Assessment of sediment sampling techniques for ESS environmental monitoring programme

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SUMMARY

Radionuclides released and discharged into the environment from nuclear and other radiation-related facilities, such as the European Spallation Source (ESS), may accumulate in aquatic bottom sediments. Sediments should therefore, as recommended by the IAEA, be monitored regularly. This report describes the setting up of a methodology for zero-point assessments of the radiation levels in sediments of relevance for possible future releases from the ESS.

Two types of sediment sampling devices have been tested: a grab sampler of the Lamotte type, and a stationary bottom trap consisting of a 5-L bucket placed on the bottