an altitude of 11.2 – 19.3 m. Three trenches were excavated at the site down to the bedrock surface, and sediment thickness varies among the excavation sites from 1.6 – 2.15 m. In two sections till lies directly on the bedrock with a thickness of 70 and 60 cm and is covered by a 60 cm thick interval of fine-grained marine gravel with interlayers of sand and pebbles. The latter deposit is laying directly on the bedrock in the third section at PED. In all three cross-sections, a 40-70 cm thick gravel and shingle interval dominated by limestone clasts is capping the section.

The gravelly sandy beach sediments located immediately on the bedrock or covering the till were accumulated during the Litorina Sea period. The beach ridge and/or spit system on top of the bedrock height at 19 – 11 m a.s.l. were also accumulated during the Litorina Sea period in the conditions of a continuously decreasing RSL when the top of the height emerged and existed as a tiny Litorina Sea islet. According to the RSL data, the coastline receded from this bedrock height, and the ridge-swale system was formed between 6.5 and 4 ka BP.

5.5. Geomorphic processes and geohazards

Due to the tectonic stability of the Estonian territory, the very flat terrain and the location in the transition zone of the temperate maritime and continental climate, dynamic geomorphological processes that are active, fast and/or with catastrophic consequences, are rare. Coastline displacement and corresponding areal change in wave activity have been a major geodynamic process. They must also be taken into account in the future, during a period important to the safety of the disposal facility. Therefore, an overview and risk assessment of possible dynamic geomorphic processes - mass loss, slope processes, channel erosion, aeolian processes, karst phenomena, flood and wave erosion - is presented.

5.5.1. Geodynamic processes related to coastline change

The global eustatic sea-level rise and isostatic land uplift are the main factors determining the relative sea-level (RSL) changes in the coastal area with the potential disposal facility sites. The area is located in the periphery of the Fennoscandian uplift area, which has experienced significant transgressive and regressive episodes in RSL change owing to the melting of the continental ice sheet, the damming and drainage of the basins. The last marine transgression occurred here around 8.4 – 7.5 ka BP when RSL rose at about 5 m. Over the next seven millennia, land uplift prevailed over the sea-level rise, causing a 22 – 23 m RSL fall and extensive shoreline regression.

Over the last seven millennia, land uplift, in the coastal area holding the potential disposal sites, prevailed over the sea-level rise, causing a 22 – 23 m RSL fall and extensive shoreline regression. However, due to human-induced climate warming, sea-level rise has significantly accelerated during the past decades. It will probably exceed the land uplift rates on the southern coast of the Gulf of Finland in the coming decades.

In the case of a very high greenhouse gas (GHG) emission scenario (SSP5-8.5, global surface temperature rises 4.4 °C for 2081 – 2100), the global mean sea-level (GMSL) is likely to rise up to 0.63 to 1.01 m (median 0.77 m) by 2100, relative to the 1995 – 2014 mean sea level. According to the IPCC regional atlas and SSP5-8.5 sea-level scenario, 0.6 m RSL rise is projected for the SE part of the Gulf of Finland (Narva-Jõesuu area) by 2100. There are no regional IPCC prognostic scenarios available for the PAL-PED-ALT areas. However, considering the uplift rates of 2.9 mm/a in PED and ALT and 3.0 mm/a in PAL, the expected RSL rise is slightly less than in Narva-Jõesuu, between 0.3 to 0.7 m (median 0.5 m) by 2100 AD (Table 5.1). Local RSL scenarios are derived by subtracting the land-uplift component relative to geoid from the IPCC projected GMSL rise. For comparison, the land uplift rates and RSL rise scenarios are also given for the Narva-Jõesuu area, where IPCC regional atlas data are available. Those scenarios where the sea-level rise exceeds the topographic altitude are marked in red.

Table 5.1. Relative Sea-Level rise scenarios for the PAL, PED and ALT sites in case of very high GHG emissions for 2100 AD, 2300 AD and 2400 AD, and in case of extreme marine ice cliff instability scenario for 2300 AD

	Altitude, m a.s.l.	Land uplift relative to geoid (mm/yr)	RSL rise 2100 AD (SSP5-8.5), m	RSL rise 2300 AD (SSP5-8.5), m	RSL rise 2300 AD (marine ice cliff instability), m	RSL rise 2400 AD, m**
PAL	26.7-17.9	3.0	0.3-0.7 (0.5)	0.8-5.9	up to 15	1.1-7.9**
PED	8.0-19.3	2.9	0.3-0.7 (0.5)	0.8-5.9	up to 15	1.1-7.9**
ALT	4.5-6.1	2.9	0.3-0.7 (0.5)	0.8-5.9	up to 15	1.1-7.9**
Narva-Jõesuu	-	1.7	0.5-0.8 (0.6*)	-	-	-
Global mean sea level rise by IPCC (2021)	-	0.0	0.63-1.01 (0.77)	1.7-6.8	up to 16	-

*median value from the IPCC (2021) regional atlas

**linear extrapolation from the IPCC 2300 AD (SSP5-8.5) scenario values

Table 5.1 presents relative sea-level rise scenarios for PAL-ALT-PED area in case of very high GHG emission by IPCC for 2100 AD, 2300 AD and 2400 AD and in case of marine ice-cliff instability scenario for 2300 AD, the latter was considered by IPCC as scenario with 'deep uncertainty' due to the absence of sufficient data and conclusive or precise probabilistic descriptions of the risks.

Summing up the data presented in Table 3, even with the very high GHG emission scenario, sea-level rise likely will not affect PAL, PED, and ALT sites by 2100 AD. According to the SSP5-8.5 scenario, the ALT area will be partly flooded by 2300 AD while PED and PAL sites remain at safe altitude. If a low-confidence and highly uncertain marine ice-cliff instability scenario by IPCC is realised, also the PED site may be partly flooded by 2300 AD. There are no IPCC scenarios available for 2400 AD. However, by extrapolating RSL rise scenario (2300 AD) the ALT site will be flooded, and PED site may remain within the storm surge zone (1.9 m by ELB) by 2400 AD (Table 5.1). PAL candidate site remains at safe altitude during the reasonable time period for the safety of disposal sites (300-400 yrs).

5.5.2. Slope processes

Due to the almost flat terrain at the sites and in the surroundings, it is obvious that neither rock falls or -slides nor unconsolidated mass movements, including landslides, pose a threat to the current terrain. The most active cliffs with rapid mass wasting processes (rock falls) are located ~5 km from the PAL site, and the rate of cliff recession has been measured at ~25 cm/yr. This dynamic geomorphic process creates no risk to the PAL disposal facility site. In the reasonably foreseeable future, climate change and sea-level rise will not change these processes catastrophically. In some scenarios (RSL rise above 12 – 15 m), active wave erosion and cliff recession will decrease considerably as more resistant to erosion limestones will be abraded instead of soft sandstone.

5.5.3. Fluvial erosion

There are only a few larger rivers (max temporary discharge 60 – 80 m^3/s) with a prolonged rate of downcutting (<1 cm/yr) and lateral erosion (~1.5 cm/yr) in the surroundings of candidate sites. Fluvial systems closest to the sites are of artificial origin with no signs of fluvial geomorphic activity within ~50 yr since creation. The PAL and PED sites are at a distance of ~6 km and 10 – 15 m higher altitude from such rivers. The ALT site is at a distance of 3.5 km and 4 – 5 m higher altitude. It could be concluded that the prolonged rate of fluvial processes and the hypsographic position of the sites exclude a geomorphic threat to the current terrain at the sites or their surroundings. The expected RSL rise (>5 m in 2300) will raise the base level of rivers, which certainly declines the downcutting. However, it does not necessarily activate the lateral erosion as the valleys are very shallow, and a base-level rise of already a few meters will cause flooding of the area surrounding the rivers rather than activation of fluvial erosion in the future.

5.5.4. Aeolic processes

Currently, there are no active aeolian geomorphic processes going on at the territory of the LHLM and in the surrounding areas to candidate sites. In light of the future climate scenarios that predict continued warming and an increase in precipitation, the risk of aeolian geomorphic processes is unlikely.

5.5.5. Karst phenomena

There are no footprints of (surface) karst phenomena in the PAL and ALT sites. The PED site is located at a bedrock elevation with extremely thin sediment cover, favouring rapid recharge and surface water movement into deeper rocks. In this site, recharge is concentrated into karst surface depressions and is moving deeper through the swallow fissures, indicating possible karstification in the deeper rocks. Thus, karst phenomena pose a threat to the PED site. The predicted increase in temperature is ~2.73 to 4.28 °C, and an increase in mean annual precipitation by 14 – 19% by the end of 2100 will speed up the surface karstification in the future but not necessarily in deeper rocks. The karst phenomenon questions the suitability of the PED site as a disposal facility location.

5.5.6. Floods

The possibility of extreme floods (~2 m) on the southern coast of the Pakri Bay at the mouth of the Kloostri River must be considered a potential hazard for the ALT area. The PAL and PED potential disposal facility sites are deemed not to be at flood risk caused by coastal flooding or the overbank flooding in river systems. The predicted RSL rise of 2 m is a clear risk to the ALT site (no drainage from the site), and the RSL rise of 5 m, predicted for the year 2300, will inundate the area. According to the 5°C warming scenario, the lowermost part of the PED area will be flooded or remain within the storm surge zone (1.9 m by ELB) by 4000 AD.

5.5.7. Wave erosion

While the potential disposal facility sites PED and PAL are well protected against coastal dynamic processes, the ALT site is at threat due to coastal floods rather than wave erosion/accumulation. The coastal processes closest to the ALT site coastal section, in the back of the Pakri Bay are prolonged. The sheltered exposition of this coastal section and a shallow water abrasional terrace prevent high-energy waves from reaching the beach. In the future (beyond 2100), if a very high GHG emission scenario will realize, the ALT and PED sites could be affected by wave erosion processes from 2300 and 4000 AD, respectively.

5.6. Summary

Due to the tectonic stability of the Estonian territory, the very flat terrain and the location in the transition zone of the temperate maritime and continental climate, dynamic geomorphological processes that are active, fast and/or with catastrophic consequences, are rare. GIA-induced coastline displacement and corresponding areal change in wave activity have been a major dynamic geomorphic process. Predicted future RSL rise in connection with the climate change is the main future threat to the geomorphological features and any facilities at the candidate sites. Thus, the predicted RSL rise may inundate the ALT site by the year 2300-2400 AD and the storm surge area may reach the PED site by the year 2400 AD. PAL potential depository site will remain at the safe altitude during the period relevant for the safety of disposal facility.

An overall comparison of the candidate disposal sites in terms of the analysed specific geomorphological features are summarize in Table 5.2.

Table 5.2. Overall ranking of candidate disposal sites in terms of specific geomorphological features

Assessment criteria		**PAL**	**ALT**	**PED**
Geomorphological features		1	2=3	2=3
Quaternary sediments		1=2	3	1=2
Current dynamic geomorphic processes		1	2	3
Links between climate and tectonics		1=3	1=3	1=3
Links between climate, biota and rocks		1	3	2
Risks associated with the dynamic geomorphic processes in connection with climate change and sea-level rise	Slope processes	1=3	1=3	1=3
	Fluvial processes	1=3	1=3	1=3
	Aeolic geomorphic processes	1=2	3	1=2
	Karst phenomena	1=2	1=2	3
	Flood risk, wave erosion and future sea-level rise	1	3	2
Overall ranking in terms of specific geomorphological features		**1**	**3**	**2**

The argument is the sites' topography, sediment stratigraphy and soil cover which all have been artificially affected while negative impact to the site by means of geomorphology, due to development, is the smallest. The most important argument is the location of a site at a sufficient altitude, which insures the safety in the light of predicted climate change and future RSL rise even the worst scenarios are to be realized.

5.7. Conclusions

1. In terms of specific geomorphological features, the preferred site for the disposal facilities is the PAL candidate site.

2. ALT and PED sites less acceptable for construction of NSDF than the PAL site, and are roughly equivalent in preferences if flood risk is not considered.

6. Sub-activity 2.6. Analysis of hydrogeological conditions

This study is devoted to description of the hydrostratigraphical settings of NW Estonia, and hydrogeological conditions and groundwater flow of the three selected disposal facility locations.

The detailed results are presented in an Appendix 6. The study includes analysis of available information, such as the geological base map, geological/geophysical reports, and literature. The work was performed by Argo Jõeleht and Raul Paat, reviewed by Jüri Plado (University of Tartu, Department of Geology).

6.1. Hydrogeological setting of north-western Estonia

6.1.1. Hydrostartigraphy

The groundwater system of Estonia is divided into three principal hydrostratigraphic units: (i) non-consolidated Quaternary deposits, (ii) Paleozoic and Neoproterozoic (Ediacaran) sedimentary bedrock, and (iii) crystalline basement that consists of the Meso- and Palaeoproterozoic igneous and metamorphic rocks. Only the first two units are important in the scope of the current study. The weathered topmost part of the crystalline basement is hydraulically connected to the lowermost bedrock aquifer, the Cambrian–Vendian (Ca-V) aquifer system whereas deeper parts of crystalline have very low porosity and permeability.

The patchy distribution of different sediment types and relatively small thickness makes Quaternary overburden generally permeable to precipitates. The exceptions are glaciolacustrine sediments that are common in bedrock valleys (e.g., on both sides of the Pakri peninsula) and klint bays (e.g., surrounding of the ALT site). Fine sands, silts and especially varved clays may form local aquitards that separate groundwater flow systems above and below it. In the Gulf of Finland, glaciolacustrine sediments are relatively common hindering or blocking groundwater-seawater outflow-inflow.

Depending on location and extent of incision, glaciofluvial deposits can connect aquifer(s) on both sides of the valley. The upper part of buried valleys is usually filled by low permeability glaciolacustrine varved clays that, being often at the level of the Lükati-Lontova aquitard, isolate groundwater flow systems from the seawater and also from the upper aquifers on land.

In the study area, only rocks of the Ordovician System are present whereas Silurian rocks appear southward. The lateral and vertical hydraulic conductivity vary in a wide range being mainly controlled by lithology of rocks and depth. In general, the uppermost few tens of meters are fissured and fractured, cavernous and karstified and may attain lateral conductivity up to 50 m/d, sometimes even more. With increasing lithostatic pressure the fissures get closed and conductivity decreases to a few meters per day or less at depth greater than 50 m. Clayey limestone and marl units form aquitards within the aquifer system.

The O-Ca aquifer system consists of Lower Ordovician and Cambrian sandstones and siltstones. In the study area this aquifer is 25–35 m thick.

In northern Estonia, claystones and siltstones of the Lower Cambrian Lükati Formation and Lontova Formation (Kestla and Mahu Members) form a regional aquitard. In western Estonia the aquitard is laterally replaced by siltstones and sandstones of Voosi Formation.

In the study area, the lower part of the Lontova Formation (Sämi Member) contains intercalating sandstones and claystones. Sandstone layers are at least locally thick enough to be utilized as a groundwater aquifer. The lower part of the Sämi Member contains more clay separating the Sämi aquifer part from the underlying aquifer in the Ediacaran sandstones. Together, these two water-bearing sandstone units form the Ca-V aquifer system.

6.1.2. Groundwater formation and flow

Groundwater flow in Estonia is gravity driven, i.e., water flows from the higher potential (water level in unconfined aquifers, hydraulic head in confined aquifers) toward lower potential. In the LHLM, the Quaternary deposits and Ordovician aquifer are precipitation-fed since climatically precipitation exceeds evapotranspiration. The average precipitation in 1991–2020 varies from 570 mm/year to 750 mm/year with a mean value of 660 mm/year. However, the net infiltration (groundwater recharge minus evapotranspiration) is typically only 5–15% for a large part of the country reaching 20–30% only in the uplands. Thus, along with lithology of overburden and topmost bedrock, the local topography is one of the main parameters controlling groundwater recharge-discharge and local flow systems. Local elevated areas are groundwater recharge areas where groundwater is a few meters below ground surface whereas topographic lows need often artificial drainage network to conduct away discharging groundwater.

The O-Ca aquifer in LHLM is precipitation-fed only in outcrop areas, mostly near the cliff. In most part of the LHLM, this aquifer is confined by O1 aquitard with low permeability. In general, the O-Ca groundwater in LHLM flows from the south and southeast (hydraulic head in LHLM at least 10 m asl) in northern directions and discharges to the Gulf of Finland.

In natural conditions Ca-V aquifer system would discharge to the Gulf of Finland. Since the 1950s the aquifer system has been extensively exploited in northern Estonia, especially in coastal areas, where it is the only groundwater aquifer. Due to increasing pumping, large groundwater depression cone developed in the Harju County with a center at Tallinn where hydraulic head was down to 30 m b.s.l. At the end of Soviet period, water consumption dropped to about half of that before due to collapse of industry and more efficient water usage and as a result the minimum hydraulic head rose to 15 m b.s.l. in about 10 years.

Extensive groundwater pumping from the Ca-V aquifers reversed the flow direction in the northern sectors of depression cone. Despite, seawater inflow to the Ca-V aquifer apparently brackish sea water has not reached groundwater intakes in the mainland. Increased salinity in some Ca-V aquifer wells has been explained with salt water upcoming.

6.2. Methods

In order to study the hydrogeological conditions 4 groundwater monitoring wells were **drilled** at every preselected sites (PAL, ALT, and PED). These monitoring wells were constructed for groundwater sampling, water level monitoring and aquifer testing. They open the Ordovician, Ordovician-Cambrian and Cambrian-Vendian aquifers (presented in Figure 6.1). Two wells open the Cambrian-Vendian aquifer in order to study interconnectivity of upper (Sämi Member) and lower (Ediacara) parts of the aquifer. Coring wells PAL-401, ALT-402 and PED-403 were initially drilled to about the base of Sämi Member to get the full core of Lontova stage, and then the bottommost 9–11 m were filled with clay in order to be sure that the well itself does not connect upper and lower aquifers.

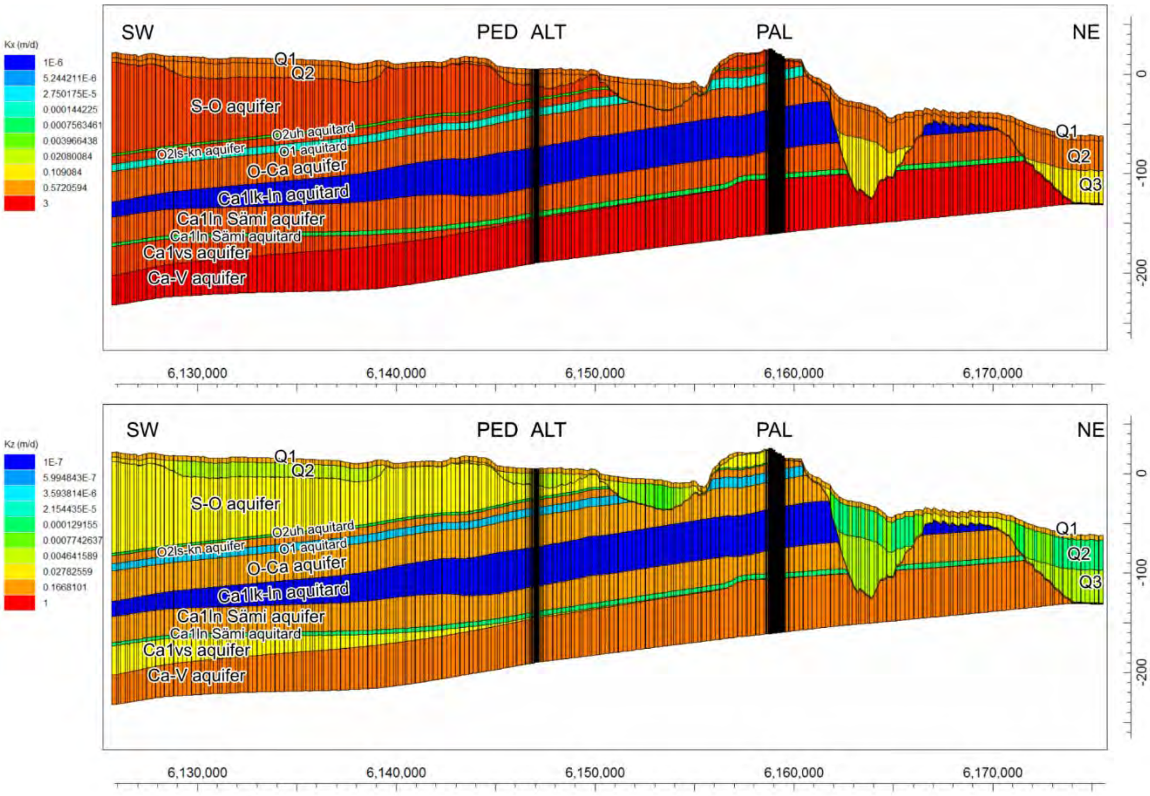

Figure 6.1. Model cross-sections in SW-NE. Model layers are coloured according to lateral (Kx) and transversal (Kz) hydraulic conductivity.

The detailed information about the drilling and the construction of the wells is presented in Appendix 3 “Analysis of the geological-lithological composition of the Earth's crust”.

Pumping tests were conducted in all wells. The pumping was carried out at a rate of 3-4 m3/h and lasted for two to three hours, followed by a recovery phase. Changes in water level were continuously monitored using automatic loggers and verified through manual measurements. Water quality was assessed using a multimeter to measure temperature, electric conductivity, pH, redox potential, and dissolved oxygen during the pumping process. At the end of the pumping phase, water samples were collected to analyze their chemical and isotopic composition.

The water level recovery data obtained from the tests were utilized to estimate hydraulic parameters. Recovery curves are more stable and less influenced by random changes in influx to newly drilled boreholes. The Jacob-Cooper solution was employed to calculate transmissivity.

Groundwater level monitoring served to gather information on hydraulic heads and their variations in different aquifers and to estimate the specific storage of confined aquifers. Submerged automatic loggers (Eijkelkamp MiniDiver) recorded absolute pressure at 10-minute intervals. The recorded pressures were adjusted against air pressure, which was logged by the BaroDiver located in one of the wells at the site (the nearby ALT and PED sites shared the same barometric logger). Water levels in the wells were monitored for a period of 5-8 months.

The loggers were equipped with high sampling rates to enable the calculation of aquifer hydraulic parameters using data recorded from Earth tides. When dealing with porous rocks containing groundwater, the crustal deformations, known as earth tides, can also be observed in groundwater levels.

Groundwater modelling was performed with MODFLOW-6 software package using program ModelMuse v.5 for pre and post-processing. The model area is 45 x 45 km and covers LHLM area on land and extends northward to the Gulf of Finland where bedrock aquifers outcrop beneath the Quaternary deposits. Model boundaries are set about 20 km from the potential repository sites. Model area is discretized to 200 x 200 m grid that is refined to 25 x 25 m grid in site areas. The model has 13 layers (Table 6.1 and Figure 6.1). All layers cover the entire model area, but they have a minimum thickness of 0.15 m in areas where they do not physically exist. Several layers were included in the model to account for local lithological changes.

6.3. Results

6.3.1. Hydrogeological conditions at the three repository candidate sites

Hydrogeological conditions at the repository candidate sites were assessed by recording groundwater levels and performing pumping tests in the monitoring wells. Groundwater level observations in the monitoring wells at the PAL site (Figure 6.2) indicate that the aquifers are separated from each other by aquitards. The highest groundwater level is observed in the Ordovician aquifer, ranging from 7 to 9 m below ground level. This aquifer also exhibits seasonal water level fluctuations. The hydraulic head in the O-Ca aquifer is approximately 1 to 2 m a.s.l., which is ~15 m lower than the overlying Ordovician aquifer. There are no clear indications of seasonal water level fluctuations or leakage from the aquifers above. This is further supported by the oxygen isotopic composition of PAL-201, which suggests that the water has a glacial meltwater origin (see Appendix 8). The water level in the aquifer is close to sea level, which is not surprising considering that the aquifer outcrops at the coast, ~1.7 km NE of the well.

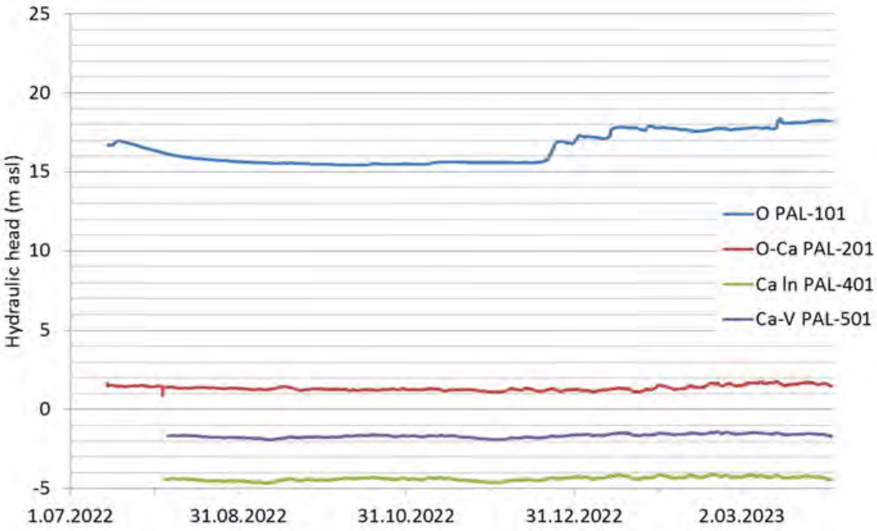

Figure 6.1. Groundwater levels in the monitoring wells at the PAL site. The ground altitude near the wells is 24–25 m asl.

The smooth variations in groundwater levels observed in the Ordovician wells **ALT-102** suggest that the covering glaciolacustrine sediments provide isolation for the aquifer from seasonal changes (Figure 6.3). In contrast, the **PED-103** well appears to be strongly connected to the surface, as evidenced by the significant water level rises during thawing events in the winter of 2022-2023 (Figure 6.4). The O-Ca wells ALT-202 and PED-203 exhibit a seasonal water level rise of approximately 0.5 m. However, this rise does not necessarily indicate a substantial flow through the O1 aquitard. The specific storage of the O-Ca aquifer, approximately 3×10^{-6} l/m, indicates that only a limited amount of water is required to cause a change in hydraulic head within the confined aquifer.

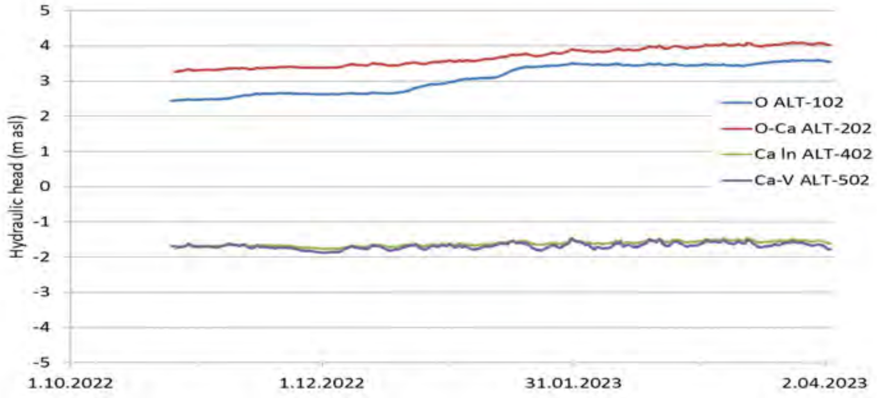

Figure 6.3. Groundwater levels in the monitoring wells at the ALT site. The ground altitude near the wells is about 5 m asl.

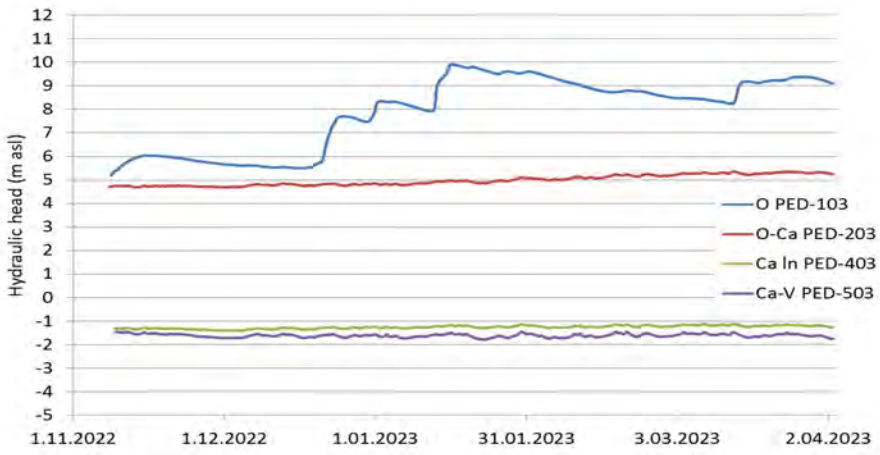

Figure 6.4. Groundwater levels in the monitoring wells at the PED site. The ground altitude near the wells is about 12 m asl.

The water levels in ALT-402 and ALT-502 wells are essentially the same. However, it may appear that the groundwater level in ALT-502 fluctuates more, but this can be attributed to variations in air pressure. Wells in confined aquifers respond differently to changes in air pressure at the wellhead. In aquifers with high hydraulic conductivity and barometric efficiency, water is pushed from the well into the aquifer, resulting in similar variations in water levels across all O-Ca, Sämi, and Ca-V wells at all sites. In the case of PED-403 and PED-503 wells, the water levels differ by a few decimeters, likely due to pumping in a nearby Ca-V well.

6.3.2. Groundwater flow in the aquifers

The hydraulic heads simulated in the Quaternary (Q), Ordovician (O), Ordovician-Cambrian (O-Ca), Sämi, and Cambrian-Vendian (Ca-V) aquifers are depicted in Figures 6.5 to 6.9. These figures also illustrate the pathlines of groundwater flow, including the movement of water-soluble contaminants. The pathlines are color-coded based on the flow time, ranging from blue (indicating zero time) to red (representing 1000 years). It is important to note that the pathline calculations assume consistent conditions throughout the thousand-year period, including constant well locations and pumping rates. Additionally, the transport calculations assume that water-soluble contaminants directly enter the respective aquifer without the need to flow through the Lükati-Lontova claystone in the case of the IDDF.

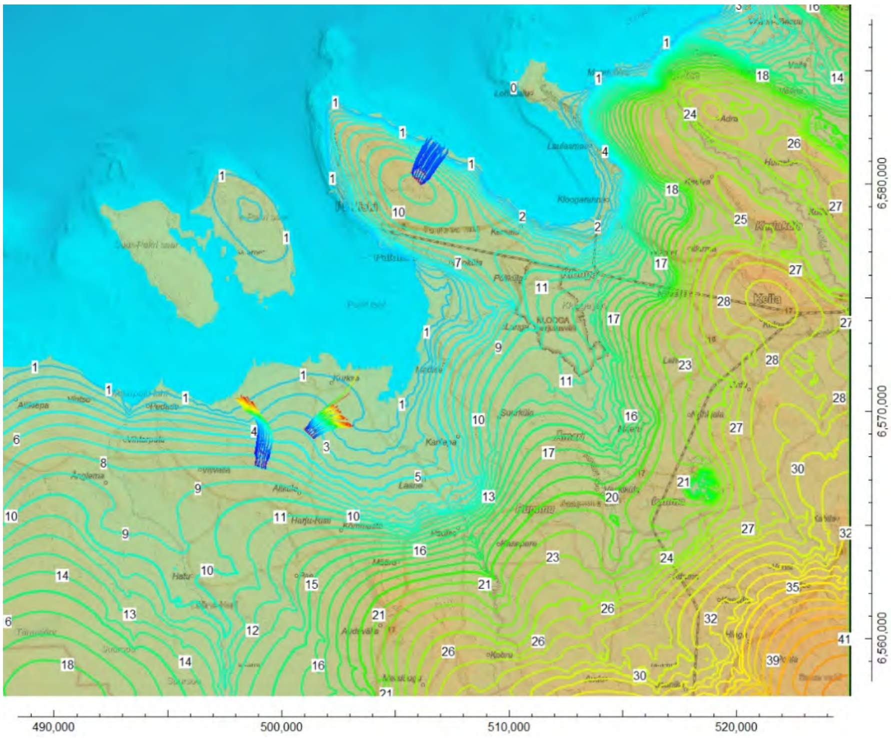

Figure 6.5. Simulated hydraulic head in topmost Quaternary layer (isolines) and contaminant transport from the potential repository sites (coloured pathlines).

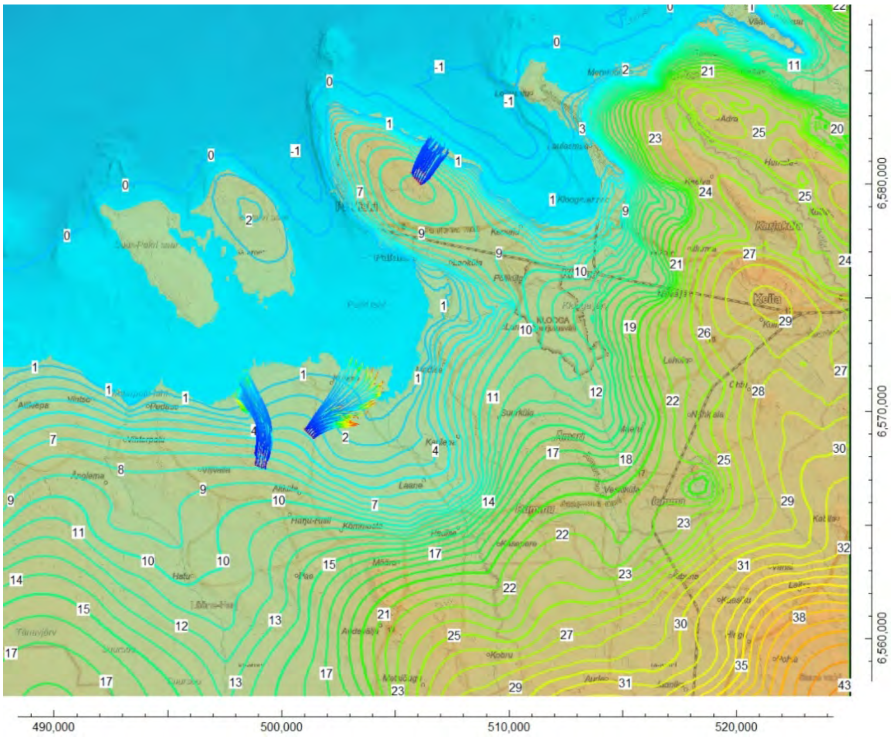

Figure 6.6. Simulated hydraulic head in Ordovician aquifer (isolines) and contaminant transport from the potential repository sites (coloured pathlines).

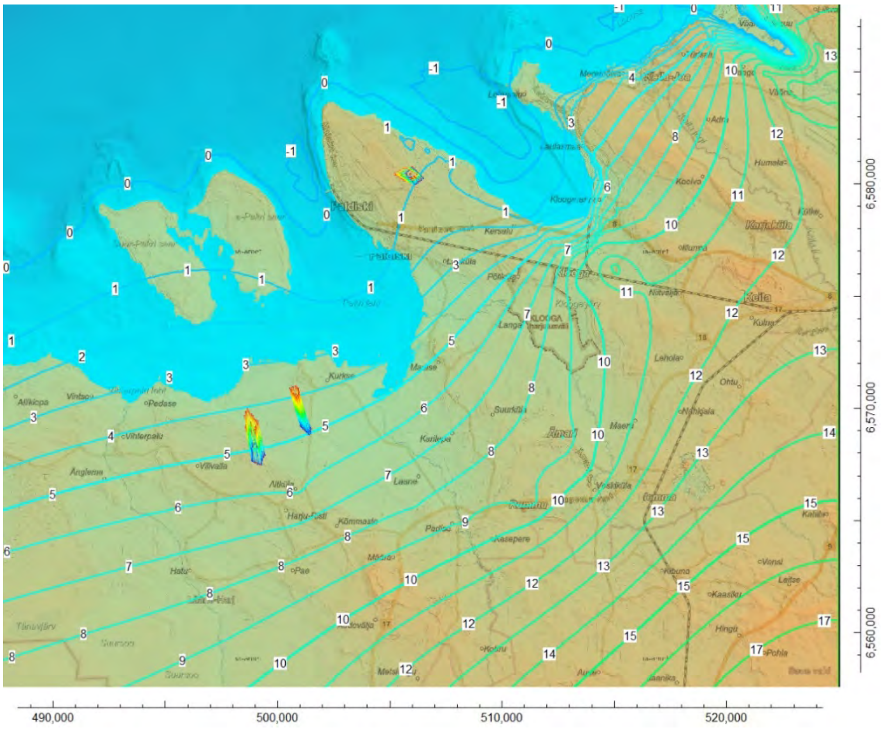

Figure 6.7. Simulated hydraulic head in Ordovician-Cambrian aquifer (isolines) and contaminant transport from the potential repository sites (coloured pathlines).

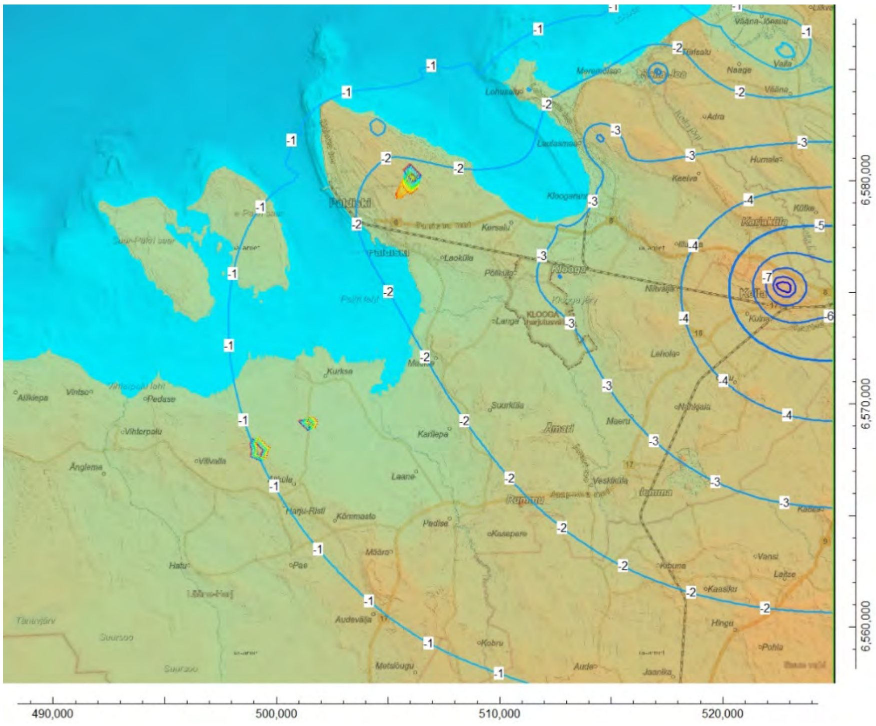

Figure 6,8. Simulated hydraulic head in Sämi aquifer (isolines) and contaminant transport from the potential repository sites (coloured pathlines).

Figure 6.9. Simulated hydraulic head in Cambrian-Vendian aquifer (isolines) and contaminant transport from the potential repository sites (coloured pathlines).

Groundwater flow in the **O-Ca aquifer** is heading NW direction (Figure 6.7). The flow system might be more complicated in vicinity of buried valleys and cliffs. Higher hydraulic head values in SE do not necessarily indicate substantial groundwater recharge in these areas. Isotopic and chemical compositions of O-Ca aquifer (Appendix 8) do not support flushing of this aquifer with modern precipitation during the post-glacial period.

According to the simulation, the possible contamination at the ALT and PED sites is transported in a relatively limited distance of 3-4 km in the NNW direction over a period of 1000 years. The O-Ca aquifer outcrops on three sides of the Pakri Peninsula, resulting in a hydraulic head that is close to sea level and very low hydraulic gradients. This indicates a lack of driving force for potential contaminant transport in the NW direction from the PAL site, with an estimated distance of about 1 km over a 1000-year period.

The flow regime in the Sämi aquifer is affected by groundwater pumping activities. The pumping of groundwater in areas such as Tallinn and its satellite towns, including Keila, has caused hydraulic heads in the Sämi aquifer to drop below sea level (Figure 6.8). This situation has resulted from the extensive pumping of the aquifer in the Laulasmaa-Lohusuu area, where numerous wells are extracting water. When hydraulic heads in an aquifer drop below sea level, it creates the potential for seawater intrusion into the aquifer. However, in the case of the Sämi aquifer, the recharge area is located several kilometers away from the coastline, and there is limited or no inflow through the buried valleys. As a result, the water quality in the Sämi aquifer has not been significantly impacted thus far. Simulation indicate that in the event of a contaminant release, the flow distances for the contaminants would range from hundreds of meters to less than a kilometer at the disposal facility sites. This suggests that the potential transport of contaminants in the Sämi aquifer would be relatively limited in extent.

The hydraulic heads in the Ca-V aquifer are also dominated by groundwater pumping (Figure 6.9). However, in the case of the disposal facility sites, the impact of pumping comes from Paldiski town rather than the wells in the Laulasmaa and Lohusuu area. It is important to note that it is highly unlikely for contamination from the IDDF in the Lükati-Lontova aquitard or the NSDF to reach the Ca-V aquifer. Even if contamination were to somehow enter the aquifer, for example, through the PAL-501 monitoring well, it would take 200-300 years for the contaminants to reach the groundwater intake well in Paldiski.

The hydraulic heads in the Ca-V aquifer are also dominated by groundwater pumping (Figure 6.9). However, in the case of the disposal facility sites, the impact of pumping comes from Paldiski town rather than the wells in the Laulasmaa and Lohusuu area. It is important to note that it is highly unlikely for contamination from the IDDF in the Lükati-Lontova aquitard or the NSDF to reach the Ca-V aquifer. Even if contamination were to somehow enter the aquifer, for example, through the PAL-501 monitoring well, it would take 200-300 years for the contaminants to reach the groundwater intake well in Paldiski.

6.4. Summary

Studies of groundwater monitoring wells and hydrogeological modelling results indicate that the Leetse-Türisalu, Lükati-Lontova and Sämi aquitards have very good hydraulic isolator capabilities in natural condition. Even though the lower two aquitards are cut by deep valleys, the valley-filling varved clays and other glaciolacustrine sediments fill the gap in aquitard. These observations are supported by isotopic and chemical composition of groundwater indicating glacial meltwaters being still present in O-Ca and deeper aquifers. Also, continuity of groundwater depressions across the valleys indicate no or only limited leakage through the buried valleys in the neighbourhood of Pakri peninsula. Thus, contaminant spillage into one aquifer more likely do not threaten another aquifer.

6.5. Conclusions

1. All three sites are equally suitable for construction of the IDDF as bedrock aquifers and aquitards have similar hydrogeological conditions and possible contaminant transport is slow.

2. Conditions vary for the NSDF. None of the sites provide natural low-permeability barriers against accidental contaminant leakage. In all cases the leaked contaminant transport occurs at shallow depth and could be discharged at a few hundred meters to one kilometer away. PAL and PED site remain above sea level for longer time whereas ALT site will be probably submerged in a few centuries. Therefore it is less preferable, while PAL and PED sites are considered equally.

7. Sub-activity 2.7. Hydrographic studies

The objectives were to characterise a hydrographic situation in three pre-selected potential disposal facility sites, to conduct hydrological relief analyses within the GIS software environment, to identify groundwater infiltration and discharge areas, to delineate sinkholes and seasonally flooded areas, to analyse satellite (Sentinel) data products for seasonally flooded areas, to calculate general water balance, and to identify hydrological characteristics of rivers, ditches, or other surface water watercourses relevant for drainage of the three sites and transfer of radionuclides.

The detailed results are presented in Appendix 7. The study includes analysis of available information, such as the geological base map, geological/geophysical reports, and literature. The work was performed by Marko Kohv (University of Tartu, Department of Geology) and Tõnu Oja (University of Tartu, Department of Geography) and reviewed by Jüri Plado (University of Tartu, Department of Geology).

7.1. Analysis of digital elevation models and derivates

PAL potential disposal facility area is situated near the highest point of the Pakri Peninsula, with an elevation ranging from 19 to 25 m a.s.l. The Pakri Peninsula is known for its active coastal cliff, reaching a maximum height of ~22 m at its tip. The Paldiski site is located at the watershed, and its drainage is artificially controlled by the NW border ditch, which directs water flow towards the northern coast (Figure 7.1). Overall, the site benefits from effective natural slopes and artificial drainage, resulting in good drainage conditions.

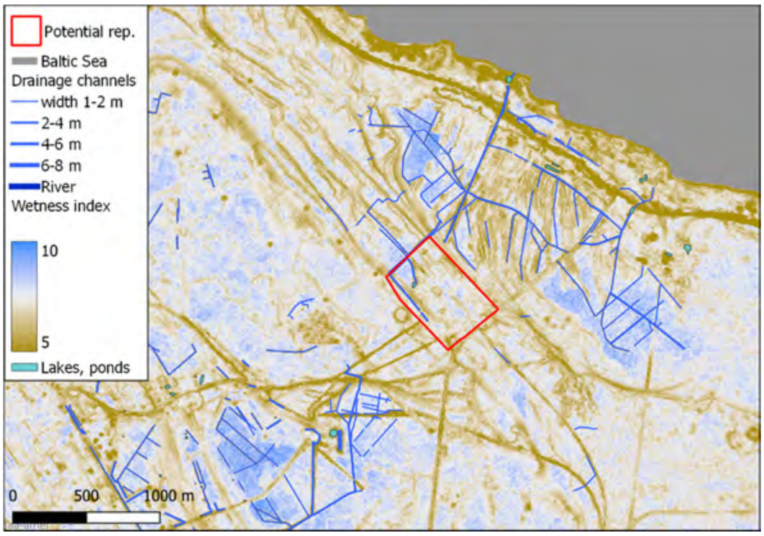

Figure 7.1. Wetness index, water bodies and drainage network around the PAL site.

Some noticeably wetter areas occur in the surrounding area, characterised by a higher wetness index, located ~200 m NW and NEE directions. These areas have a history of human presence so numerous non-connected ditch sections can be found. However, due to the construction of newer infrastructure, such as road embankments, these ditches no longer function as effective water courses.

The hydrological analysis identified closed depressions (Figure 7.2). In the Estonian climate, where precipitation exceeds evapotranspiration by about one-third, such depressions would typically contain at least temporary water bodies unless there is a pathway for surface water to infiltrate the groundwater system. One notable feature is a significant wetland area SW from the site, particularly noteworthy due to its higher altitude.

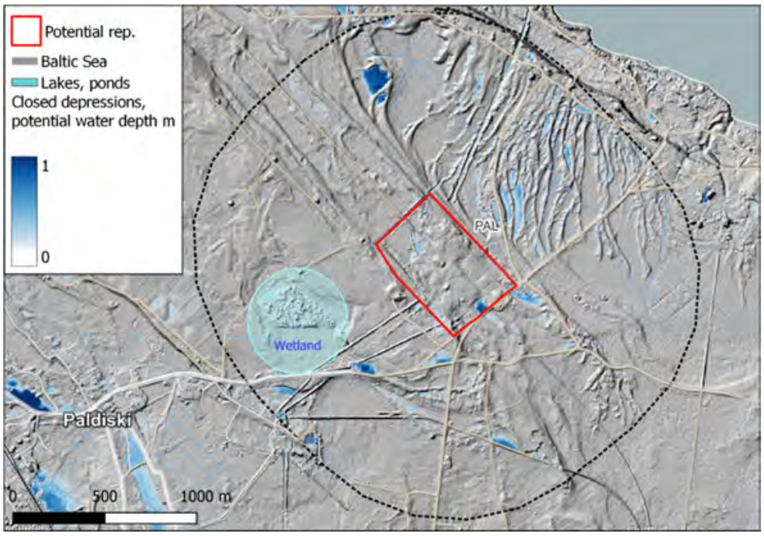

Figure 7.2. Closed depressions at the Paldiski area. Shaded relief in the background.

This large wetland in the vicinity likely serves as a significant local infiltration area that supplies water to the lower wetlands and springs situated NE and NEE of the potential disposal facility site. The wetland is located at a higher relief than the PAL site and is drained through a culvert beneath the main road. This culvert is connected to a ditch that redirects water flow from the wetland towards the south, effectively managing water movement.

If the culvert is closed (Figure 7.3), the water level in the wetland would need to rise to 25 m a.s.l. to initiate flow in the SE direction and potentially cross the road. However, the ground surface between the wetland and the potential disposal facility site currently sits at a minimum elevation of 25.7 m a.s.l., which can be easily raised to at least 26.5 meters a.s.l. by filling some unconnected ditch sections. Consequently, there is no significant risk of flooding at the PAL site, even with a closed culvert, as long as the road bordering the wetland is not further elevated and the unconnected ditch sections between the wetland and the PAL site are filled.

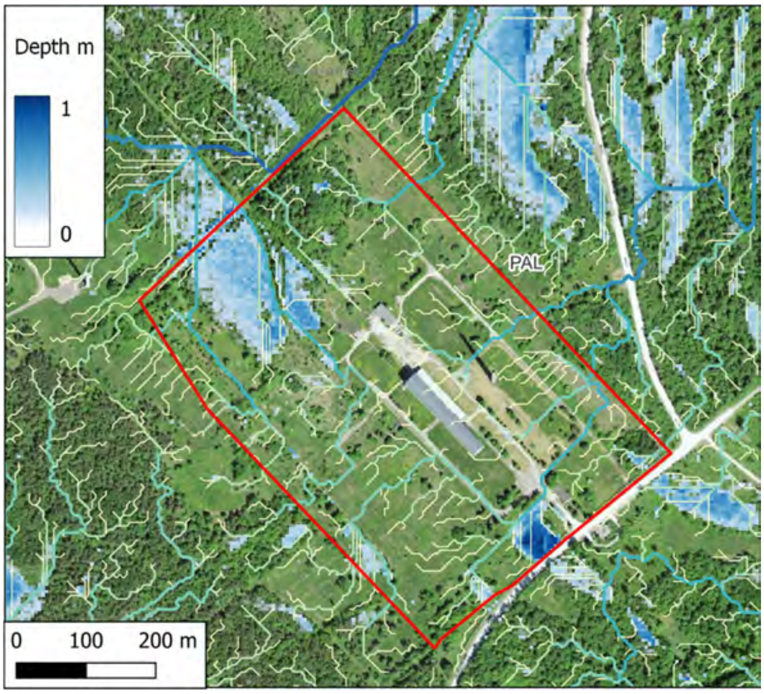

Figure 7.3. Potential flooding and water routing at the PAL site if artificial drainage is blocked.

A minor flood risk is observed in the NW corner of the PAL area, mainly when the artificial drainage network is blocked and infiltration to groundwater is impeded. This risk is influenced by various factors, including the partial enclosure of the area by earthworks, the presence of a spring within the PAL site, and the connection to the ditch network via a small culvert. The limited drainage capacity of the culvert can lead to water accumulation during periods of heavy rainfall, contributing to the potential for flooding, with water levels rising to 0.4 m in that specific subregion. Additionally, a more minor closed depression at the SE border of the PAL site may experience even deeper flooding, up to 1 m. However, for most of the area, the risk of flooding is minimal.

ALT potential disposal facility area has an average altitude of 5.1 m a.s.l. The site is characterised by its flat topography, with an average slope of <2°. The steepest slopes in the area are typically associated with artificial landforms such as road embankments and ditches. The site is situated at the highest point of a low-profile tombolo, a narrow sand spit connecting the mainland with an island or another landmass. The tombolo is surrounded by a flat plain intersected by several artificial drainage ditches (Figure 7.4).

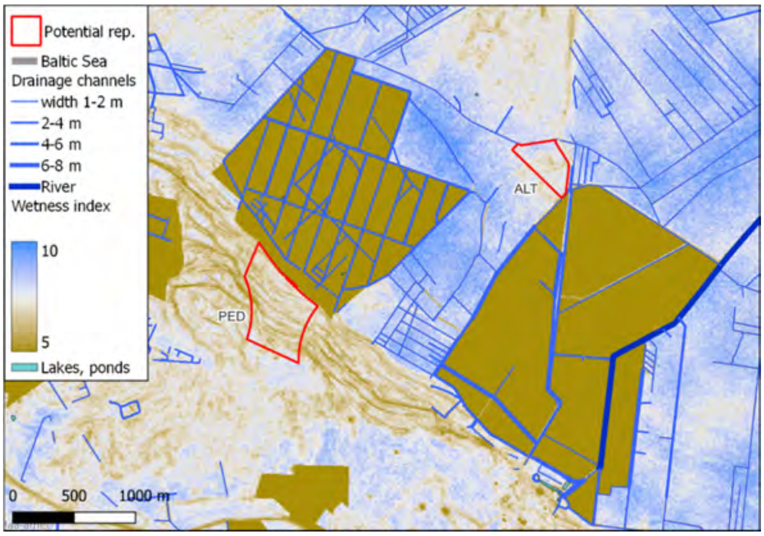

Figure 7.4. Wetness index, water bodies and drainage network around the ALT and PED sites.

The PED site is situated on higher ground, with an average altitude of 15.1 m a.s.l. The site is on a regional slope covered with sandy shoreline berms. These berms' presence contributes to the PED site's elevation and topography. The sloping terrain causes good natural drainage of the site. However, within or close to the site are multiple closed depressions formed by the intersecting berms. Additionally, numerous karstic sinkholes can be found at the bottom of these depressions. These sinkholes allow surface water to infiltrate the underlying limestone aquifers. Consequently, no surface channels are present in the terrain due to the water entering the sinkholes.

There is a contrast in terms of drainage between the ALT and PED sites (Figure 7.4). The ALT site relies on artificial drainage channels to effectively manage water flow (Figure 7.5). Without these drainage channels, the ALT site would function as a transitional zone between the nearby wetlands and the relatively higher former tombolo crest indicated by the road. A general flow direction at the ALT site is towards NNE, while at the PED site (Figure 7.6), it is towards NE. Both sites have smaller upslope areas compared to their overall size.

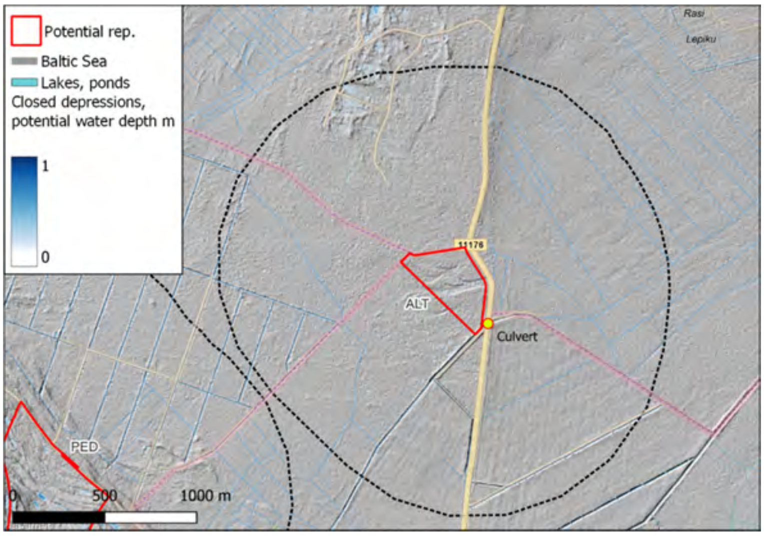

Figure 7.5. Closed depressions on the ALT site and surroundings. A critical culvert is marked with a yellow circle.

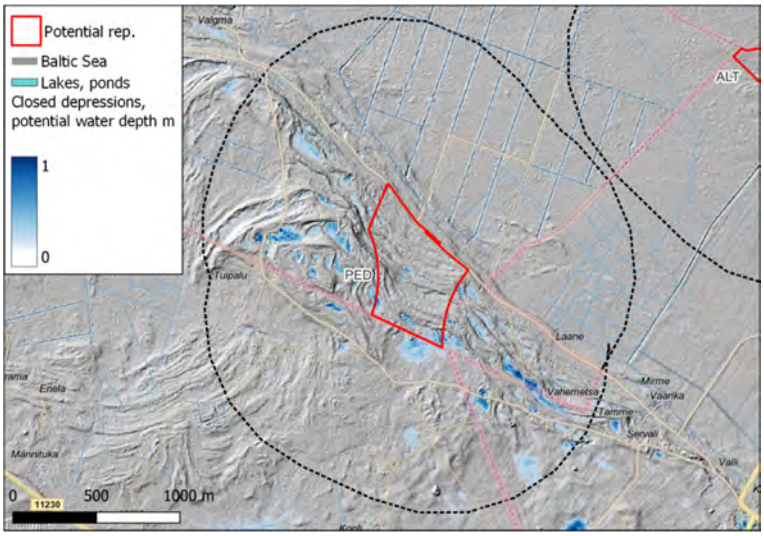

Figure 7.6. Closed depressions on the PED site and surroundings.

ALT and PED sites have nearby agricultural underground drainage systems, but their significance is more remarkable for the ALT site than the PED site. It is because the PED site is situated at a significantly higher elevation than the drainage network. The drainage situation poses a higher risk for the ALT site due to its location in the middle of an extensive flat plain.

Despite the presence of an artificial ditch network in the drainage system, the minimal slope of the area, combined with its low altitude, makes the ALT site vulnerable to potential obstructions, such as beaver dams between the Baltic Sea and the site. If the artificial drainage network, especially the critical culvert beneath the road, were to be closed or obstructed, the water level at the ALT site would rise close to the surface, approximately 5 m a.s.l., before starting to flow over the road (Figure 7.7).

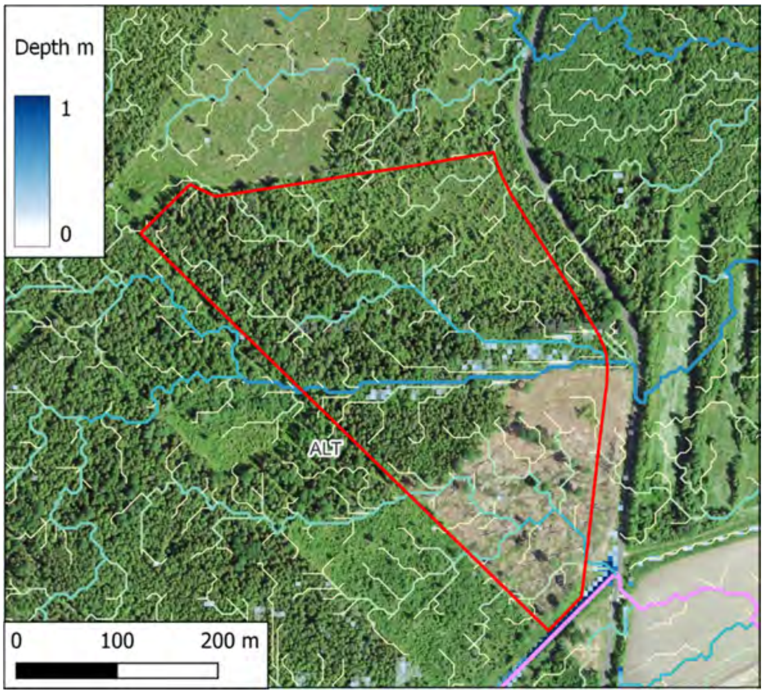

Figure 7.7. Potential flooding and water routing at the ALT site if the artificial drainage is blocked.

The road surface altitude is crucial as a threshold for water overflow at the site. Currently, the road level is ~5 m a.s.l., similar to the site's ground level. If the road surface were to be raised, the water level would need to rise correspondingly to overflow. It is important to note that a substantial catchment area is located behind the critical culvert. The water level would rise rapidly in a blockage due to the accumulated water in the catchment area.

The PED site does not rely on artificial drainage as it is not artificially drained. Instead, it features karstic sinkholes and areas enclosed by former coastal berms. These sinkholes can experience blockages due to ice formation, leading to localised flooding. The water routing and potential flooding scenarios are illustrated in Figure 7.8. The largest flooded area would occur to the south and upslope from the PED site. However, due to the natural relief of the terrain, the water would be directed away from the site. Consequently, the overall risk of flooding at the PED site is minimal.

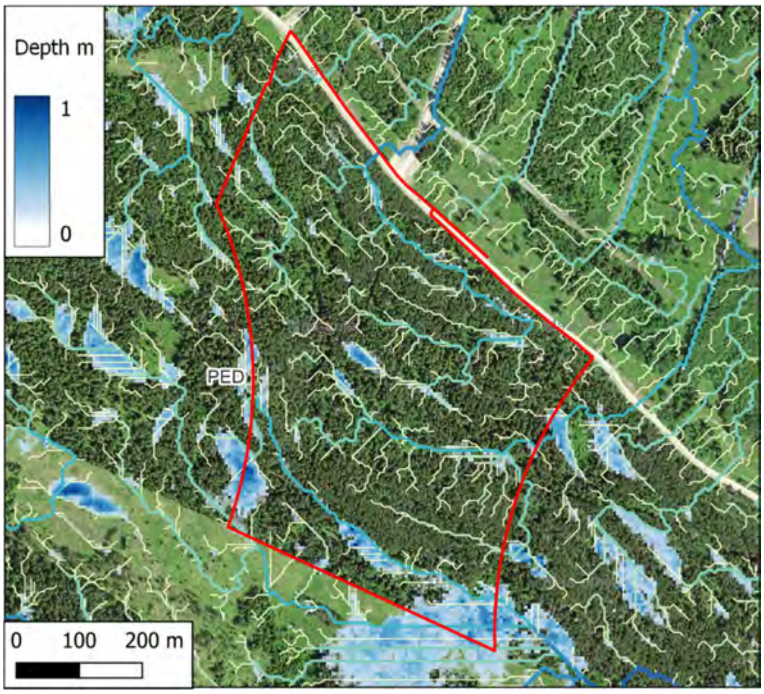

Figure 7.8. Potential flooding and water routing at the PED site if the artificial drainage is closed.

7.2. Hydrological characteristics

7.2.1. Drainage density

The areas with the highest drainage density within the LHLM correspond to former wetlands that have undergone conversion for peat extraction, agricultural purposes, or forestry activities (Figure 7.9). Among the sites, ALT exhibits the highest drainage network density (0.035 m/m^2) due to the presence of extensive agricultural drainage systems in its vicinity. Both PED and PAL sites display a relatively lower drainage network density (0.02 m/m^2). The PAL area has numerous non-connected ditch sections around the site. These ditches are not effective water courses as they have been interrupted by newer infrastructure such as road embankments.

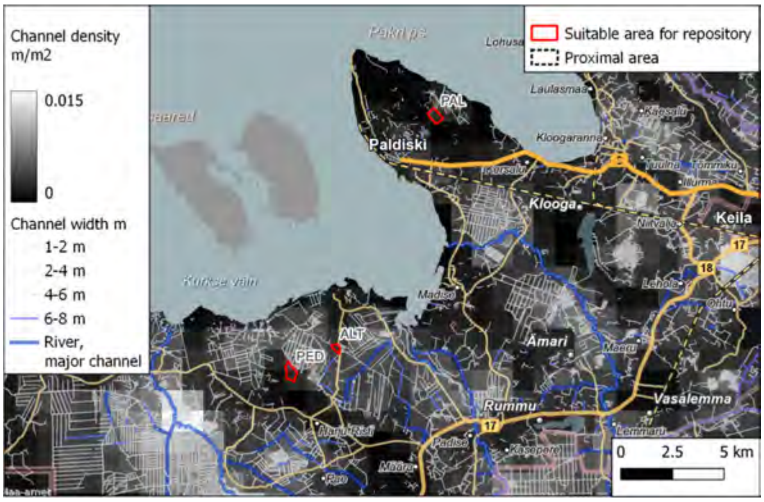

Figure 7.9. Drainage network and density.

7.2.2. Watersheds

PAL (fully) and PED (mostly) disposal facility areas are located in the coastal subwatershed. The ALT respository area is fully located in the stream subwatershed (Figure 7.10). PED watershed is 23.52 km^2, ALT 39.14 km^2 and PAL 43.17 km^2.

Figure 7.10. PED (mostly) and PAL are located in the coastal subwatershed, ALT and PED (partly) are in the stream sub-watershed.

During the study period, the main watercourses discharge and temperatures were measured in certain locations (Figure). Catchment sizes behind the measuring points are very variable: the largest one is behind the Vihterpalu 2 (485.53 km^2) and the smallest one behind Piskjõgi 1 (12.6 km^2). However, some systems are more complex than a single linear watercourse. For example, after the Kloostrijõgi 2 measuring point, the Kloostrijõgi river branches off into the manmade Piskjõgi, resulting in two separate channels through which it flows to the sea. We excluded such peculiar systems from further analysis.

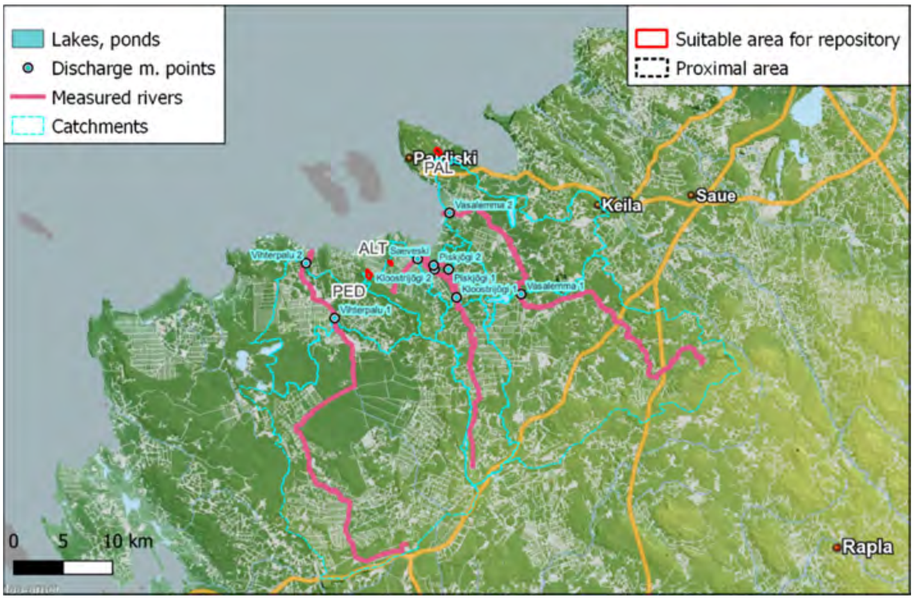

Figure 7.11. Catchment areas of the discharge measurement points.

The calculations of specific discharge (Figure 7.12) indicate that each square kilometer of the catchment produced a discharge ranging from 20 to 30 L/s on 03.02.23. Two months later, the same value ranged from 19 to 24 L per second. It can be observed that during this period specific discharge is inversely related to drainage channel density: the greater the number of channels, the lower the specific discharge (Figure 7.12). This most likely indicates a more rapid and responsive reaction to specific precipitation or snow melt events, rather than a decrease in the amount of water per catchment area.

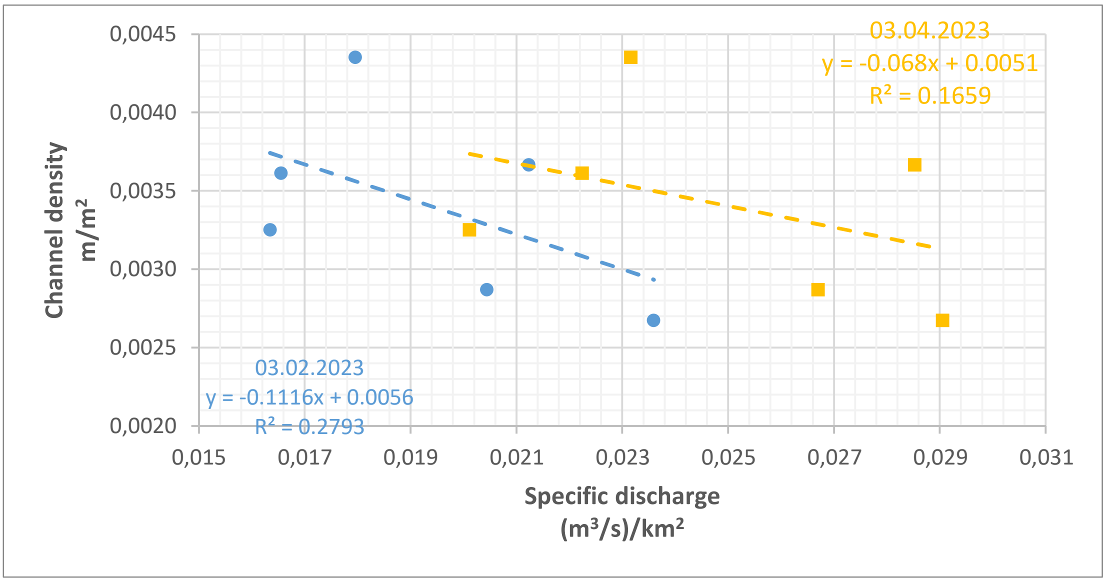

Figure 12. Relationship between specific discharge and channel density.

The only long term hydrological monitoring station nearby is situated on the Vihterpalu river, it was established in 1929, automated in 2007 and is still functioning. The watershed area behind the station measures 474 km^2 and it is located ~900 m upstream from Vihterpalu 2 monitoring point in Figure 7.11. While this river is away from the sites, it is the only available long-term monitoring series that could show regional trends over longer timeperiod.

7.2.3. General water balance

The region surrounding the potential disposal facility sites is equipped with several weather stations, including the Vihterpalu Hydrometry station, Paldiski Coastal Station (which does not measure precipitation), Pakri Meteorological station, and Keila Hydrometry station. Of these stations, the Paldiski station is the closest to the PAL site, while the Vihterpalu station is in proximity to the PED and ALT sites.

While the Vihterpalu station provides valuable data, it is important to note that none of the three potential repository sites fall within the watershed area monitored by the Vihterpalu station.

The Pakri Meteorological station is situated within the Pakrineeme military cordon. It has an elevation of 23.12 m above sea level and has been operational since 1865, with automation implemented in 2003. This station records various meteorological parameters, including air temperature, air humidity, air pressure, precipitation, wind direction and speed, visibility, and more. Precipitation data from the Pakri Meteorological station is particularly relevant for this study as it aids in assessing the precipitation patterns in the region.

At the Vihterpalu station, the monthly precipitation exhibits a range of variability. The lowest recorded monthly precipitation was 2.5 mm in March 2022, while the highest recorded monthly precipitation was 159.9 mm in August 2021. Monthly precipitation at the Pakri station ranges from 2.5 mm in March 2022 to 159.9 mm in August 2021.

To estimate water losses from evapotranspiration (ET), we calculated reference ET for the year 2020 using data from the Pakri weather station. Unfortunately, there was insufficient data available for the Vihterpalu station. Various methods exist for calculating ET, but most of them require solar radiation data, which was not available for the region. Therefore, we utilised the freely available ETCalc tool. The calculated reference ET ranged from 87% to 93% of the actual precipitation. Additionally, Aleksander Maastik evaluated the actual ET for the region to be approximately 380 mm per year.

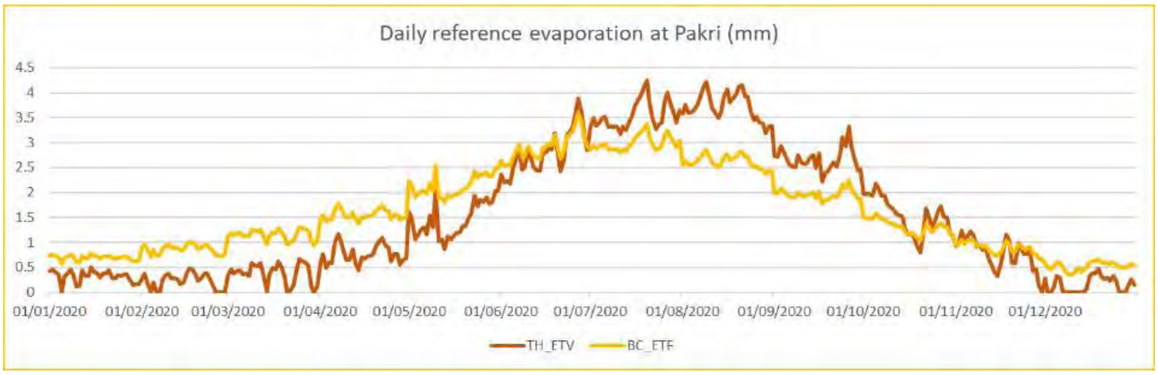

Figure 7.17. Reference evapotranspiration for the region in 2020.

7.2.4. Satellite image analysis

According to the risk management evaluation, the potential reprository sites are not within officially desingnated flooding zones (See Report for Sub-activity 2.5 for more details). However, during periods of snow melting or heavy rainfall, the upper layers of soil may become saturated, resulting in temporary and minor flooding. To analyse such events, Sentinel products can be utilised. Sentinel 1 SAR images are commonly used for flood mapping, but for short-term, minor flooding, Sentinel 2-based products are even more suitable.

Images and derived products for this study were obtained from the Estonian Land-board EstHUB site. In this study, the most suitable index for detecting flooding events was the NDPI (Normalised Difference Pond Index). The NDPI is calculated as NDPI = (SWIR-Green)/(SWIR+Green), where SWIR represents the reflectance of short-wave infrared radiation and Green represents the reflectance of green light. This index is effective because the reflectance properties of water in the SWIR range are significantly different from those of dry surfaces. Water reflects very little SWIR radiation, while dry terrestrial surfaces have different reflectance properties. The NDPI amplifies the reflectance differences between water-saturated and dry areas, allowing for the distinction between them. In the images, strongly negative values correspond to water-rich areas (shown as blue), while the yellow end of the scale, corresponding to positive values, represents dry sites.

Various images from the EstHUB satellite image warehouse, encompassing the complete Sentinel-2 data period since 2015 were examined. The selection process is focused on images showcasing greater variability in the landscape, emphasising areas with comparatively higher moisture content (Figures 7.18 – 7.24). During the winter season, it is common for the entire landscape to exhibit wet conditions, while in drought periods, the landscape tends to be predominantly dry. It is worth noting that the situation can change rapidly, indicating that flooding events are typically short-lived in nature.

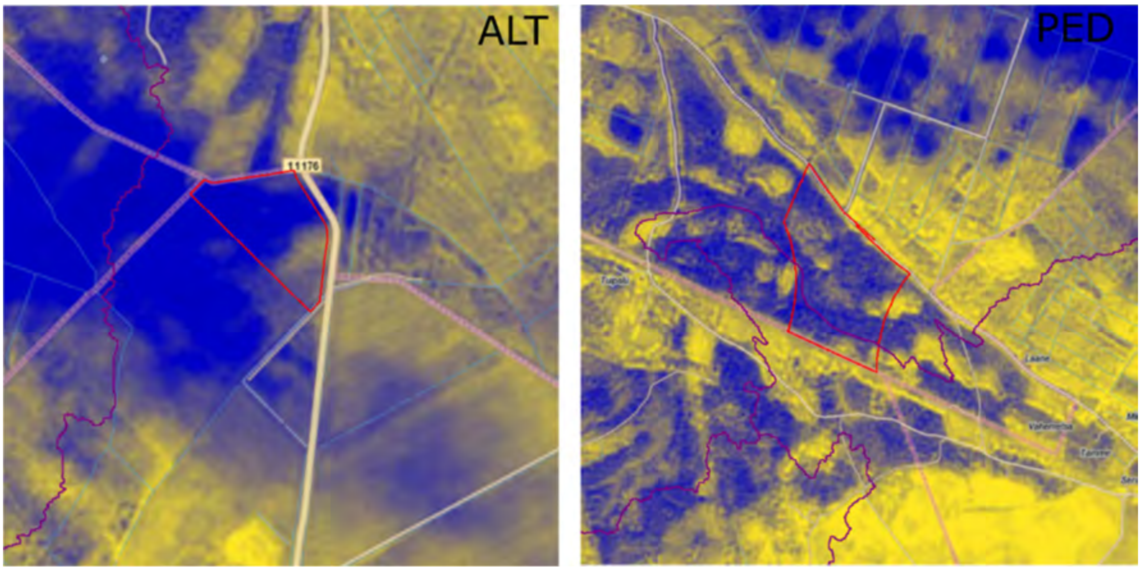

Figure 7.18. NDPI values around the PED and ALT sites. Some impact of the temporary flooding (blue end of the colour palette) can be seen nearby the sites—Sentinel 2 NDPI values for 2023.04.09 from the EstHUB Estonian Landboard.

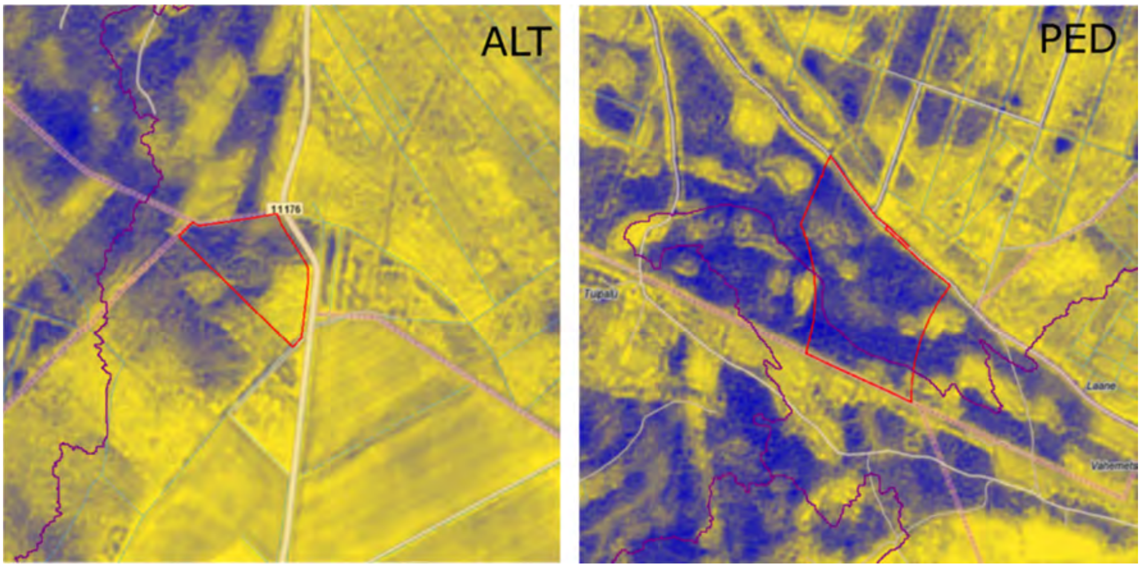

Figure7.2. NDPI values around the PED and ALT sites. Some impact of the temporary flooding (blue end of the colour palette) can be seen nearby the sites—Sentinel 2 NDPI values for 2023.04.14 from the EstHUB Estonian Landboard. Comparison with Figure 18 exemplifies how the region dries in 5 days.

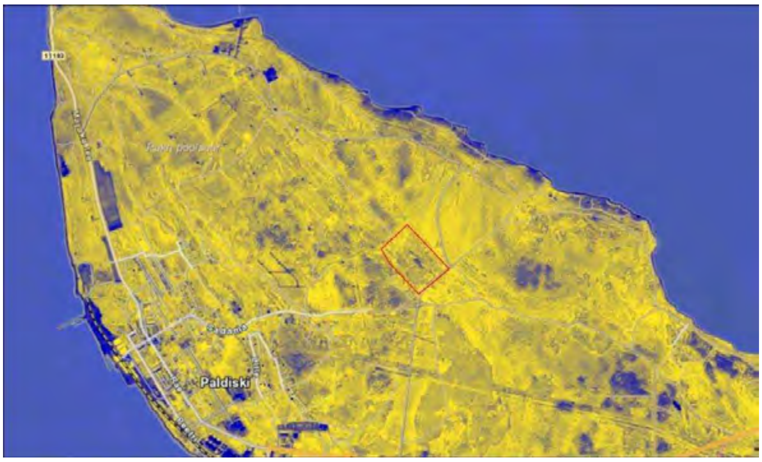

Figure 7.20. NDPI values around the PAL site. No impact of the temporary flooding (blue end of the colour palette) can be seen nearby the sites—Sentinel 2 NDPI values for 2023.04.09 from the EstHUB Estonian Landboard.

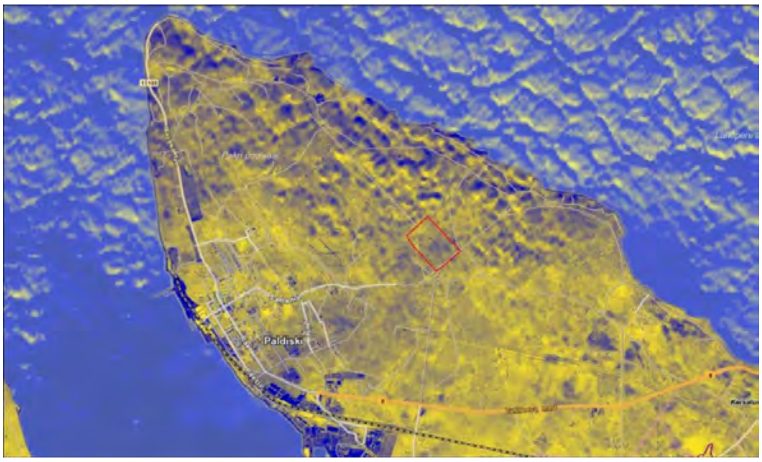

Figure 7.21. NDPI values around the PAL site. No impact of the temporary flooding (blue end of the colour palette) can be seen nearby the site—Sentinel 2 NDPI values for 2023.04.14 from the EstHUB Estonian Landboard.

Although 2020 was a year with relatively high precipitation, the temporary flooding is almost not detectable. Still, compared to the surrounding region around the PED and ALT sites, the area is a bit wetter (Figure 7.22).

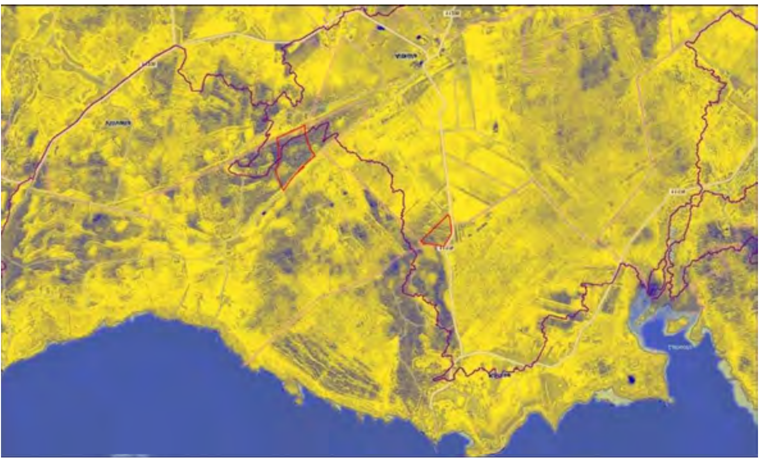
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Figure 7.22. NDPI values around the PED and ALT sites. Some impact of the temporary flooding (blue end of the colour palette) can be seen nearby the sites—Sentinel 2 NDPI values for 2020.04.07 from the EstHUB Estonian Landboard.

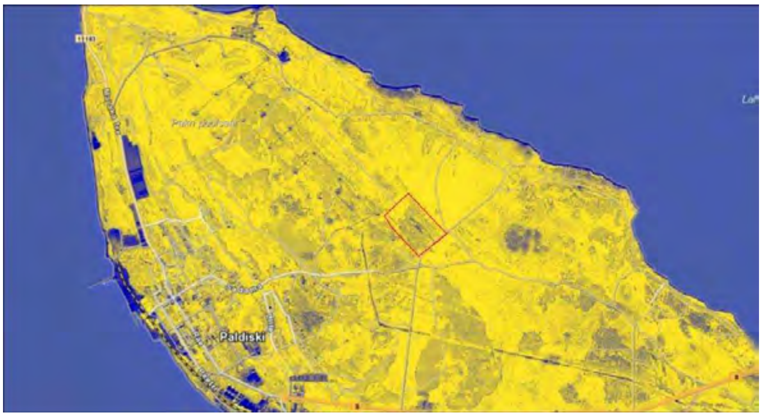


Figure 7.23. NDPI values around the PAL site. No impact of the temporary flooding (blue end of the colour palette) can be seen nearby the site. Sentinel 2 NDPI values for 2020.04.07 from the EstHUB Estonian Landboard.

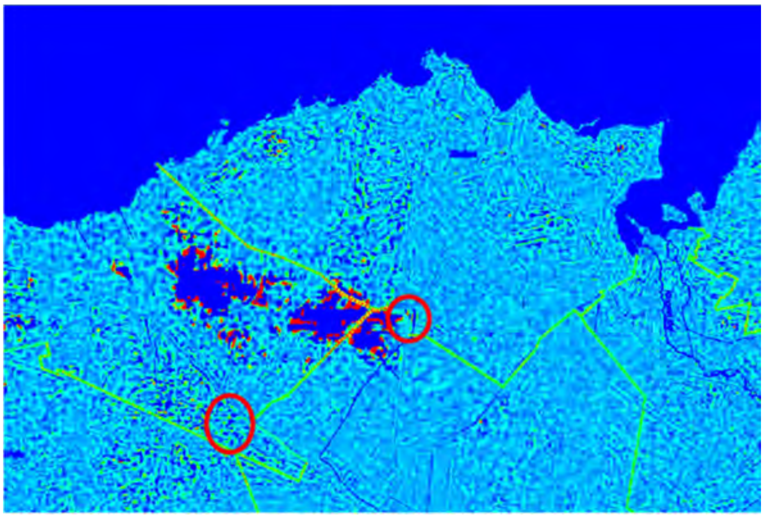


Figure 7.24. The NDPI processed by SNAP for Sentinel 2 image from 2023.04.09. Analysis yielded similar results, clearly delineating the flooded areas located NW of the ALT site.

7.3. Summary

The hydrographic analysis of the ALT site reveals a vulnerability to surface water flooding. The drainage situation poses a high risk for the site due to its location in the middle of an extensive flat plain. Its current drainage system relies on the artificial drainage network, and the clogging of a culvert or drainage system would result in a rise of water level close to the surface. Additionally, this site is at risk of flooding due to ongoing and anticipated sea level rise, which is expected to pose an increasing threat within the next century (refer to reports 2.5 and 2.4 for detailed information).

The PED site is situated at a higher elevation and is relatively safe from the risk of surface water flooding. Its location on a steep slope and the presence of numerous karstic sinkholes contribute to efficient surface water drainage and minimise the risk of flooding.

The hydrographic analysis of PAL site also reveals a partial, minor flooding risk. This risk is influenced by several factors, including the partial enclosure of the area by earthworks, the presence of a spring within the PAL site, and the connection to the ditch network through a small culvert. The blockage of this culvert and artificial embarkment around the site can result in water accumulation during heavy rainfall at the NW corner, contributing to the potential for minor flooding (up to 0.4 m above) in that specific subregion. Upslope from the PAL area, there is a potential water accumulating area (a wetland) that is drained by a culvert. However, even if the culvert is blocked, the water would naturally flow away from the PAL site, over the road to the south direction, as long as the road surface remains current. Additionally, filling the old ditch sections between the PAL site and the wetland would reduce the risk of flooding to a minimum.

7.4. Conclusions

1. ALT site is vulnerable to surface water flooding. Its drainage system relies heavily on the artificial drainage network. Improper functioning of this network would result in a rise of water level at the site. Additionally, this site is at risk of flooding due to anticipated sea level rise.

2. PED site is situated at a higher elevation on a slope and has efficient natural surface water drainage minimising the risk of flooding.

3. The hydrographic analysis of PAL site reveals a partial, minor flooding risk. Engineering measures can be needed to exclude or reduce the risk of flooding to a minimum.

Overall ranking in terms of hydrography is the following: 1. PED, 2. PAL, 3. ALT.

8. Sub-activity 2.8. Studies of the chemical composition and properties of groundwater and surface water

Investigation of water chemical composition and properties are the main objective of the current study. The hydrogeological and hydrostratigraphical settings of NW Estonia and chemical composition of groundwater in three potential locations of the disposal facility (PAL, ALT and PED) are provided. The detailed results are presented in an Appendix 8. The study includes analysis of available information, such as the geological base map, geological/geophysical reports, and literature. The work was performed by Enn Karro and reviewed by Jüri Plado (University of Tartu, Department of Geology).

8.1. Hydrogeological setting of the study area

The deepest Cambrian-Vendian aquifer system lies on the Palaeoproterozoic crystalline basement, Ediacaran, and Cambrian sand- and siltstones alternating with claystones. The claystone interlayers between the aquifer-forming sandstones and siltstones are thin. Consequently, the entire sequence can be considered as a single hydrostratigraphic unit, known as the Cambrian-Vendian aquifer system (see Figures 8.1-8.3 for hydrogeological units and the depths of the opened intervals of the monitoring wells).

The Cambrian-Vendian aquifer system is overlain by the Cambrian Lontova and Lükati Formations, composed of claystones that form the laterally continuous Lontova-Lükati aquitard. This aquitard has a thickness of 40 meters and exhibits strong isolation capacity. Above the aquitard lies the Ordovician-Cambrian aquifer system, which consists of the Cambrian Tiskre and Kallavere Formations composed of sandstones. The Ordovician-Cambrian aquifer system has a thickness ranging from 25 to 30 meters.

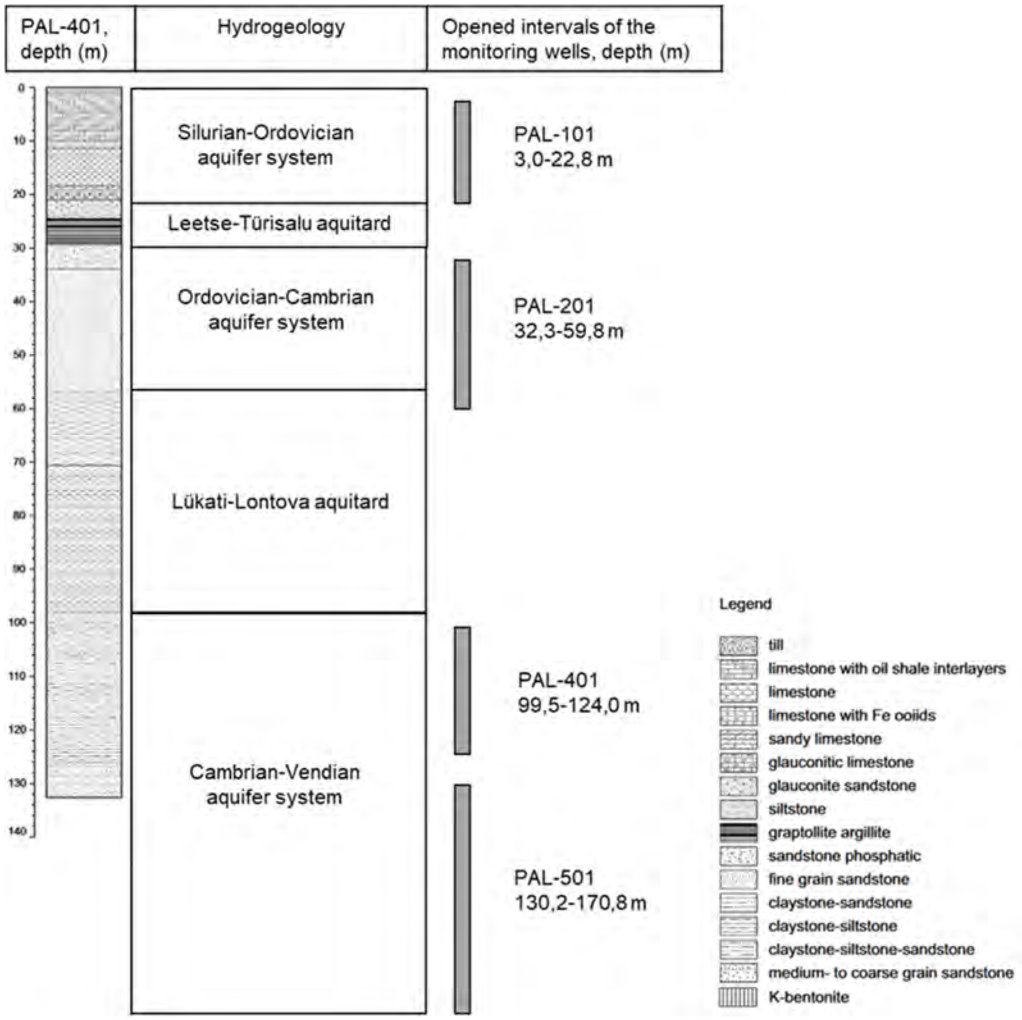


Figure 8.1. Lithological profile, hydrogeological units and the positions (depths) of the opened intervals of the monitoring wells at the PAL site.

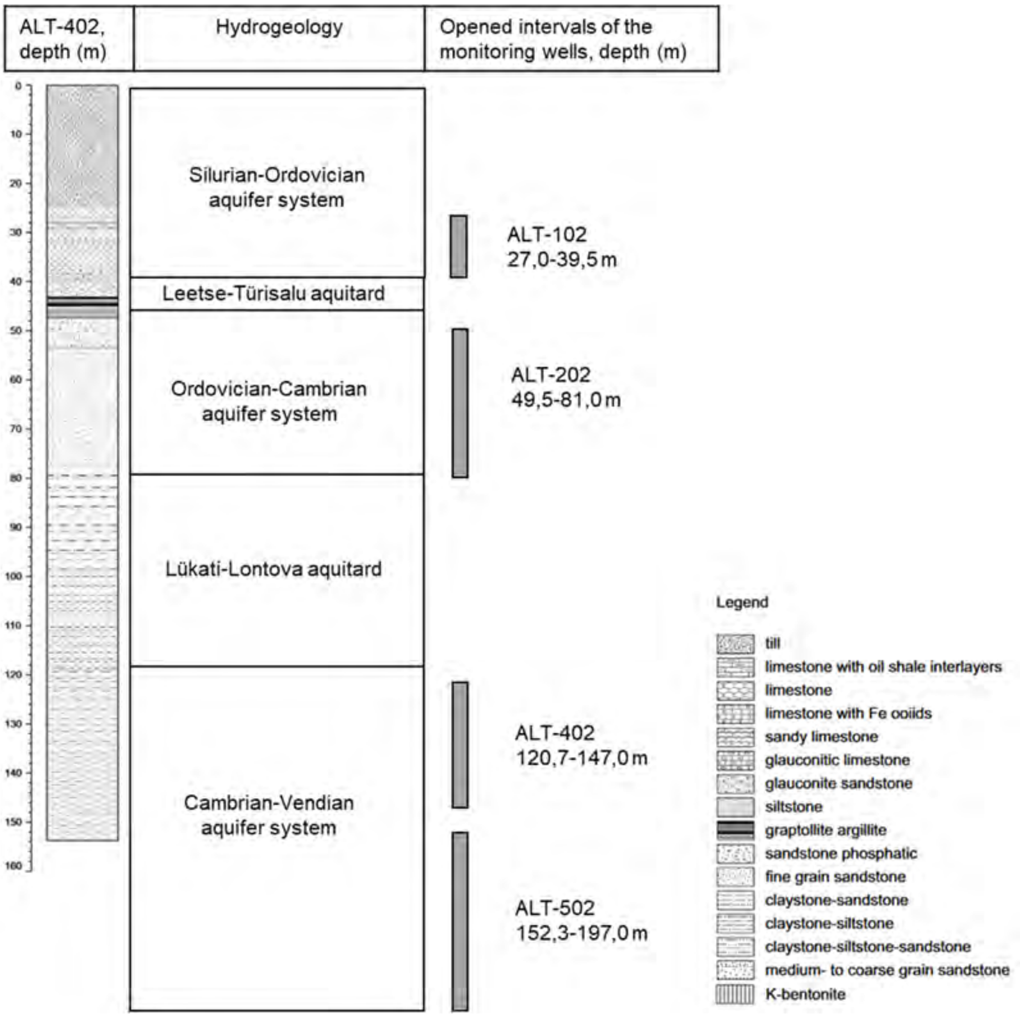


Figure 8. 2. Lithological profile, hydrogeological units and the positions (depths) of the opened intervals of the monitoring wells at the ALT site.

The lower portion of the Ordovician sedimentary rocks forms a 9-10 m thick Silurian-Ordovician regional aquitard, consisting of glauconite sand- and siltstones of the Leetse and Varangu Formations and black shale (graptolite argillite) of the Türisalu Formation. Above this aquitard lies the Silurian-Ordovician aquifer system, where the water-bearing rocks consist of limestones and marls with clayey interlayers from the Ordovician System. Silurian rocks are missing in the studied area.

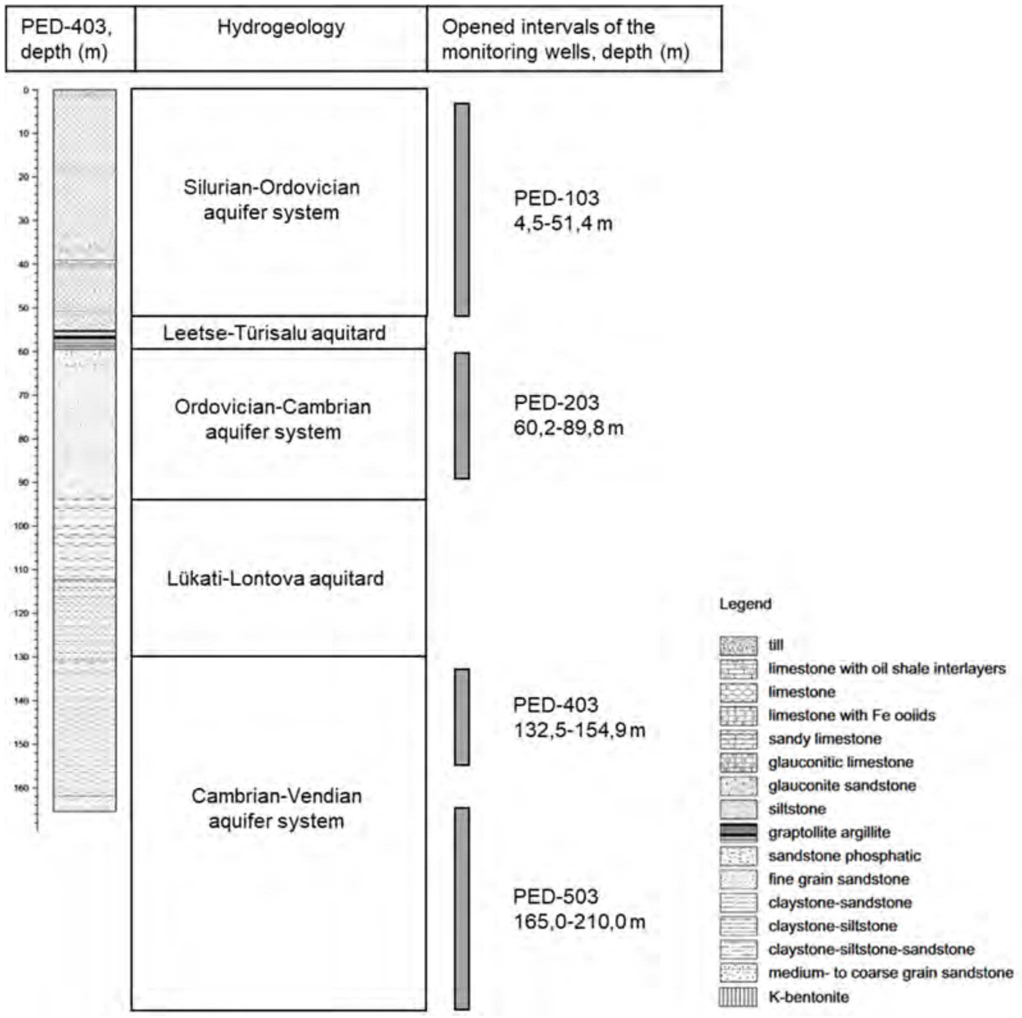


Figure 8.3. Lithological profile, hydrogeological units and the positions (depths) of the opened intervals of the monitoring wells at the PED site.

8.2. Methodology

8.2.1. Groundwater monitoring wells

To study the groundwater chemistry at three specific sites, a total of 12 groundwater monitoring wells were drilled, with 4 wells in each site. The depth and construction of these wells were carefully planned based on previous knowledge of the local geological and hydrogeological conditions. Consequently, the groundwater monitoring wells were specifically constructed for sampling and studying the aquifers present in the area, namely the Ordovician, Ordovician-Cambrian, and Cambrian-Vendian aquifers.

8.2.2. Field measurements and laboratory analyses

In 2022, groundwater sampling and analysis were conducted. After conducting pumping tests with a duration of 3-4 hours and stabilizing the field parameters such as temperature, pH, and redox potential, water samples were collected. Groundwater samples were collected in 1.0 L polyethylene bottles, stable isotope samples were stored in 15 ml high-density polyethylene bottles, and water samples for radioactivity analyses were collected in 4.0 L polyethylene canisters. Samples for trace element analysis were filtered on-site using 0.45 nm Cellulose

Acetate syringe filters. These filtered samples were then collected in 12 mL acid-washed polypropylene vials and acidified on-site using HNO_3. To maintain sample integrity, all collected samples were placed in a cool box and transported to the laboratory at the end of the sampling day.

In situ measurements of pH, redox potential, electrical conductivity, and temperature were conducted using a WTW Multi 3320 multimeter. To ensure accurate field measurements, a flow-through cell (Eijkelkamp) was utilized, wherein the electrodes were placed. Groundwater samples were collected and analyzed for radioactivity (Ra-226 and Ra-228), stable isotopes (O-18, H-2), as well as for major compounds, trace elements, and microbiological composition.

The concentration of total dissolved solids (TDS), main compounds (Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, HCO_3^-) and microbiological composition (number of colonies at 22°C) was determined in the laboratory of the Estonian Environmental Research Centre. Trace element concentrations were measured in the laboratory of the Department of Geology, University of Tartu, using Agilent 8800 QQQ ICP-MS. Stable isotope (O-18, H-2) analyses were performed at the Environmental dating laboratory, University of Latvia, utilizing the Picarro L2130-I instrument. Radioactivity analyses, specifically for radium isotopes Ra-226 and Ra-228 in water, were conducted at the Laboratory of Nuclear Spectroscopy, Testing Centre of the University of Tartu. The calculated indicative dose is based on the activity concentrations obtained through these analyses.

8.3. Results

8.3.1. Main compounds and chemical type of groundwater

The results of the field measurements, concentrations of total dissolved solids (TDS), main compounds (Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, HCO_3^-) and microbiological composition (No of colonies at 22 °C) are presented in Table 8.1.

Table 8.1. The values of field parameters and laboratory determinations. T – temperature, EC – electrical conductivity, ORP - oxidation-reduction potential, TDS – total dissolved solids

Monitoring well	**T**	**pH**	**EC**	**ORP**	**TDS**	**HCO_3**	**Cl**	**SO_4**	**Ca**	**Mg**	**K**	**Na**	**Colonies 22 °C**
	°C		**µS/cm**	**mV**	**mg/L**								**No/1mL**
Paldiski site													
PAL_101	8.3	7.2	584	19.5	330	370	4.3	22.0	84	24.0	4.3	7.9	73
PAL_201	8.0	7.9	480	-71.1	240	170	52.0	22.0	35	15.0	8.0	36.0	2000
PAL_401	8.7	8.8	328	-155	180	110	34.0	25.0	25	8.9	5.9	26.0	1100
PAL_501	9.4	8.1	794	-89	460	130	160.0	20.0	58	15.0	10.0	64.0	230
Altküla site													
ALT_102	6.3	7.4	711	67	483	326	41.0	53.0	85	25.0	5.1	30.0	38
ALT_202	7.3	7.8	775	72	405	186	130.0	32.0	39	15.0	9.9	92.0	>300
ALT_402	8.5	8.9	424	-125	224	126	57.0	13.0	31	7.3	6.8	45.0	>300

ALT_502	8.8	8.4	694	45	393	117	140.0	24.0	47	13.0	9.0	60.0	>300
Pedase site													
PED_103	8.3	7.3	651	105.8	345	302	48.0	27.0	72	20.0	4.8	41.0	>300
PED_203	8.4	7.8	631	-106.9	319	192	97.0	9.4	35	13.0	9.8	74.0	>300
PED_403	8.5	8.5	442	-156.4	265	125	89.0	9.5	32	11.0	7.3	54.0	>300
PED_503	8.4	11.7	1277		396	203	120.0	24.0	58	5.0	39.0	70.0	0

Groundwater in all three studied sites is dilute, the TDS value is within the range of 180-460 mg/L (PAL), 224-483 mg/L (ALT) and 265-396 mg/L (PED). The results of the laboratory determinations of the current study coincide well with previously referred data – the groundwater in the topmost 50 m of the Silurian-Ordovician aquifer system is mainly of Ca-Mg-HCO_3 type with TDS concentrations between 300 and 500 mg/L. Considering the main compounds in groundwater (Table 8.1), the water chemistry is fairly similar in all preselected sites. Groundwater chemistry data presented as Piper diagram (Figure 8.4) show that the chemical type of the groundwater is Ca-Mg-HCO_3 or mixed.

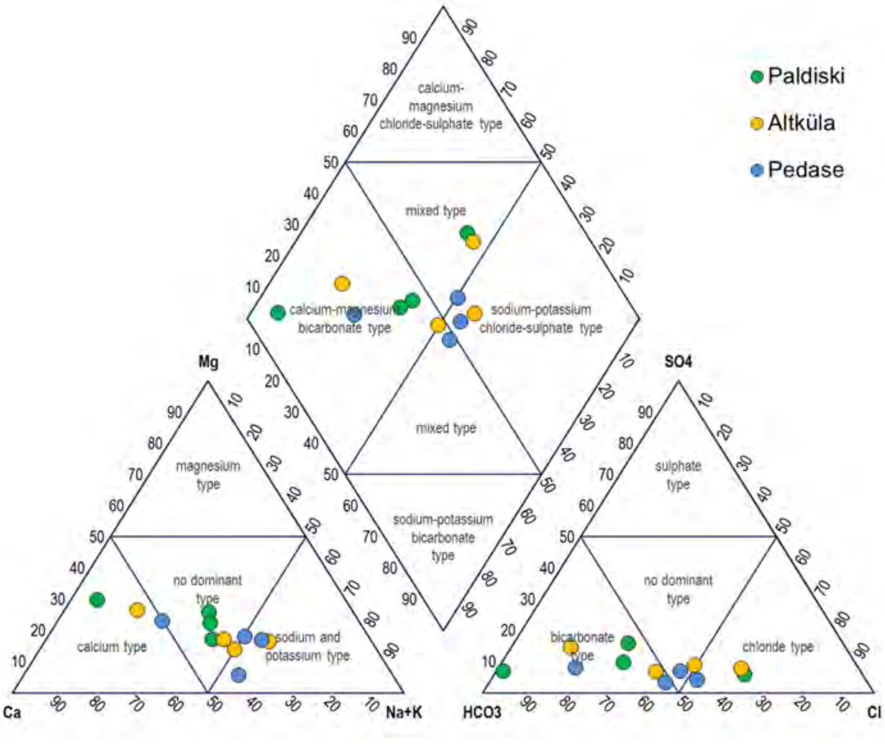


Figure 8.4. Piper diagram describing the chemical composition and chemical type of groundwater in preselected sites.

The highest HCO_3 values are observed in the uppermost carbonate Silurian-Ordovician aquifer system (PAL_101, ALT_102, PED_103), where infiltration occurs and water exchange is most intensive. Furthermore, the concentrations of Na and Cl in groundwater increase with depth in the hydrogeological profile. Generally, the amount of dissolved chemical substances in groundwater increases with depth due to slower water exchange and longer residence time in rocks, resulting in the replacement of Ca by Na through ion-exchange processes. Thus, in the Cambrian-Vendian aquifer system, specifically in the PAL site (PAL_501) and the ALT site (ALT_502), Cl-type groundwaters are present when considering solely the chemical composition. The most similar aquifer systems in terms of water chemistry are the Ordovician-Cambrian and Cambrian-Vendian aquifer systems in the PED site (Table 8.1). However, as mentioned earlier, the variations in water chemistry across aquifer systems and selected locations are minimal. Some changes in water chemistry are observed with increasing depth, such as a decrease in HCO_3 and an increase in Cl, Na, and K concentrations. Additionally, regardless of the location, the groundwater in the upper part of the Cambrian-Vendian aquifer system (Sämi Member) exhibits the lowest salinity.

Field measurements indicate an increasing trend in pH and temperature values with increasing depth along the geological profile. Additionally, the in situ measured electrical conductivity (EC) values show a strong correlation with the total dissolved solids (TDS) values measured in the laboratory. Water samples were also collected to assess the microbiological quality. The analysis results indicate the presence of microorganism colonies in practically all samples. This is likely attributed to the recently drilled monitoring wells from which the samples were obtained, as the water may contain fresh pollution resulting from the drilling activities. Additionally, it is important to note that the equipment used for test-pumping is not sterile and could potentially contribute to contamination of the water sample in terms of microbiological quality.

In order to provide an overview of the spatial variability of groundwater chemistry in the Lääne-Harju local municipality, the content of the main cations and anions in groundwater abstraction wells is summarized in Table 8.2. The dataset clearly demonstrates that the chemical composition of groundwater does not exhibit lateral changes in both aquifer systems. The presence of fresh HCO3-Ca water type is present in the O-Ca and Ca-V aquifer systems, while a slight increase in Cl content is noticeable in the deeper Cambrian-Vendian aquifer system compared to the Ordovician-Cambrian groundwater. The chemical composition of groundwater in the monitoring wells of pre-selected sites aligns with the analytical results presented in Table 8.2, thus confirming the spatial uniformity of groundwater chemical composition within the Lääne-Harju local municipality.

Table 8.2. The content of main compounds in groundwater abstraction wells in the Lääne-Harju local municipality. Data from Estonian Nature Information System

Aquifer system	**No of well**	**Depth**	**Abs height**	**HCO_3**	**Cl**	**SO_4**	**Ca**	**Mg**	**K**	**Na**
		m	**m a.s.l.**	**mg/L**						
Ordovician-Cambrian	1183	115	23	189.2	74.1	13.8	31.7	9.0	6.0	67.3
	22745	43	5	164.7	30.8	36.6	30.1	17.0	6.0	29.0
	22912	58	20	213.6	9.9	8.2	24.4	10.1	5.3	40.0
	22982	71	10	183.1	45.4	3.3	28.1	9.7	7.0	44.0
	24839	55	16	207.4	15.2	18.9	27.9	12.6	7.0	35.6
	25351	67	8	201.4	67.4	23.9	26.1	12.2	7.7	67.3
	25437	51	16	158.6	8.5	12.8	30.7	12.6	7.2	12.8
	25441	40	30	207.5	23.8	20.2	33.9	14.8	7.0	23.8
	25522	68	26	176.9	33.0	26.7	30.8	12.6	7.0	31.1
	25730	78	10	128.1	74.1	25.1	23.8	10.8	5.2	51.1
	25939	77	6	244.0	29.8	140.7	67.5	24.1	11.0	43.3
	26055	57	16	146.4	31.2	22.6	27.9	13.2	6.5	24.1
	30590	40	15	329.4	29.4	53.5	71.3	23.7	10.9	31.9
	30607	37	32	256.3	19.5	20.0	39.1	23.7	8.0	23.0

	30795	44	13	164.7	55.7	26.3	37.7	14.5	8.4	32.5
	30823	54	22	170.8	33.7	25.1	28.9	15.1	6.0	23.8
	30887	39	13	128.1	67.4	31.7	29.3	12.9	15.0	46.7
	30944	38	12	274.5	11.3	36.2	82.6	13.1	2.7	5.3
	51454	66	31	183.1	38.6	38.7	31.3	20.3	9.0	31.4
	51456	46	20	353.9	15.2	20.2	60.5	35.5	8.5	10.0
	51872	100	17	366.1	20.2	27.2	89.8	19.0	5.5	17.1
	52097	45	9	85.4	74.1	49.0	10.8	5.5	20.4	61.7
	52438	60	33	176.9	23.8	14.0	29.9	12.0	6.7	29.5
Cambrian-Vendian	535	209	24	128.1	221.6	18.7	67.7	20.5	10.0	72.3
	540	203	22	61.0	180.0	29.0	42.8	11.5	10.3	68.1
	547	163	13	122.0	226.9	21.0	64.9	18.0	10.6	89.1
	577	104	6	115.9	130.5	38.7	47.7	13.2	7.7	47.1
	599	121	10	146.4	36.5	28.0	31.1	18.8	6.7	26.7
	1118	160	15	97.6	91.1	45.3	39.3	8.4	6.3	48.6
	1144	205	3	73.2	84.4	18.1	9.0	14.0	10.0	63.3
	15246	118	8	109.8	109.2	23.9	43.9	11.2	8.0	50.0
	16632	150	21	128.1	104.6	26.3	44.1	12.8	6.6	47.1
	51690	98	3	109.8	42.2	23.0	24.0	6.4	5.0	28.6
	51874	135	27	231.8	45.0	14.0	46.4	16.4	8.0	32.4
	51884	100	3	114.0	52.0	24.0	27.0	10.0	8.1	30.0

One of the objectives of this sub-activity was to assess the potential changes in the chemical composition of groundwater in relation to variations in water consumption within the region or the establishment of a pumped-storage hydroelectricity plant. These are the questions that the groundwater flow modeling (as reported in Appendix 6) aims to address. However, considering the territorial homogeneity of the available hydrochemical data, it can be assumed that the possible shifts in water flow directions resulting from more intensive groundwater pumping are unlikely to significantly alter the chemical composition of groundwater in the immediate vicinity of the pre-selected sites.

8.1. Trace elements in groundwater

Generally, the trace element content in groundwater samples (as shown in Table 8.3) is low, and in many cases, the concentrations of the analyzed elements are below the limit of detection (LOD). The highest values are observed for strontium (Sr) and boron (B). The concentration of Sr increases with depth, reaching its highest levels in the monitoring wells drilled into the deeper part of the Cambrian-Vendian aquifer system (PAL_501, ALT_502, PED_503). This observation suggests the geochemical influence of the crystalline basement rocks on the aquifer located above it.

Table 8.3. The concentration of trace elements (µg/L) in the monitoring wells. LOD – limit of detection

Well	**Li**	**B**	**Al**	**P**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**
Paldiski site													
PAL_101	6.57	249.06	5.43	2.92	0.09	0.88	23.01	79.80	0.21	0.98	0.08	0.00	0.35
PAL_201	14.09	649.87	<LOD	1.75	0.09	<LOD	30.05	62.99	0.20	0.12	<LOD	1.71	0.39
PAL_401	7.61	388.21	11.95	23.77	0.08	0.58	33.17	159.25	0.09	0.27	0.37	1.93	0.19
PAL_501	10.61	206.67	<LOD	11.59	0.36	<LOD	35.45	49.36	2.69	<LOD	0.19	<LOD	2.14
Altküla site													
ALT_102	7.19	129.09	1.86	<LOD	0.15	0.13	16.35	281.22	0.27	0.53	0.49	2.23	0.18
ALT_202	21.33	701.23	<LOD	<LOD	0.36	0.14	29.61	56.32	0.13	0.37	0.06	<LOD	<LOD
ALT_402	10.71	571.95	2.25	<LOD	0.17	0.12	20.54	169.33	0.07	0.11	<LOD	<LOD	<LOD

ALT_502	14.41	227.28	1.64	3.86	0.75	0.16	18.95	14.95	0.50	0.43	<LOD	<LOD	4.05
Pedase site													
PED_103	8.83	239.57	1.83	1.43	0.36	0.10	6.11	4.63	0.27	0.63	0.78	<LOD	0.18
PED_203	22.78	633.24	5.75	3.28	0.35	0.19	28.76	81.53	0.27	0.15	0.25	<LOD	<LOD
PED_403	11.81	546.78	<LOD	<LOD	0.21	0.17	25.08	165.83	0.16	0.13	<LOD	<LOD	<LOD
PED_503	8.80	132.09	2.67	<LOD	53.32	0.25	<LOD	19.03	0.19	0.20	<LOD	<LOD	2.85
Well	**Se**	**Rb**	**Sr**	**Mo**	**Cd**	**Sb**	**Cs**	**Ba**	**Bi**	**Pb**	**Th**	**U**	
Paldiski site													
PAL_101	0.08	2.44	311.18	0.95	0.01	0.63	0.12	231.81	<LOD	<LOD	0.00	0.06	
PAL_201	0.09	3.30	435.81	32.96	0.01	0.31	0.17	81.06	<LOD	<LOD	<LOD	0.33	
PAL_401	<LOD	2.74	306.42	6.93	0.01	6.18	0.15	72.37	<LOD	0.15	0.00	0.03	
PAL_501	0.12	5.46	539.47	13.71	0.00	0.16	0.35	186.29	<LOD	<LOD	0.00	2.21	
Altküla site													
ALT_102	<LOD	1.91	180.69	1.25	0.01	0.01	0.03	65.25	<LOD	0.13	0.00	0.23	
ALT_202	<LOD	3.78	400.85	5.17	0.00	0.10	0.04	61.46	<LOD	0.04	0.00	0.13	
ALT_402	<LOD	2.72	349.78	2.50	0.00	0.01	0.04	112.65	<LOD	0.01	0.00	0.02	
ALT_502	<LOD	6.63	561.28	5.63	0.00	0.16	0.09	78.21	<LOD	0.03	0.00	0.73	
Pedase site													
PED_103	0.04	2.98	177.50	1.64	0.01	0.13	0.03	27.68	<LOD	0.05	0.00	0.57	
PED_203	<LOD	5.08	385.82	2.18	0.01	0.14	0.05	162.41	<LOD	0.07	0.01	0.09	
PED_403	<LOD	2.95	428.88	2.30	0.00	0.03	0.06	183.34	<LOD	0.02	0.00	0.03	
PED_503	0.47	67.43	538.11	87.44	0.01	1.38	0.27	76.35	<LOD	<LOD	0.00	0.04	

Boron and lithium are trace elements that are commonly associated with clayey materials, and their concentrations tend to be highest in the Ordovician-Cambrian and the upper section of the Cambrian-Vendian aquifer system. It is possible that the elevated levels of boron and lithium are influenced by the nearby extensive clayey Lükati-Lontova aquitard. Additionally, the aquifers themselves contain interlayers of clay, or the terrigenous materials forming the aquifers are inherently silty or clayey in nature.

The highest concentrations of uranium (U) are found in the deepest section of the Cambrian-Vendian aquifer system, specifically at the PAL and ALT sites. The presence of U in groundwater within the Cambrian-Vendian aquifer system can be attributed to the influence of the underlying crystalline bedrock. The results of the radioactivity analyses (Ra-226, Ra-228, indicative dose) presented in Table 8.4 demonstrate a similar trend and validate the geochemical interaction between the terrigenous aquifer and crystalline bedrock.

Table 8.4. The results of the radioactivity (Ra-226, Ra-228, indicative dose) and stable isotope (O-18, H-2) analyses

Monitoring well	**Ra-226**	**Ra-228**	**Indicative dose**	**O-18**	**H-2**
	mBq/L	**mBq/L**	**mSv/y**	**‰**	**‰**
Paldiski site					
PAL_101	41	<23	0.008	-10.90	-76.23
PAL_201	103	<23	0.021	-19.68	-148.50
PAL_401	30	104	0.059	-19.85	-150.78
PAL_501	533	572	0.397	-21.41	-164.08
Altküla site					
ALT_102	26	<16	0.005	-11.53	-81.33
ALT_202	139	149	0.103	-19.02	-143.53
ALT_402	<18	<22	<0.012	-19.82	-150.14
ALT_502	284	205	0.161	-21.37	-162.91
Pedase site					
PED_103	31	<14	0.006	-13.20	-94.07

PED_203	190	149	0.114	-19.32	-142.71
PED_403	101	443	0.244	-19.83	-147.38
PED_503	126	95	0.074	-19.01	-142.43

8.1. Radioactivity of groundwater

The concentrations of Ra-226 and Ra-228 isotopes are highest in the lowermost part of the Cambrian-Vendian aquifer system at the PAL and ALT sites, as well as in the uppermost part of the same aquifer system in PED. Notable indicative doses were calculated based on the concentrations of Ra-226 and Ra-228 found in four monitoring wells (PAL_501, ALT_502, PED_203, and PED_403). The results of the radioactivity analyses presented in Table 4 confirm the hydraulic connection between the Cambrian-Vendian aquifer system and the underlying rocks, while also providing a natural background level for Ra isotopes.

Studies conducted on groundwater radioactivity in Estonia have revealed a long-standing issue of high Ra activity concentrations in the Cambrian-Vendian aquifer system, which has been known for over two decades. The elevated Ra activity in this aquifer system is attributed to prolonged contact with radioactive rocks present in the crystalline basement, where higher concentrations of Ra precursors, such as U and Th, have been observed.

The activity concentrations of Ra-226 and Ra-228 in the PAL, ALT, and PED sites are lower compared to those observed in the Tallinn area of northern Estonia. Among the sites, the highest values (Table 8.4) were recorded in the Cambrian-Vendian aquifer system at the Paldiski site (PAL_501; Ra-226 = 533 mBq/l, Ra-228 = 572 mBq/l) and the Pedase site (PED_403; Ra-228 = 443 mBq/l). It is likely that the radioactivity in the groundwater at these sites is attributed to the same natural sources observed in the Viimsi peninsula. In the Ordovician-Cambrian aquifer system, the recorded Ra activity values (103-190 mBq/l; Table 4) can be traced back to the black shale (graptolite argillite) of the Türisalu Formation. This formation contains notable amounts of rare metals (Mo, V) and radioactive elements (U, Th).

8.1. Stable isotope composition of groundwater

Glacial meltwater typically exhibits low O-18 and H-2 values and low TDS concentrations. These characteristics serve as key indicators for identifying groundwater of glacial origin.

The results of the O-18 and H-2 analyses conducted in this study provide compelling evidence that the groundwater in the study sites has been significantly influenced by glaciations and recharged by glacial meltwater. The O-18 values ranging from -19‰ to -21.5‰ and H-2 values ranging from -142‰ to -164‰ were observed in the monitoring wells drilled into the Cambrian-Vendian and Ordovician-Cambrian aquifer systems (Table 8.4). The most depleted isotope values were found in the deepest part of the Cambrian-Vendian aquifer system in Paldiski (PAL_501) and Altküla (ALT_502), while the same trend was not observed in the Pedase site.

The isotopic composition of the uppermost Ordovician aquifer system (PAL_101, ALT_102, PED_103) differs significantly from that of the Cambrian-Vendian and Ordovician-Cambrian aquifer systems (Table 8.4). The O-18 values ranging from -10.9‰ to -13.3‰ indicate the influence of modern precipitation and intensive water exchange. It is worth noting that the annual weighted mean O-18 value in modern precipitation in Estonia varies between -10.2‰ and -10.7‰. The remarkably negative isotope values in the Ordovician-Cambrian aquifer system suggest the effective isolation properties of the Leetse-Türisalu aquitard.

A diagnostic threshold value below -14‰ for O-18 and below -102‰ for H-2 isotopic composition of groundwater serves to distinguish between waters with a significant glacial palaeowater component and groundwater originating from modern recharge. The dating of palaeowater in the northern part of the Baltic Artesian Basin has indicated that waters with such isotopic composition are at least 10,000 years old.

Consequently, based on the isotopic data, it can be concluded that the groundwater in the Ordovician-Cambrian and Cambrian-Vendian aquifer systems (both above and below the Lükati-Lontova aquitard) at all 3 sites has been significantly influenced by glaciations and recharged by glacial meltwater. Additionally, glacial meltwater is characterized by low TDS concentrations, which in the studied sites range from 180-460 mg/L (PAL), 224-483 mg/L (ALT), and 265-396 mg/L (PED). The preservation of recharged glacial meltwater in deep-seated aquifer systems indicates their isolation and a lack of water exchange.

To gain insight into the spatial variability of the isotopic composition of groundwater in the Lääne-Harju local municipality, the distribution of O-18 values was studied in the Ordovician-Cambrian and Cambrian-Vendian aquifer systems. The isotopic data obtained from the Baltic groundwater isotope-geochemistry database clearly demonstrate that the isotopic composition of groundwater remains consistent laterally within both aquifer systems. The O-18 values range from -17.9‰ to -22‰ in the Cambrian-Vendian aquifer system and from -18.7‰ to -20.3‰ in the Ordovician-Cambrian aquifer system, which align well with the isotope determinations of the current study (Table 8.4). Therefore, similar to the chemical composition, the isotopic composition of groundwater exhibits lateral uniformity.

One of the objectives of this sub-activity was to assess the potential changes in hydrogeologically or geochemically significant parameters over a 1,000-year timeframe. The strongly negative isotope values provide confirmation of the preservation of glacial meltwater that is at least 10,000 years old in the Cambrian-Vendian and Ordovician-Cambrian aquifer systems. This indicates that the situation is likely to remain relatively unchanged over the next 1,000 years, and significant alterations in the chemical composition of the deep groundwater are not anticipated.

8.2. Conclusions

1. Measurements of stable isotope composition of groundwater indicates very slow water exchange in aquifer systems relevant for safety of IDDF.

2. The aquifers themselves contain interlayers of clay, or the terrigenous materials forming the aquifers are inherently silty or clayey in nature.

3. Relying purely on the chemical composition of groundwater it is not possible to bring out which of the suggested site is the best, which is second and which is third. The PAL, ALT, and PED alternatives are roughly equivalent in preference in terms of groundwater chemical properties.

9. Sub-activity 2.9. Study of the soil and its deeper layers

The report describes the geotechnical conditions of the Quaternary soils and bedrock in each potential repository location. The geotechnical conditions affecting design of the disposal facility are discussed, and suggestions are provided.

The studies were performed by Annette Talpsep (Department of Geology, University of Tartu, Estonia); detailed results are presented in an Appendix 9.

9.1. Methodology

9.1.1. Quaternary soils

To describe the Quaternary soils, three boreholes with a depth of 16.0–19.0 m (ALT) or investigation pits with a depth of approx. 2 m (PAL, PED) were prepared by OÜ Inseneribüroo Steiger. Soil samples for laboratory analyses were collected from the investigation pits or drill core. In addition, three penetration tests (PT) with a depth of 17.0–17.3 m were conducted in ALT to assess the mechanical properties and heterogeneity of the Quaternary soils. The testing was done by IPT Projektijuhtimine OÜ using the GM 65 GTT device that combines Dynamic Penetration Testing (DPT) and Cone Penetration Testing (CPT).

The soil samples were tested in the Laboratory of the Department of Geology, University of Tartu and in the Geotechnical Laboratory of the Estonian Environmental Research Centre. Grain size distribution and number of physical properties were determined, including water content, specific gravity of solids, density, dry density, void ratio, and hydraulic conductivity. In addition, swelling and soaking properties of clayey soils were determined.

Shallow groundwater samples were collected into plastic bottles from the investigation pits in PAL and ALT. No groundwater appeared into the pits in PED. The shallow groundwater samples were analyzed in the Tartu Department of the Estonian Environmental Research Centre. The pH, electric conductivity, and the concentrations of the main cations and anions were measured. The content of aggressive CO_2 was determined to assess the aggressivity of the groundwater towards the concrete.

The activity concentrations of the Quaternary soil samples from each site were measured in the Nuclear Spectroscopy Laboratory of the Testing Centre of the University of Tartu, Estonia using gamma spectrometric analysis of solid samples. The analyses included five radionuclides: Ra-226, Ra-228 and Th-228, K-40, and Cs-137.

To study the bedrock on each site, a deep borehole with a depth of 132.7–165.4 m was drilled using the triple barrel wire-line core drilling method. The drill cores were photographed, placed into wooden core boxes for further logging, and transported to the drill core repository.

The drill cores were described after the fieldwork. The following characteristics were assessed: RQD (Rock Quality Designation index), number and description of the discontinuities (type, discontinuity length, aperture, surface roughness and weathering, and infilling). The properties of intact rock were assessed by UCS (Uniaxial Compressive Strength) tests performed in the laboratory.

Then, the abovementioned data were used to assess the rock mass quality of each bedrock unit, using the Rock Mass Rating (RMR) classification which combines the strength properties of intact rock with conditions of discontinuities present in the rock mass. Six parameters are used in the classification: UCS of an intact rock; RQD value; spacing of discontinuities; condition of discontinuities; groundwater conditions; and orientation of discontinuities.

9.2. Quaternary cover and shallow groundwater conditions

9.2.1. PAL site

The PAL site is situated at an outcrop area of Ordovician limestones covered by a thin layer of Quaternary soils. Due to the industrial/military background, the natural ground has been changed significantly by filling and excavation activities. The thickness of Quaternary soils, including the fill layer in the investigation pits, was less than 2 m (Figure 9.1). Geotechnically, the soils can be divided into three layers: artificial fill (layer 1), shingles and gravel (layer 2), and glacial till (layer 3).

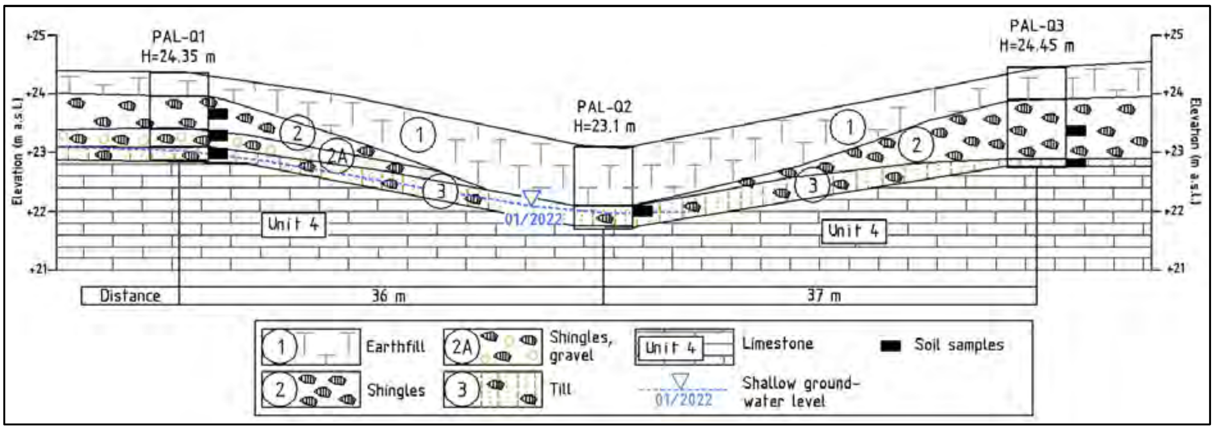


Figure 9.1. Cross-section of Quaternary soils in PAL site.

9.2.2. ALT site

The ALT site is situated at the slope of a buried depression cut into the sedimentary rocks. The thickness of the Quaternary cover is about 20–25 m. The cross-section of the Quaternary cover is shown in Figure 9.2. The topsoil (layer 1) is underlain by marine sand (layer 2) and lacustrine silty sand, and sandy silt (layer 3). Below the sandy soils, a layer of glacial lacustrine varved clay (layer 4) occurs. The lowermost section of the Quaternary cover consists of a glacial till (layer 5). The bedrock surface lies at a depth of ~24 m from the ground surface.

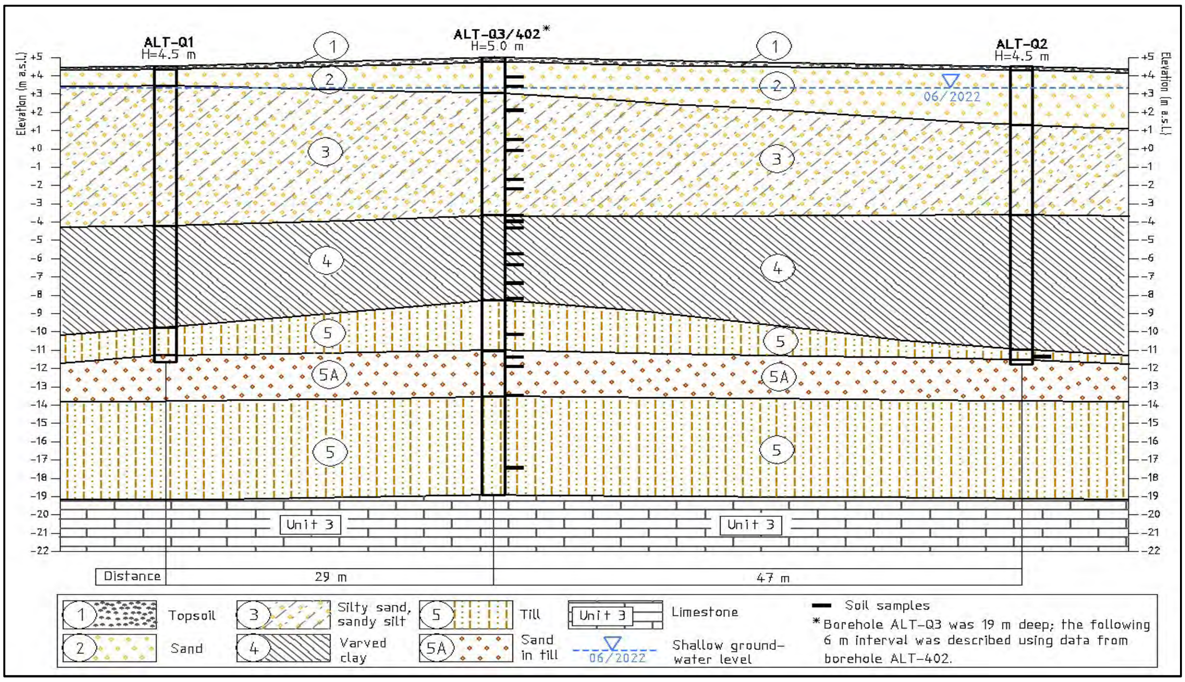


Figure 9.2. Cross-section of Quaternary soils in ALT site.

9.2.3. PED site

The thin (<2 m) Quaternary cover is underlain by Ordovician limestone (unit 1). The cross-section of the site is shown in Figure 9.3. The site is situated on the slopes of coastal ridges and spits. As on the PAL site, the Quaternary soils are represented by shingles (layer 2), gravel, sand, and pebbles in varying proportions (layers 3 and 3A), and the glacial till (layer 4). The uppermost layer is formed of humic topsoil (layer 1). The physical and mechanical properties of the Quaternary soils are listed in Table 9.4.

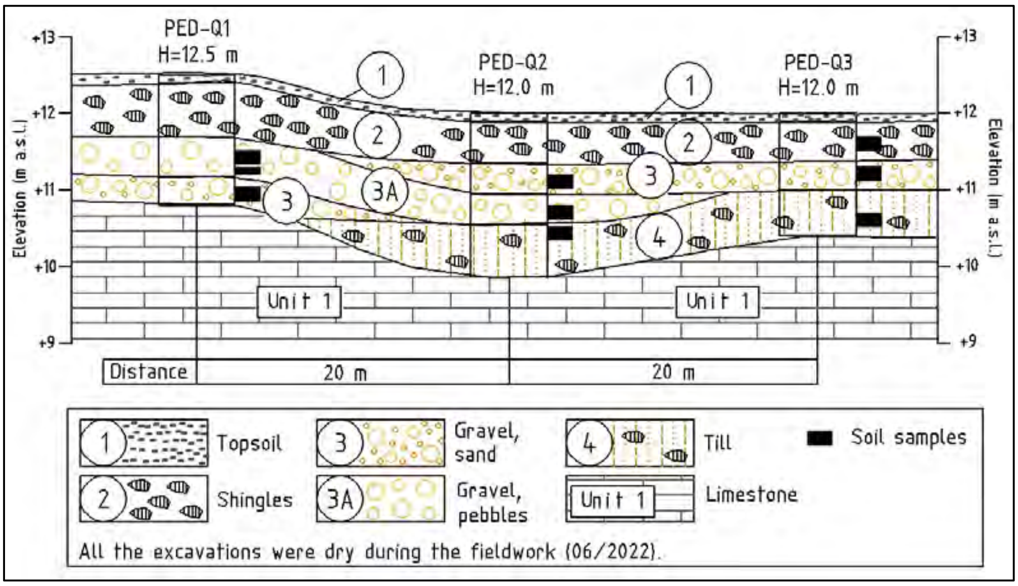


Figure 9.3. Cross-section of Quaternary soils on the PED site.

9.2.4. Radionuclide content in Quaternary soils

The measured radionuclide activity concentrations are presented in Table 9.5. They correlate well with the average values of the corresponding sediment types reported in literature. As assumed, varved clay (layer 4 in ALT) exhibits the highest activity concentration values. Anthropogenic Cs-137 was not detected in any of the samples (i.e., was below the detection limit). Thus, the results indicate background values of primordial radionuclides and their decay products.

Table 9.5. Activity concentrations of radionuclides in soil samples

Site	Soil type	Layer No	Sample ID	Activity concentration (Bq/kg)			
				Ra-226	Ra-228	Th-228	K-40
PAL	Shingles	2	PAL-Q3_1.0-1.4	24.2	17.9	16.7	543
	Glacial till	3	PAL-Q2_1.0-1.4	19.4	14.8	13.2	262
ALT	Silty sand	3	ALT-Q3_2.8-3.0	31.6	45.7	39.6	557
	Silt	3	ALT-Q3_6.6-6.8	35.4	44.7	39.2	739
	Clay	4	ALT-Q3_10.65-10.85	76.0	83.2	84.0	1131
	Glacial till	5	ALT-Q3_15.05-15.25	26.6	21.9	19.2	387
	Sand	5A	ALT-Q3_16.8-16.9	12.9	19.9	13.9	290
PED	Cobbles with gravel	3	PED-Q2_0.8-0.9	6.6	6.6	5.2	135
	Glacial till	4	PED-Q3_1.3-1.4	15.7	17.6	14.0	297

9.3. Description of bedrock

According to the technical specification of the procurement, a disposal facility of intermediate depth (~30–50 m) is proposed. In this depth, different rocks are present:

- in PAL, sandstones (units 10 and 11);
- in ALT, the lower interval of carbonate rocks (units 5–7) and upper interval of terrigenous rocks (glauconitic sandstone, graptolite argillite, and sandstone; units 8–10);
- in PED, carbonate rocks (units 3–6).

Geotechnically, the repository can be built in these rocks, but the natural conditions would be more favorable in the deeper-lying Cambrian clayey rocks (units 12–13). They are dominated by clay- and siltstones of low permeability, which serve as natural isolation around the repository. These rocks occur at different depths in the potential repository locations:

- In PAL they are closest to the ground, where unit 12 starts at a depth of 57 m from the ground (elevation -33 m a.s.l.). The total thickness of units 12 and 13 is ~41 m.
- In ALT unit 12 starts at a depth of ~78 m from the ground (elevation -73 m a.s.l.), and the total thickness of units 12 and 13 is also 41 m.
- In PED, unit 12 starts even deeper – ~94 m from the ground (elevation -81 m a.s.l.). The total thickness of units 12 and 13 is ~37.5 m.

The recommendations regarding the bedrock geotechnical conditions are same for all three sites:

- The carbonate rocks (units 1–7) are probably strong enough to serve without support during the shaft's construction, but it should be confirmed. The deeper rocks (from unit 8) must be supported. The sandstone units contain intervals of low cementation, which behave more as soil than rock.
- The planned construction methodology does not require dewatering of the excavation. Still, if there is a need to assess the inflow to the excavation, it should be noted that larger inflow is expected from the upper interval of carbonate rocks and sandstones (units 10 and 11). Although, in general, the clayey rocks of Cambrian (units 12–13, and partially 14) form an aquitard, they contain sandy intervals, which also contribute to groundwater inflow.
- High uplift pressure applies to the bottom of the silo-type repository.
- Graptolite argillite (unit 9) and Cambrian claystones (units 12–14) are sensitive to exposure to atmospheric conditions due to their high clay content. During the construction, they should be covered as fast as possible.
- Precaution measures must be applied when handling graptolite argillite (unit 9). In its natural state, it does not pose any threat. However, when excavated and placed on the ground, it exhibits self-ignition properties due to the combination of pyrite (up to 6%) and organic matter (up to 20%) content. Even the temporary piling of excavated graptolite argillite in large heaps must be avoided. Instead, the material should be placed by thin (0.2 m) compacted layers between other, preferably fine-grained soil to decrease oxygen access.

9.4. Summary

9.4.1. Quaternary soils

PAL and PED sites

In general, the geotechnical conditions of Quaternary soils in PAL and PED are favorable; however, some recommendations can be presented:

- The strong and practically incompressible limestone lies near the ground surface (<2 m); thus, removing the Quaternary soils and placing the foundations of on-ground buildings onto the limestone is recommended.
- The heterogeneous fill in PAL should be removed below buildings, roads, and parking lots because its properties are unpredictable. It might be frost susceptible because different natural soils have been used for filling.
- The shingles, gravel and sand layers should be compacted before the construction of roads and other facilities supporting this layer because it may have uneven relative density and, as a result, cause uneven settlement of the facilities placed on this layer.
- The average frost depth of soil in the area is 1.15 m (max 1.9 m). It should be considered that till is moderately frost susceptible. Also, the coarse-grained soil contains silt in places, making it slightly frost susceptible. The glacial till also exhibits slight plastic properties and may soften in the excavations if exposed to weather conditions.

ALT site

Compared to the other two sites, the geotechnical conditions in ALT are the most unfavorable:

- The uppermost sand (layer 2) has rather fair strength properties, the silty sand/sandy silt (layer 3) has very low relative density and poorer strength properties.
- (Varved) clay (layer 4) is very compressible, and settlement due to loads placed above it will occur. The settlement due to the compressible soils must be calculated when designing a near surface disposal facility. If it exceeds the allowable settlement value, a pile foundation supporting onto till or limestone layer should be used instead.
- When making excavations, the Quaternary soils must be supported by retaining walls. Sandy silt (layer 3) and clay (layer 4) are prone to soaking, and cohesionless sand must be supported. Till (layer 5) is a relatively strong, cohesive soil, but it is plastic and softens when its water content increases.
- Silty sand/sandy silt (layer 3) and till (layer 5) are highly frost susceptible, and clay (layer 4) is moderately frost susceptible. The same frost depth values apply in PAL (average 1.15 m; max 1.9 m). The frost susceptibility of the deeper soils should be considered if the soils are removed and used as fill.
- Due to the high shallow groundwater level, excavations must be drained. When excavations reach the till layer, larger water inflow can be expected from the sandy zones occurring in otherwise low permeable till.
- The shallow groundwater level was measured 1.2–1.7 m below the ground surface. Currently, its level is controlled by the network of drainage ditches. Still, if the drainage system should be closed or damaged, a significant rise is expected as the area is naturally wet. The laboratory analyses indicated that the pH of the water is acidic (6.0), and due to the presence of aggressive CO_2 the shallow groundwater is moderately aggressive towards concrete.

9.4.2. Ranking of the sites

In PAL, the geotechnical conditions for constructing both the Near Surface and Intermediate Depth Disposal Facilities are most favorable. The thin Quaternary cover characterizes the site, and the most suitable rocks for the Intermediate Depth Disposal Facility (Cambrian claystones) lie the nearest to the ground (57 m). The ALT and PED sites are less favorable than the PAL site. On both sites, the Cambrian claystones lie deeper than in PAL; 78 m in ALT and 98 m in PED. When considering Near Surface Disposal Facility, the conditions in PED are comparable to the PAL site, but in ALT the conditions are poorer. The actual ranking of ALT and PED sites depends on the selected repository type and construction costs, which are unknown now; thus, they are ranked equally.

Overall ranking in terms of geotechnical conditions considering both, the Quaternary cover, and the bedrock: 1. PAL; 2.–3. ALT and PED.

9.5. Conclusions

1. In general, the geotechnical conditions of Quaternary soils in PAL and PED are favorable as strong and practically incompressible limestone lies near the ground surface (<2 m); thus, removing the Quaternary soils and placing the foundations of on-ground buildings onto the limestone is recommended.; however, some recommendations can be presented:

2. It is recommended to remove the heterogeneous fill in PAL site below buildings, roads, and parking lots because its properties are unpredictable. It might be frost susceptible because different natural soils have been used for filling.

3. The shingles, gravel and sand layers at PAL and PED sites should be compacted before the construction of roads and other facilities supporting this layer because it may have uneven relative density and, as a result, cause uneven settlement of the facilities placed on this layer.

4. The average frost depth of soil in the area is 1.15 m, while max depth is 1.9 m. It should be considered that till is moderately frost susceptible. Also, the coarse-grained soil contains silt in places, making it slightly frost susceptible. The glacial till also exhibits slight plastic properties and may soften in the excavations if exposed to weather conditions.

5. Compared to the other two sites, the geotechnical conditions in ALT site are the more unfavorable due to the presence of weak and compressible soil layers in the Quaternary cover making facility design more sophisticated and construction more expensive. The settlement due to the compressible soils at ALT site must be taken into consideration when designing the NSDF (for example, application of a pile foundation supporting onto till or limestone).

6. The groundwater level is very shallow at ALT site (1.2–1.7 m below the ground surface). Currently, its level is controlled by the network of human created drainage ditches. A significant rise is expected in the future, as the area is naturally wet.

7. The ground water at ALT site is acidic, and due to the presence of aggressive CO_2 the shallow groundwater is moderately aggressive towards concrete.

8. Geotechnically, the IDDF can be built in depth of 30 to 50 m in sandstones, carbonate rocks or terrigenous, as foresenn in the Technical specifications, however, conditions would be more favorable in the deeper-lying Cambrian clayey rocks. They are dominated by clay- and siltstones of low permeability, which serve as natural confining barrier for the disposal facility.

9. The clayey rocks occur at different depths in the potential sites: in PAL they are closest to the ground (starts at a depth of 57 m in PAL site), in ALT the depth of ~78 m and in PED, they start even deeper (~94 m from the ground).

10. Precaution measures must be applied during construction when handling graptolite argillite, because of self-ignition properties (oxygen access must be controlled.

11. When considering suitability for NSDF, the conditions in PED and PAL sites are comparable, while ALT site is more unfavorable.

12. Suitability for the IDDF depends on the excavation depth. PAL site is best one, followed by ALT and PED.

13. Summarizing the findings, the geotechnical conditions for constructing facilities of the both types are most favorable in PAL site.

10. Sub-activity 2.10. Monitoring atmospheric air

The general objective of the current sub-activity is to present an overview of the current state of the quality of atmospheric air in the vicinity of the three possible alternative repository locations and to assess the possible impact on air quality during the different phases (construction, operation and closure) of the repository and to assess the projects conformity to the applicable national regulations. The scope of the study consists of:

- Assessing the existing background air quality in the three possible repository locations.
- Assessing the expected emission sources and quantities of pollutants emitted to the atmosphere during the three phases of the project.
- Modelling the dispersion of identified pollutants emitted to the atmosphere during the construction, operation and closure phases of the project.
- Assessing the project's impact on the quality of ambient air in the three possible locations and conformity with national limit values set in the legislation;
- Elaboration of mitigation measures for compliance with national regulations and standards, if needed taking into account the investigation results.

For the assessment of the existing background air quality, short-term continuous measurements of selected pollutants (SO_2, NO_2, CO, O_3, NMHC, PM_{10}, BTX) were carried out at the three candidate locations. The rest of the study results is based on existing data from national databases. The detailed results are presented in an Appendix 10. The work was performed by Priit Kallaste, an Environmental specialist, Engineering Bureau STEIGER LLC.

10.1. Air quality legislation

The requirements and normative values of regulated pollutants are set by the Minister of Environment in regulation No 75 "Limit and target values of air quality, other limit values of air quality and assessment limits of air quality". The regulation describes the limit and target values for a list of regulated pollutants.

Air quality limit values are indicators of the level of air pollution and must be ensured primarily in public and residential areas. Exceeding the limits is assumed to have a significant negative impact on the environment.

10.2. Existing air quality at the alternative locations and emission sources

Both the ALT and PED sites are situated in the western part of the Lääne-Harju municipality and are located approx. 2 km apart from each other. There are no big centers nearby, the closest being the Altküla settlement center about 2 km to the south or southeast and Kurkse settlement center about 2 km to the north from the ALT site. Around all the three sites the nearest sensitive areas are located quite far (more than 0.7 km), which in terms of air pollution results in good conditions for the concentrations to disperse in the atmosphere.

To assess the existing background level of air quality in the vicinity of the three possible alternative repository locations, on-site short-term continuous measurements of concentrations of selected pollutants were carried out by Estonian Environmental Research Center in July and August of 2022 and in January of 2023.

The measured pollutants were selected according to the monitored pollutants at the nearest air quality monitoring stations, which were Paldiski and Õismäe (Tallinn) stations and were the following:

- Sulphur dioxide (SO_2)
- Nitrogen dioxide (NO_2)
- Carbon monoxide (CO)
- Ozone (O_3)
- Fine particulate matter (PM_{10})
- Non-methane hydrocarbons (NMHC)
- BTX (benzene, toluene, xylene)

In general, according to the results the current level of ambient air quality was stated to be very good. Since the concentrations of pollutants in ambient air may originate from human activities or occur from natural processes, the measured concentrations depict normal background levels of air quality that are a mixture of both sources. At the PAL site the impact of existing transport and industrial areas on the air quality level is higher whereas at the ALT and PED sites local heating in combination with transport is the main source.

According to the permit registry there are 11 businesses with air pollution permits in the vicinity of the PAL site. The radius of the observable area is selected to be 4 km. To compare the measured background concentrations and the overall air quality in the area of the PAL site, modelling of emissions from the active sources according to the permit registry was performed using Airviro modelling environment. According to the results the air quality at the PAL site is quite good and limits of the main pollutants are not exceeded, Table 10.1.

At the ALT and PED sites there are no registered air pollution sources within a 7 km radius. The closest emission sources according to the permit registry are located at approx. 7 - 8 km in the east at Padise and Rummu settlements. Considering the dominating wind directions in the region, these sources do not affect the local air quality in at the ALT and PED sites. Hence, at those locations the air quality is affected mainly by dispersed transport and industrial concentrations on a larger scale and local household heating in the winter, illustrating background levels of pollutants.

The on-site measurements and the background concentration modelling show that none of the potential sites are affected significantly by the air pollution.

10.3. Predictions of future changes of air pollution

In the Lääne-Harju comprehensive spatial plan the future vision of settlement areas is the following:

- PAL site: the city is primarily seen as an industrial and port city that will continue to stay that way. From known big developments in near future, the Paldiski Pumped-Hydro Energy Storage construction will take place in the city of Paldiski. Most of the infrastructure will be located underground and the project will not have an important impact on the air quality.

- ALT and PED sites: the closest settlement mentioned is the Harju-Risti settlement where areas of land are mentioned as potential development areas with mixed functions. The forest in the eastern part of the settlement has an important recreational function that must be preserved.

According to the green network plan of the Lääne-Harju municipality all three locations are situated on or next to the supporting areas of the green network: the PAL site next to the Pakri peninsula support area, the ALT site next to Pedase-Kurkse support area and the PED area is located on it. The probability of large-scale industry or other developments (infrastructure) is unlikely. In case of new developments, the assessment of air pollution in combination with existing background emission sources has to be conducted and the developments must conform with the national limit values.

Since currently the information available is on conceptual level, the detailed project solutions for the disposal facility are unknown, certain assumptions, generalizations and simplifications have been made in order to assess the possible impact on atmospheric air quality

In terms of atmospheric emissions, the construction and closure phases are the most important. The operational phase in between, which mainly includes transport and emplacement of radioactive waste inside the facilities, does not have an important impact on atmospheric air quality since the above ground facilities will be covered with weatherproof shelters and equipped with a gantry crane for unloading the waste packages. The crane as well as the administrative buildings (heating, ventilation) on site will be operating on electricity which is not accompanied by emissions to air. Therefore, the impact of operating the facility on the atmospheric air is considered irrelevant and will not be assessed further.

During the closure phase, the facilities will be finalized according to the conceptual design: the shaft of the IDDF will be backfilled with clay and the NSDF will be covered with multiple layers using excavated soil and transported construction materials (clay, sand, gravel, boulders). The handling of these materials may generate particulate matter (or dust) emissions to some extent during the closure works. However, considering the relatively small amounts of materials needed and the temporary duration of the works, these emissions do not pose an important effect on (long-term) air quality. In addition, appropriate mitigating measures can be applied when necessary. These measures would include:

- the use of sprayed water cannons to wet the handled materials;
- using the gantry crane from the operational phase to transport the backfilling materials to needed location;
- performing the (back)filling operations under a covering tent to limit the transmission of dust particles;
- avoiding dusty operations under strong wind conditions when possible.

The applicable mitigating measures are need-based, meaning that the appropriate solution will be applied according to the current conditions of the situation.

Considering the description above, there are two main sources with relevant emissions to be expected: fuel consumption of the machinery used for construction and closure works of the repository and transportation of construction materials.

10.3.1. Emissions from construction equipment

The diesel-powered construction equipment is considered as fuel combustion sources from which the emitted emissions are estimated. The fuel consumption of selected machinery and other working parameters are presented in Table 10.2 while the estimated emissions of the main pollutants from diesel fuel are presented in Table 10.3

Table 10.2. Parameters of selected diesel-powered construction machinery

Emission source	Source units	Average fuel consumption, kg/h*	Working hours, h	Efficiency factor	Nominal heat output B_1, MWth
Excavator	1	9.6	1680	0.35	0.33
Soil compactor	2	10.4			0.35
Vibratory roller	1				

Table 10.3. Calculated exhaust emissions of main pollutants for the construction machinery.

Pollutant	Specific emissions of diesel fuel, g/GJ	Instantaneous emissions, g/s	
		Excavator	Soil compactor / vibratory roller
Nitrogen dioxide (NO_2)	111	0.036	0.039
Carbon monoxide (CO)	42	0.014	0.015
Non-methane hydrocarbons (NMHC)	5	0.002	0.002
Particulate matter (PM_{10})	40	0.013	0.014
Sulphur dioxide (SO_2)*	based on sulfur content	0.0001	0.0001

* For diesel fuel, the allowed content of sulphur is ≤0.10 %.

10.3.2. Emissions from transport

In addition to construction activities taking place within the facility area, transport can also be considered as a source of pollution. Emissions from transport depend mainly on the traffic intensity, but also on the type of road surface, driving speed, vehicle fleet composition (vehicle categories, age and proportion of heavy traffic, fuel type and consumption), driving speed, the width of the road etc.

The report of sub-activity 2.15 estimates the traffic increase from transportation of various materials for the construction of the facility and radioactive waste to be disposed of. The estimation, based on a conservative approach, is as follows:

- During the construction of the facility, the transport of construction materials (mainly concrete) to the disposal site is needed, in total of 207 truckloads averaging to 2 truckloads/day during a 120-day period.

- During the operational phase, the transport of radioactive waste containers and the reactor vessels along with concrete for grouting will be executed, in total of 264 truckloads averaging to 1 truckload/day (for one year period) or 8 truckloads/day (for one month period).
- During the closure phase, inactive construction materials, such as clay, sand/gravel, boulders and concrete, will be transported to the disposal site, in total of 384 truckloads averaging to 5 truckloads/day during a 120-day period.

Therefore, the transport related to the disposal site during different phases of the project varies between 1 to 5 truckloads/day. The abovementioned traffic intensities are rounded up calculations which means the effect of transportation will not be any greater and in reality, even smaller (conservative approach).

For the operational phase the increase in traffic is minimal and even if done during a one-month period, the value is an overestimation. If the transport is extended for the longer period e.g., year, then the impact is decreased.

All vehicles moving on publicly accessible roads have to meet technical standards and exhaust emissions are normalized by EURO standards. Therefore, emissions from transportation are out of scope of current assessment and will not be analysed for such relatively low traffic volumes. In addition, taking into consideration that the construction of the facility will start around the year 2030 or later, the emission standards are probably even stricter than today, and thus the impact from road transport smaller. Therefore, the traffic emissions from operational phase are not assessed any further.

According to the report of sub-activity 2.15 the public road sections with gravel surface leading to the ALT and PED sites are suggested to be stabilized and covered with a permanent cover. In such cases, the particulate emissions from the road surface are negligible. The road leading to PAL site (Leetse tee) has been recently reconstructed with a permanent cover.

However, all the three locations need access roads to the disposal facility of different lengths. The on-site roads are temporary, e.g., they will not be used after closing the facility. The roads can be constructed as asphalt roads, but for the modelling using a conservative approach, the on-site roads are inputted with gravel surface as sources for fine particulate matter emissions. The assumed parameters of modelling emissions from on-site roads are listed below:

- PAL site: an additional road about 200 m long, 6 m wide;
- ALT and PED sites: an additional road about 500 m long, 6 m wide.

All three alternative locations require the same amount of construction materials. Considering a daily 12-hour period for transport of materials, the average traffic intensity for construction and closure phase is 0.42 truckloads/hour. For a 6-m wide road, the instantaneous emission for the on-site roads used in modelling equals to $1 \cdot 10^{-6}$ g/m$^2 \cdot$s.

For modelling the dispersion of atmospheric pollutants, the most important weather parameter that influences the dispersion is wind speed and direction. Other weather factors, like temperature, sunshine, relative humidity etc. influence the effect on the dispersion, but to a lesser degree.

As the construction works at the sites are of relatively low intensity the emissions from the construction/closure phases do not have an important impact on the air quality. None of the limit values of modelled pollutants are exceeded and the modelled situation conforms with the national regulations. The level of air quality changes minimally at the surroundings of the sites when compared to the existing background concentrations.

The nearest sensitive areas (households) are located quite far from all of the alternative sites; therefore, it is not likely that the concentrations would exceed limit values even if real life conditions (e.g., strong winds from unfavourable direction) would deviate from the modelled averages.

The highest concentrations are associated with CO and NO_2 emissions, however the maximum values are at least 50 times and 1.4 times lower than the national limit values, respectively. The extremely low values of SO_2 concentrations are due to the low allowed sulphur content in diesel fuel (<0,1 %). The rest of the concentrations are in good correlation with the existing background levels of air quality. The modelled values at the PAL site were slightly higher than at the other locations due to the existing background sources in the area, but the difference is insignificant.

Considering the existing background emissions, the construction and closure activities have very little or no impact at all on the air quality level at the nearest residential areas of the alternative locations. Hence, application of mitigating measures is currently not necessary. In case the activities of the different phases of the project are specified in later stages, the emission of pollutants can be re-evaluated.

10.4. Summary

The phases of the project (construction, operation, closure) are all similar for the three sites compared, except for the necessary transport of radioactive waste from the PAL site to ALT and PED sites. In the current context of the assessment, on-site construction works and transport of required materials are considered as the relevant sources of pollution.

According to the results of on-site measurements, the existing air quality level at the three locations is quite good and none of the observed pollutant concentrations exceed the limit values. The measured results depict dispersed pollution from various background sources like industry, transport and local heating, and are not associated with a certain activity or source. The measured values of pollutants correlate to the typical seasonal changes in air quality.

From the available spatial planning documents possible future developments do not impose an important change in air quality level around the three alternative locations.

The emissions to atmospheric air from the construction and closure activities of the repository were calculated and modelled around the sites. The effect of the operational phase of the project was considered negligible and was not included in the assessment. Since currently the design of the repository is on a conceptual level, a number of assumptions were made. From the ambient air dispersion maps it was seen that none of the concentrations of the select pollutants exceeded the national limit values. The maximum modelled values appeared at the sites while at the nearest sensitive areas (households) the level of air quality is similar to existing background levels. All of the three alternative locations are located quite far from the nearest sensitive areas that results in good conditions for pollution dispersion.

All three alternative locations are equal in terms of air pollution. The effect of construction and closure phase of the repository on the existing air quality level is minimal and application of mitigating measures are not necessary. If the activities related to air pollution are specified in the later stages of the project, the emissions can be re-evaluated.

10.5. Conclusions

1. According to the results of on-site measurements, the existing air quality level at the three locations is quite good and none of the observed pollutant concentrations exceed the limit values.
2. All three alternative locations are equal in terms of air pollution. The effect of construction and closure phase of the repository on the existing air quality level is minimal and application of mitigating measures are not necessary.
3. It was found that none of the concentrations of the select pollutants will not exceed the established limit values.
4. Future developments at the potential sites do not impose an important change in air quality level around the three alternative locations.

11. Sub-activity 2.11. Study of the climatic conditions

The main goals of the study were to determine the climatic conditions of the three potential locations and to describe the impact of climate change on the potential sites and the disposal facility in the long term, as well as the associated risks.

No fieldwork was conducted during the analysis and all works were done in desktop mode. The detailed results are presented in an Appendix 11. The work was performed by Mait Sepp (University of Tartu).

11.1. Climatic conditions of the study area

Landscape-wise, Lääne-Harju municipality is located on the border of two landscape districts: the eastern part of the study area (Pakri peninsula and its surroundings) is in the Harju Plateau and the western part (Harju-Risti, Vihterpalu) in the West Estonian Lowland. PAL is entirely located on the Harju Plateau, as PED and ALT are in the lowlands of Western Estonia.

There are two main questions about a more accurate analysis of the climatic peculiarities of alternatives to disposal sites. The biggest obstacle is the lack of long-term and reliable observational data: there is only one continuously operating weather station in the study area. The data of the Pakri weather station can be extrapolated across the Pakri peninsula, but the data from only one station is not enough to assess the climate of other planning sites. Second, it can be argued that possible features of local climate cannot be decisive in the choice of alternatives to the disposal of radioactive waste, since the climate of the entire region is determined by the fact that Lääne-Harju municipality is located directly on the coast.

The climate of Lääne-Harju municipality has not been directly studied previously. The whole region has a more marine climate and is milder for weather conditions than the Estonian average:

- The average annual air temperature is 5 °C, the coldest month is February, with an average temperature of -5 and a lowest -34 °C. The warmest month is July (average 16.5, maximum of 33 °C);
- A permanent snow cover occurs in early January and ends at the end of March. The period with permanent snow cover lasts 90-100 days a year;
- The average annual wind speed is 5-6 m/s. The winds are predominantly from the west;
- Since all three alternative areas are located relatively close to the seashore, it is unlikely that there will be significant differences in precipitation in these places.
- Based on the data presented in the "Estonian Radiation Climate Guide", it can be assumed that the indicators of several radiation regimes in the study area (e.g., UV index, duration of sunshine, etc.) have somewhat higher values than the Estonian average. As with precipitation, the decisive factor here is that there are fewer clouds on the coast than inland. Given the location of the three alternative areas, it is unlikely that there will be significant radiation regime differences between them.

According to previous studies, high wind speeds and drought may be common climate risks of the region.

11.2. Methodology

The weather data analysed in the study are obtained from the Estonian Environment Agency. The data of automatic weather stations (since 2004) were downloaded from the website of the Environment Agency "Weather" and previous data was obtained from the customer service of the Environment Agency.

The period analysed was 1966-2021. The periods 1971-2000 and 1991-2020 have been studied separately. The work separately outlines the climate norms in force at the national level, which are found for the period 1991-2020. Weather stations used:

- Pakri weather station,
- Lääne-Nigula weather station (for reference),
- Kuusiku weather station (for reference),

In general, the quality of the data is poor: there are significant gaps in observation rows, the places and methodologies of observation have changed. To alleviate homogenity problems, the average calculated based on data from the Pakri, Lääne-Nigula and Kuusiku weather stations, i.e. the climate conditions of Northwest Estonia have been used.

Since the planned disposal site for radioactive waste is an artificial installation in terms of land use, it can be assumed that all or at least a large part of the area of this site will be of the type of landcover that could be considered to not bind greenhouse gases under the LULUCF principles. As mentioned, the environmental performance of the object in this case depends on many planning, architectural and engineering decisions. Based on the idea of LULUCF, the overall objectives when planning the disposal site should be the potential energy efficiency of the site and the minimum possible land use change. When choosing the best site, it is necessary to consider the smallest possible impact on carbon-sequestering communities, as few new artificial surfaces as possible, and as much high greenery should be preserved as possible.

11.3. Results

11.3.1. Air temparature

The long-term average annual air temperature in Northwest Estonia is 5.1-6.7 °C, depending on the period and station. The average annual minimum and maximum temperatures are within 1-4 and 8-9 °C, respectively. In general, all average temperature indicators have increased by about 0,8 °C over the period of the old and current normal climate.

11.3.2. Length of vegetation period

The long-term average length of the frost-free period is (depending on the period and the station) 133-194 days. At the same time, the closer to the sea the station is located, the longer the period. The length of the general vegetation period is 179-196, and the length of an active period is 124-138 days. The lengths of all vegetation periods have increased somewhat in recent decades.

11.3.3. Precipitation

Long-term annual precipitation amounts are (depending on the period and station) 560-745 mm (Figure 11.1). In general, there is less rainfall in the coastal region.

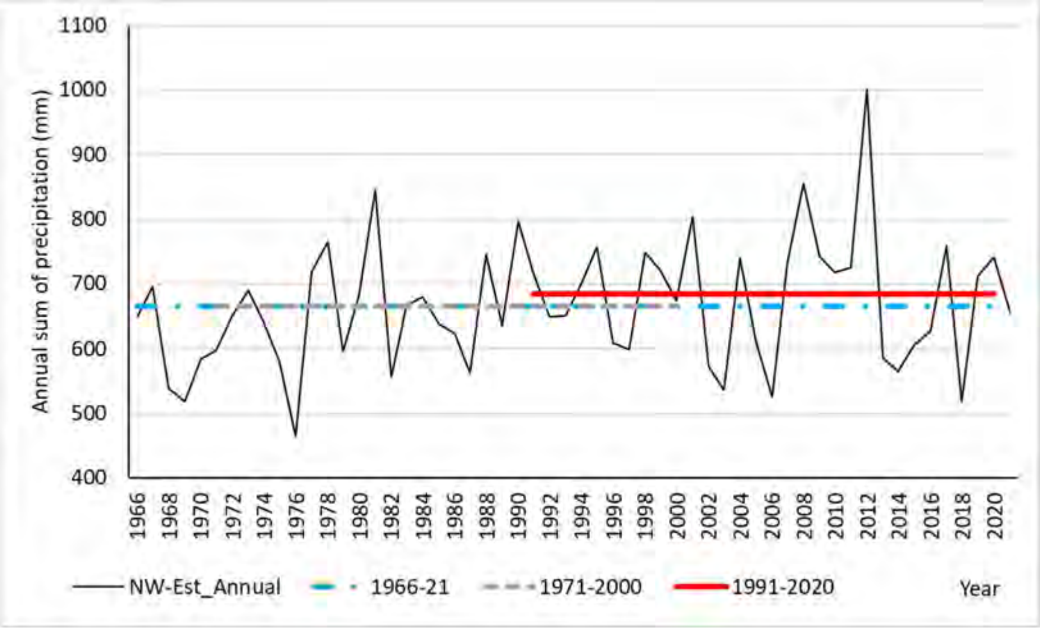


Figure 11.1. The annual rainfall amounts in Northwest Estonia in the period 1966-2021 and the

The average snow cover duration is 90-100 days, and the average maximum water reserve is in the range of 20-50 mm. In general, precipitation has increased in recent decades, but this change is small against the intra-annual variability. A risk of flooding is greater for site ALT.

11.3.4. Wind

The quality of wind data (Figure 11.2) is poor, as the location, observation tools and methodology of the weather station have been repeatedly changed during the period under consideration.

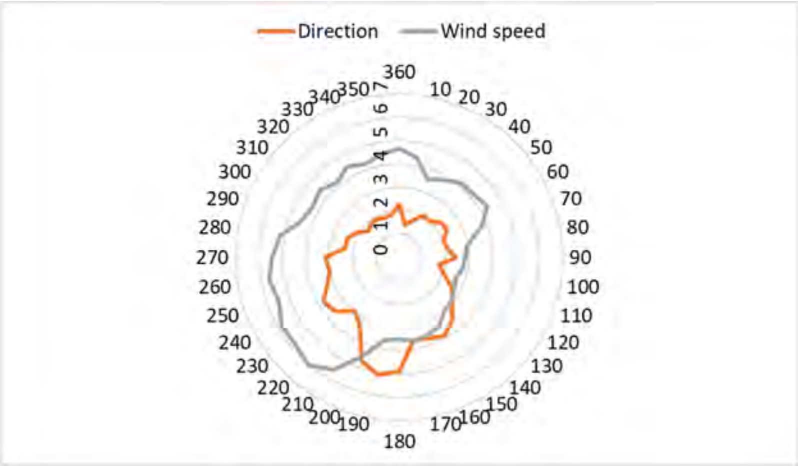


Figure 11.2. Wind directions and average wind speeds measured at the Pakri weather station in the period 1991-2020 by sectors of 10 degrees. The wind direction is given as a percentage relative to all the times of measurement and the wind speed in m/s.

A tendency in recent decades has been a decrease in average wind speeds. Thus, earlier in the literature, the average annual wind speed has been indicated as 5-6 m/s, while here it is 4.1 m/s. Both completely windless and storm days are in Pakri for about 1% of all days.

11.3.5. Solar radiation indicators

As the radiation regime depends largely on cloudiness, the radiation indicators in the study area are somewhat higher than the Estonian average.

The amount of sunshine for a long-term year here is in the order of 1900 hours (Figure 11.3). Annual average albedo 27.5%. The sum of the annual radiation is in the order of 3,500 MJm^{-2}. The number of days with sunshine is 253.

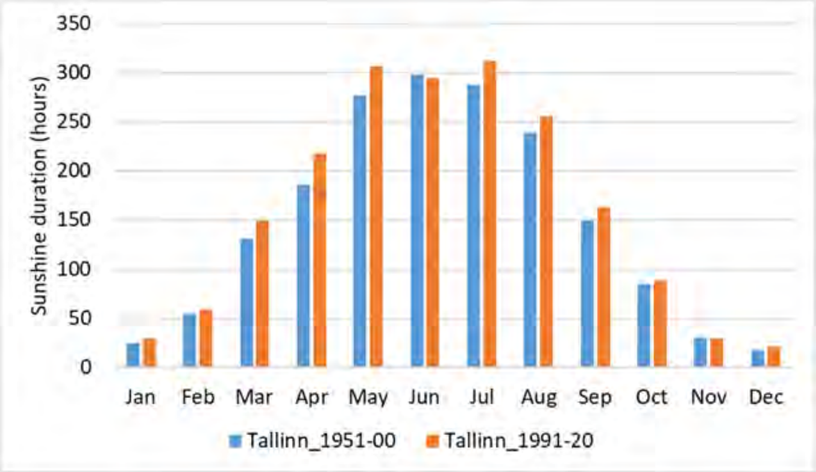


Figure 11.3. Monthly average amounts of sunshine duration (in hours) measured at the Tallinn-Harku weather station in the periods 1951-2000 and 1991-2020.

11.3.6. Actual and potential evaporation

Evaporation is one of the most complex weather indicators in climatological terms, since the process of evaporation of water in nature depends on a combination of many meteorological, biological and landscape factors. Since evaporation depends on several landscape factors, there can potentially be a significant difference between alternative areas. From a practical point of view, these differences are likely to be less than the variability between the years of evaporation.

The long-term average annual sum of the total evaporation is 358 mm in North-West Estonia. The sum of the long-term average potential evapotranspiration in Northwest Estonia is 575 mm.

11.3.7. Weather extremes

As all three location alternatives of the disposal site are located relatively close to the sea, the incidence of extreme (≥ +30 or ≤ -30 °C) air temperatures here is much lower than in the internal areas of Estonia. Based on Estonian weather records, it cannot be ruled out that extremely low temperatures (below -40 °C) may also hit the region in the long term. Against the background of global warming, the incidence of very high air temperatures has increased in recent decades. It is quite likely that in the long term, extreme summer temperatures can reach +40 degrees.

In the case of extreme precipitation, it is necessary to consider their high spatial and temporal randomness. This means that in the long run, any alternative disposal site could be hit by extreme rainfall.

The impact of extreme rainfall on the object depends on the terrain, water drainage systems and the engineering solutions of the object. From a landscape point of view, ALT and PAL may be at a disadvantage. Near the first there are plane areas with high groundwater level, where flooding can occur. PAL is located on a relatively flat plateau, where rapid drainage of large amounts of water may be difficult.

In the case of PAL, the above-average risk of drought must also be considered.

Due to the geological characteristics of the area, the risk of erosion is very low. Wind erosion (deflation) is associated with high wind speeds and is a serious natural hazard in many parts of the world. There is some theoretical possibility that deflation could damage the capping system of the NSDF. However, this phenomenon depends primarily on soil properties and moisture conditions and is mainly a problem in regions with an arid climate. In regions with a boreal climate, such as Estonia, deflation usually occurs only when incorrect tillage techniques are used in agriculture. From the point of view of the planned object, it is important that there are no open areas without vegetation. For example, the preservation of the forest around ALT and PED or the establishment of high greenery around PAL excludes any possibility for wind erosion. Vegetation must also be given great attention when designing the capping system of the NSDF.

In general, the risks of so-called summer storms in the study area can be considered very small but cannot be excluded. Given their temporal and spatial randomness, it may be quite likely in the 500 and 1000-year perspective that some tornado will also hit the disposal site of radioactive waste, regardless of its choice of location.

The risk of hail damage to the object is extremely low and theoretically possible only during the period of operation of the facility. However, it is extremely unlikely that during these 10-15 years the facility will be hit by hail that would cause material damage or disrupt the normal functioning of the facility. There is no reason to believe that hail could affect the disposal site in any way after the closure of the facility.

In the long term and against the background of rising sea levels, coastal erosion can become a significant problem. In a 500-year perspective, sea levels may rise so high that it threatens the ALT area.

Based on the measurements made at the Tallinn-Harku meteorological station, it can be stated that negative temperatures can reach a depth of 80 cm and probably deeper.

To the extent that this may affect the choice of the site, it requires a separate construction geological analysis.

11.3.8. Impacts of climate change on the region

The analysis of climate change took a look at the climate change that has already occurred in the period 1966-2021 (Figure 11.4) and the projected changes by 2100. The average annual air temperature has risen by 2.4 degrees according to the trendline, especially the winter months have warmed up rapidly; the vegetation period has increased. Rainfall amounts have generally increased, but since the variability between years is very large, the result may depend on which period is analysed. Average wind speeds have decreased. The occurrence of storm surges has decreased, but their strength has increased. There is a clear downward trend in snow-related statistics.

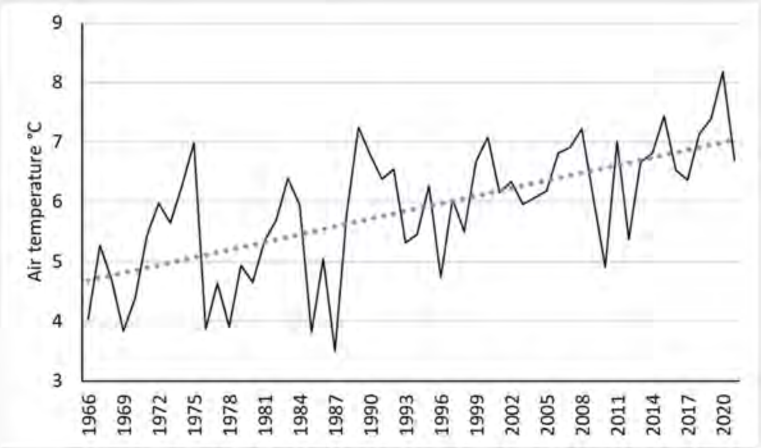


Figure 11.4. Average annual air temperatures in Northwest Estonia in the period 1966-2021 and a linear trendline.

The climate in Estonia has warmed rapidly over the past half century, and the average annual temperature has risen by about 2 degrees. Forecasts for the future predict the continuation of warming with its accompanying processes: an increase in the amount of precipitation and storminess, a shortening of winters and an extension of the vegetation period.

A more direct threat of climate change to the planned disposal sites is sea level rise and the resulting intensification of coastal erosion. Of these factors, the area potentially most at risk is ALT. PED may also be at risk if the most pessimistic future scenarios materialize.

11.4. Weather-related risks for the disposal of radioactive waste

Weather-related risks are relatively low in the research area and their impact can be easily reduced by engineering and planning techniques. It can be assumed that the risks outlined below are the same in the PAL and PED and ALT areas. The main risks are as follows:

- Low air temperature. Although the study area has a relatively milder climate than in Estonia in general, it is necessary to consider the possibility that in winter there may be an air temperature of ≤ -30 °C. Thus, the planned object must have a well-thought-out and active heating system that would remain in working order even in the event of prolonged cold waves. In the coming decades, the risk will decrease, but will not disappear.
- High air temperature. Although the study area has a relatively milder climate than in Estonia in general, it is necessary to consider the possibility that in summer there may be an air temperature of ≥ +30 °C. Thus, the planned object must have a well-thought-out and active cooling system that would remain in working order even in the event of prolonged heat waves. In the coming decades, the risk will increase.
- Extreme snow conditions. Although the study area has a relatively milder climate than in Estonia in general, it is necessary to consider the possibility that in winter there may be acute snowfalls and drizzles, which paralyze traffic and cut off the external

power connection. Thus, the planned object must have an autonomous power supply, which will allow the normal continuation of activities even in isolation and without external electrical power. In the coming decades, the risk will decrease, but will not disappear.

- Summer torrential rains. Although the study area has relatively less rainfall than in Estonia in general, it is also necessary to consider the possibility that the region will be hit by heavy rainfall. Thus, the planned object must have a well-thought-out and functional water drainage system that would prevent local flooding from occurring. In the coming decades, the risk will increase.
- Spring high water and summer floods. In general, the study area is not threatened by flooding by rivers, but when choosing the location of the object, it is necessary to consider the risk that during spring high water level in the rivers rises much higher than the annual average. However, the overall risk from floods is minimal. When constructing an object, the hydrological network of the area must be thoroughly examined, and a functioning drainage system must be established. In the coming decades, the risk from spring high water will decrease, but will not disappear, the risk of flash floods will increase.
- Drought. In the study area, drought is more likely to occur than the Estonian average. This may interfere with the availability of domestic water, especially when surface water is used. In the coming decades, the risk will increase.
- Windstorms. The study area is windier than the Estonian average, the average wind speeds are higher here and windstorms are more frequent. Average wind speeds of 25 m/s for 10 min and gusts of ≥ 30 m/s must be considered. The main danger lies in power outages; therefore, the planned object must have an autonomous power supply, which allows the normal continuation of activities even without an external source; external electrical connections should be built as underground lines. When constructing buildings, it must be considered that storm winds occurring here can cause damage to buildings. In the coming decades, the risk will increase.
- Stormwater. If the adverse circumstances coincide, the sea level in the study area may rise by up to 2 m, and this will flood extensive beach areas. The risk will increase in the coming decades. Along with rising sea levels, this risk will change to a large area of ALT in the 500-1000 yr perspective.
- Tornadoes and other summer storms. In the perspective of 500-1000 years, it is likely that the object will be hit by summer storms and will not depend on the location of the disposal site. However, it is unlikely that this would result in significant destruction if the facilities are planned to withstand gusting winds of ≥ 30 m/s.
- Thunderstorm. The study area has a lower-than-average risk of thunderstorms in Estonia. With modern lightning protection systems, the risk from lightning strikes can be effectively mitigated. Somewhat more dangerous may be other extraordinary natural phenomena accompanying convective clouds (gales, torrential rains, hail).
- Hail. The study area has a lower risk of hail than the Estonian average. However, in the perspective of 500 to 1000 years, the possibility cannot be ruled out that the disposal area will be hit by some incident of hail, which can cause certain damages to facilities.

- Freezing of the soil. In general, the risk of frost heaving in the study area is lower than in the Estonian average. However, at depths of both 20 and 80 cm, negative surface temperatures can occur in harsher winters.
- Sea level rise. As the climate continues to warm, Estonia will start to lose land due to the rising sea level. The rise in the water level itself is relatively imperceptible – the change is a few millimeters per year. In the short term, however, rising sea levels act as one of the leverage forces of coastal erosion. In the coming decades, the risk will increase. However, in the perspective of 500-1000 years, the loss of land due to rising sea levels can be significant. This can directly threaten the area ALT.
- Coastal erosion. As a result of rising sea levels due to climate change, coastal erosion is intensifying. When adverse circumstances coincide, this process can be extremely extensive for some storms. In the coming decades, the risk will increase. In the short term, it does not threaten any planned disposal site. However, in the perspective of 500-1000 years, both ALT and PED are threatened.

Thus, the risks can be divided into short-term (0-5 years at the time of construction of the site), long-term (0-500 years during the operation of the disposal site) and ultra-long term (500-1000 years). In Apendix 11, the frequency of climate risks during these periods is indicated on a relative scale: excluded (the occurrence of an event is not possible during a given period), not excluded (risk is negligible, but not excluded), common (an event that is likely to occur during the period under consideration), normal (an event that probably occurs during the period under consideration). Three alternatives to the disposal sites have been compared. As the alternative areas are located relatively close to each other, there are no significant differences in terms of risks. In the ultra-long term, more serious problems may arise with the ALT area due to rising sea levels and the risks it entails (coastal erosion, stormwater rise).

All three locations have an unsignificant climatic differences, since the weather conditions in the entire region are determined from the immediate vicinity of the sea. Given the effects of climate change and the possible locations of the object, more attention should be paid to the increase in predicted wind speed and storminess when developing PAL. The Pakri Peninsula is somewhat more open to the winds than the alternative PED and ALT. In the case of the latter, flooding from stormwater and a combination of sea level rise can be identified as a threat in the long term. Namely, the ALT's height above sea level is 5 m (PED is about 16 and PAL 22 m). ALT, as well as PAL alternatives, can be dangerous due to very intense rainfall. This means that some attention should be paid to the design of drainage systems in these areas.

In the descriptions of the main weather risks presented in the previous chapter, it has been repeatedly emphasized that in the event of a storm, as well as other extreme weather phenomena, the electrical connection may be lost. This can become a significant problem, which, however, can be solved by duplicating electrical systems, backup generators and underground communications.

In the case of PAL, the risk of frequent droughts has also been highlighted, but this is unlikely to be a critical shortcoming for the functioning of the radioactive waste disposal site.

11.5. Conclusions

Based on the analysis, the preferred location for the disposal site is PAL. In this location, climate risks are relatively smaller or easier to manage. The strongest arguments in favor of PAL are the site's suitability for LULUCF principles and resilience to expected sea level rise and its impacts.

Second in terms of suitability would be PED. Its weakness is non-compliance with LULUCF principles. In the long term, this place may also be threatened by the rise of the sea water level and the accompanying coastal erosion.

ALT would be the least desirable of the three alternatives. This also does not comply with LULUCF principles. But in addition, there is some risk of flooding in this site. However, the biggest threat could be sea level rise, the effects of which would reach the ALT site significantly earlier than the alternatives PED or PAD.

12. Sub-activity 2.12. Study of the environment

Objectives of the study were to study features of flora, fauna, habitats, habits of species of the three potential sites proposed for location of the disposal facility. The condition of the environment at the sites and the extent of disturbance as well as possibilities of minimising the environmental impacts during the periods of construction, operation, closure and post-closure should be assessed.

Fieldworks were conducted during the analysis. The detailed results are presented in an Appendix 12. The work was performed by Raimo Pajula (SKEPAST&PUHKIM OÜ).

12.1. Methodology

12.1.1. Vegetation inventory

The purpose of this work was to map and describe the vegetation types of the site alternatives for vegetation. Forest communities were described in terms of both forestry and natural values. The nature conservation values of the sites were also assessed, both in terms of natural plant communities and species protection (protected plant species). The aim of the work was not a detailed forestry or dendrological inventory. During the inventory, the habitats of protected plant species were recorded. Fieldwork on vegetation inventory was carried out on in July 2022 and January 2023.

12.1.2. Fauna inventory

The methodology used for the fieldwork was to fix traces of animal movements and other traces of activity. The areas were walked through, and the location data of tracks and the species of animal were recorded. All traces of movement and activity of animals, such as trail tracks, droppings, sleeping lairs, rooting places, bathing places of pigs, were recorded. The winter trail census was conducted in the area of the location alternatives of Altküla and Pedase in snow-covered conditions. In the case of the Paldiski alternative, no trace counting was done from the snow, as the area is surrounded by a fence and large mammals cannot access the area. For all traces of movement and activity, their location was recorded using a hand-held GPS device, the species of animal and the number of specimens were recorded. Fieldwork on the fauna inventory was carried out on July 2022 and on January 2023.

The assessment of the likely larger-scale movement patterns of fauna in the area of location alternatives was also based on the region's green network dataset – the location of support areas and green corridors relative to location alternatives.

Data from national game monitoring and game hunting statistics were used as background material, i.e. to get an overview of the game fauna in the wider area.

12.2. Results

12.2.1. PAL location

All in all, the Paldiski location alternative area is dominated by vegetation that has spontaneously developed on glacial lands and grassland areas. Half of the area (14.7 ha) consists of open or tree-and-shrub glacial lands and grasslands. Spontaneously formed and mostly relatively young forests cover nearly a quarter (5.6 ha) of the area. A fifth of the area (6.2 ha) consists of a maintainable (mowed) green area in the built-up area, together with high greenery.

The site has value as a green area but given the wide distribution of natural or semi-natural areas in the surrounding area, the value of this area is relatively small. The plant communities spreading in the area do not have any value as a nature reserve.

The fauna of Paldiski's location alternative, especially the mammalian fauna, is strongly influenced by the fact that the area is surrounded by a concrete fence, which most mammal species cannot cross. Climbing species such as toadstools and squirrels are likely to escape. Only small mammals, such as mice, are likely to crawl through between the panels that make up the garden. Therefore, there are no major players in the area. There are suitable habitats for both roe deer and wild boar in the area, but no traces of activity of these species were detected in the area, which is explained by the fact that cloven-hoofed animals simply cannot enter the area.

The area of the Paldiski location alternative is not included within the green network area defined by the Harju County Plan 2030+ (Figure 4), nor will it remain in the area of the green network to be specified in the general plan of Lääne-Harju Parish. The Paldiski area is bordered by a green network on both the northeast and northwest sides, but does not overlap with it. The area would not qualify as a green network area as it is fenced.

12.2.2. ALT location

The area of the Altküla location alternative is located throughout the forest landscape. Just over half (6.3 ha) of the area is made up of middle-aged until mature forests. About a quarter (2.8 ha) are fresh clear-cut areas and nearly a fifth (2.2 ha) are juveniles. The area is a managed forest, there are no natural forest communities. More valuable in type are the sloping and boggy forests located on the lower relief forms. The forest communities spreading in the area do not have a nature conservation value.

Five habitats of protected plant species were found in the Altküla location alternative area. The protected species found in the area are relatively common in the area, and the conservation value of the small collections found is relatively small.

The game fauna of the area is relatively abundant, which is due to the landscape articulation of the site (the distribution of different forest types and age groups) and its location near the boundary between the larger forest array and the agricultural landscape.

12.2.3. PED location

The area of the Pedase location alternative is practically entirely covered by woodland, only the northern edge of the site is about 10 m wide in the local road. Most of the area is covered by pine and spruce majority creative forests, which belong to the type of place of growth of the caste log. To a lesser extent, there are meso-eutrophic boreo-nemoral hillock forests belonging to the blue-flowered habitat type. A small part of the area is made up of fresh clear-cut areas.

The Pedase location alternative area is a pine or spruce majority coniferous forest, which belongs to most of the caste species and to a lesser extent to the liverwort habitat type. Forests are mostly middle-aged or ripening, in a smaller part mature. In its entirety, these are the economic forests of the country. Forests meeting the criteria for forest habitat types protected by the Habitats Directive were not identified in the area, nor were sites corresponding to the characteristics of precious habitats found. Individual older forest allocations, the stands of which have a more natural structure, have the potential to develop into a type of forest habitat old natural forests in a perspective of about 30 years (if they are not affected by logging, which is not likely in the area).

In the Pedase site, one site of the bird’s nest orchid (*Neottia nidus-avis*) of a protected category III plant species was identified.

The Pedase location alternative area is in the forest landscape around a large forest array. There are no agricultural landscapes in the vicinity of the site. Area on the southern border runs the target of the high-voltage line. The area is relatively homogeneous in terms of forest types and age group, with spruce and pine as the main trees, and relatively few deciduous trees. These circumstances rather reduce the assumptions for the species richness of the fauna.

The area's game fauna is characteristic of a large coniferous forest array, but species abundance is probably not high. Branch forests with relatively homogeneous in age and type are relatively poor feeding areas for several game species. Apparently, the low winter abundance of cloven-hoofed animals is also due to the lack of juveniles and more humid forest areas. Compared to the Altküla location alternative area, the fauna of the Pedase alternative area is somewhat poorer in terms of both species and specimen abundance.

12.3. Conclusions

The most preferred alternative from the point of view of vegetation is the existing location of PAL, as the area has been heavily influenced and redeveloped by human activity, and the secondary vegetation cover formed on the site does not have a significant natural value.

The second-best alternative is ALT, in which a managed forest landscape is spreading, a large part of which consists of a recent clear-cut area and a forest glade. The area is of some natural value due to the swampy and overgrown forests. Due to the forest communities found in the site and the protected orchids, the value of the site is higher than that of the PAL alternative, but slightly lower than the value of the PED site, as the forests of the latter are older and less affected by logging.

The worst or least preferred alternative is the PED alternative, as the forest communities found in this area are less affected by logging and have a slightly greater value than the forest communities of the ALT alternative, which are more strongly managed. With the PED alternative, the impacts on vegetation in the form of deforestation would be greatest.

The most preferred alternative from the point of view of fauna is the one with the lowest value as a habitat for fauna and on which the establishment of a radioactive waste disposal facility would therefore cause the least effects.

The most preferred is the existing location PAL, since the area is heavily influenced by human activities as a habitat and is surrounded by a fence, which prevents game from entering the area. Therefore, the area has the poorest fauna of the candidate sites.

The second-best is the alternative location PED, whose fauna is somewhat poorer than that of the ALT area, whose fauna is richer due to its landscape layout and the diversity of the stands. However, the area of the PED alternative is significantly more valuable as a habitat for fauna than the PAL area.

The worst or least preferred alternative is the ALT alternative, since its location on the border of the forest array and the agricultural landscape, together with its alternating age and composition of the stand, results in a richer fauna compared to the PED alternative.

Overall, the PAL site, which has a significantly lower value in terms of both flora and fauna, is significantly better than the other alternatives, and in which the negative impact of biota loss due to development is the smallest.

ALT and PED sites are roughly equivalent in preference since the flora of the ALT site is of lesser value, but the fauna is of greater value compared to the PED alternative. Therefore, with the choice of one or another alternative, the effects on wildlife will be approximately equal.

13. Sub-activity 2.13. Study of the social situation

The purpose of the study was to determine the social situation of alternatives in order to evaluate which pre-selected site is the most preferred. The study was broadly divided into two parts:i) creating a profile of Lääne-Harju rural municipality, and ii) finding out the attitudes of the residents.

The work was performed by Jaan Urb (Cumulus Consulting OÜ). The detailed results are presented in Appendix 13.

13.1. Methodology

The applied methods and investigated aspects are detailed in Table 13.1.

Table 13.1. Aspects that were investigated and methods of data collection

Aspect to be investigated	**Method of data collection**
Social structure of the population – population dynamics, composition, main age groups	Data processing based on population register records
Spatial pattern, distribution of population, location of main public services	Data processing based on the public data of the population register, the Land Board and Lääne-Harju rural municipality
The socio-economic profile of the rural municipality, including employment of residents, entrepreneurship structure, financial indicators of the rural municipality	Data processing based on the data of the Estonian Tax and Customs Board, the Unemployment Insurance Fund, the population register, Statistics Estonia, and the Ministry of Finance
Customs, habits and behaviour of the people in the area	Online survey and focus group interviews
Leisure habits of the population	
Stances and attitudes of the population towards the establishment of a final disposal site	

The largest part of the study was the collection of primary data through a population survey. For this purpose, a request to participate in the survey was sent to the e-mail addresses of all residents of Lääne-Harju rural municipality over the age of 15. The necessary addresses were obtained from the population register. In total 9,058 e-mails were sent out, of which 405 were returned with an error message. Thus, there were 8,653 working e-mail addresses among the recipients. As of 1 January 2023, 13,410 people lived in Lääne-Harju rural municipality, of whom 11,231 were over 15 years old. Thus, an invitation to participate in the survey was sent to 77% of the population of the rural municipality.

The questionnaire was in both Estonian and Russian and it consisted of 16 questions. The first part of the questionnaire was about the respondent's profile, the second about their leisure habits, the third about the awareness of radioactive waste, and the fourth about the respondent's attitude towards radioactive waste. It was mostly a multiple-choice questionnaire, but it was possible to add additional information or comment on almost every question. The questionnaire was drawn up based on the Eurobarometer survey on radioactive waste.

The survey results were analysed in MS Excel by comparing the answers to different questions. The settlement pattern of the rural municipality was also analysed, including the location of residents in relation to three alternative sites. In order to analyse the settlement pattern, the settlement units were grouped into four types according to the number of residents, location, character of the settlement (former cottage areas, existence of a densely populated area according to the comprehensive spatial plan), and area: 1) low density area (number of residents up to 20 people per km2), 2) densely populated settlement (number of residents more than 50 people per km2), 3) densely populated recreation area (number of residents more than 20 people per km2), and 4) the town of Paldiski as a separate unit.

In addition, a binary logistic regression analysis was used to check, whether and to what extent the survey respondents' socio-demographic background, knowledge and attitudes towards radioactive waste shape their preferences regarding their final disposal site. Three regression models were prepared, where preferences (dependent variable) were defined as follows: 1) in the existing intermediate storage site, 2) further than 20 km from my place of residence, 3) the location does not matter as long as safety is 100% guaranteed, 4) somewhere else. Regression analysis was not performed for the option "Further than 5 km from my place of residence" because the number of those who indicated this preference was small. Regression analysis was performed in the program SPSS (Statistical Package for the Social Sciences).

In order to interpret the analysis results, focus group interviews with community representatives were further conducted. The purpose of the interviews was to supplement the survey results with qualitative information, including residents' fears and expectations. The interviews took place in Paldiski and in Harju-Risti.

There were 7 participants in Paldiski (21st of February 2023) and 51 in Harju-Risti (22nd of February 2023). The latter consisted of more participants since the local communities asked their members to take part and protest against the plan to position the deposit site into their neighbourhood. However, after explaining the purpose of the meeting (interview), the questions were answered, and necessary input was given.

Both interviews started with the brief introduction of the necessity of the meetings. The explanation about the planning process was given as well. The analysis report comprises three parts. The first addresses the profile of Lääne-Harju rural municipality, creating a necessary overview of the existing situation. The second part presents the results of the residents' survey, including the profile of the respondents, residents' habits, awareness and attitude. The third part summarises the results of the analysis and presents the main conclusions.

13.2. Results

13.2.1. Profile of the municipality

According to the population register data, 13,410 people lived in Lääne-Harju rural municipality as of 1 January 2023. The average annual change in the period 2008–2023 has been -0.1%. At the same time, it should be kept in mind that it has varied from period to period. Over the last five years, the population has instead grown by 1.6% per year.

The population growth is not evenly distributed within the rural municipality (Figure 13.1). The majority of the growth has been concentrated in the territory of the former Keila rural municipality, where in recent years construction activity has accelerated near the city. The number of residents has also increased in the Padise area. Paldiski and Vasalemma, on the other hand, are shrinking.

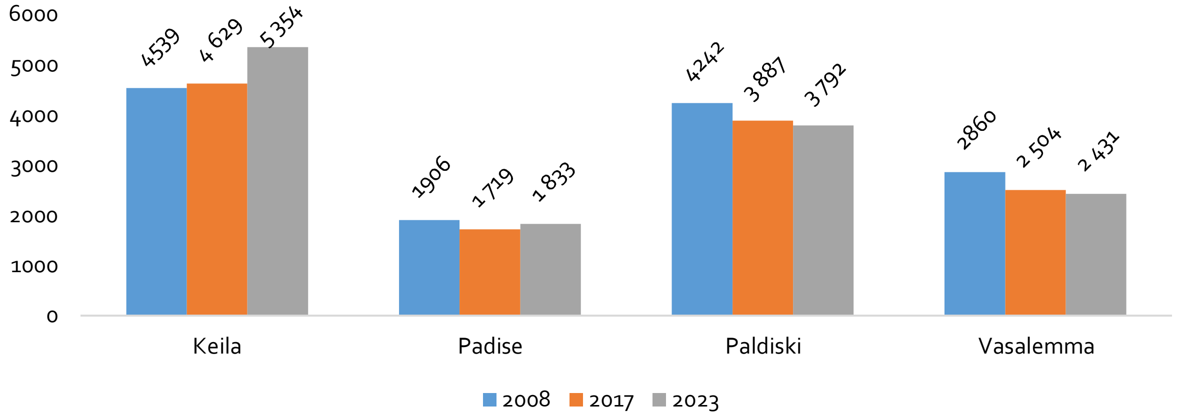


Figure 13.1. Population change by areas.

The distribution of the population by settlement type is shown in the figure below (Figure 13.2). There is a clearly distinguishable tendency where the population has grown outside the larger settlements. Above all, over the last six years, the population of recreation areas has increased (by 25%), but so has the number of people living in low density areas (by 11%). On the other hand, more densely populated units have shrunk.

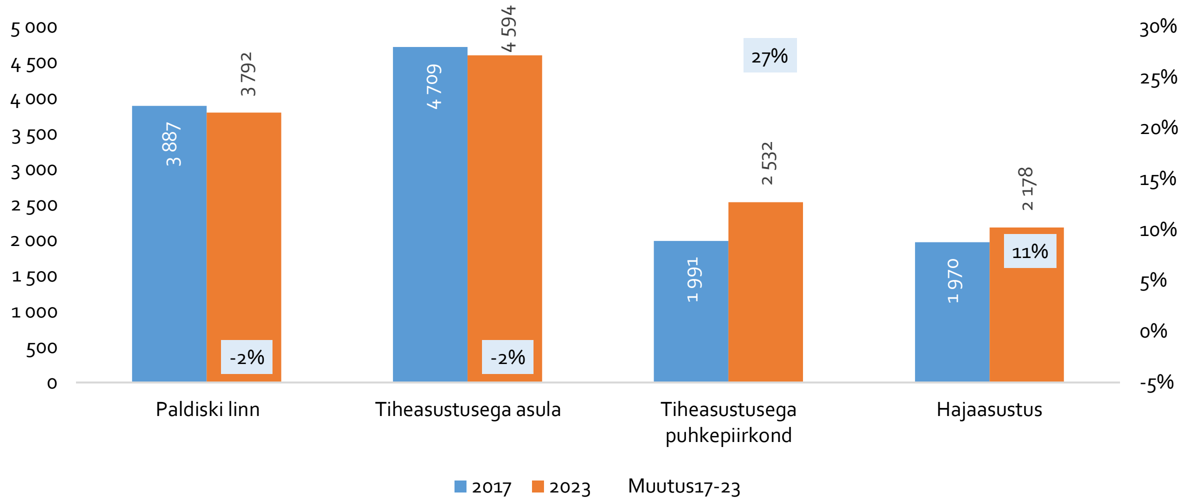


Figure 13.2. Distribution of the population by settlement type (Paldiski town, densely populated settlements, densely populated recreation areas and low density areas).

Lääne-Harju rural municipality is largely a low-density area. The most densely populated areas are the town of Paldiski and larger small towns (Vasalemma, Rummu, Padise, Harju-Risti). Recreation areas (Laulasmaa, Kloogaranna, Meremõisa) are also more densely populated (Figure 13.3). It can be seen that the alternative for the location with the highest population concentration is the existing intermediate storage site, i.e. the town of Paldiski.

Thus, this location has the largest number of potentially affected people. For the other two, it is of the same order of magnitude.

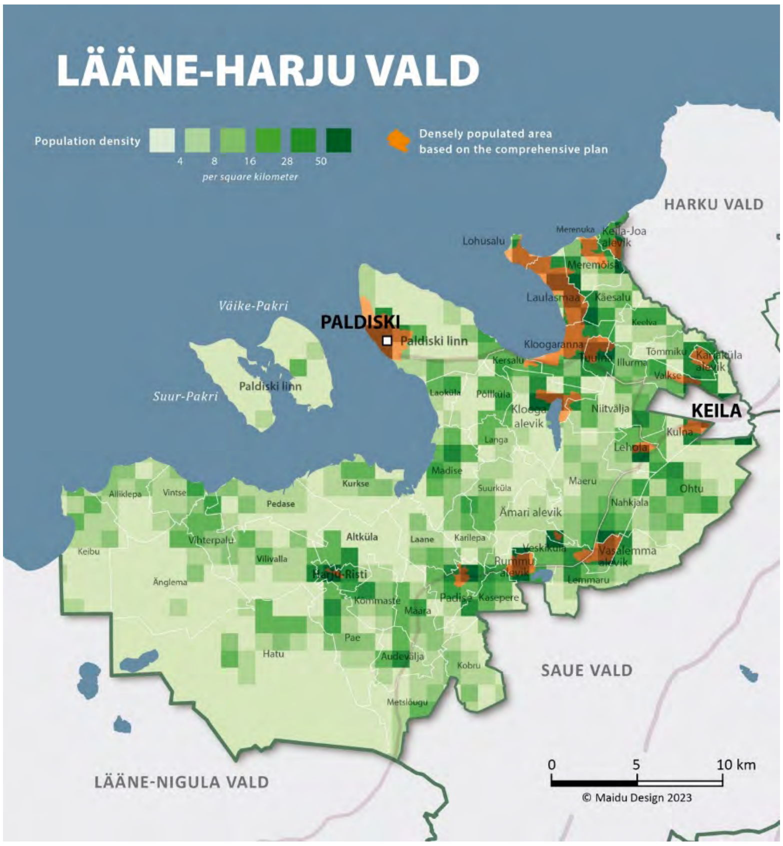


Figure 13.3. Population density in Lääne-Harju rural municipality according to municipality's comprehensive plan.

13.2.2. Results of the survey of residents

Of the 9,058 e-mail addresses sent out, 8,653 were functional. 1,198 people answered the survey in Estonian and 493 in Russian (total 1,691). 1,285 people filled in the questionnaire completely, 923 of them in Estonian and 362 in Russian. Only complete responses have been taken into account in the analysis.

The most respondents were from the town of Paldiski, the least from the village of Tõmmiku (Table 4 and Figure 9). None of the respondents were from Suurküla. A total of 11% of 15-year-old and older residents of the rural municipality responded to the survey.

72% of the respondents filled in the questionnaire in Estonian and 28% in Russian. 45% of the respondents were men and 55% were women. The majority (64%) of the respondents were between the ages of 30 and 59. As expected, younger and older people are somewhat underrepresented and middle-aged people are overrepresented.

The majority of the respondents (61%) are salaried employees, 15% are pensioners, and 10% are entrepreneurs. In terms of the level of education, most of the respondents had secondary vocational education (23%), followed by secondary education (22%). Respondents with a university education (bachelor's, master's or doctorate) constitute a total of 30%.

The residents of Lääne-Harju rural municipality most often spend their free time in their backyard/urban region – 59% of all respondents mentioned this. The next most frequent is spending free time more than 20 km away from the place of residence (34%). Considering the location of the rural municipality, this most likely means the city of Tallinn. Picking berries/mushrooms in the surrounding area is also popular. Therefore, it can be said that for the residents of the rural municipality, spending time where they are located is important – as such, what is happening in the surrounding area is also important to them.

The focus group interview in Paldiski showed that less free time is spent in the town itself. As many are working in Tallinn, they also tend to spend their free time there. At the same time, several sports opportunities (swimming, football, etc.) have been created for the younger population, which are being actively used. There are also community events (town days, fairs, etc.). One way to spend free time is hiking, barbecuing, etc. in the surrounding recreation areas.

The interview in Harju-Risti showed that the main ways to spend free time are related to working in the garden and being in nature. Mushroom and blueberry forests of the Nõva and Risti regions were highlighted as important destinations. Thus, on-site discussions confirm the survey results – local nature is important to residents.

In general, it can be said that awareness of radioactive waste is not high. 8% of all respondents consider themselves to be very knowledgeable, while there is the same order of magnitude of people who are not informed at all (10%). 31% of the respondents have very little awareness and 52% of the respondents know something. Thus, the awareness of 40% of the population of Lääne-Harju rural municipality is very low according to the respondents themselves. This must be kept in mind when communicating future activities. It is difficult, if not impossible, to talk about the establishment of a final disposal site for radioactive waste if many people do not know what it is and what it entails.

In two aspects, the answers were very clear – disposal of radioactive waste should be resolved in the near future (average rating 8.9 on a 10-point scale) and should not be left to future generations. In other aspects, the variability of responses is greater. It also appears that according to 40% of the respondents, there is no safe solution for disposal. This is also confirmed by the opinion that the risk of leakage of finally disposed of waste is not small (39% think so).

In order to determine the location preference, residents were asked where the final disposal site for radioactive waste could be established in Lääne-Harju rural municipality. 27% of the respondents found that the existing intermediate storage site is suitable, 29% found that the location does not matter as long as safety is 100% guaranteed, 22% wanted it to be more than 20 km from the place of residence, and 2% wanted it to be more than 5 km away. A fifth of the respondents thought that the final disposal site should be established somewhere else. There were 329 such respondents, of whom 261 had also filled in the comment column. Of these, 146 found that the location should be somewhere far away and/or away from human habitation and/or the sea, 39 thought that it should not be built anywhere, and 24 were meaningless comments in the style of “why do we need it in the first place”. The rest of the answers were given only in a few cases.

Preferences vary somewhat by settlement type. The difference is most clearly evident in the case of the option “In the existing intermediate storage site", where only 17% of the residents of Paldiski have chosen this option. At the same time, as many as 38% of people living in low density areas have preferred it. Therefore, the residents of Paldiski prefer the final disposal site to be established elsewhere, while the people living in low density areas prefer it in Paldiski (the existing site).

13.3. Summary

In summary, the following can be said about location preferences:

Existing intermediate storage site:

- Compared to respondents with Russian mother tongue, respondents with Estonian mother tongue are three times more likely to prefer the existing intermediate storage site.
- Men are 1.2 times more likely than women to prefer the existing intermediate storage site.
- People living in a private residence or farm are more likely to prefer this option.
- Respondents who rate the need to find a solution for disposal of radioactive waste in the near future lower are more likely to prefer this option.

More than 20 km from my place of residence:

- People under the age of 40 (so-called young people) are 1.7 times more likely to prefer this location compared to older age groups. The age variable is statistically significant only in this model with low descriptive power.
- People with higher education are more likely to prefer this option than those without higher education.
- In this model, neither awareness nor attitude questions explain location preference.

The location does not matter as long as safety is 100% guaranteed:

- Compared to respondents with Russian mother tongue, respondents with Estonian mother tongue are 1.59 times more likely to prefer this location.
- Women are 1.3 times more likely than men to prefer this option.
- Groups other than salaried workers are 1.4 times more likely to prefer this option.
- Compared to respondents with higher education, respondents without higher education are 1.5 times more likely to prefer the location option.

Somewhere else:

- Compared to respondents with Estonian mother tongue, respondents with Russian mother tongue are 1.5 times more likely to prefer it.
- Compared to other employment groups, entrepreneurs (including self-employed persons) are 1.6 times more likely to prefer this location option.
- People with higher education are more likely to prefer this option than those without higher education. At the same time, an increase in the level of higher education (MA and PhD) does not lead to a greater preference for this option (people with a lower

level of education than a Master's and a Doctorate degree are more likely to prefer this option).

- Respondents with higher subjective awareness are more likely to prefer this option (while objective awareness does not explain location option preferences).

The main findings of the focus group interviews are summarized as follows:

- Knowledge of radioactive waste is rather inconsistent. There is no distinction between nuclear fuel and radioactive waste. There are few people who are competent in the topic.
- Existing waste is considered extremely hazardous. There is also no certainty that no waste will be brought from other countries to the proposed final storage site.
- The keywords that pass through in relation to radioactive waste are: eery, dangerous, unpleasant, polluting, toxic.

The plan to build a radioactive waste disposal facility in the territory of the municipality is accompanied by a certain amount of confusion. The first question is why locations are being considered only in Lääne-Harju municipality and not all over the country. Several participants said they felt cut off from the information, and there is fear that decisions will be made without the knowledge of residents. Not all participants were familiar with the exact locations or the number of location alternatives. Some do not take locations other than the existing one seriously – if the waste is currently in Paldiski, it is logical to secure the existing site.

The main values of Lääne-Harju are considered to be nature, including forest, seashore, silence, image. There is also a lot of dissatisfaction with the developments so far – a lot of the forest has been taken down, etc. There are fears that further development will worsen the situation.

It is emphasized that the municipalitys territory as a whole and Paldiski are very different – one is natural, the other is industrial. At the same time, there are many things worth protecting on the Pakri peninsula – orchids, etc. There is bitterness that the state and businesses are pursuing their interests in the city, ignoring local residents and the natural environment. It is considered very important to ensure access to the sea for the townspeople.

The main recreational habits, including for the residents of Paldiski, are related to nature. The main fears associated with the construction of the disposal facilty vary somewhat from region to region. In Paldiski, fears remained that the existing site would leak at some point. There were also fears of a decline in the value of real estate. From the point of view of entrepreneurs, the construction of a final storage site in Paldiski will not cause problems – it is certain that the risk of leakage is minimized. However, the population of Harju-Risti is afraid of significant disturbance, including large-scale construction with the accompanying infrastructure. In addition, there are fears of the destruction of the natural environment and the reputation of the region.

The population of the Harju-Risti region does not agree under any circumstances to the establishment of a disposal facility in their area. The participants of Paldiski were somewhat more lenient – the construction of the disposal facility was seen as an instrument with which to obtain additional investments from the state. However, in both cases, it must be taken into account that the participants in the focus groups do not represent the entire population of the regions, but, above all, their opinion.

Thus, location preferences generally do not depend on the respondent's background, but on other factors. The analysis also does not reveal specific location preferences, but various arguments and aspects to take into account. The main ones are presented below, considering the results of both the survey and focus group interviews:

- Lääne-Harju rural municipality is largely a low density. However, one of the location alternatives is located in an area (Paldiski) from which approximately three-quarters of the population lives within a 10 km radius. The other two are located in sparsely populated areas. In this view, the latter could be preferred, as the number of people potentially directly affected is significantly smaller.
- On the other hand, in the case of Paldiski, it is an industrial area where the final disposal site would be better suited, given the profile. In the case of Paldiski, it would also not be necessary to start building access roads, etc. The residents of the Harju-Risti region are very afraid of the scale of construction works. Deciding in favour of Paldiski would also mean that there would be no need to start transporting the existing waste anywhere.
- The residents of Harju-Risti are very much against the establishment of the final disposal site. If it were decided to establish the site in one of the locations in the vicinity, widespread dissatisfaction can be expected. At the same time, it should be taken into account that a similar situation may arise in the case of Paldiski, in which case the residents of recreation areas (Laulasmaa, Kloogaranna, etc.) would probably also feel affected.

Based on the survey results alone, the most preferred final disposal site is the existing site (27% of the respondents chose this option). At the same time, it must be taken into account that it primarily reflects the opinion of those people who do not live in Paldiski. The latter would prefer a location either somewhere else or more than 20 km from their place of residence.

Many questions are related to people's awareness:

- 40% of the respondents are not or are very little familiar with the topic of radioactive waste. Before moving on to substantive discussion, it is necessary to raise awareness.
- On average, three-quarters of the respondents consider all kinds of radioactive waste to be very hazardous. Obviously, the less known about the matter, the greater the opposition everywhere.
- Approximately half of the respondents do not believe that the final disposal site is safe. Additional outreach by reliable sources (scientists, international organisations) would probably help to ease tensions.
- Residents do not seem to have complete information about the process (events), results, etc. According to the residents, the name of the project, "Rajala", also does not unambiguously and clearly reflect its content.

13.4. Conclusions

Rather contradicvting results are received comparing different aspects of the sites.

1. When the reference is given to locations with fewer people living nearby and fewer services, ALT and PED sites are more preferable than PAL

2. If preference is given to locations whose profile is more suitable for large-scale construction work, where there is decent access and transport connections, PAL site is preferred while other two are nearly equal.

3. If preference is given to locations that were highlighted more often in the survey, order is the following: PAL site followed by ALT and PED sites.

14. Sub-activity 2.14. Assessment of noise and vibration

The objective of the noise and vibration assessment sub-activity is the assessment of the existing noise and vibration levels at the three disposal locations and an assessment of the project conformity to the applicable national standards and project-based requirements in the construction, operation, and closure phases.

The study, including fieldworks, was performed by Kaarel Sepp and Marko Ründva (KAJAJA ACOUSTICS OÜ). The detailed results are presented in an Appendix 14.

14.1. Methodology

The main legislation regarding noise in Estonia is the Atmospheric Air Protection Act. The Act describes two different normative levels:

- limiting value of noise – the maximum permitted level of noise the exceeding of which causes environmental nuisance and the exceeding of which requires enforcement of reduction measures;
- target value of noise – the maximum permitted level of noise in new comprehensive plan areas.

The Act also defines noise categories used in Estonia. The requirements and normative values of environmental noise are set by the Minister of Environment. According to the the Minister of Environment Regulation no issued in 2016 the limits are the same as the industrial noise limit values with respect to time of day and noise category. Limits for construction works are set from 9 PM to 7 AM.

The limit value of industrial noise for the relevant noise category is applied as the limit value for impulse noise. Work that causes impulse noise, such as blasting, ramming, etc., can be performed on weekdays from 7 AM to 7 PM.

The disposal facility project must comply with the industrial noise limit values with respect to the noise categories at noise sensitive areas during the construction phase. The requirements and normative values of vibration levels in residential and public buildings are set by the Minister of Social Affairs in regulation no 78 of 2002.

The Estonian legislation and commonly used international standards do not describe the vibration limit values for buildings with such special purposes as radioactive waste disposal facilities. The project-based vibration limit values for the disposal facility must be defined in the next project phases as engineering terms of reference by the developer based on the specific requirements – safety of the repository itself and the functionality of technology inside the repository.

The project is divided into 3 main phases: construction, operation, and closure. There are two main sources of noise and vibration expected: repository construction and closure works (including transportation of building materials) and transportation of radioactive waste to the disposal site.

14.2. Results

14.2.1. Existing situation

The existing noise levels from road traffic, railway traffic and wind parks have already been assessed in the noise study for Lääne-Harju municipality comprehensive plan. The noise maps show that none of the candidate locations are affected by traffic noise.

The existing measured background noise levels at the PAL site were 41 to 48 dB at measurement point 1 and 38 to 51 dB at measurement point 2.The existing vibration levels at the Paldiski site location were ≤0,02 and ≤0,65 mm/s mm/s in lateral and vertical axes respectfully (at measurement point 1) and ≤0,20 and ≤2,3 mm/s in lateral and vertical axes respectfully (at measurement point 2). These are maximum recorded vibration levels during the measurement period.

The existing measured background noise levels at the Altküla site location were 32 to 47 dB at measurement point 4. The existing measured vibration levels at the ALT location were ≤3,50 mm/s in X axis, ≤2,40 mm/s in Y axis and ≤4,00 mm/s in Z. These are maximum recorded vibration levels during the measurement period (possibly affected by forest felling works nearby), typical vibration levels were ≤0,05 mm/s in all axes.

The existing measured background noise levels at the PED site location were 32 to 50 dB at measurement point 3. The existing measured vibration PPV levels at the Pedase site location were ≤0,10 mm/s in X axis, ≤0,8 mm/s in Y axis and ≤2,60 mm/s in Z axis at measurement point 3. These are maximum recorded vibration levels during the measurement period (possibly affected by forest felling works nearby), typical vibration levels were ≤0.05 mm/s in all axes.

14.2.2. Construction phase

Construction phase is expected to be the main source of noise and vibration in this project. Noise and vibration will be generated by the construction machinery (excavation, shaft construction, ground compacting etc.) and the transportation of the machinery. An analytical model of noise propagation was used to assess the noise levels during the construction phase near the construction site and nearest noise sensitive buildings and areas.

As the distances between the possible repository locations and nearest residential buildings are large (≥ 700…2200 m) it is not foreseen that the Estonian noise limits during construction phase will be exceeded.

PAL site

The residential buildings are located ≥900 700 m south-west from the possible PAL construction site. The calculated noise levels for the closest residential buildings are ≤ 45 and ≤ 45 dB for day- and night-time respectfully.

ALT site

Since the nearest residential buildings are located ≥1600 m north (Männiku residential building) and ≥2200m south (Kotka residential building) of the Altküla site the calculated construction noise levels for these are ≤ 40 dB during day-time and ≤ 40 dB during night-time.

PED site

The calculated noise levels for the closest residential buildings (Tuipalu and Laane) are ≤ 45 dB for day-time and ≤ 45 dB for night-time. The residential buildings are located ≥800 m west and east from the site.

14.3. Conclusions

All three potential locations are with relatively low existing background noise and vibration levels. However, this could change with the development of additional areas near the disposal locations (for example with construction of new wind parks, Paldiski underground Pumped-Hydro Energy Storage or other developments).

According to the most recent Lääne-Harju municipality comprehensive plan, the PAL site is situated right next to industrial areas. These areas are currently mostly empty, but this is most probably subject to change in the future once the plans are realized. The site is the location with the largest amount of potential outside sources of noise and vibration: existing infrastructure and wind turbines, potential perspective industrial areas, Paldiski Pumped-Hydro Energy Storage.

The disposal facility project has to fulfil all of the limit values regarding noise and vibration levels no matter which location will be chosen for the repository. This means that all of the alternatives can be treated as equal from the noise and vibration impact.

The alternative ALT and PED sites are in remote locations and do not border with perspective industrial, residential etc. areas. At the time of this report no large-scale developments are known nearby. The sites are comparable to each other since they both are in remote locations and at the time of this report no new outside sources of noise and vibration are planned in the vicinity of these locations. This means that ALT and PED sites are preferred from the noise and vibration impact standpoint.

15. Sub-activity 2.15. Analysis of roads and infrastructure

The purpose of sub-activity 2.15 has been to provide information on existing communication roads to the potential waste disposal sites relevant for transportation of the waste to be disposed of and materials for construction and closure of the facility. Availability of infrastructure and good communication roads are important in all phases of radioactive waste disposal program: site characterization, construction, operation, closure and post-closure. It makes significant influence to the disposal cost but is safety relevant too. Connection roads are also important in case of emergencies too. The following aspects have been analysed:

- Changes in traffic within the coming 30 years in connection with the establishment, operation and closure of the repository, transport of dangerous goods; including plans of the state and the local government. The conditions of existing roads, determining the need for and the estimated cost of new roads;
- Description of the ports and railway in the vicinity (up to 40 km), frequency of service of ships/trains, numbers of passengers and an overview of the main goods being transported. Probable changes in the activities of the ports and railway traffic, considering the plans of the state and the local government;
- The nearest airports and the impact of their activities on the repository. National plans for establishing new airports.

The infrastructure and transport analysis is based on the existing data from national databases. No fieldwork was conducted during the analysis and all works were done in desktop mode. The detailed results are presented in an Appendix 15. The work was performed by Ain Kendra (T-Konsult OÜ) and Anna-Helena Purre (Engineering Bureau STEIGER LLC).

15.1. Expected transport activities

Taking into account the available A.L.A.R.A. waste conditioning experience, about 800 concrete containers weighting approximately 5 ton each will be delivered for disposal. It is assumed that one truck will take about 5 standard size containers. Non-standard and most radioactive containers may by transported one at a time.

The reactor vessels are the largest components that must be transported. Assuming that the reactor vessels will be placed into specially designed containers made of concrete, the expected weight of the containers with the reactor vessels could vary from 75 to 100 tons. These deliveries will not exceed dimensions in the traffic regulations but will be overweight, so needing up to 100-ton class (4 + 16 axles) vehicles. The containers for the reactor vessels could be either horizontal or vertical, as there are no overhead bridges, two-level crossings or similar obstacles limiting height.

According a preliminary estimations, in total up to about 330 truck trips will be needed deliver the loads to the disposal facility. In addition to radioactive waste transport, construction materials have to be delivered to the disposal site. The main materials to be transported to the site for construction, operation and closure of the facility are concrete, clay, sand, gravel, boulders, while the local soil removed from the construction site, will be suitable for certain protective layers, slope formation or backfilling during closure. Therefore, the excavated soils should be stored on the site, and be later used for protective layers to minimise transportation. Indicative amounts of materials, estimated taking into account the conceptual design features of the disposal facility.

Duration of the operation phase largely depends on the intensity of reactor dismantling works and suitable weather conditions for waste disposal and transportation (positive temperature, no extreme weather events, no rain or strong winds). The following assumptions were made to estimate transport intensity:

- To minimise weather impacts on the structures the construction will be done during summer periods only. The disposal facility could be constructed during two summer periods (two vaults in one summer and the shaft in another summer or vice versa).
- Waste disposal activities will be carried out only in the warm season and will last for 5 years (this is a conservative value, considering that waste emplacement activities will not cover the entire 10-year period allocated for disposal in the strategy).
- Closure activities after waste disposal will last two summer periods.
- The local soil (including organic soil) needed for closure will be available at the site.

According to the calculation results, the highest additions from the project related transportations to the traffic frequency are during the closure period, when about 5 truck trips per day are needed for the transportation of construction materials, whereas during construction and operational phase only 2 and 0.1 truck trips are needed respectively.

15.2. Suggested transport routes

Suggested transport route includes only road transport. For the transport of radioactive waste from existing storage to locations ALT and PED four alternatives exist (Fig. 15,1). If the existing location (FPNS) in PAL is chosen for the disposal facility, the transport outside of the site is not needed, so transport routes and impact on frequencies will not be analysed further. Based on the existing road network, road length, road bearing capacity and possibilities to avoid more crowded areas, optimal route was chosen through Paldiski – Padise – Harju-Risti with the total length of 30.5 km in case of both alternative locations (PED and ALT). As these locations are close by to each other, so the main part of the route is the same, whereas only final part differs.

Figure 15.1. Optimal transport routes and alternative routes for radioactive waste transport from FPNS to Pedase and Altküla sites and traffic frequencies on the routes.

On the optimal route there are no roads, used for transporting dangerous goods. Dangerous goods from and to Paldiski port are mainly delivered via railway or Tallinn-Paldiski highway no. 8.Those roads are mainly also planned for transport of construction materials during the construction, operation and closure of the disposal facility.

15.2.1. Traffic frequencies

Current frequencies of the traffic are presented in Figure 15.1. Currently there is no significant heavy traffic on the optimal route for radioactive waste transport. An increase in traffic frequency, including heavy traffic frequency is most prominent on smaller roads in the beginning and end (Leetse road, Paldiski – Kurkse – Harju-Risti road, and Valgma road) of the transport route, where baseline traffic frequency is low. Also, the effect of traffic frequency is stronger if the transport to the repository is done during short period (i.e. month), whereas using longer period for transport decreases the effect on traffic frequency. In these roads, additional traffic, especially heavy traffic frequency can have a significant effect if radioactive waste transport is done during short period. If the transport is extended for the longer period e.g. year, then the impact is mitigated. The traffic frequency estimates are conservative in this analysis, therefore the real traffic frequency related to the radioactive waste transport to the Pedase and Altküla alternative locations is probably even smaller.

Traffic frequency estimations for transport of construction materials during three phases of the disposal (construction, operation, closure) were done based on the available general information. As the sources of these construction materials are currently not known, following assumptions were made by the AS A.L.A.R.A and expert group: concrete – from Keila (Tõmmiku); clay – from Tallinn direction (clay quarries are located east from Tallinn, the clay on site may not be suitable, therefore conservative approach is used); sand, gravel – Audevälja; boulders – Tallinn.

15.2.1. Needed road construction works

The following road construction works should be considered, but need further on-field studies:

- 11174 in two sections it is necessary to reconstruct due to military heavy traffic requirements (reconstructed distance about 2.7 – 3.0 km) and study the conditions of Jõesuu bridge plates, possibly construction works needed. Expected cost about 300,000€, but this investment most probably will be done independently to the project, within NATO framework.
- 11230 black pavement since 1974, probably needs renewing but currently this will not create problems.
- 11235 should be stabilised due to additional heavy traffic (TS/Stabilroad), Estimated cost per meter of 6-meter wide local road – 60 €, length of 11235 – 1.6 km – ca € 100,000.
- 11176 (2.6 km) on case of ALT should be stabilized, ca € 150,000, or
- Local Valgma road on case of PED should be stabilised (TS/Stabilroad), ca € 240,000.

The price of these works can be specified in detail after further studies, where road conditions will be inspected on site and needed works clarified. There is no need for additional roads or road improvement for the transport of construction materials to three alternative sites, as this is already covered in previous list. In case of Paldiski site, Leetse road was recently reconstructed, and other transport roads are similarly, in good conditions.

15.3. Summary

Various modes of transport (water, rail and road) were examined. Road transport has been found the only method suitable for waste transportation.

In this analysis, study concentrated on the three chosen locations (existing site in Paldiski, alternatives Pedase and Altküla) for disposal facility of radioactive waste. In case of Pedase and Altküla alternatives, radioactive waste must be transported to these alternative locations from the existing site in Paldiski. The optimal route for the transport of radioactive waste was determined with length of about 30 km (nearly equal to the both sites). Most of the routes to the both locations overlap. If disposal facility will be built at Paldiski site, there is no need for transport for radioactive waste on public road, no need for off-site road improvements and no costs related with that, and waste can be transported within one cadastral unit.

Differently from radioactive waste, construction materials for disposal facilities must be transported to all three site alternatives. From this point of view the all three sites are nearly equal.

The route is Leetse road (no. 5800008), Paldiski-Padise road (no. 11174), Keila-Haapsalu road (no. 17), Harju-Risti-Riguldi-Võntküla road (no. 11230), Harju-Risti road (no. 11235), in case of Altküla alternative: Padise-Kurkse-Harju-Risti (road no. 11176) and in case of Pedase alternative: Valgma road (no. 5621014). Application of this road minimises the need for road construction and improvement work, and negative effect on traffic frequency and interfering with transport of other dangerous goods. Some road improvement works are still needed, while for specifying and estimating their price further on-site studies are needed.

In addition, four alternative routes to the optimal routes were proposed.

In addition to road transport analysis, current situation, and further plans in maritime transport (port infrastructure), railroads and airports were analysed. Currently, three proposed locations of waste repository do not contradict or have coeffect with transport infrastructure. According to the spatial planning documents, there are no plans with building new airports to the study area or significantly extend existing airports. There are some plans for extending railroad network, but the plans are still uncertain and do not affect planned activities related to the radioactive waste repository. There are some plans for building additional ports on the coast of Lääne-Harju municipality, especially the plan for LNG-terminal/cargo port in Pakrineeme. These development plans do not significantly affect the Paldiski radioactive waste disposal facility and the possible transport routes.

15.4. Conclusions

1. The PAL site has the best accessibility. Construction technique and building materials can be transported to the site via sea, railway and road. The radioactive wastes will be produced on the site, so transportation will not be needed at all. No road construction is needed for the PAL site.

2. The both alternative sites (PED and ALT) are only accessible by land. The waste must be transported to these sites on public roads. They are located next to the existing road network, so there is no need for building additional access roads, except roads inside the sites themselves. These sites are equal in terms of accessibility and suitability for transporting waste and construction materials.

16. Sub-activity 2.16. Preparing a safety assessment

Three potential sites were selected as candidates for further investigation (Report for Activity 1, 2022): PAL, PED and ALT. The current Safety Assessment Report (SAR) is devoted to investigation possibilities to establish the planned disposal facility at these sites. The SAR is developed in the stage of site selection and its main purpose is to compare suitability of these three sites for waste disposal as well as to investigate suitability of the proposed concept to the local site specific conditions.

The current SAR is based on results of characterisation of the above-mentioned three sites. The characterisation programme included the following investigations: tectonic, seismic, geological, geodetic, geomorphologic, hydrogeological, hydrographic, chemical, climatic, environmental, social studies as well as analysis of roads and infrastructure. It is necessary to point-out that that due to lack of data this SAR has preliminary character only. It has to be significantly updated taking into account results of more detailed characterisation of the site and features of the facility's Technical Design, i.e. Final SAR has to prepared for licencing purpose.

The detailed safety assessment is presented in Appendix 16. The assessment was performed by a team of experts. Sections on safety during construction, operation and closure as well as waste acceptancy for disposal were prepared by Evaldas Maceika (FMTC), post-closure assessment was analysed by Maksym Gusyev (National Academy of Science of Ukraine), a section on waste inventory was developed by Grigorijus Duškesas (FMTC) and Evaldas Maceika. Design concept and implementation schedule was elaborated by Stasys Motiejūnas (UAB Eksortus). Closure and postclosure costs vere assessd by Ramūnas Kunigėlis (UAB Eksortus).

16.1. Safety criteria

Radiation Act of the Republic of Estonia and other legislative documents define the principles and basic safety requirements for protecting people and the environment from the adverse effects of ionizing radiation. The following principles of radiation protection have been established:

- Justification of radiation practices: planned radiation practices have to be justified by proving that they are the best based on their economic, social or other benefits in relation to the potential health detriment they may cause.
- Optimization of radiation protection: any exposure shall be kept as low as reasonably achievable, taking into account the economic and social factors.
- Dose limitation: the sum of exposure doses shall not exceed established limits.

The following dose limits are established for occupational exposure:

- the effective dose limit for occupational exposure is 20 mSv per year;
- the limit of the equivalent dose to an exposed worker per year is:

  - 20 mSv or 100 mSv in the lens of the eye for any five consecutive years, provided that one annual dose does not exceed 50 mSv;
  - 500 mSv in the skin;
  - 500 mSv in extremities.

Moreover, while considering the impact of radiation factors on workers, it is necessary to take into account the criteria that are established for various categories of workers. The Radiation Act defines the following categories of workers exposed to radiation:

- exposed workers of category A who may incur an effective dose exceeding 6 mSv or exceeding 0.3 (three tenths) of the equivalent dose limit for the lens of the eye, skin and extremities;
- exposed worker of category B who are exposed workers and who are not classified into exposed workers of category A.

Dose limits for public exposure:

- the effective dose limit of the public is 1 mSv per year;
- the limit of the equivalent dose of the public per year is:
  - 15 mSv in the lens of the eye;
  - 50 mSv in the skin (this limit applies to the average annual dose per any area of 1 cm² excluding the area exposed).

Radiation protection optimisation approaches for post-closure stage of radioactive waste disposal facilities have been elaborated by International Commission on Radiological Protection. Two broad categories of exposure scenarios have to be considered: natural processes and human intrusion. Optimisation should explore and apply reasonable measures to reduce the probability and magnitude of exposures due to natural processes. The key criterion is the individual source related dose constraint. The Commission has recommended dose constraint of 0.3 mSv in a year as a highest dose in normal exposure situations. This corresponds to a risk constraint of the order of 10^{-5} per year. Constrained optimisation is the main approach to evaluating the radiological acceptability of a waste disposal option.

This dose constraint is not applicable in evaluating the significance of human intrusion. The Commission has advised that an annual dose of around 10 mSv per year may be used as a reference level below which intervention is not likely to be justifiable, while annual dose of 100 mSv per year may be used as a reference level above which intervention should be considered.

16.2. Wastes to be disposed of: waste sources and inventory

The National strategy provides technical management solutions for each of the 3 waste sources:

- legacy waste in storage,
- currently produced institutional waste, and
- future decommissioning waste from the Paldiski reactors.

The waste to be managed as part of the National Programme is classified into three main types:

1. Low and intermediate activity short-lived waste (more than 90% of waste amount);
2. Low and intermediate activity long-lived waste (a few percents);
3. NORM waste (contaminated scrap metal), making up to few percents.

Most of the currently available radioactive wastes in Estonia originate from deactivation and decommissioning projects. Fifty percent of the overall waste volume is already characterised and is assessed to have a total activity ca 900 TBq. Uncharacterised waste is mostly low active and its contribution to overall activity is small. Most of radionuclides is concentrated in spent sealed sources of Sr-90, Cs-137, Co-60 and Pu-Be, which account for only ca 10% of the total amount of waste. The total volume of the already conditioned waste is about *460* m^3, In addition, there is about *1180* m^3 of unconditioned waste stored at Paldiski site.

The amount of the decommissioning waste is estimated to be *about 395* m^3 by 2040, when the beginning of the decommissioning activities is scheduled. It is also considered that waste streams from the radiation practices will be consistent also in the future (less than 1 m^3 annually) and significant changes are not foreseen.

Tammiku RW disposal facility was in use from 1960 until 1995 for institutional waste disposal. After that the waste was retrieved. Substantial part of the legacy waste (from previous Tammiku and Paldiski dismantling activities) is already conditioned and characterised. However, there is also uncharacterised cemented waste as well as not cemented yet wastes.

The waste was characterised before cementation using gamma spectrometer. The presence of beta and alpha radionuclides is not controlled. The cementation process is properly documented – each container with conditioned waste has individual passport. There is also characterised and uncharacterised waste from decommissioning of Tammiku site, which is concreted in standard concrete containers. Not fully characterised waste from previous decommissioning activities is concreted inside submarines shells of RC1 and RC2 as well as stored unconditioned in 200 L drums.

16.2.1. Containers intended for waste disposal

Currently, several different types of containers are used for waste conditioning and storage. It is assumed, they will be applied for disposal too.

Standard concrete containers. A concrete container designed by Studsvik Nuclear AB with external dimensions of 1.2 m × 1.2 m × 1.2 m and a wall thickness of 10 cm (Figure 16.1) is the predominant type of container (hereafter referred to as a standard concrete container). The upper 10 cm layer in containers is filled with “clean” concrete to protect waste against dispersion. In addition, a 10 cm thick concrete lid is fixed by bolts on the top of the containers.

Figure 16.1. Standard concrete containers with cemented waste.

Metal containers. Metallic containers with 5 mm thick walls and external dimensions 1.2 m ×1.2 m ×1.2 m are used for storing cemented sediments. To prevent waste from spreading the top 10 cm layer is made of "clean" concrete.

Cylinders. During refuelling the reactor 1, the control rods were replaced. The spent rods are conditioned in cylindrical containers. The containers are made of steel tubes with a diameter of 1.2 m and a height of 2 m. Control rods were loaded and immobilised with concrete.

Big concrete containers. 3 m high concrete containers are made of ferroconcrete. Containers dimensions: height 3.0 m, width 1.2 m and depth 1.2 m; minimum wall thickness 25 cm; weight 8640 kg. This type of container is used for most active wastes retrieved from Tammiku (including DSRS).

The following waste packages are expected to be disposed of:

1. Standard-size concrete containers with cemented RW (in the Interim Storage),
2. Metal containers with cemented RW (in the Interim Storage),
3. Cylindrical containers with cemented spent control rods,
4. Big 3 m high concrete containers with RW from Tammiku facility,
5. Standard-size containers with grouted beta sources from Tammiku facility,
6. Standard-size containers with grouted with boxes spent sealed sources from RC1,
7. Standard-size containers with grouted organic RW (rags, overshoes, film, brushes, etc.) from RC’s,
8. Standard-size containers with grouted metal waste (tools, equipment, etc.) from RC’s,
9. Standard-size containers with grouted concrete waste from MTB,
10. Standard-size containers with grouted HEPA filters,
11. Reactor vessels with internals.

Vessels of the reactors will be disposed of entire, not fragmented. All other dismantled equipment will be fragmented into small pieces .The major amount of waste will be produced due to fragmentation of steam generators and connected pipelines and shielding tanks of the reactors. Amounts of waste arising from the reactor decommissioning as well as properties has been evaluated during implementation of Activity 4 of the current project.

There are uncharacterised HEPA filters used for the air ventilation of the Main Building of the reactors. They have a total volume of 12.43 m^3. There are various ways of managing such waste after characterisation. However, it was conservatively assumed that the filters will be placed into standard concrete containers and grouted before being disposed of in NSDF. In such a case, it is necessary to have 22 standard concrete containers with a total volume equal to about 38 m^3 and a mass equal to about 30 t.

In addition, only small amount waste is expected from medical institutions in the future.

16.2.2. Inventory of the NSDF

Estimated amount of waste suitable for disposal in a NSDF and their radionuclide composition is presented in Tables 16.1 and 16.2 respectively.

Table 16.1. Waste packages to be disposed of in NSDF

Package type	Quantity, pcs	Volume, m^3	Mass, t
Standard-size metal containers with SL waste	134	231.6	511.4
Standard-size metal containers with re-packed 200 L drum (SL waste)	76	131.3	339
Standard-size concrete containers with already conditioned SL waste	92	159	308
Standard-size concrete containers with unconditioned waste not exceeding NSDF WAC	34	102	264
Standard-size concrete containers with future reactor decommissioning waste not exceeding NSDF WAC	204	352.5	769
Standard-size metal containers with waste stored in ISO containers	502	866	2241
Standard-size metal containers for waste stored in nonstandard containers	13	22	56
Standard-size metal containers with spent nuclear fuel pool demolition waste (concrete)	190	328	846
Total	**1245**	**2061**	**5334**

Table 16.2. Activities of radionuclides in NSDF (referred to 2041)

Radionuclide	Activity, Bq	Radionuclide	Activity, Bq
H-3	6.2E+10	**Pu-239**	5.0E+05
Co-60	9.3E+09	**Pu-240**	1.4E+05
Ni-59	4.7E+07	**Am-241**	5.9E+09
Ni-63	2.2E+9	**Ba-133**	5.1E+05
C-14	6.1E+08	**Ra-226**	3.9E+09
Sr-90	1.3E+12	**Ra-228**	9.0E+03
Nb-94	3.8E+07	**Th-232**	1.4E+05

Cs-137	2.4E+13	**U-234**	2.2E+03
Eu-152	5.9E+08	**Kr-85**	6.7E+09
Eu-154	9.4E+07	**U-238**	5.8E+08
Pu-238	2.3E+05		

16.2.3. Inventory of the IDDF

Amounts of wastes intended for disposal in IDDF and their radionuclide composition are presented in Tables 16.3 and 16.4 respectively. Vessels of the reactors will be disposed of entire, not fragmented. All other dismantled equipment will be fragmented into small pieces and packed into appropriate containers.

General information on various waste packages expected to be disposed of in the IDDF is presented in Table 16.3. For most of the packages the mass is provided after conditioning, except the reactor vessels. They will be transferred to the disposal facility unconditioned. In addition, there are few containers of non-standard dimensions. In order to estimate the space occupied in the disposal facility, an effective volume of non-standard packages was calculated, taking into account the volume of a standard container and the number of occupied positions (an integer). For example, a big concrete container have the same footprint as a standard container, but it extends in height through three container layers. Therefore, volume of three standard-size containers is assigned to one big container.

Table 16.3. Waste packages to be disposed of in IDDF

Radioactive waste	**Quantity, pcs**		**Mass, t**		**Volume, m^3**	
	Number	Effective number	Actual	Effective	Actual	Effective
Reactor vessel from RC1	1	36	30	170	14.9	62.2
Reactor vessel from RC2	1	45	50.4	222	23.8	77.8
Cylinders with cemented spent control rods	4	8	25	36.5	9	13.8
Big concrete containers with waste from Tammiku	2	6	35	39.3	8.6	10.4
Standard-size metal containers with conditioned (cemented) waste from Paldiski site potentially exceeding WAC for NSDF	2		7.5		3.5	
Standard-size metal containers with re-packed 200 L drums potentially exceeding WAC for NSDF	22		88		38	
Standard-size concrete containers with conditioned SL waste potentially exceeding WAC for NSDF	10		40		17.3	
Standard-size concrete containers with uncharacterised	37		156		63.9	

yet disused sealed sources and wastes potentially exceeding NSDF WAC						
Standard-size concrete containers with disused sealed sources from boxes embedded in concrete	5		22		8.6	
Standard-size concrete containers with reactor decommissioning waste potentially exceeding NSDF WAC	186		949		321.4	
Standard-size concrete containers with unconditioned DSRS and wastes potentially exceeding NSDF WAC	35		140		60.5	
Total	**305**	**392**	**1543**	**1870**	**570**	**677***

* Total volume means the volume occupied in the disposal facility, not taking into account technological gaps between containers to be backfilled.

Table 16.4. Activities of radionuclides in IDDF (referred to 2041)

Radionuclide	Activity, Bq	Radionuclide	Activity, Bq
H-3	6.7E+10	**Eu-154**	1.2E+12
Co-60	3.8E+12	**Pu-238**	4.6E+12
Ni-59	1.3E+12	**Pu-239**	2.7E+11
Ni-63	8.1E+13	**Pu-240**	8.1E+07
C-14	1.4E+13	**Am-241**	2.1E+11
Sr-90	6.9E+14	**U-238**	4.6E+12
Nb-94	1.1E+11	**Ra-226**	2.6E+10
Cs-137	1.0E+14	**Kr-85**	1.1E+10
Eu-152	6.9E+12	**Th-232**	2.6E+05

16.3. Site conditions

As part of this project, a preliminary characterization of the three candidate sites (PAL, ALT and PED) was carried out with the ultimate goal of selecting a preferred one. The site characterisation results are detailed in Interim reports for Sub-activities 2.1 to 2.15 of the current project (Appendices 1 to 15 to the Report for Activity 2). The three candidate sites are close to each other, therefore, many of general characteristics, such as the deep structure of the Earth crust, volcanism, seismicity, climate, are nearly identical or similar for all three sites. Estonia, including the study area, experiences modest seismicity, there are no active tectonic processes in vicinity of the sites as well as no risk of landslides. However, topographical analysis has revealed a significant concern regarding the ALT site; its proximity to the sea, combined with the anticipated rise in sea levels and more severe storms, poses a growing threat within the next centuries in connection to global warming predictions.

16.4. Basic principles for construction, operation and closure

16.4.1. Conceptual Design

Considering the small amount of waste and looking for the most efficient means of operation and maintenance, it was decided to locate the two disposal facilities of different types on the same site. Both disposal concepts are flexible enough, i.e. easily adaptable to different waste volumes and waste packages as well as to conditions of the particular site.

The conditioned Low-Level Waste is to be emplaced into concrete vaults with protective clay layer. The NSDF would consist of two such disposal vaults located on the ground surface with dimensions of about 15*12.5*6 m. After finishing waste emplacement activities (operation stage) of the NSDF, it will be closed by installation of a multi-layer capping system protecting against infiltration of water, human and bio-intrusion and erosion (Figure 16.2). If groundwater level is very high, a bottom bed layer beneath the concrete vaults must be established protecting waste against lateral ingress of rainwater and capillary rising of the ground water (at least about 2 m above water table). The floor and walls of the vaults are cast on well compacted soil layer with mechanical stiffness sufficient for expected loads of the waste and heavy structures. Steel reinforcement could be used to assure the required mechanical properties of the concrete if needed.

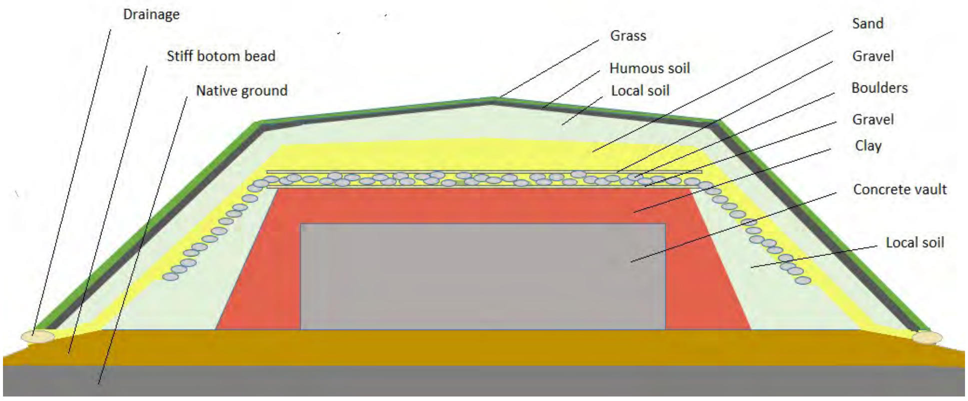


Figure 16.2. Closed NSDF with waste containers: cross section of concrete vault.

Intermediate level waste is defined as waste that contains long lived radionuclides in quantities that need a greater degree of containment and isolation from the biosphere than is provided by Near Surface Disposal. Disposal in a facility at a depth of between a few tens and a few hundreds of metres is indicated for Intermediate Level Waste. Disposal at such depths has the potential to provide a long period of isolation from the accessible environment if both the natural barriers and the engineered barriers of the disposal system are selected properly. In particular, there is generally no detrimental effect of erosion and other surface related processes at such depths in the short to medium term.

Considering very small amounts of wastes requiring intermediate depth disposal, an Intermediate Depth Disposal Facility (IDDF) of shaft type (Figure 16.3) was proposed in 2015 within project '*Preliminary studies for the decommissioning of the reactor compartments of the Former Paldiski Military Nuclear Site and for the establishment of a radioactive waste repository'*. The foreseen minimal depth of the IDDF is 30 m. Such depth has been accepted as the lower level of the normal residential intrusion zone (a depth beyond which human intrusion is limited to drilling and excavation activities), therefore is commonly used to differentiate between near surface and intermediate depths disposal.

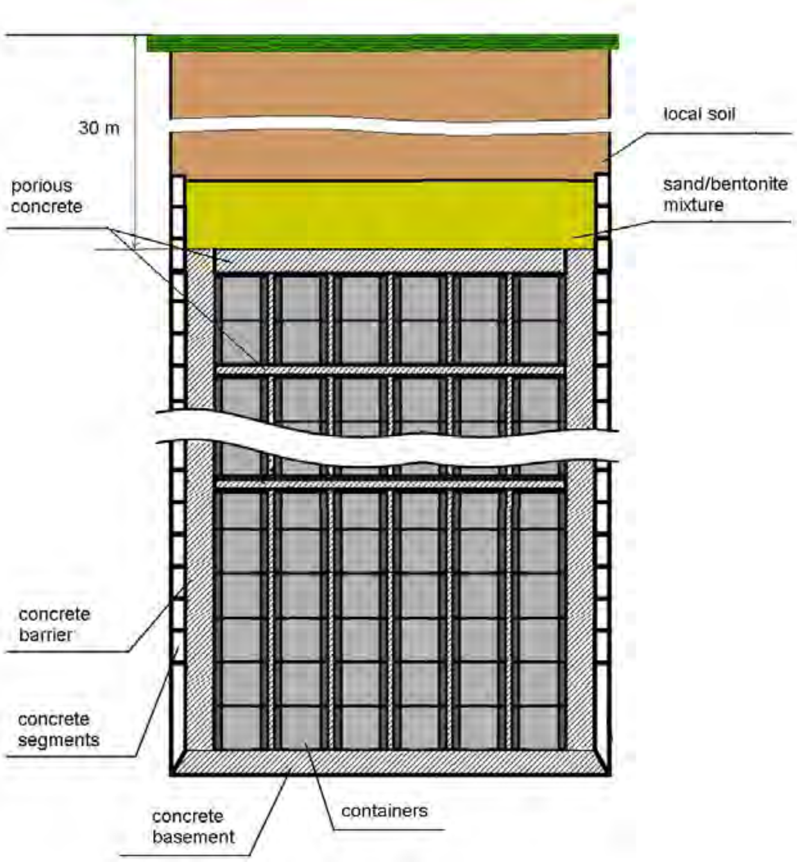


Figure 16.3. Conceptual design of IDDF: cross section of closed shaft-type disposal facility. The shaft lining is made of precast concrete segments.

Another important advantage of disposal at intermediate depths is that, in comparison to NSDF, the likelihood of inadvertent intrusion (i.e., human- and bio- intrusion) is greatly reduced. Consequently, long-term safety for disposal facilities at such intermediate depths will not depend on the application of institutional controls.

Technologies for shaft boring in various soils and rocks are well known and mature. They are widely used for mining and tunnelling. An example of such commercially available technique is a Vertical Shaft Sinking Machine. The assumed external diameter of the shaft is about 10.5 m, while height of waste colon is up to 20 m, however, the geometrical parameters can easily adapted according to needs (amount of waste). The shaft sinking method is applicable in a wide variety of ground conditions, i.e. in soft soils and rocks. The method is particularly suitable below groundwater table. During excavation the shaft is completely flooded with water, therefore no water lowering is needed. The excavated material is removed by pumping out the slurry. The bottom of the excavated shaft is sealed by an underwater concrete plug and an annular gap between the lining and rocks is filled with cement grout. The concrete plug serves as an engineered barrier against vertical radionuclide movement.

The exact depth depends on site specific geological conditions. During geological investigations, a thick layer clayey sediments was found at all three candidate sites, the results are presented in reports for Sub-activities 2.3 and 2.9. Application of the natural clay barrier minimises need of an additional engineered concrete barrier. The proposed waste disposal depths are approximately 60 to 80, 78 to 98 and 90 to 110 m, respectively for PAL, ALT and PED sites (Figure 16.4).

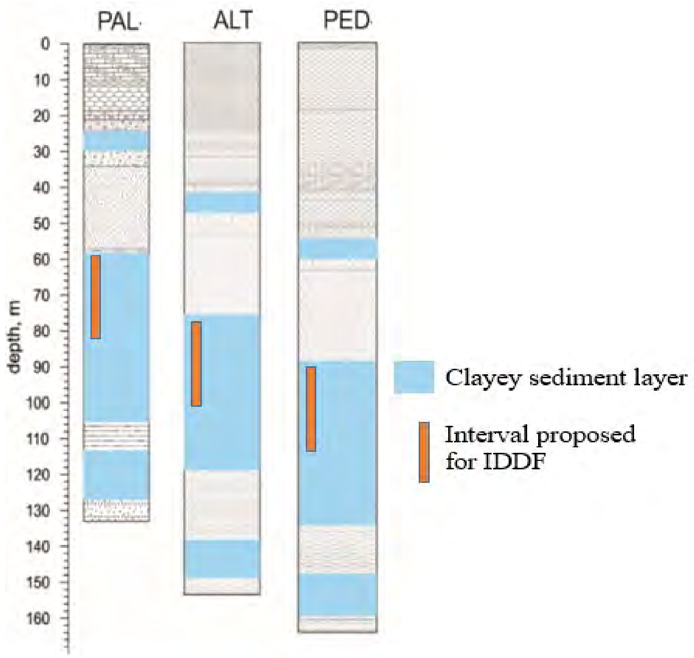


Figure 16.4. Vertical position of the IDDF for the three candidate sites

In order to minimise the negative impact of the atmosphere, temporary shelters will be installed over the disposal vaults and the shaft. The shelters would also mitigate consequences of potentially possible accidents (for example, drop of a waste package). In Figure 16.5 presented a bigger shelter covering the both vaults. The shaft will be equipped with another similar but smaller shelter. The cranes must be equipped with handling tools applicable to all types of containers. The shelters and the cranes will be dismantled during closure of the repository.

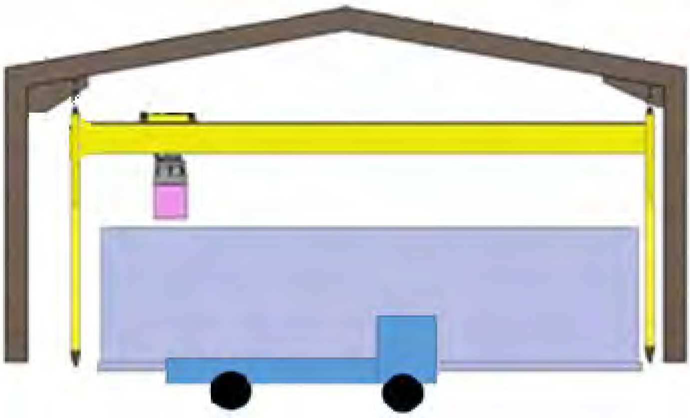


Fig. 16.5. Shelter covering concrete vaults and a crane.

16.4.2. Waste emplacement

Compliance of waste packages with Waste Disposal Criteria must be checked prior to the disposal. A thorough checking and verification of each package are to be done at the FPNS before transportation to the disposal facility.

After arrival to the disposal facility each package is to be verified and once again. This procedure will include checking of container passport data (type, number, position according the Package Emplacement Schemes). The Package Emplacement Schemes are to be elaborated for the facilities of the both types considering package type, radioactive content and other properties of the package. In order to minimise the risk of source damage in case of drilling a borehole through the IDDF, containers with immobilised DSRS would be placed in the lower layers under the reactor compartments. The reactor metal would prevent inadvertent drilling.

Reactor walls are dozen centimeters thick and made of high grade stainless steel. They present a nearly indestructible obstacle to penetrate through drilling large diameter water supply or geothermal borehole. Theoretically, the reactor wall can be penetrated using only a special device with diamond drill bits. Considering the sedimentary bedrocks (limestone, sandstone and claystone) available at the sites, it would very doubt if somebody accidentally would drill into the IDDF using drill bit capable to cope with hard steel. Also, when drilling into an IDDF, drillers should quickly realize from the taken material that they are not drilling natural geological material but have encountered something anthropogenic. The driller would know immediately that something is wrong, as pieces of core steel will be visible when pulled out.

The checked and recorded waste packages are to be stacked in the disposal vault or the shaft layer by layer. As soon as waste emplacement is completed, the gaps in the vault are backfilled by pouring cement grout.

16.4.3. Closure methods

16.4.3.1. Installation of capping system for the NSDF

The NSDF built on the surface are usually protected by specially designed capping system. The closure system should be designed to satisfy a number of requirements to ensure the long-term safety of the disposal facility. The general requirements to the cap design are the following

- Impermeability — the amount of rain water penetrating the cap and coming into contact with the waste is expected to be low to limit radionuclide leaching and subsequent migration;
- Integrity — the waste, cap, and surrounding structures will be designed to retain the required material integrity under all possible environmental conditions, including climatic extremes, subsidence, natural events such as fire and earthquakes, chemical and microbial degradation of soil and barrier materials, and mechanical load;
- Resistance to degradation — the waste form, cap, and surrounding structures are designed to prevent degradation due to external forces such as erosion, freeze-thaw processes, and biological intrusion; the disposal cap is designed to be sufficiently thick and made of appropriate materials to protect the disposal units from such external processes;
- Reparability — while performance requirements are stringent, the probability of failure of one or more components of the system can not be ruled out, especially over long time frames.

As soon as a vault is filled with waste and backfilled, a reinforced concrete slab (about 0.4 m thick) must be cast on top of the vault. It would shield ionising radiation and protect the waste from water ingress. Gases, generated in the disposal vaults would escape through joints of the concrete slab with the walls. After completing waste disposal and installing the concrete slabs above the both vaults, they are covered with a multilayer capping system. The capping system must restrict surface water infiltration into the waste and to reduce the potential for contaminants to leach out.

In order to protect the clay infiltration barrier, it should be covered by a sufficiently thick soil layer. The main functions of the soil cover above the clay are the following:

- protection against clay barrier freezing,
- protection against erosion caused by wind and precipitations,
- protection against bio-intrusion caused by burrowing animals and roots of plants,
- protection against clay barrier desiccation during draughts followed by formation of cracks,
- storage of water needed for optimal grow of plants,
- reducing human intrusion risk.

A grass-covered "hill"-shaped cover is proposed (Figure 16.2). Vegetation cover is an inexpensive, but highly effective mean in a repository closure cap. Roots of plants reinforce slopes and protect them from erosion caused by wind and water. The grassy slopes are the easiest to maintain. Also, the grass or shrubs covered slopes are the most natural in the landscape of North Estonia. However, trees growing on the “hill” are not desirable as deep penetrating roots of the trees can enter into the disposal system.

16.4.3.2. Sealing the IDDF

After completing waste emplacement and backfilling the gaps, a concrete slab should be cast on the top of the waste packages, Figure 16.3. It would provide stability and shield ionising radiation.

Compacted sand/bentonite mixture or natural clay are proposed for sealing of the disposal shaft. The main function of this confining barrier is protection against vertical infiltration of ground water. Assumed thickness of this water impervious layer is about 5 m. The volume above the confining barrier would be filled with the local soil and compacted.

16.5. Preliminary Safety Assessment for construction, operation, closure and post-closure

At the stage of the disposal facility siting , when no design of the facility is available, the safety assessment and risk analysis are based on a conceptual design and on some general assumptions regarding properties of the radioactive waste and characteristics of the facilities, their structure and operation. As the goal of the study is comparison of alternative locations, the emphasis is paid to different properties of the locations and their impact on safety rather than specific details of operation. During the later stages of the design when more details about the facilities become clear, safety assessment and risk analysis are to be updated at a higher level of specific details.

16.5.1. Construction phase

Soils in Estonia are rich in uranium and radium. Radium decay progeny radon Rn-222 can accumulate in the shaft air and therefore cause exposure to workers. A conservativelly estimated dose to the workers can reach aproximatelly 0.03 mSv/h. The potential doses of workers may exceed the dose limit of 1 mSv/a, depending on the time that people will have to work in the shaft. Dependence on site specific conditions (depth and soil properties) is insignificant.

Although concrete lining of shaft will reduce radon emanation, the problem can also be solved by ensuring proper ventilation during implementation of works. Impact on the general public would be negligible.

16.5.2. Waste transportation

In the case of ALT and PED sites, the containers with radioactive waste must be transported on public roads. This should be done in accordance with the requirements of the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). It can cause exposure of habitants. The estimated doses to reference members of the public due to transportation of radioactive waste to the disposal site is very low (about 0.036 mSv), significantly lower than the annual dose constraint of 0.3 mSv.

Transportation of the waste by the public roads would satisfy ADR requirements and would not exceed the limits for the population and vehicle driver. The PAL site is favorable because there would be no need to transport waste on public roads.

16.5.3. Operation of the disposal facility

16.5.3.1. Normal operation

Doses to workers performing typical jobs associated with waste disposal at NSDF were estimated conservatively. The predicted maximum dose for a worker performing routine activities at the NSDF site during the entire waste disposal process is 5.44 mSv. It doesn’t depend on the disposal site. The estimated maximum dose is far below the annual dose limit of 20 mSv.

The conservatively calculated maximum dose of a worker working at the IDDF established PAL site is about 0.74 mSv only. The woker exposure dose would even lover for ALT or PED sites, however track driver exposure in this case would be similar (about 0.6 mSv). The estimated doses are significantly below the established limits.

16.5.3.2. Anticipated operational events and accidents

There is expected, that anticipated operational events and design based accidents are mostly dependent on internal hazards as well by external hazard (an earthquake). However, the beyond design accidents could be due to external events such as fall of large aircraft and explosion at the disposal sites. A list of possible anticipated operational events, design based accidents and beyond design accidents was screened, appropriate scenarios were selected and consequences were analysed. The summarised exposure doses in case of the selected scenarios are presented in **Error! Reference source not found.** Table 16.6. Identified operational events and accidents at the disposal facility and respectfully for workers or emergency staff and for members of the general public.

Table 16.5. Identified operational events and accidents at the disposal facility and expected exposure of workers

Event	**Dose, mSv**		
	PAL	**PED**	**ALT**
Fault during on site movement at NSDF	1.13E-03		
Failure of truck on route to NSDF	0	4.68E-03	4.68E-03
Spread of contamination at NSDF	2.04E-04		
Operators access top of the vault to examine/fix some problem due to incorrect positioning of WP at NSDF	1.58E+00		
Fault during on site movement at IDDF	8.00E-3		
Failure of truck on route to IDDF	0	1.65E-02	1.65E-02
Spread of contamination at IDDF	1.99E-04		
Additional operations of staff to access remotely shaft to examine/fix problems at IDDF	1.63E-02	6.28E-03	8.34E-03
Earthquake at NSDF site	1.09E+01		
Accident during preparation of vault to operate	1.06E-02	6.36E-02	6.36E-02
Transportation of WP to NSDF with dose rate higher than currently determined	2.33E-04	1.40E-03	1.40E-03
Transport accident during WP transportation to NSDF	1.31E-02	1.44E-02	1.44E-02
WP drop and damage of grouted WP on NSDF site	2.98E-02		
Hanging WP at NSDF	1.58E+00		
Fire hazards related to NSDF	1.29E-03		
WP drop and damage of vault structures	1.09E+01		
Earthquake at IDDF site	2.09E+00		
Transport accident during WP transportation to IDDF	3.22E+00	3.22E+00	3.22E+00
WP drop and damage of grouted WP on IDDF site surface	2.09E+00		
WP drop and damage of grouted WP into shaft or damage of WP	4.23E+00	2.79E+00	3.14E+00

in the shaft			
Hanging container at IDDF	6.46E-01	6.36E-01	6.38E-01
Fire hazards related to IDDF	1.87E+00		
Damage to packages within the vault (plane crash)	3.30E+01		
Damage to packages within the shaft (plane crash)	3.55E+01	2.36E+01	2.66E+01

Table 16.6. Identified operational events and accidents at the disposal facility and predicted general population exposure

Event	**Dose, mSv**		
	PAL	**PED**	**ALT**
Fault during on site movement at NSDF	0		
Failure of truck on route to NSDF	0	4.92E-04	1.33E-04
Spread of contamination at NSDF	4.97E-10	8.32E-10	3.11E-10
Operators access top of the vault to examine/fix some problem due to incorrect positioning of WP and etc at NSDF	0		
Fault during on site movement at IDDF	0		
Failure of truck on route to IDDF	0	4.00E-03	2.00E-03
Spread of contamination at IDDF	3.90E-09	6.55E-09	2.44E-09
Additional operations of staff to access remotely shaft to examine/fix problems at IDDF	0		
Earthquake at NSDF site	1.74E-02		
Accident during preparation of vault to operate	0.00E+00	9.99E-05	9.99E-05
Transportation of WP to NSDF with dose rate higher than currently determined	0	1.10E-06	1.10E-06
Transport accident during WP transportation to NSDF	0	1.03E-03	4.18E-04
WP drop and damage of grouted WP on NSDF site	5.70E-06		
Hanging WP at NSDF	5.63E-06		
Fire hazards related to NSDF	2.92E-09		
WP drop and damage of vault structures	1.74E-02		
Earthquake at IDDF site	2.05E-05		
Transport accident during WP transportation to IDDF	-	9.08E-01	6.24E-01
WP drop and damage of grouted WP on IDDF site surface	2.05E-05		

WP drop and damage of grouted WP into shaft or damage of WP in the shaft			
- Spectator	2.73E-05	2.73E-05	2.73E-05
- Inhabitant	2.09E-06	3.51E-06	1.31E-06
Hanging container at IDDF	6.43E-05		
Fire hazards related to IDDF	1.0E-05		
Damage to packages within the vault (plane crash)			
- Spectator	2.71E-05	2.71E-05	2.71E-05
- Inhabitant	2.44E-05	3.40E-05	1.80E-05
Damage to packages within the shaft (plane crash)			
- Spectator	1.24E-03	1.24E-03	1.24E-03
- Inhabitant	2.31E-04	3.51E-04	1.59E-04

Evaluated doses for the possible design basis accidents do not exceed 11 mSv for NSDF and 2.1 mSv for the IDDF. The doses are below the annual dose limit for workers (20 mSv).

Whereas, in the case of the beyond design accident such as big aircraft crash and explosion, the expected doses for the workers are higher and can reach up to 36 mSv, however they do not exceed the reference level for emergency workers (100 mSv) in a single year. The exposure dose does not significantly depend of a site. The estimated doses for the nearest inhabiting population would be insignificant (less than 1 µSv/year).

No accidents and no considerable exposure of the population are expected in the Closure period of NSDF and IDDF at all disposal sites. Worker would receive small doses (0.24 mSv at NSDF and 0.028 mSv at IDDF) during closure period regardless of a site.

16.5.4. Post-closure safety

16.5.4.1. Assessment scenarios

Post-closure safety assessment of a radioactive waste disposal facility is generally undertaken to provide an assurance to stakeholders (such as government, regulatory authorities, the general public and other technical/scientific groups) that the facility has been or will be sited, designed, constructed, operated and closed in such a manner as to ensure protection of humans and the environment over long timescales. It is important to underline that the entire safety assessment process is iterative and that the first iteration in the process will usually be followed by one or more iterations. Subsequent iterations will often contribute to decisions on whether the safety case is adequate or if there is a need for further improvements.

Long time frame is considered when assessing safety of the waste disposal facilities and the scenario, which is a hypothetical sequence of processes and events, is devised for the purpose of illustrating the range of future behaviours and states of a disposal system, for the purposes of compiling a Safety Case. Uncertainty is inherent in any safety assessment at different stages of the safety analysis is a major factor in the acceptance of the safety assessment case by technical audiences including the regulatory authorities. Scenario uncertainty is related to the definition of an exposure scenario and is often a significant source of uncertainty related to the long term future behaviour of the disposal facility.

For evaluation of the potential impact of the planned NSDF and IDDF through the groundwater pathway, the reference group is considered. The reference scenario considers that the waste can be leached by water infiltrated through the barriers. The contaminants in the leachate can reach the groundwater. In case of near surface disposal the main water pathway relevant to the radionuclide migration within groundwater considers rain water seepage through unsaturated zone and the confining layer downwards to the semi-confined aquifer and lateral groundwater flow towards Baltic Sea. In the case of IDDF shaft diffusion of the radionuclides from the Shaft and consequent upward lifting of the contamination groundwater through the fractures and faults towards the well and the Baltic Sea is possible. The use of the water from the well for domestic needs implies that the contaminants may be introduced into the food chain and may therefore contaminate the reference person through ingestion of contaminated food and inhalation of dust.

The post-closure scenarios were assessed for the residential water well, which pumps 510 L/year and is located at the site boundary (about 200 m away from NSDF and IDDF), using the RESRAD-Offsite model version 4. The model is used to estimate the radionuclide concentrations and associated doses to reference group taking into account effects of dilution, dispersion, decay, and sorption on radionuclide migration and simulates multiple radionuclides as well as different hydrogeological conditions and behaviour scenarios. The model is based on radionuclide specific transfer coefficients, representing transfer of radionuclides from one environmental compartment to another, for example, uptake of the radionuclides from soil to plants (Figure 16.6). The values of transfer coefficients are based on empirical data and literature reviews and have been tabulated by IAEA.

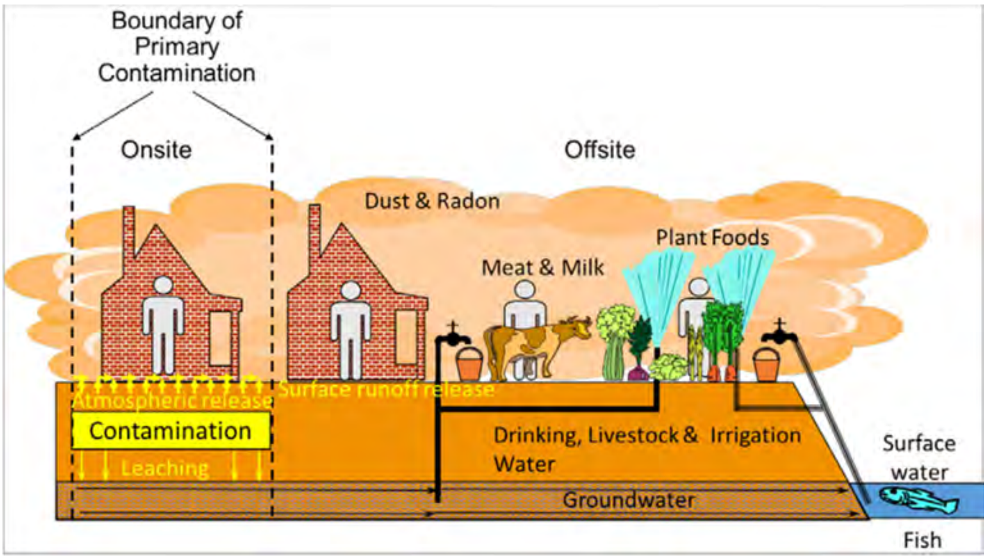


Figure 16.6. Environmental human exposure pathways considered in the model.

The model simulates the exposure due to ingestion of water, plant-derived food, meat, milk, and aquatic food. Consumption of the following products was considered:

- the human ingestion of 1) leafy vegetables and (2) fruit, grain, and nonleafy vegetables irrigated with contaminated water and grown at the site of primary contamination and contaminated by root uptake and foliar deposition, at the site of secondary contamination and contaminated by root uptake and foliar deposition
- the human ingestion of meat from an animal grazing at the site of primary contamination, and/or grazing at the site of secondary contamination, and consuming contaminated water.
- the human ingestion of milk from a milk-producing cow grazing at the site of primary contamination, and grazing at the site of secondary contamination, and consuming contaminated water.

Nine different storage development scenarios were considered (Table 16.7). These include normal evolution of the disposal system, rapid degradation of barrier and potential human intrusion.

Table 16.7. Post-closure safety assessment scenarios

Scenario	**Description of simulation**
Reference – Normal evolution	The Reference scenario is one in which change to the repository system occurs solely as a result of the intrinsic dynamics of the disposal system itself (i.e., the FEPs relevant to human activity are not considered) simulated by RESRAD-Offsite model.
Earthquake - Early IDDF degradation	The earthquake scenario can be simulated by RESRAD-Offsite model using instantaneous release at 300 years as the early physical degradation of barriers.
Inundation - Early degradation relevant for NSDF at ALT site	Due to potential rising of the sea level the disposal facility can be impacted by the Sea. Marine exposure pathway simulated in Sub-activity 2.19. However, there are additional another exposure pathways, for example, external exposure due to staying on the bank of the sea during process of degradation on “nude” waste making it the most critical scenario. The reference people are, for example, a fisherman, climber on concrete walls or birdwatcher, i.e. recreational habits.
Bathtubbing - Early degradation relevant for NSDF	This scenario was simulated following the IAEA-TECDOC-1380 using the Excel model from 0 to 1000 years.
Road construction - Human Intrusion relevant for NSDF	This scenario was simulated following the IAEA-TECDOC-1380 using the Excel model from 0 to 1000 years.
Borehole - Human Intrusion for IDDF	In the case of intact barriers, the borehole drilling through the IDDF to reach the productive aquifer below the IDDF after 300 years simulated by the RESRAD-Offsite model.
On-site residence/ Human Intrusion relevant for NSDF	This scenario was simulated following the IAEA-TECDOC-1380 using the Excel model from 0 to 1000 years.
Explosion/ Human Intrusion/NSDF	The explosion scenarios are assessed as BDBA1 and BDBA2 for 0 years.
‘What if’ instantaneous release for IDDF and NSDF	The instantaneous release at 100 years is simulated by the RESRAD-Offsite model for IDDF and NSDF.

16.5.4.2. Assessment results

The starting point is the Reference scenario, which envisages the disposal facility with the near field evolution based on the disposal design and conservative assumptions regarding engineered barriers degradation. Information on the geosphere and biosphere is based on the current understanding, with conservative assumptions regarding human behaviour and diet. Examples of the performed dose simulation resultes are presented in Figures 16.7 and 16.8. A comparison of the maximum doses to members of the reference population obtained from the modelling of different scenarios is presented in Table 16.8.

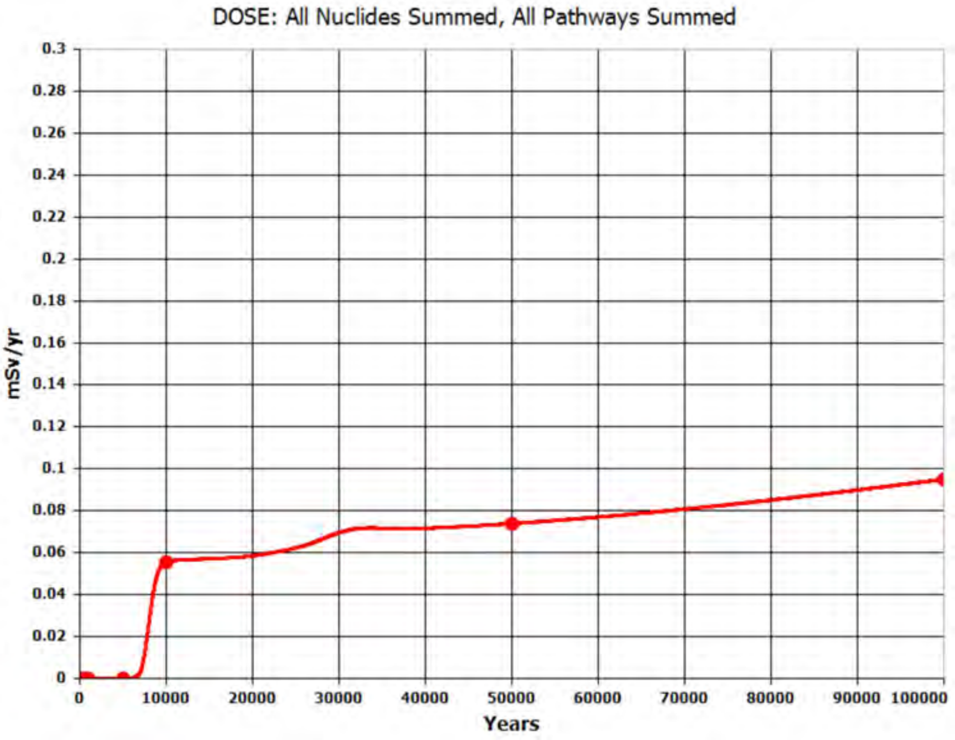


Figure 19.7. Simulated annual dose due to all nuclides for the IDDF at PAL site and 500 years delayed release with the increasing non-linear degradation rate.

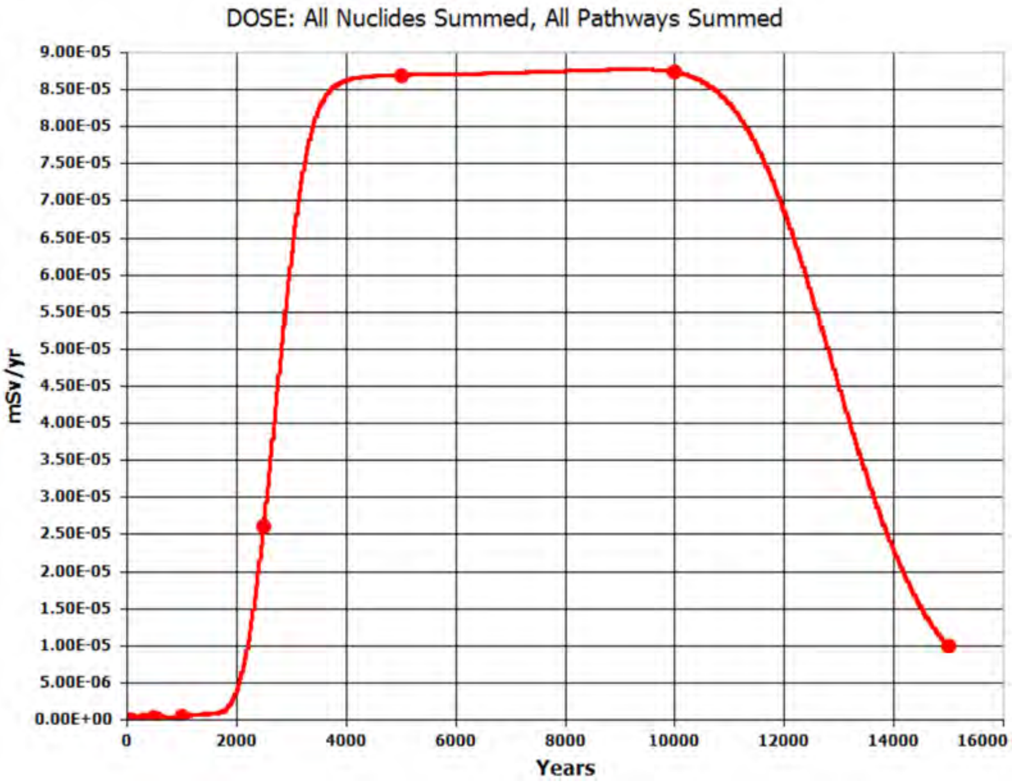


Figure 19.7. Simulated annual dose due to all nuclides for the NSDF at PAL site and 300 years delayed release with the increasing linear degradation rate.

Table 16.8. Peak doses and time of their appearance for the investigated scenarios

Scenario	Most relevant exposure pathway	Maximum dose due to drinking water and intrusion, mSv/y	Peak time, years after repository closure
Reference – Normal evolution IDDF after 500 years NSDF after 300 years	Drinking water	 0.00008 0.877E-04	 After 100000 After 9100
IDDF increased degradation - linear after 500 years - step-wise after 500 years	Drinking water	 0.094 0.095	 After 100000 After 100000
Inundation - Early degradation relevant for NSDF at ALT site	External exposure	60.7	After 100
Bathtubbing - Early degradation relevant for NSDF	Drinking water	6.7E-03	After 510
Road construction - Human Intrusion relevant for NSDF	Drinking water	5.3E-03	After 310
IDDF borehole intrusion - after 300 years	Drinking water	0.1789	After 100000
On-site residence for NSDF	Drinking water	1.4	After 310
'What if' instantaneous release IDDF at 100 years IDDF at 300 years NSDF at 100 years NSDF at 300 years	Drinking water	 0.0949 0.0945 0.0024 0.877E-04	 After 100000 After 100000 After 330 After 8500

To investigate the effects of **early degradation and human intrusion**, it was assumed that human intrusion into a disposal facility could occur once institutional controls will ended. For example, the IDDF can be demerged by a borehole drilling after 300 years of operation. A model, described in IAEA-TECDOC-1380 was used to simulate three early degradation and human intrusion scenarios of bathtubbing, road construction, and on-site residence for NSDF from 0 to 1000 years.

Processes associated with accelerating climate warming threaten to cause significant sea level rise. The sea level rise, along with more severe storms, will begin to threaten the ALT site over the next hundred years as regional isostatic land uplift does not compensate the potential sea level rising. This potential situation is addressed in the 'Inundation scenario'. Based on the climate warming scenario, was conservatively assumed that intense flood-induced degradation of the NSDF could occur 100 years after site closure, i.e. after the period of active institutional control. It is assumed that during the first hundred years, the effects of sea level rise will be mitigated by active controls. Due to high sea level and frequent storms, intensive wave erosion can destroy the capping system of NSDF and lead to direct contact of the salted sea water with the concrete of engineering barriers. It would significantly accelerate degradation of the vault concrete walls and roof and grouted waste could potentially appear uncovered. It was conservatively assumed in Sub-activity 2.19 that whole inventory of the disposed waste is dissolved in water of Paldiski bay. This situation was assessed as sufficiently safe even for people living near the disposal facility. However, the processes of degradation of the engineered barriers, including the waste matrix and the leaching of radionuclides, can last several decades. During that time, a highly contaminated "hot" spot would exist and a possibility of human presence in this zone becomes very likely. Conservatively assessed dose of external exposure to the reference person may rise up to about 60 mSv/year (Table 16.8). The dose of potential exposure is hundreds of times higher than the dose constraint value (0.3 mSv/year) and is therefore unacceptable.

16.6. Waste Acceptance Criteria

An assessments of radionuclide limiting activities are performed for the proposed conceptual design of near surface type disposal facility (NSDF) as well for planned shaft type disposal facility (IDDF), dedicated for disposal of radioactive waste, contaminated with higher levels of long lived radionuclides and for spent sealed sources. Development of WAC for this type of facilities includes analysis of scenarios and calculations of radionuclide dispersion with resulting estimation of the dose rates to the personnel of the facility and the public. "What if" type for the scenarios are not considered in derivation of the resulting limiting activities of WAC, but are presented for the demonstration of the safety margins and robustness of the assumptions. Non-radiological acceptance criteria are also considered.

Limitations for radioactivity in the packages intendent for disposal were derived taking into account all investigated scenarios, except an unrealistic "What if scenario". The calculation results are presented in Tables 16.9 and 16.10. The limits derived for IDDF are applicable regardless of site selection, while NSDF limits are only applicable to PAL and PED sites only, because the ALT site was excluded from further consideration due to risk of the Sea inundation. The elaborated WAC present maximum activity concentrations and total activities, still satisfying radiation protection limits established in national and international legislation.

Table 16.9. Calculated waste activity limits for the NSDF

Radio-nuclide	**Limiting activity concentration, Bq/kg**	**Limiting total activity, Bq**	**Critical scenario**
H-3	4.7E+13	2.5E+20	Earthquake
Co-60	1.4E+06	7.5E+12	Drop and Damage
Ni-59	7.9E+06	4.2E+13	Earthquake
Ni-63	6.2E+09	3.3E+16	Bathtubbing
C-14	3.8E+07	2.0E+14	Earthquake
Sr-90	3.1E+08	1.7E+15	Bathtubbing
Nb-94	1.1E+06	5.9E+12	Bathtubbing
Cs-137	7.3E+06	3.9E+13	Drop and Damage
Eu-152	3.5E+06	1.9E+13	Drop and Damage
Eu-154	2.9E+06	1.5E+13	Drop and Damage
Pu-238	1.4E+08	7.3E+14	Road construction
Pu-239	2.6E+05	1.4E+12	Earthquake
Pu-240	1.1E+07	6.0E+13	Road construction
Am-241	2.2E+07	1.2E+14	Road construction
Ba-133	1.6E+07	8.7E+13	Drop and Damage
Ra-226	7.9E+04	4.2E+11	Bathtubbing
Ra-228	N/L	N/L	
Th-232	1.2E+07	6.3E+13	Road construction
U-234	3.1E+05	1.6E+12	Earthquake
Kr-85	N/L	N/L	
U-238	3.8E+05	2.0E+12	Earthquake

Table 16.16. Calculated waste activity limits for the IDDF

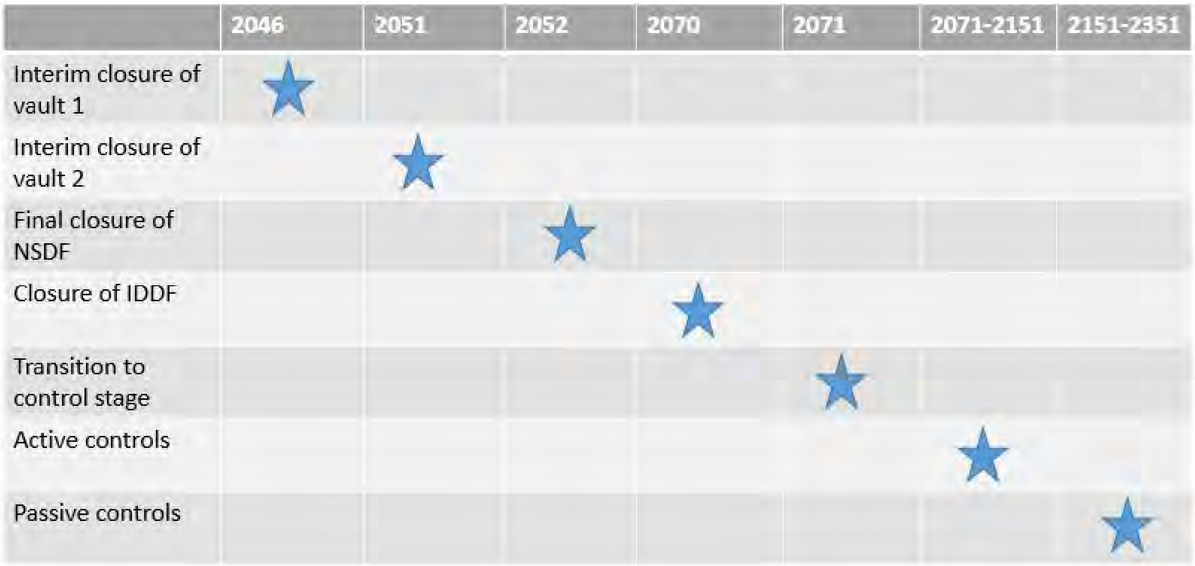
Radio-nuclide	**Limiting activity concentration, Bq/kg**			**Limiting total activity, Bq**			**Critical scenario**
	PAL	PED	ALT	PAL	PED	ALT	
H-3	6.5E+17	9.7E+17	8.7E+17	1.0E+24	1.5E+24	1.3E+24	Drop and Damage
Co-60	3.9E+14	5.8E+14	5.2E+14	6.7E+17	9.0E+20	8.0E+20	Drop and Damage
Ni-59	9.0E+07	9.0E+07	9.0E+07	1.4E+14	1.4E+14	1.4E+14	Earthquake
Ni-63	6.1E+15	N/L	8.1E+15	9.4E+21	N/L	1.2E+22	Drop and Damage
C-14	1.8E+09	1.8E+09	1.8E+09	2.8E+15	2.8E+15	2.8E+15	Earthquake
Sr-90	7.6E+13	1.1E+14	1.0E+14	1.2E+20	1.8E+20	1.2E+20	Drop and Damage
Nb-94	6.0E+08	6.0E+08	6.0E+08	9.3E+14	9.3E+14	9.3E+14	Earthquake
Cs-137	3.0E+14	4.5E+14	4.0E+14	4.7E+20	7.0E+20	4.7E+20	Drop and Damage
Eu-152	3.8E+14	5.7E+14	5.0E+14	5.8E+20	8.7E+20	5.8E+20	Drop and Damage

Eu-154	2.5E+14	3.7E+14	3.3E+14	3.8E+20	5.8E+20	3.8E+20	Drop and Damage
Pu-238	1.1E+10	1.7E+11	1.5E+11	1.7E+17	2.5E+17	1.7E+17	Drop and Damage
Pu-239	5.5E+06	1.5E+11	1.3E+11	1.5E+17	2.3E+17	1.5E+17	Drop and Damage
Pu-240	1.0E+11	1.5E+11	1.3E+11	1.5E+17	2.3E+17	1.5E+17	Drop and Damage
Am-241	1.3E+09	1.9E+11	1.6E+11	1.9E+17	2.9E+17	1.9E+17	Drop and Damage
Ba-133	N/L	N/L	N/L	N/L	N/L	N/L	
Ra-226	1.3E+12	1.9E+12	1.7E+12	1.9E+18	2.9E+18	2.6E+18	Drop and Damage
Ra-228	N/L	N/L	N/L	N/L	N/L	N/L	
Th-232	N/L	N/L	N/L	N/L	N/L	N/L	
U-234	N/L	N/L	N/L	N/L	N/L	N/L	
Kr-85	N/L	N/L	N/L	N/L	N/L	N/L	
U-238	7.9E+06	7.9E+06	7.9E+06	4.2E+13	4.2E+13	4.2E+13	Earthquake

16.7. Preliminary closure plan: time schedule of the closure and costs

Estonian Radioactive Waste disposal program includes several stages: construction (2027 – 2040), operation (2041 – 2050) and closure (2050 – 2060). According to the Program, waste disposal will last up to 10 years, until 2050. It is expected that by this date all the reactor decommissioning waste as well as the stored waste will be disposed of. Based on the provided Program, it is assumed that the first vault of the NSDF will be filled with the waste in 2046, followed by its interim closure. The interim closure of the second vault is planned for 2051, immediately after the decommissioning of the reactor and waste disposal. Based on these assumptions, the final closure of the NSDF could begin in 2052. Immediately after finishing the reactor decommissioning and the disposal of suitable wastes interim closure of the second vault in 2051 is foreseen. Based on these assumptions, the final closure of the NSDF can be started in spring 2052. The proposed sequence of the closure steps is shown in Table 16.11.

Table 16.11. Schedule of stepwise closure of the disposal facility and post-closure



	2046	2051	2052	2070	2071	2071-2151	2151-2351
Interim closure of vault 1	★						
Interim closure of vault 2		★					
Final closure of NSDF			★				
Closure of IDDF				★			
Transition to control stage					★		
Active controls						★	
Passive controls							★

It is also assumed that all the wastes from decommissioning requiring intermediate disposal will be emplaced into the IDDF in 2050 too. However, certain small amount of the institutional waste will be produces even after decommissioning of the reactors. Therefore, a disposal possibility must be maintained for few decades more. As the future waste properties are unknown, it would be reasonable to leave the IDDF operational for another 20 years. This facility is more universal, suitable for accommodation of wide range of wastes. In addition, it is less sensitive to atmospheric impacts.

After closure of the NSDF in 2052, institutional control program should be implemented. However, the control measures will be overlapping with operation of the IDDF, the institutional control program should take it into account. Therefore, the institutional control program must be revised after closure of the IDDF in 2072.

The closure cost estimation is based on methodology used to predict expenses for building construction and associated works. The cost rate includes the following expenses components: equipment, devices, materials, machinery (or its rental), transportation, labour, contingencies as well as overheads and company profits. VAT is not included in the calculations. In cases where devices or complete equipment systems are required, a survey of potential suppliers has been conducted and approximate prices were used. In these cases, the estimates include installation costs. The results are presented in Table 16.12.

The most expensive closure of the disposal facility is at ALT site. The lowest price was obtained for the PAL site. It is lower than disposal in the two alternative locations because of more favourable geological conditions (depth of the suitable geological formation and water drainage) and opportunity for efficient use of already existing buildings and infrastructure.

Table 16.12. Estimated disposal facility cost, kEUR

Activity	**PAL**	**PED**	**ALT**
NSDF construction	1836	1836	1843
IDDF construction	6997	8738	8042
Infrastructure	708	2252	2187
NSDF closure	2260	2360	2431

IDDF closure	387	446	423
Dismantling of infrastructure	0	1	1
Total cost	**12 288**	**15 632**	**14 926**

The cost estimates are based on current prices for materials, labour and services. As the disposal facility must be closed after about 30 years, the prices may change rather significantly due to inflation, new construction techniques, methods and standards may also be introduced, therefore, the cost estimates need to be revised at the end of the planning phase.

16.8. Record keeping

Article 17 of the Joint Convention identifies needs for institutional measures after closure of radioactive waste disposal facilities. Each Convention Party shall take the appropriate steps to ensure that the following measures are implemented after closure of a disposal facilities: records of the location, design and inventory of that facility required by the regulatory body are preserved; active or passive institutional controls such as monitoring or access restrictions are carried out, if required; if, during any period of active institutional control, an unplanned release of radioactive materials into the environment is detected, intervention measures are implemented, if necessary.

To comply with the regulatory requirements and for planning of future action, waste disposal institution should establish a system for generation and storage of documents and records with up-to-date information. The following general information on the disposal facility should be stored:

- Site selection and characterisation data,
- Coordinates of the location of the disposal facilities,
- Technical Design documentation,
- Safety Assessment Report(s), including data and parameters used in the assessment and the assessment results,
- Waste acceptance criteria,
- Operating manuals,
- Authorisation for disposal of waste,
- Emergency preparedness plan,
- Waste emplacement scheme indicating emplacement of waste,
- Closure and long term surveillance procedures,
- Information on closure of the facilities, including backfilling and engineered barriers,
- Environmental monitoring programme.

Waste Emplacement Records should contain the following information on the disposed of waste packages:

- Details of the contents of waste packages or containers, including origin and form of waste, content of radionuclides, applied waste treatment and conditioning,
- Volume and weight,
- Radionuclide composition (activities of relevant radionuclides),

- The locations of the waste packages within the structures of the disposal facility (disposal module, position and layer),
- Date of disposal,
- Deviations, if any.

Environmental Monitoring Records should include external radiation monitoring around the NSDF. Records of analysis of air, water (ground water and surface water), soil and vegetation samples monitoring should contain the following information:

- Date of sampling;
- Location of sampling;
- Methods of analysis;
- Measurement results (activities for important nuclides or gross activity);
- Deviations, if any.

Operation Records should encompass pre-operational, operational, closure and post-closure data. The data on each phase should be documented and recorded separately. Safety significant events such as flooding, failure of the disposal facilities, fire, maintenance and remedial actions should be recorded and maintained. The occupational exposure records of all employees exposed to radiation in the course of their work, including accidents and incidents, is to be retained by the appropriate authority according a procedure established by the radiation protection authority.

The records on the disposed of waste and the disposal facility shall be kept at least until the end of the institutional control period (for 300 years) preferably in two separated locations, one of which could be a national archive.

16.9. Conclusions

1. The operational safety analysis shows that the safety standards (dose limits for workers and the general public) would not be violated regardless of the chosen location. The differences between the analyzed candidate sites are minor.

2. As a result of the post-closure assessment the all three candidate site are acceptable for IDDF. From the safety point of view the differences are insignificant.

3. The results of the post-closure assessment of the NSDF has shown that the inundation scenario is the most critical one. The estimated doses potential exposure of members of the public due to progressive degradation of the facility’s structures are unacceptably high. As only ALT site may be inundated under predicted global warming, it is recommended to exclude it from further considerations. The other two sites PAL and PED are rather equally suitable for near surface waste disposal.

3. Waste disposal cost is largely determined by the depth of the IDDF. Disposal of intermediate-level waste at PAL would be the least deep and therefore much cheaper than disposal at the other two sites.

4. An additional advantages of the PAL site are possibilities to use the infrastructure existing on the site and to optimize waste disposal-related processes. Implementation of the disposal program at this site can be faster.

5. Overall conclusion is that the PAL site is better than PED site, while ALT site can be used for intermediate depth disposal only.

17. Sub-activity 2.17. Environmental and Radiation Monitoring

Environmental and radiation monitoring is the continuous surveillance of the status of the environment and the factors affecting it. It involves environmental observations, collection, processing and storage of data, analysis and storage of the results. According the IAEA recommendations the monitoring programs of disposal facilities for radioactive waste has the following five broad objectives:

- To demonstrate compliance with regulatory requirements and with the licence conditions, i.e. to assure that exposure of personnel and population do not exceed the established dose limits.
- To verify that the disposal system is performing as expected and to warn about any deviation. This means that the components of the disposal system are carrying out their functions as identified in the safety assessment.
- To verify that the key assumptions made and models used to assess safety are consistent with actual conditions.
- To establish a database of information on the facility, the site and its surroundings. This database is to be used to support future decisions when proceeding from siting to construction, operation, closure and the period after closure. The database is also used to support decisions relating to updating concepts and procedures for monitoring.
- To provide information for the public. In addition to its technical objectives, the monitoring programme is a suitable tool for enhancing public confidence.

The monitoring programme was elaborated by Stasys Motiejūnas (UAB EKSORTUS) and is detailed in an Appendix 17.

17.1. Design of a Monitoring Programme for Radioactive Waste disposal facilities

The monitoring programme should be designed during pre-operational period and further refined throughout the operational and post-closure periods of the facility. It should be adjusted accordingly for each of these periods. It should include baseline monitoring performed before and during the construction stage and during pre-operational periods.

The monitoring programme must cover relevant radionuclide migration and population exposure pathways. Particular attention should be paid to the critical pathways and the critical radionuclides. The implementation of the program must allow the collection of sufficient data to assess the activity of radionuclide leakage, if any, its short-term changes and doses to members of the reference group. Monitoring of disposal facilities involves balancing the benefits of gains in information on the behaviour of certain components of the disposal facility against any detriment that might result from monitoring. The nature of the monitoring programme will change at different stages of the facility. At the pre-operational stage, environmental monitoring is aimed to establish existing activity concentrations in the environment.

The monitoring programme is a tool to confirm that the performance of the engineered and natural barriers is not compromised by operational activities. Monitoring is needed to evaluate any changes either in the actual performance of the facility or in processes or parameters that might influence the performance of the facility. In addition, an appropriate level of control shall be applied to protect and preserve the passive safety features, so that they can fulfil the functions assigned in the safety case for safety after closure. The monitoring must be effective both under normal conditions of the disposal facility and in case of emergencies.

The monitoring programme is subject for periodic revisions to ensure that measurements continue to be relevant for their purpose and that no significant routes of discharge or environmental transfer or no significant exposure pathways have been overlooked. The monitoring programme may be revised during the design of the repository, while performing the safety analysis or after data on waste to be disposed of are revised; it may become clear that this programme pays not sufficient attention to certain migration routes of radionuclides, while other routes are not important. The programme revision could also be performed after constructions of the disposal facility taking into consideration new information and results of the final safety assessment.

The monitoring programme should be fundamentally changed during the closure of the repository and the commencement of the post-closure control measures. The further periodic revisions are recommended one year after the start of the institutional control and every five years afterwards.

17.2. National radioactivity monitoring

The National Environmental Monitoring Program in Estonia consists of sectoral subprograms; one of them is the Radiation Monitoring Program, which is managed by the Environmental Board. The National Radioactivity Monitoring includes systematic sampling and analysis of the following components: air, surface water, seawater, biota, bottom sediments, drinking water, milk, food and soil as well as continuous monitoring of the ambient gamma radiation dose rate and in addition independent monitoring around the territory of the Former Paldiski Nuclear Site (FPNS).

17.3. Source monitoring of the Disposal Facility: monitoring of discharged water

Source monitoring is aimed to identify and control the potential discharges of radionuclides arising during waste disposal activities. It consists of systematic control of radioactive effluents from the facility.

There will be two aquatic pathways during operational stage that are easily controlled during process of waste emplacement:

- water used for sanitary cleaning, decontamination and in a shower,
- collected water that penetrated into the disposal vaults and the shaft.

During waste emplacement, the disposal modules will be protected against entering of rain water. However, rain water as well as ground water can accidentally enter the disposal vaults and shaft. The water will enter the water collection tanks purposefully installed in the floor of the disposal systems. The collected water will be sampled for laboratory analysis, the measured parameters are presented in Table 17.1. If activity concentration does not exceed the established values, the water will be discharged to the rain water drainage system. Water with a higher activity concentration will be treated as liquid radioactive waste.

Table 17.1. Monitoring of disharged water: samples of and measurements

	Measured parameter	**Measurement frequency**
1	Water amount	Each time before discharging
2	Activity concentrations of gamma emitters	Each time before discharging
3	Activity concentration of H-3	Each time before discharging
4	Gross beta activity	Each time before discharging
5	Gross alpha activity	Each time before discharging

During the operation of the disposal facility, water will be used for sanitary cleaning, shower and decontamination. It will be collected and sampled for laboratory analysis detailed in Table 17.1. If radionuclide concentrations do not exceed the established clearance values, the water will be discharged to the waste water treatment plant. The monitoring of the discharged waters will continue during waste disposal stage and will be terminated during closure of the facility.

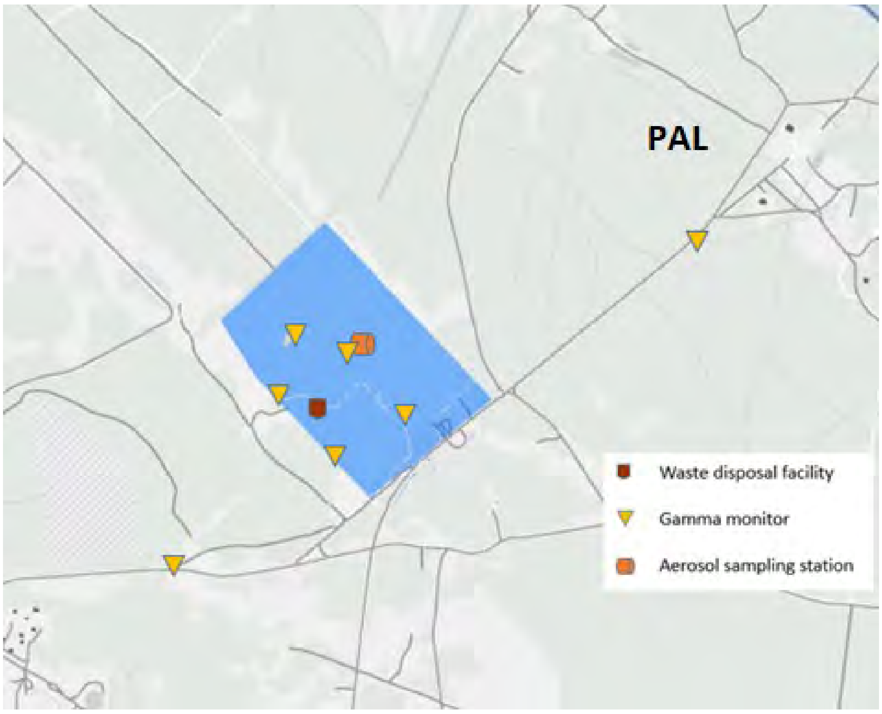
17.4. Environmental monitoring of radioactive contamination

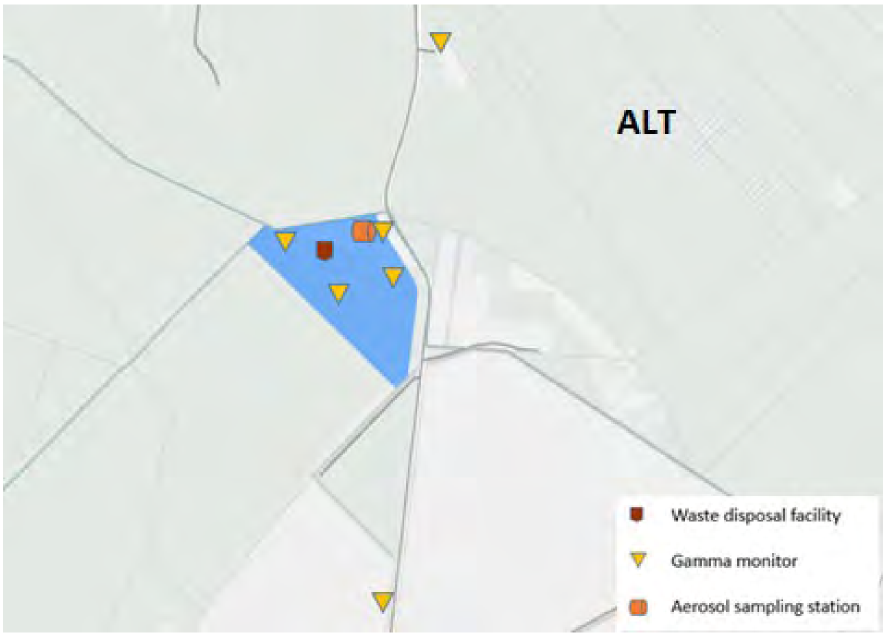
Environmental monitoring covers measurements of the dose rate of ionising radiation in the environment and content of radionuclides in various environmental components. The selection of environmental objects belongs on importance of the radionuclides accumulating in these objects for the exposure of population. It is planned to terminate the Environmental monitoring at the end of active institutional control period, i.e. 100 years after end of waste emplacement activities.

17.4.1. Gamma monitoring

Continuous measurements of ionising radiation intensity are performed in representative locations of the disposal area and in directions to the nearest residential areas. The gamma monitoring system performs function of early warning in case of emergencies.

Approximate locations of the gamma monitoring stations for each candidate site are shown on Figure 17.1. Exact positions of the gamma stations will be defined in the Detailed Design of the disposal facility. The gamma monitoring system will be installed during construction of the disposal facility. The measurements will be started before start of waste disposal and will continue during closure of the disposal facility and after closure (during an active institutional control period) without significant modifications.


PAL
Waste disposal facility
Gamma monitor
Aerosol sampling station


ALT
Waste disposal facility
Gamma monitor
Aerosol sampling station

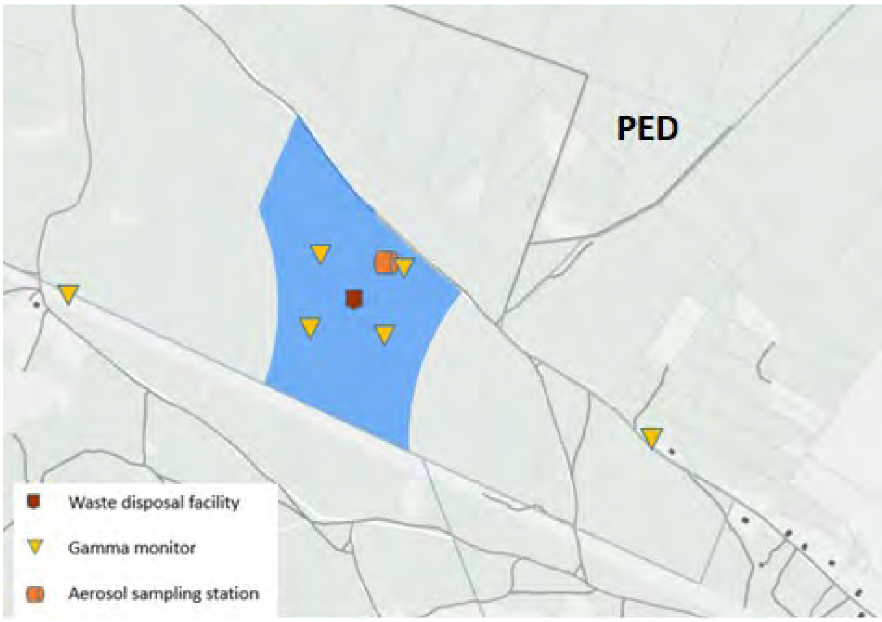


Figure 17.1. Gamma monitoring network and aerosol sampling station at PAL, ALT and PED sites

17.4.2. Air monitoring

In general, the release of radioactive substances into the atmosphere should be negligible, i.e. below detection limits. However, radioactive contaminants can be detected in the air in case of accidents; therefore an automatic air monitoring station located near the disposal facility is proposed. The location for this station is selected taking into account prevailing wind direction. Aerosol filters coupled to air pumps are capable of accumulating particles from large volumes of air onto a small surface, their radioactive content can be determined.

The air monitoring station will be installed during construction of the disposal facility and the measurements will be started before start of waste disposal. Operation of the air monitoring station will continue during closure of the disposal facility. The shutdown of this station may be considered after the closure in order to optimise the system. In addition to the national monitoring network, an automatic meteorological station is recommended to install (good knowledge of meteorological conditions is relevant for predicting situations in case of emergencies).

17.4.3. Ground water monitoring

Groundwater is the component of the environment that is most sensitive to an impact of the disposed waste. Radionuclides detected in the groundwater may signal the failure of the relevant barriers of the disposal facility.

The monitoring boreholes should be established during closure of the facility and will be operational in the post-closure period. An exception makes PAL site, where ground water monitoring is already ongoing in the framework of the National Monitoring Program (Figure 17.2). The existing monitoring boreholes will be integrated into the monitoring system of the disposal facility and the ongoing measurements will be continued during construction, waste disposal and closure stages.

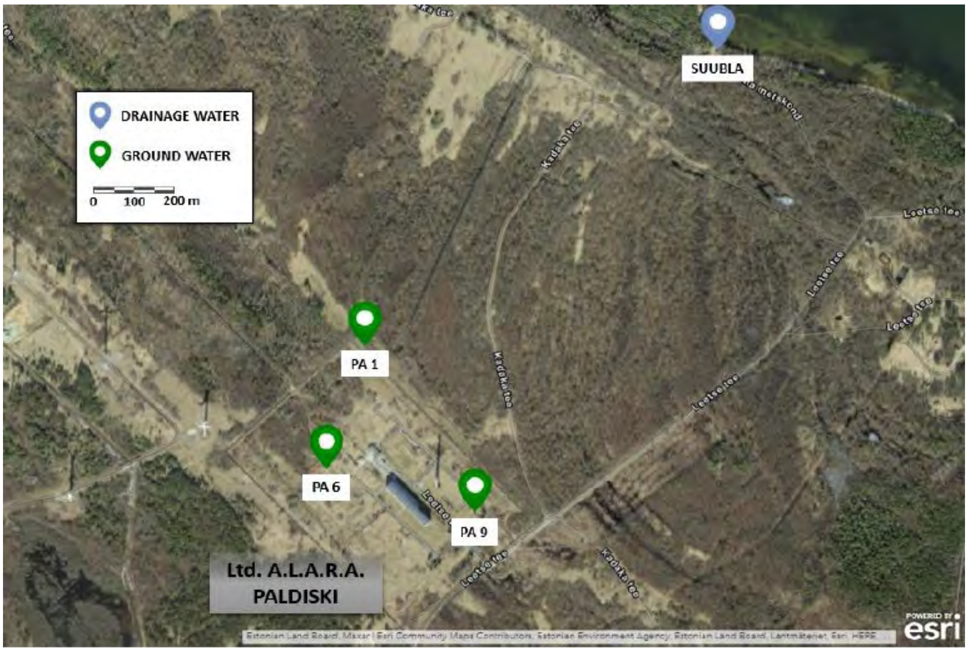


Figure 17.2. Existing water sampling points next to Paldiski reactors.

A system of monitoring boreholes will be built near the disposal modules. When choosing observation points, it is necessary to take into account the direction of ground water flow and its possible changes in direction. A proposed scheme for positioning the boreholes is in Figure 17.3. It is very important that the installation of monitoring boreholes do not violate the leak-tightness of the disposal facility, i.e. integrity of the engineered barriers made of clay and concrete. Therefore, the boreholes should be located few meters away from the engineered structures of the facility. Boreholes adjacent to NSDF vaults will be relatively shallow, reaching water-saturated layers, but the depth of the borehole controlling the IDDF must be similar to the depth of the disposed waste.

Lay-outs of the ground water monitoring system adapted to each candidate site are presented in Figure 17.3. Exact locations for the monitoring boreholes will be defined in the Detailed Design of the facility. The ground water samples will be regularly taken for laboratory analysis until the end of the active institutional control period. The following measurements of radioactivity will be performed: content of H-3, gross beta activity and gross alpha activity as presented in Table 17.2.

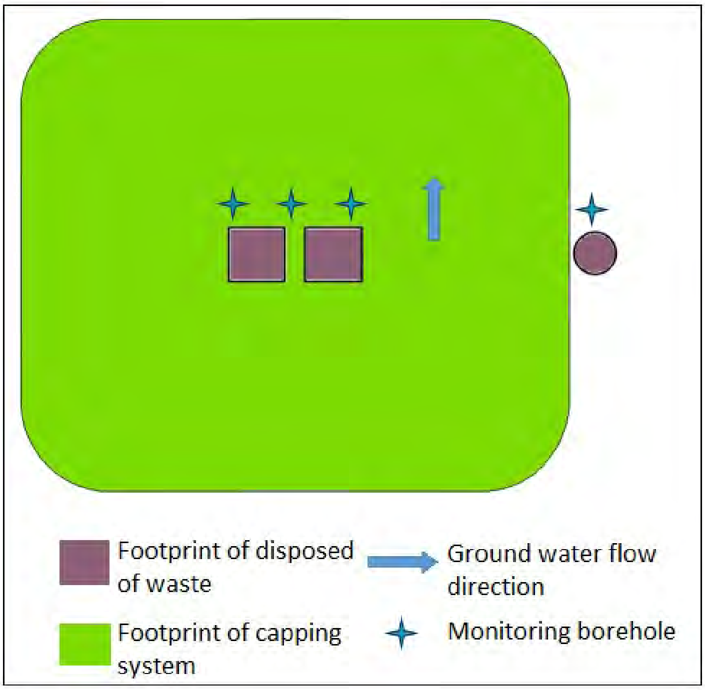


Figure 17.3. Typical generic lay-out of boreholes for ground water monitoring.

Table 17.2. Monitoring of water ecosystem: samples of and measurements

Samples	Number of sampling points	Frequency	Measured parameter
Rain water drainage	1	Once a month during operational stage	Activities of gamma emiters
Ground water	7 on PAL, including the existing monitoring boreholes 4 on ALT& PAD	Once a quarter during post closure	Activity concentration of H-3 Gross beta activity[4] Gross alpha activity[4]
Surfase water	3 on PAL, including the existing drainage water monitoring station "SUUBLA" 2 on ALT& PED	Once a quarter during stages of operation, closure and post closure	Activity concentration of H-3 Gros beta activity[4] Gros alpha activity[4]
Bottom sediments	2	Once a year during stages of operation, closure and post closure	Activity concentrations of gamma emiters
Aquatic plants	2	Once a quarter during stages of of operation, closure and post closure	Activity concentrations of gamma emiters

17.4.4. Monitoring of surface water ecosystem

During the stage of operation of the disposal facility, a rain water drainage system will be built in the area of the disposal modules. A location for drainage water sampling will be foreseen during development of the Detailed Design and equipped during facility construction. The water sampling and analysing shall start before beginning of waste disposal activities and continued till the closure. The water will be sampled and the required analysis performed on a monthly basis, if feasible (Table 17.2). The amount of drained water will be calculated according to the amount of precipitation registered at the meteorological station, if needed for assessment of amount released radioactive substances.

Radionuclides eventually released from the closed disposal facility can migrate with surface water along the rivers and channels. Therefore, the most typical environmental samples should be regularly taken for laboratory analysis at places of the highest expected concentrations of released radionuclides, including points of discharge of drained water from the site. The following samples should be taken and analysed:

- water,
- bottom sediments,
- aquatic plants.

Due to absence of large water bodies monitoring of fish is not feasible.

17.4.5. Monitoring of terrestrial ecosystem

During eventual accidents, radioactive fallouts can contaminate the surrounding soil and grass. Therefore, accumulation of the radioactive substances will be controlled by taking the samples and analysing them in laboratory. In order to determine the background contamination, the monitoring of soil and grass must be started at least one year before operation. Grass and soil samples (Table 17.3) will be taken from the same plot. The sampling plot will be selected on the disposal site during development of Detailed Design, taking into account the prevailing direction of wind (i.e. in direction of the highest probability of radioactive fallouts). Grass samples will be taken from 1 square meter. Upper 5 cm soil layer will be sampled, amount of sample should be about 1.5 kg (taking into account gamma spectrometer calibration geometry). High resolution gamma spectrometer will be used for analysis of the grass and soil samples, capable to identify the relevant radionuclides (Co-60, Cs-137, Ra-226, Am-241).

Table 17.3. Monitoring of terrestrial ecosystem: samples taken and measurements

Samples	Number of sampling points	Frequency	Measured parameter
Soil	1	Once a year during operation, closure and the first 5 years after closure Then every 5 years	Activity concentrations of gamma emitters
Grass	1	Once a year (at the end of summer)	Activity concentrations of gamma emitters

Gamma spectroscopy method is suitable method for monitoring as it is a simple and universal. No complicated sample preparation is needed. Alpha and beta radionuclides get importance in case of operational accidents or due to malfunction of barriers after closure.

17.4.6. Monitoring of marine ecosystem

Radioactivity in the marine environment is already monitored in the framework of the national monitoring program. There are two monitoring stations (PE and PW) in the Gulf of Finland next to PALsite (Figure 17. 7). Regular sampling of water, bottom sediments and biota is done each year for measurements of technogenic radionuclides Sr-90 and Cs-137. These two stations of the national monitoring network are fully sufficient if the disposal facility is located on the PAL site. However, in case of PED and ALT sites additional stations are needed, respectively in Vihterpalu bay or Pakri bay, Table 17.4. The marine monitoring will start before facility construction and continued until end of the active control.

Table 17.4. Monitoring of marine ecosystem: samples of and measurements

Samples	Frequency	Measured parameter
Sea water	Once a quarter	Activity concentration of H-3 Gross beta activity Gross alpha activity Activity concentration of Cs-137
Bottom sediments	Once a year	Activities of gamma relevant emitters
Aquatic plants, preferably Bladderwrack (*Fucus vesiculosus*) or algaes	Once a year	Acticivity concentrations of relevant gamma emitters
Fish (preferably Baltic herring)	Once a year	Acticivity concentrations of relevant gamma emitters

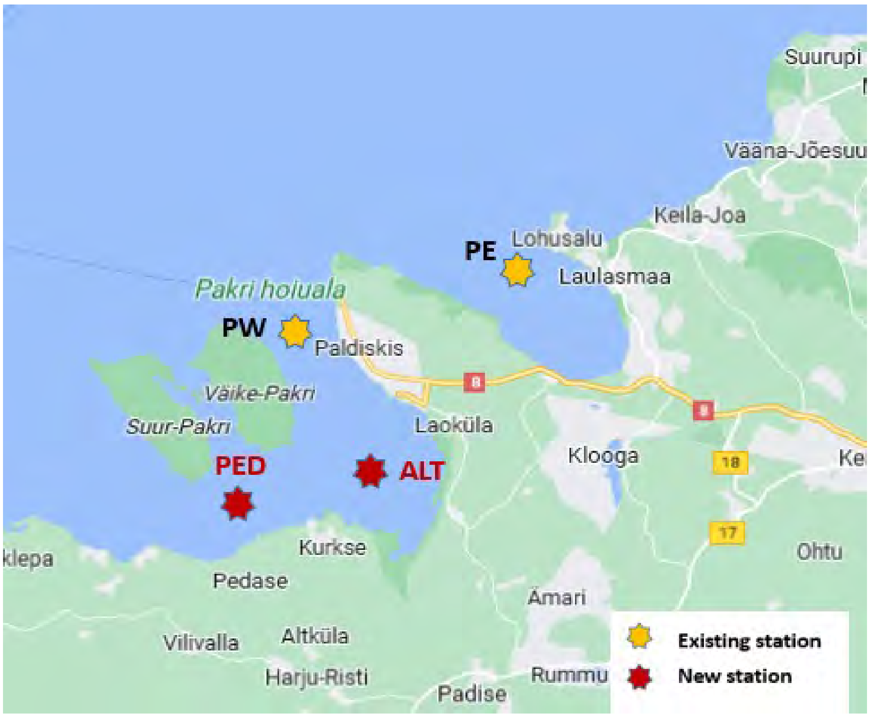


Figure 17.4. Marine monitoring stations.

17.5. Data recording and reporting

The following data shall be recorded and stored by the operator of the disposal facility:

- General information about activities (disposed of waste);
- Results of all measurements provided by the monitoring programme;
- Unplanned releases of radionuclides into the environment, accidents and other important information, including assessed doses to members of reference group caused by the released radionuclides (if any).

17.6. Summary

Environmental Radioactivity Monitoring must begin before the start of waste disposal and continue until the end of the period of active institutional control. The duration of the period of active institutional control is 100 years. Monitoring results should be stored until the end of passive monitoring, i.e. 300 years. During closure of the facility the environmental monitoring program has to be significantly modified and adapted to the post-closure needs. Periodic revisions of the program are recommended taking into account the available results of monitoring.

The Environmental Radioactivity Monitoring should cover the normal operation of the disposal facility as well as emergencies.

The monitoring activities must not compromise performance of the disposal system. Installation and operation of monitoring system should not violate integrity of the engineered barriers and natural barriers and not create additional pathways of radionuclide spread. These aspects have to be taken into account during development of the Technical Design of the disposal facility.

The most common worldwide approach is that the license holder is responsible for monitoring of environmental radioactivity. However, the Radiation Act of the Republic of Estonia stipulates that the Environmental Board performs the monitoring of radioactive waste disposal facilities.

17.7. Conclusion

Considering the complexity of the monitoring program, there are no significant differences between the three studied sites. However, priority is given to the PAL site, the same monitoring system will serve both the disposal facility and decommissioning of the reactor. Therefore, in this case optimization of the monitoring system is possible. Moreover, there will be no need to expand the sea monitoring program.

18. Sub-activity 2.18. Risk analysis and assessment

When the candidate sites are identified, next tasks are to compare them by different attributes and properties and to choose the most suitable one. Safety Assessment performed under Sub-activity 2.16 provides a deterministic analysis of possible accidents during different lifetime stages of planed radioactive waste repositories. Second step in the repository evaluation is risk analysis performed under current report. Risk analysis allows to compare emergency events that are expected for the considered candidate sites, by their probabilities and possible consequences. A risk, that is actually a combination of probability and consequences of an event, allows to measure and compare undesirable events. Risk analysis allows to understand and compare expected levels of risks for each candidate site.

The risk analysis and assessment by its nature comes along or follows deterministic safety assessment. The risk analysis and assessment developed following relevant Estonian regulations and using Contractor experience and worldwide practice for mapping of the risk induced by planed decommissioning activities.

Ten emergency scenarios, including seven internal scenarios and three external scenarios, were analysed under risks assessment. Most of the scenarios have negligible probabilities and severities.

Risk preventive measures were suggested for all considered scenarios. Implementation priority might be given to risk preventive measures for the higher-risk category.

The detailed risk analysis and assessment is presented in an Appendix 18. The assessment was performed by Roman Voronov and Egidijus Babilas.

18.1. Risk analysis and assessment methodology

Risk Analysis for possible locations of radioactive waste repositories in Estonia is performed using graded approach directed to available data about the sites and further radioactive waste disposal facilities, following best available international practice, recommendations and in accordance with Regulation No. 28 of the Minister of the Interior of 19 June 2017, ‘Requirements for an emergency risk assessment and procedure for the preparation of a risk assessment’. The procedure provided by Regulation 28 was adopted for the purpose of this study and extended with the methods and data used in Probabilistic Safety Analysis for nuclear facilities, following best available international practice and recommendations. Risk analysis included the following steps:

- Development of emergency scenarios;
- Assessment of the probabilities of the emergency scenarios;
- Assessment of the consequences of the emergency scenarios;
- Risk categorization of the emergency scenarios;
- Comparison of risk categories for each candidate site.

18.2. General assumptions

The risk analysis provided in this report was based on the following approach and assumptions:

- Information regarding the disposal facilities, including properties and number of waste packages together with considered emergency scenarios was obtained from Safety Assessment Report developed in the course of sub-activity 2.16;
- Information used for the analysis of external emergency scenarios regarding the area and candidate sites' characteristics including climate, and seismology, was obtained from reports of Activity 2 „ Studies of the three repository locations“, e.g. Study of the climatic conditions in course of Sub-activity 2.11.
- The worst possible consequence is assumed for each emergency scenario.
- Specific assumptions, data used and supporting calculations are provided in the scope of analysis of each emergency scenario.

18.3. Development of scenarios

A list of emergency scenarios subject to the risk analysis was developed based on the Safety Assessment, Sub-activity 2.16 and is provided in the **Error! Reference source not found.** below.

Table 18.1. List of emergency scenarios subject to the risk analysis

Scenario ID and title for Risk Analysis	Events and hazards identified in SAR	Errors and failures identified in SAR
OP-01: Exceeding waste package activity	DBA2: Accident during preparation of vault/vault group to operate	NSDF1.2 Errors in verification process
	DBA3: Transportation of WP to NSDF with dose rate higher than acceptance criteria	NSDF2.3 Human error in verification process at the RB, e.g. selection of wrong WP
	AOE3: Spread of contamination at NSDF	NSDF2.5 Failure of the verification process to detect contamination of WP (surface contamination).
		NSDF2.6 Transfer of contamination from WP (surface contamination).
	AOE7: Spread of contamination at IDDF	IDDF2.4 Failure of the verification process to detect contamination of WP (surface contamination).
		IDDF2.7 Transfer of contamination from WP (surface contamination).
OP-02: Transport accident	AOE1: Fault during on site movement at NSDF	NSDF2.1 Driver fails to leave the reception bay area in an appropriate time
	AOE2: Failure of truck on route to NSDF	NSDF2.4 Failure of truck on route
	DBA4: Transport accident	NSDF2.2 Transport accident on

Scenario ID and title for Risk Analysis	Events and hazards identified in SAR	Errors and failures identified in SAR
	during WP transportation to NSDF	route (e.g. collision)
	AOE5: Fault during on site movement at IDDF	IDDF2.1 Driver fails to leave the reception bay area in an appropriate time
	AOE6: Failure of truck on route to IDDF	IDDF2.3 Failure of truck en route
	DBA10: Transport accident during WP transportation to IDDF	IDDF2.2 Transport accident en route (e.g. collision) results in damage to WP.
OP-03: Waste package drop and damage	DBA5: WP drop and damage of grouted WP on NSDF site	NSDF2.8 Grip failure
		NSDF3.1 Dropped WP on site
		NSDF3.2 Dropped Load on WP
	DBA11: WP drop and damage of grouted WP on IDDF site surface	IDDF2.6 Grip failure and drop of WP on surface
		IDDF3.1 Drop of WP on site surface; Incorrect Calibration.
		IDDF3.2 Dropped heavy Load on WP at the site (on surface)
OP-04 Loss of power supply	DBA5: WP drop and damage of grouted WP on NSDF site	NSDF3.9 Electric power supply fault in the gantry crane
	DBA11: WP drop and damage of grouted WP on IDDF site surface	IDDF3.9 Electric power supply fault in the gantry crane motor during operations involving transfer of WP
OP-05: WP drop damaging the repository	DBA8: WP drop and damage of vault structures	NSDF3.4 WP collision with wall or another WP
		NSDF3.8 Drop of WP into vault due to grip failure, insecure grip on WP; misalignment error by operators.
		NSDF4.3 Drop of load or equipment on WP
		NSDF5.2 Dropped load or equipment on the vault roof
	DBA12: WP drop and damage of grouted WP into shaft or damage of WP in the shaft	IDDF3.4 WP collision with wall or shaft or another WP

Scenario ID and title for Risk Analysis	Events and hazards identified in SAR	Errors and failures identified in SAR
OP-06. Hanging load	AOE4: Operators access top of the vault to examine/fix some problem due to incorrect positioning of WP and etc at NSDF	NSDF3.5 Incorrect positioning of WP
		NSDF5.1 Operators access top of the vault to examine/fix some problem (high dose WP stored near the top; more than expected background dose rate), Increased duration of operation due to the access requirements or restrictions;
	DBA6: Hanging WP at NSDF	NSDF3.3 Hanging load
	AOE8: Additional operations of staff to access remotely shaft to examine/fix problems at IDDF	IDDF3.5 Some problems during loading of shaft with WP (e.g. incorrect positioning of WP)
		IDDF5.1 Additional operations of staff to access remotely top of the loaded Shaft to examine/fix any problems (high dose WP stored near the top), Increased duration of operation due to the access requirements or restrictions;
	DBA13: Hanging container at IDDF	IDDF3.3 Hanging load
OP-07: Fire	DBA7: Fire hazards related to NSDF	NSDF2.7 Transport fire as a result of vehicle accident
		NSDF3.6 Oil leakage from crane operations
		NSDF3.7 Electrical cabling fault
		NSDF4.1 Oil leakage from crane operations
		NSDF4.2 Electrical cabling fault
	DBA14: Fire hazards related to IDDF	IDDF2.5 Fire Transport fire as a result of vehicle accident.
		IDDF3.6 Oil leakage from crane operations
		DDF3.7 Electrical cabling fault
OP-08: Earthquake at the	DBA1: Earthquake at NSDF site	NSDF Ext.5 SL2 earthquake

Scenario ID and title for Risk Analysis	Events and hazards identified in SAR	Errors and failures identified in SAR
repository location	DBA9: Earthquake at IDDF site	IDDF Ext.5 SL2 earthquake
OP-09: Aircraft crash at NSDF	BDBA1: Damage to packages within the vault (NSDF case)	NSDF Ext.1 Extreme Wind. High wind speed *(covered by Aircraft crash)*
		NSDF Ext.6 Aircraft crash. Falling of aircraft on the NSDF *(most dangeros case considered in analysis and covers all others)*
OP-10 Aircraft crash at IDDF	BDBA2: Damage to packages within the shaft (IDDF case)	NSDF Ext.1 Extreme Wind. High wind speed *(covered by Aircraft crash)*
		NSDF Ext.6 Aircraft crash. Falling of aircraft on the IDDF *(most dangeros case considered in analysis and covers all others)*

A scenario includes three main parts:

- Initiating event (or initiator, which starts a scenario);
- Scenario or events sequence;
- Consequences.

As can be seen from the table above, in many cases scenarios having different initiators, have the same consequences.

Emergency scenarios are considered separately for NSDF and IDDF and for three candidate site locations. If the initiating event probability, events' sequence or consequences differ depending on the type of the disposal facility or location of the candidate site, such difference is highlighted by the analysis

18.4. Assessment of probabilities

Assessment of probabilities of the emergency scenarios is performed in accordance with the requirements of § 5 and of the Regulation 28 and is based on the historical data, generic data, expert judgement. Probability (frequency as probability estimate) is assessed using a five-grade scale from 'A' to 'E' (see Table 18.1 below based on Annex 2 to Regulation 28) where 'A' corresponds to the lowest, 'E' – to the highest probability.

Obtained values were then subdivided using five grades scale, based on Annex 2 to the Regulation 28 where 'A' corresponded to the lowest, 'E' – to the highest probability (see **Error! Reference source not found.** below).

Table 18.2. Probabilities assessment table

Value in acronym	A	B	C	D	E
Value in words	very low	low	average	high	very high
Criterion	less than once every 100 years	once every 50–100 years	once every 20–50 years	once every 5–20 years	more than once every 5 years
Frequency, events/year	$< 10^{-2}$	$[10^{-2}; 2{\cdot}10^{-2})$	$[2{\cdot}10^{-2}; 5{\cdot}10^{-2})$	$[5{\cdot}10^{-2}; 2{\cdot}10^{-1})$	$>2{\cdot}10^{-1}$

18.5. Human reliability analysis

Safety Assessment Report considered personnel errors as events that lead to other initiating events, both internal and external. Human reliability analysis was therefore performed in scope of risk assessment.

Evaluation of human error probabilities usually applies tabulated data based mostly on expert judgement. Recognized and widely used methods and data sources are Accident Sequence Evaluation Program (ASEP) and Technique for Human Error Rate Prediction (THERP).

Human reliability analysis is provided within probability evaluation subsections for each relevant scenario in risk analysis and assessment report (Appendix 18).

18.6. Assessment of consequences

Consequences of emergency scenarios are evaluated for the considered scenarios based on calculations provided in the Safety Assessment Report (SAR), Sub-activity 2.16. The main criterion used to evaluate severity of the consequences was radiation dose uptake by personnel or population. An additional criterion was direct financial cost.

Severity of the consequences was then subdivided using a five-grade scale from ‘1’ to ‘5’ based on Annex 3 to the Regulation 28 where ‘1’ corresponds to the lowest, ‘5’ – to the highest severity (see **Error! Reference source not found.** below).

Table 18.3. Consequences assessment table

Severity	1	2	3	4	5
Value in words	insignificant	minor	severe	very severe	catastrophic
I Life and health					
Deceased (number)	≤ 5	6–15	16–50	51–200	> 200
Injured or taken ill (number)	≤ 15	16–45	46–150	151–600	> 600

Severity	1	2	3	4	5
Value in words	insignificant	minor	severe	very severe	catastrophic
Evacuated (number)	≤ 50	51−200	201−500	501−2000	> 2000
II Property					
Direct financial cost (MEUR)	< 1	1−10	11−50	51−100	> 100

18.7. Risk estimate categorization

Risk category *R* can be expressed as a "value of risk" and is simply a multiplication of risk probability *P* and risk consequences *C*:

$$R = P \cdot C$$

In accordance with the requirements and the criteria provided in Annex 4 of the Regulation 28 risk category for each emergency scenario is defined based on the probability and severity of the considered scenario using 5x5 grid known as „risk matrix“ (see **Error! Reference source not found.** below).

Table 18.4. Risk estimate categorization table

		CONSEQUENCE				
		insignificant (1)	**minor (2)**	**severe (3)**	**very severe (4)**	**catastrophic (5)**
PROBABILITY	**Very high (E)**	average	significant	high	very high	very high
	High (D)	average	significant	significant	high	very high
	Average (C)	low	average	significant	high	high
	Low (B)	low	average	significant	significant	high
	Very low (A)	low	low	average	significant	high

Risk categories then can be used for comparing the risks and defining priorities of applying risk preventive measures.

18.8. Overview and summary

An overview of risks due to emergency scenarios is presented in **Error! Reference source not found.**.

Table 18.5. Risk categories of the emergency scenarios

Description	**Repository**	**Probability**	**Severity**	**Risk Category**

Exceeding Allowed WP Activity	All	A – very low	1 – insignificant	LOW
Transport accident	All	A – very low	1 – insignificant	LOW
Waste package drop and damage	NSDF IDDF	B - low A – very low	1 – insignificant	LOW
Loss of power supply	All	A – very low	1 – insignificant	LOW
WP drop damaging the repository	All	A – very low	1 – insignificant	LOW
Hanging Load	All	E-very high	1 – insignificant	AVERAGE
Fire	All	A – very low	1 – insignificant	LOW
Earthquake at the repository location	All	A – very low	1 – insignificant	LOW
Aircraft crash at NSDF	All	A – very low	2 – minor	LOW
Aircraft crash at IDDF	All	A – very low	2 – minor	LOW

The risk matrix for the disposal facilities is provided in **Error! Reference source not found.**.

Table 18.6. Risk matrix of the emergency scenarios

		CONSEQUENCE (SEVERITY)				
PROBABILITY		**Insignificant (1)**	**Minor (2)**	**Severe (3)**	**Very severe (4)**	**Catastrophic (5)**
	Very high (E)	🟨 OP-06	🟧	🟥	🟫	🟫
	High (D)	🟨	🟧	🟧	🟥	🟫
	Average (C)	🟩	🟨	🟧	🟥	🟥
	Low (B)	🟩 OP-03 (NSDF)	🟨	🟧	🟧	🟥
	Very low (A)	🟩 OP-01, OP-02, OP-03 (IDDF), OP-04, OP-05, OP-07, OP-08	🟩 OP-09, OP-10	🟨	🟧	🟥

Risk preventive measures were developed for the considered scenarios based on the findings of risk analysis, namely the main factors of the risk, weak points of design and operation. Developing risk preventive, recommendations provided in IAEA documents were considered as well, adopting them to the decommissioning of the reactor compartments. Overview of preventive measures is provided in **Error! Reference source not found.**.

Table 18.7. Overview of preventive measures

Scenario	**Risk Category**	**Preventive Measures**
Exceeding Allowed WP Activity	LOW	1. Dose rate measurement gates at dispatch from RB 2. Verification measurements at NSDF/IDDF entrance 3. Procedure for handling WP violating WAC

Scenario	Risk Category	Preventive Measures
Transport accident	LOW	1. Safety rules for transportation of dangerous loads 2. Observing road and weather conditions
Waste package drop and damage	LOW	1. Crane operators' skills and training 2. Detailed procedure for the reactor body handling operations 3. Reliable lifting equipment provided by the decommissioning design
Loss of power supply	LOW	1. Ensuring power supply reliability depending on the equipment safety class 2. Technical means preventing load drop in case of loss of power supply
WP drop damaging the repository	LOW	1. See OP-03 2. Limit cranes' speed and ensure safe distance to walls
Hanging Load	AVERAGE	1. Ensure possibility to move equipment to safe area 2. Minimizing repair / replacement / maintenance time 3. Radiation protection measures for in-situ works 4. Installing control cabinets in safe area
Fire	LOW	Fire safety measures to be elaborated in the design documentation
Earthquake at the repository location	LOW	1. Seismicity measurements/monitoring system; 2. Seismically qualified external equipment; 3. Preventive preparations.
Aircraft crash at NSDF	LOW	1. Flight prevention/prohibition zone; 2. Aircraft crash management.
Aircraft crash at IDDF	LOW	1. Flight prevention/prohibition zone; 2. Aircraft crash management.

Although scenarios in different locations fall in the same risk category there are still differences between locations might be considered during the decision-making process.

Difference of scenarios' probabilities depending on site location can be found only for the transport accident scenario, see Table 18.8 below:

Table 18.8. Differences in Scenarios' Probabilities

Scenario and Facility	Probability, 1/year		
	PAL	PED	ALT
Transport accident, NSDF	-	7.34E-08	6.30E-08
Transport accident, IDDF	-	2.31E-08	1.98E-08

From the scenario probability point of view Paldiski site is preffrable as it excludes transportation by public roads. However, it should be noted that order of magnitude of the transport accident scenario is so negligible than other factors like organizational issues for transportation of the radioactive waste packages could be more important.

Difference of scenarios' consequences (annual dose) for personnel depending on IDDF site location can be found for aircraft crash, WP drop, earthquake and hanging load scenarios. These annual dose differences are related to different IDDF depths considered for different locations.
From the perspective of consequences of emergency scenarios for IDDF personnel, PED site is most preferable due to its largest depth while Paldiski site is the least preferable.

Difference of scenarios' consequences (dose) for population depending on site location can be found only for aircraft crash scenario. This difference is related to different distance from the repository candidate site location to the nearest reference population.

From the perspective of consequences of aircraft crash scenario for nearest population PED site is least preferable. ALT and PAL are more suitable due to its larger distances.

18.9. Conclusions

Ten emergency scenarios based on anticipated operational events, design basis and beyond design basis accidents provided by Safety Assessment Report were analysed, including seven internal scenarios and three external scenarios. All the scenarios have insignificant severities, all of them being below the annual dose limit (20 mSv/year) for personnel and most of them being below the annual dose limit (1 mSv/year) for population. Most of the scenarios have very low probabilities sometimes several orders of magnitude below the criterion for "very low" probability provided by Regulation No. 28.

There are no internal or external emergency scenarios of significant, high or very high-risk categories. One internal scenario belongs to the "average" ("yellow") risk category. Nine scenarios, including six internal and three external events scenarios, belong to the "low" ("green") risk category.

The scenario belonging to the "average" risk category, namely "Hanging load" has very high probability resulted from conservative assumptions and reliability data of the electromechanical equipment used to estimate a probability of an overhead crane stopping during load handling.

Risk preventive measures were suggested for all considered scenarios. Implementation priority might be given to risk preventive measures for the higher-risk category.

19. Sub-activity 2.19. Possible impact of the repository on neighbouring countries

An estimation of the transboundary impacts is in line with the requirements of International Conventions and Treaties. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, Convention on Environmental Impact Assessment in a Transboundary Context as well as EURATOM Treaty require that the potential impact to other countries of radioactive waste disposal is assessed an authorization for the disposal of radioactive waste is granted by competent national authority.

The purpose of this work is to assess potential transboundary impact of radioactive waste disposal. Possible impacts and suitability of previously proposed three candidate sites (PAL, ALT and PED) is compared.

The detailed results of the impacts assessment are presented in an Appendix 19. The work was performed by Roman Bezhenar and Oleksandr Pylypenko, Institute of Mathematical Machines and Systems Problems of the National Academy of Science of Ukraine.

19.1. Methodology

The minimum distance from the Estonian coast near the location of the future radioactive waste disposal facility to coast of Finland is about 65–75 km through the Gulf of Finland. The settlements on the coastal area of Finland in front of the disposal facility was chosen as a reference group for the assessment of an impact for public health. Since Finland is the nearest country to the repository unit location, the application of the conservative scenario assures the maximum possible human dose. The conservative scenario includes the application of the maximum concentrations of radionuclides reaching the coast through the groundwater. This scenario overestimates the possible flux of radionuclides to the sea providing the maximum possible effective dose of exposure to a reference person living in the considered settlement. Increasing the distance from the release point, while maintaining all other conditions, can only reduce the dose. Therefore, if dose obtained under such conservative scenario for Finland is below the allowable limits, this assures that it will be below these limits for all other countries.

Due to natural or artificial degradation of the disposal facility barriers, the radionuclides may enter the groundwater and then to the Gulf of Finland that may lead to the contamination of seawater and seafood. Radionuclide transfer was estimated using the compartment model POSEIDON-R, which is a part of the European Decision Support System for emergency response to nuclear accidents RODOS. POSEIDON-R is the compartment model for the simulation of radionuclide transport in the marine environment including water sediments and biota, and the estimation of doses to humans from marine exposure pathways. In the model, the marine environment is represented as a system of compartments for the water column, bottom sediment, and biota. The exchange between the water column boxes is described by fluxes of radionuclides due to advection, sediment settling, and turbulent diffusion processes.

The following pathways of the radiation exposure were considered: external exposure from the water during swimming and boating, external exposure from radionuclides on seashore when human is on the coast, inhalation of radionuclides with the sea spray and consumption of contaminated seafood. Among the considered pathways the internal exposure caused by the consumption of contaminated seafood is the dominant. Usually, dose from the consumption of contaminated seafood is several orders of magnitude higher than doses from other irradiation pathways. Therefore, the estimation of individual effective doses for population is based on the doses caused by the consumption of contaminated seafood.

In the POSEIDON-R model, the area of interest is covered by a system of compartments, which can be of different sizes and shapes. The transfer of radionuclides between compartments is modelled based on average currents in the region.

An optimal size of compartments in the box model POSEIDON-R is 15x15 km. Such compartments were created in the Gulf of Finland next to the potential locations of the disposal facility (Figure 19.1). Larger boxes were placed around them to prevent excessive mixing of contamination in the large volumes of seawater. The volume and average depth of each box were calculated based on the bathymetry data. Deep boxes were vertically subdivided on a surface layer (from surface to a depth of 25 m) and a bottom layer (from a depth of 25 m to the bottom) to describe the activity stratification in the water column.

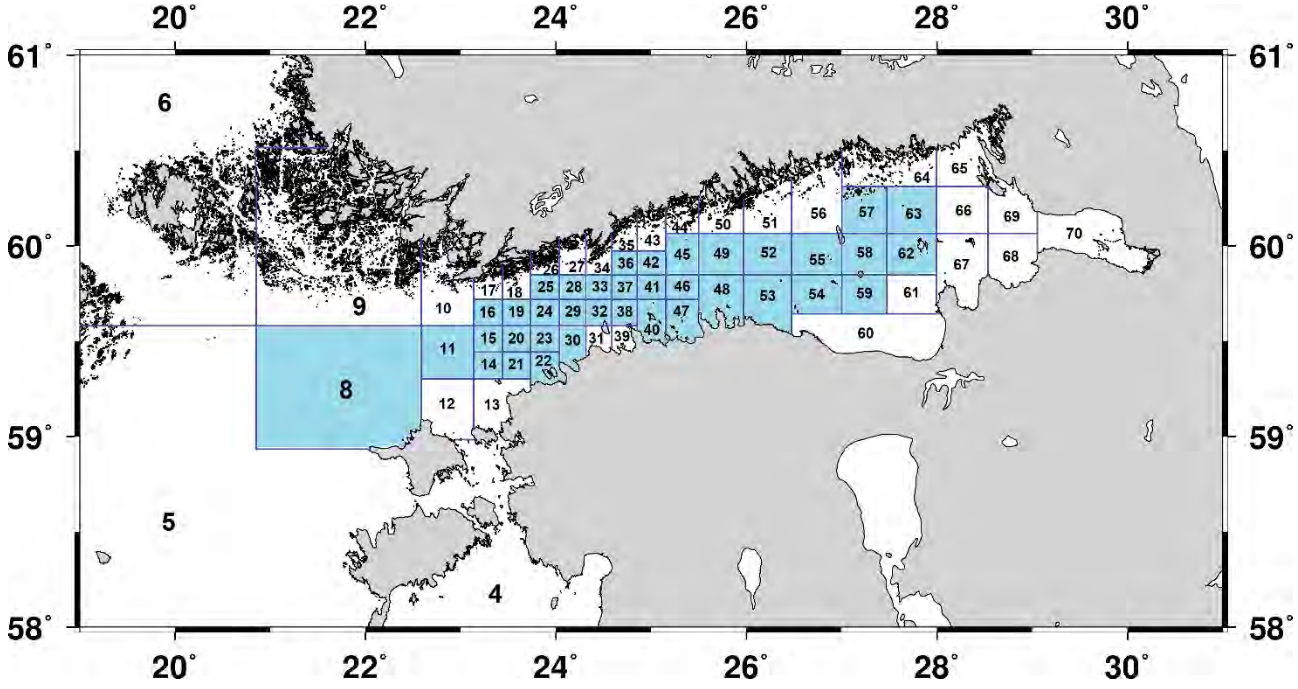


Figure 19.1. Box system in the region of interest. Blue boxes are divided on two vertical layers.

Doses to members of the reference group depend on peculiarities of a diet. According to Food and Agriculture Organization of the United Nations, the average annual human consumption of fish in Finland is 30.5 kg. It was assumed for conservative dose assessment, that the reference person (or group members) consumes fish from the Gulf of Finland only.

19.2. Scenarios for the release of radionuclides to the Gulf of Finland

19.2.1. Release of radionuclides from the NSDF to the sea by groundwater

Fluxes of radionuclides from the NSDF located at the PAL site to the Gulf of Finland were assumed as a maximum radionuclide concentrations at the coast multiplied by the volume of groundwater that flows to the sea through the part of the coast. According to the Sub-activity 2.16, the annual groundwater flow through this part of the coast was estimated as 306,563 m3. The calculated flux of radionuclides was set up as a source term for box 30 (see Figure 19.1).

Figure 19.4 includes only radionuclides, which penetrate soil with groundwater and reach the sea. They are long-lived radionuclides with low (C-14) or moderate (Ni-59, Nb-94, U-238) ability to be adsorbed by soil particles and Sr-90 that is relatively short-lived radionuclide but with low ability to adsorption. Due to short half-life, Sr-90 will almost completely decay during 920 years needed for its transfer from the NSDF to the sea by groundwater even if its initial inventory in the NSDF is quite large (see Table 19.2). Therefore, the flux of Sr-90 to the Gulf of Finland will exist but it will be very small. Other radionuclides will decay or will be completely adsorbed by soil particles on the way from the NSDF to the sea with groundwater flows. For example, Cs-137, which is the radionuclide with maximal inventory in the NSDF, has the moderate ability to adsorption, therefore it needs more time to reach the see by groundwater, and it will completely decay for this time. Such radionuclides as isotopes of plutonium and americium have very high ability to adsorption, therefore they cannot reach the sea by groundwater. Inventories of considered radionuclides in the NSDF and their activity released to the sea during 10,000 years according to results of Sub-activity 2.6 are presented in Table 19.2.

Radionuclide fluxes from the NSDF located at the ALT or PED sites to the Gulf of Finland would not differ significantly from the fluxes from the PAL site. Since the distance of the PAL site from the sea is the shortest, while the other radionuclide transport conditions differ insignificantly, it was assumed that the PAL site represents a conservative case.

Table 19.2. Parameters of radionuclides considered in the scenario of the release from the NSDF located at the PAL site

Nuclide	Half-life (y)	Inventory in the NSDF (Bq)	Released activity to the sea (Bq)	Period of time needed to reach the sea (y)
C-14	5730	6.1E+08	4.9E+07	105
Ni-59	76,550	4.7E+07	2.9E+06	5720
Sr-90	28.8	1.3E+12	6.7E-03	920
Nb-94	20,316	3.8E+07	2.7E+05	6950
U-238	4.468E+09	5.8E+08	2.2E+06	7350

19.2.2. Release of radionuclides from the IDDF to the sea by groundwater

Fluxes of radionuclides from the IDDF to the Gulf of Finland by groundwater was assumed similarly to NSDF as a maximum radionuclide concentration obtained by the RESRAD model at the coast multiplied by the volume of groundwater that flows to the sea through the same part of the coast (highlighted by blue line in the Figure 19.2). According to the RESRAD model, the annual groundwater flow through this part of the coast was estimated as 307,600 m3 for PAL site (Sub-activity 2.16). The calculated flux of radionuclides was set up as a source term for box 30 (see Figure 19.1)

List of radionuclides that reach the sea by groundwater and their activity released to the sea according to results of Sub-activity 2.6 are given in the Table 19.3. There is Pb-210 in the list, which is not among radionuclides to be disposed of. It will appear as a decay product of Ra-226. Other radionuclides from the IDDF will completely decay or will have zero or very low concentration due to adsorption by soil particles on the way from the NSDF to the sea with groundwater flows.

Table 19.3. Parameters of radionuclides considered in the scenario of the release from the IDDF located at the PAL site

Nuclide	Half-life (y)	Inventory in the NSDF (Bq)	Released activity to the sea (Bq)	Period of time needed to reach the sea (y)
Ni-59	76,050	1.3E+12	1.5E+11	9200
Nb-94	20,300	1.1E+11	2.9E+09	11,100
Pb-210	22.2	-	8.9E+09	3300
Ra-226	1600	2.6E+10	1.3E+10	3300
U-238	4.46E+09	4.6E+12	6.5E+11	13,000

19.2.3. 3.3. Release of radionuclides from the NSDF in a case of flooding

The topographical analysis carried out under Sub-activity 2.4 identified a negative aspect of the ALT site: due to climate warming, it is possible that the area will be flooded by the sea or affected by severe storms in the next century. Saline water would accelerate degradation of concrete structures, waste matrix and leaching of the radionuclides. For the potential impact assessment it was assumed that this hypothetical event happens immediately after end of active institutional control (during the period of active institutional control lasting the first 100 years after disposal, the integrity of the disposal facility should be maintained through the implementation of corrective measures). The accelerated degradation of engineered barriers could take several decades, instead of hundreds of years as foreseen in the disposal concept. However, it was conservatively assumed that the affected barriers degrade immediately (i.e. after single catastrophic event) and all inventory disposed of in the NSDF flows to the sea (sorption and retention of radionuclides in decomposed concrete and surrounding soil are neglected).

For the time of the hypothetical site flooding, the inventory stored in the NSDF will decrease due to radioactive decay. Remained inventory is considered as a source in the POSEIDON-R model. Details are given in Table 19.4.

Table 19.4. Parameters of radionuclides considered in the scenario of the release from the NSDF located at the ALT site directly to the sea due to flooding

Nuclide	Half-life (y)	Estimated inventory	Decay corrected activity released to the sea after 100 years of storage

		in the NSDF (Bq)	(Bq)
H-3	12.3	6.2E+10	2.2E+08
C-14	5730	6.1E+08	6.0E+08
Co-60	5.275	9.3E+09	1.8E+04
Ni-59	76,050	4.7E+07	4.7E+07
Ni-63	100.2	2.2E+09	1.1E+09
Sr-90	28.9	1.3E+12	1.2E+11
Nb-94	20,300	3.8E+07	3.8E+07
Ba-133	10.551	5.1E+05	7.2E+02
Cs-137	30.05	2.4E+13	2.4E+12
Eu-152	13.55	5.9E+08	3.5E+06
Eu-154	8.599	9.4E+07	3.0E+04
Ra-226	1600	3.9E+09	3.7E+09
Ra-228	5.75	9.0E+03	5.2E-02
Th-232	1.4E+10	1.4E+05	1.4E+05
U-234	2.449E+05	2.2E+03	2.2E+03
U-238	4.46E+09	5.8E+08	5.8E+08
Pu-238	87.7	2.3E+05	1.0E+05
Pu-239	24,400	5.0E+05	5.0E+05
Pu-240	6570	1.4E+05	1.4E+05
Am-241	432.2	5.9E+09	5.0E+09

19.3. Simulation of the marine environment contamination

19.3.1. Scenario for the release of radionuclides from the NSDF located at the PAL site by groundwater

The highest concentration of all radionuclides will be near the Estonian coast in the box 30 where the contaminated groundwater flows. According to Figure 3.3, C-14 will reach marine environment faster than other radionuclides, approximately 100 years after the start of radionuclide release from the NSDF. Simulation results show that the maximal concentration of C-14 in water will be about 4×10^{-6} and 3×10^{-5} Bq/m^3 near Finnish and Estonian coast, respectively (Figure 19.6), 180 years after the start of radionuclide release from the NSDF. Water currents in the region of interest are directed mostly from the Gulf of Finland to the Baltic Sea defining the dominant direction for the transport of radionuclides. In addition, this leads to their dilution by large amount of seawater. Therefore, radionuclide concentrations in the main part of the Sea will be much lower. Concentrations of C-14 in bottom sediments and fish also will be very low. Thus, maximal concentration of C-14 in bottom sediments will be 1.8×10^{-5} Bq/kg, while in pelagic non-predatory fish it will be 1.7×10^{-5} Bq/kg (Figure 4.1).

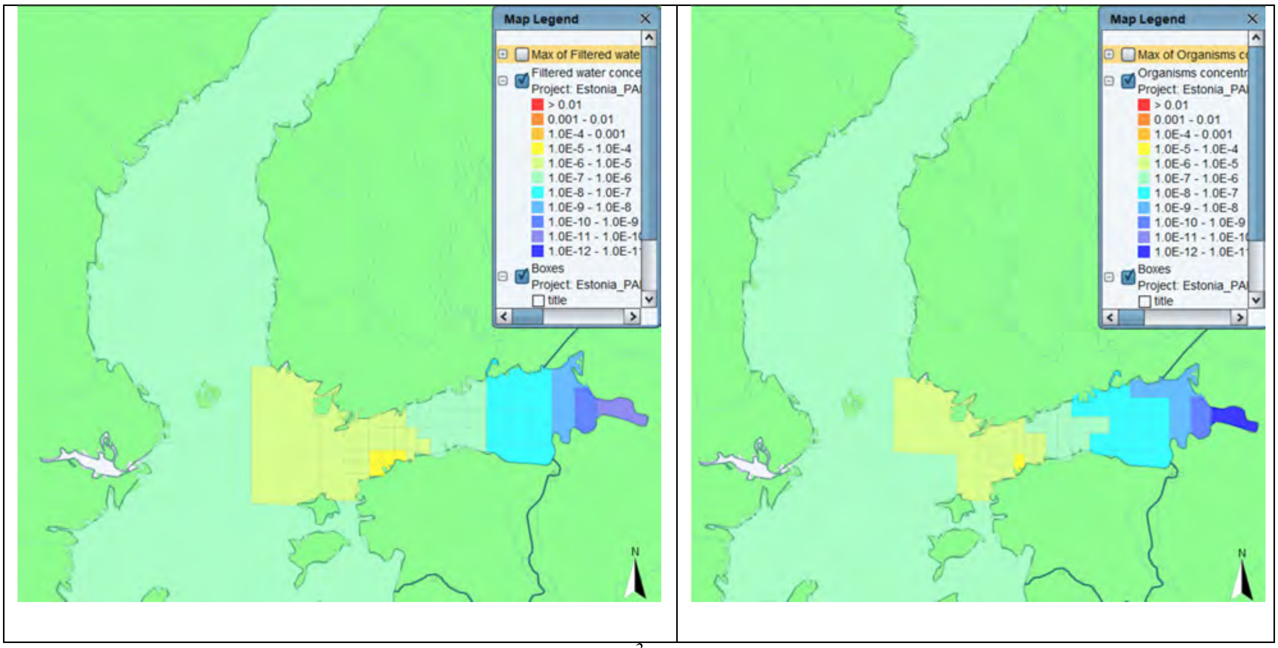


Figure 19.6. Concentrations of C-14 in water [Bq/m^3] (left) and pelagic non-predatory fish [Bq/kg] (right).

Ni-59 and U-238 will be the dominant radionuclides much later.This means that their concentrations in all components of marine environment will exceed concentrations of other radionuclides at that time. However, these concentrations will be very low – the maximum in water will not exceed 10-7 Bq/m^3 for Ni-59 and 10-6 Bq/m^3 for U-238. Water currents in the region of interest are directed mostly from the Gulf of Finland to the Baltic Sea defining the dominant direction for the transport of radionuclides. In addition, this leads to their dilution by large amount of seawater. Therefore, radionuclide concentrations in the main part of the Sea will be much lower.

After entering water, radionuclides start to interact with suspended and bottom sediments. All radionuclides have different ability to be adsorbed by sediments. For example, Ni-59 is adsorbed better than U-238. The main part of Ni-59 will be deposited near the point of release, while U-238 will be transported by water over longer distances. The concentration of Ni-59 in bottom sediments will be approximately 1 order of magnitude higher than concentration of U-238, although the opposite relation occurs in water. But, as in the case of water, the concentration of radionuclides in bottom sediments will be very low and not exceed 10^{-6} Bq/kg.

19.3.2. Scenario for the release of radionuclides from the IDDF located at the PAL site by groundwater

Similar to the scenario with the release of radionuclides from the NSDF, the highest concentration of all radionuclides resulted from their release from the IDDF by groundwater will be near the Estonian coast in the box 30. The same is that Ni-59 and U-238 will be the dominant radionuclides with concentrations higher than concentrations of other radionuclides in all components of marine environment. Obtained in the modelling concentrations are somewhat higher than in NSDF scenario but they are still quite low – the maximum in water will be 5×10-5 Bq/m^3 for Ni-59 and 2×10-3 Bq/m3 for U-238 near Estonian coast and 1.2×10-6 Bq/m^3 for Ni-59 and 4×10-4 Bq/m^3 for 238U near Finnish coast (Figure 19.9).

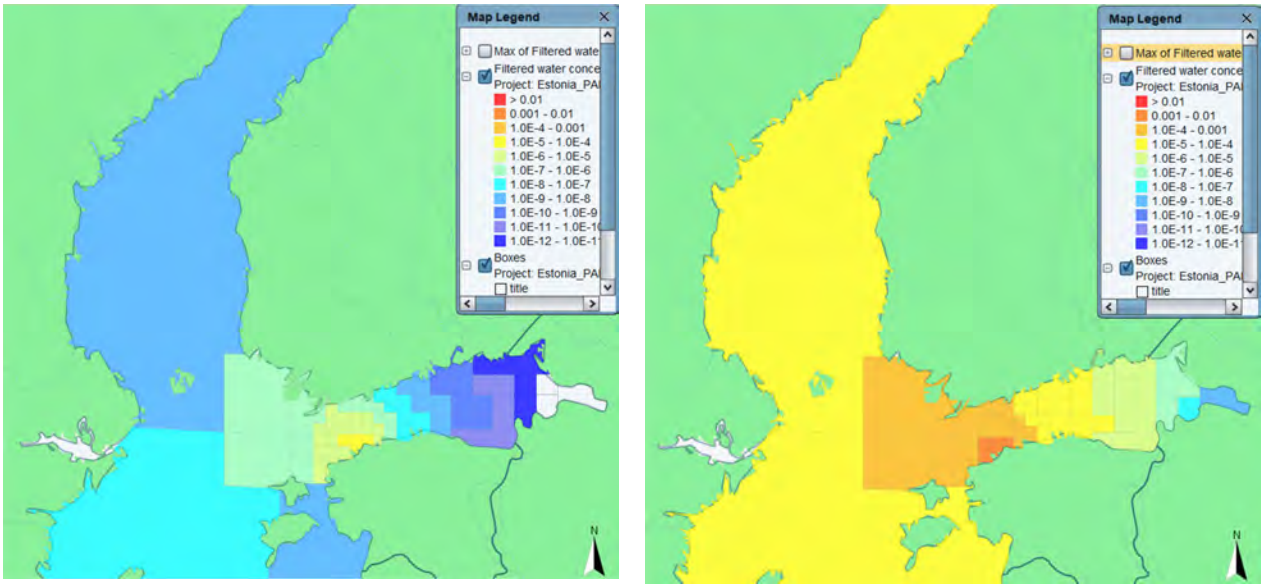


Figure 19.9. Concentrations of Ni-59 (left) and U-238 (right) in water [Bq/m^3] at the end of simulations.

Similar to the scenario with the release of radionuclides from the NSDF, the main part of Ni-59 will be deposited near the point of release, while U-238 will be transported by water over longer distances (Figure 19.10).

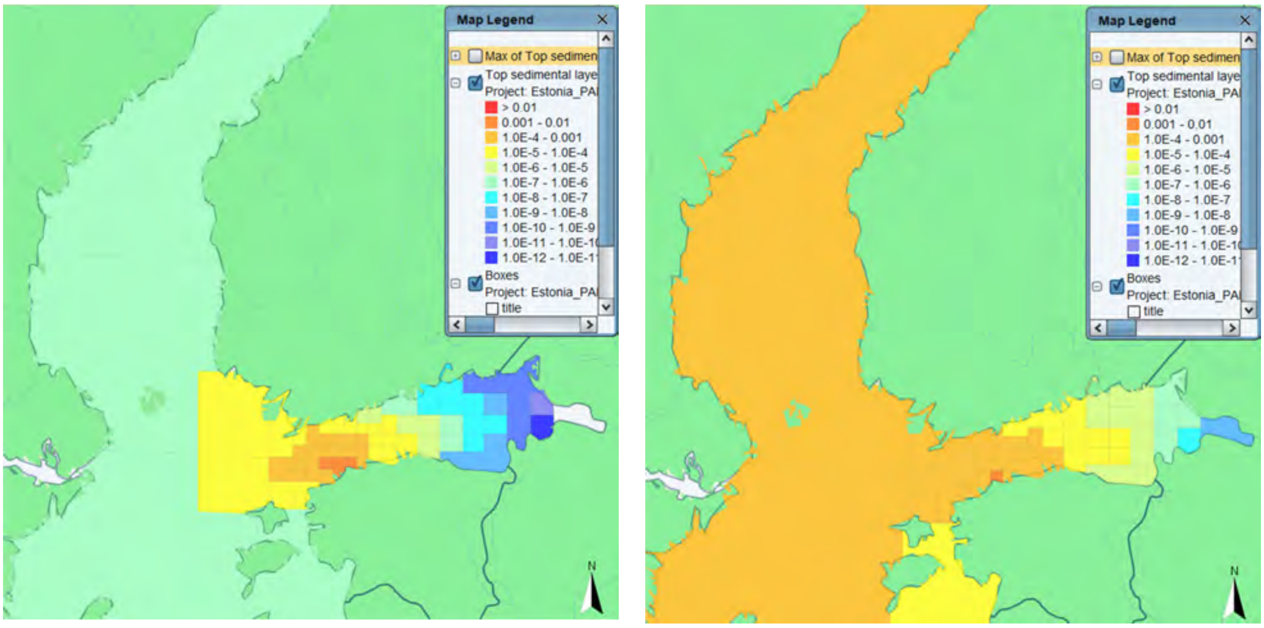


Figure 19.10. Concentrations of ^{59}Ni (left) and ^{238}U (right) in bottom sediments [Bq/kg] at the end of simulations.

19.4. Calculated maximum exposure doses for the population of Finland

Exposure doses to humans due to seafood consumption were calculated based on the estimated concentrations of radionuclides in marine organisms. Doses from other pathways of irradiation such as doses from swimming and boating activities, activity on seashore and inhalation of sea spray are usually several orders of magnitude less than doses from seafood consumption.

Very low doses were obtained for the scenarios of groundwater flow of radionuclides from the NSDF and IDDF located in the PAL site. For the release of radionuclides from the NSDF, a maximum annual dose will be in the range 1.4×10^{-9} to 4×10^{-8} microSv for Finish people living in front of Pakri peninsula. For Estonian people the corresponding maximal annual dose will be in the range 6.2×10^{-9} to 2.6×10^{-7} microSv.

For the release of radionuclides from the IDDF, a maximum annual dose will be around 8.4×10^{-5} microSv for Finish people and 4.4×10^{-4} microSv for Estonian people.

Note that all dosed were obtained for the reference person consuming all fish in their diet from the Gulf of Finland. Obtained in simulations doses to human from seafood consumption, which can be caused by groundwater flow of radionuclides from the NSDF and IDDF to the Gulf of Finland, are absolutely negligible and are far below all allowable limits.

In the case of hypothetical flooding of the NSDF located at the ALT site due to rise of sea level caused by climate change in coming centuries, the maximal annual dose to human from seafood consumption will be 6.7 microSv for the first year after flooding (Figure 19.12). Such a dose will be received by Estonian people living near the ALT site. Maximal annual dose to Finnish people will be 0.37 microSv for second year after flooding. So, even dissolving by seawater of all radionuclides placed in NSDF after 100 years of disposal will not provide doses to human that exceed allowable limits in Estonia and in neighboring countries.

Doses for all considered scenarios are summarized in Table 19.6. In the first scenario, two periods are separated: initial phase (approximately 180 years after the start of release) when C-14 flows to the sea by groundwater, and late phase (approximately 10,000 years after the start of release) when the highest concentration of other radionuclides in marine environment takes place. In the last scenario, the flooding happened after 100 years of radioactive materials storage, with the highest dose obtained during the first years thereafter.

Based on the simulation results, it can be said that none of the selected locations for NSDF and IDDF will have negative impact on neighbouring countries. But there is a probability of flooding of NSDF at the ALT site in future that can lead to release of a significant activity of radionuclides into the marine environment. Therefore, it is better to avoid placing NSDF at the ALT site.

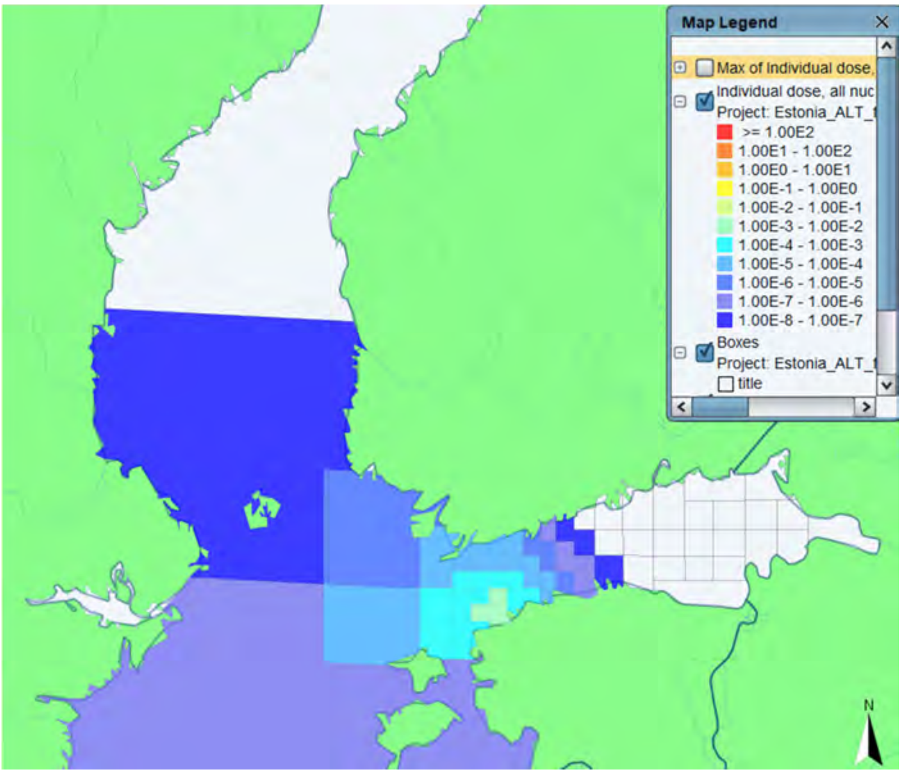


Figure 19.12. Effective annual doses to human due to seafood consumption from all considered radionuclides [mSv/y] for the first year after hypothetical flooding of the NSDF located in the ALT site.

The water of the Gulf of Finland flows into the main part of the Baltic Sea (in the direction of Sweden and Latvia). Despite this, the concentrations of radionuclides in these parts as well as the calculated doses are a couple of orders of magnitude lower (Figure 19.12).

Table 19.6. Maximum doses to human from seafood consumption. Values in brackets show time from the installing the corresponding repository unit

Scenario	Maximum annual dose to human from seafood consumption, microSv	
	Resident of Finland	Resident of Estonia
Release of radionuclides from NSDF located at the PAL site by groundwater	4×10^{-8} from C-14 (180 yrs) 1.4×10^{-9} (10,000 yrs)	2.6×10^{-7} from C-14 (180 yrs) 6.2×10^{-9} (10,000 yrs)
Release of radionuclides from IDDF located at the PAL site by groundwater	8.4×10^{-5} (25,000 yrs)	4.4×10^{-4} (25,000 yrs)
Release of radionuclides from NSDF located at the ALT site directly to the sea due to flooding	0.37 (100 + 2 yr)	6.7 (100 + 1 yr)

19.5. Summary

Obtained in simulations doses to human from seafood consumption, which can be caused by groundwater flow of radionuclides from the Near Surface Radioactive Waste Disposal Facility (NSDF) and Intermediate Depth Disposal Facility (IDDF) to the Gulf of Finland, are very low and are far below all allowable limits. For the release of radionuclides from the NSDF, a maximum annual dose was obtained in the range 1.4×10^{-9} to 4×10^{-8} microSv for Finnish people living in settlements in front of the potential disposal sites. For Estonian people the corresponding maximal annual dose will be in the range 6.2×10^{-9} to 2.6×10^{-7} microSv. For the release of radionuclides from the IDDF, a maximum annual dose will be around 8.4×10^{-5} microSv for Finish people and 4.4×10^{-4} microSv for Estonian people. Note that all dosed were conservatively obtained for the reference person consuming all fish in their diet from the Gulf of Finland.

In the scenario of hypothetical flooding of the NSDF located at the ALT site due to rise of sea level resulted from climate change in coming centuries, the maximal annual dose to human from seafood consumption will be 6.7 microSv for the first year after flooding. Such a dose will be received by Estonian people living near the ALT site. Maximal annual dose to Finnish people will be 0.37 microSv for second year after flooding followed degradation of the facility.

Calculations of radioactive contamination of water, bottom sediments and fish in the Gulf of Finland and the corresponding doses to the population as a result of the transboundary transport of radioactive releases from the planned NSDF and IDDF by groundwater showed very low, almost negligible, effects on the environment and public health in Finland. Even dissolving by seawater of all radionuclides placed in NSDF due to flooding of the ALT site caused by the sea level rise resulted from climate chance after 100 years of storage will not provide doses to human that exceed allowable limits in Estonia and in neighbouring countries. However, this will lead to the release of a significant activity of radionuclides into the marine environment.

The calculations were carried out for Finish people living in settlements located at a distance of about 65–75 km from the potential release source through the Gulf of Finland. The distance from the source to the borders with other neighbouring states by the marine pathways is about 200 km to Latvia, 280 km to Sweden, and 230 km to Russian Federation. With an increase in the distance, the concentrations of radionuclides in all components of marine environment and the associated exposure doses to the population will decrease. So, it can be said with certainty that the conclusions about the fulfilment of the established safety criteria for the population, obtained as a result of calculations for Finland, will be all the more true for other countries.

19.6. Conclusions

1. Based on the simulation results, it can be said that none of the selected locations for the disposal facility will have significant negative impact on neighbouring countries. All three sites are acceptable for construction of the disposal facility, because the radiation protection limits would not be violated. However, the decision to dispose of the wastes at the ALT site can be interpreted as a violation of the London Convention (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter), which bans the dumping into sea of radioactive wastes.

2. PAL and PED sites are evaluated nearly equally suitable: the associated exposure doses in the neighbouring countries would be significantly below the exemption level.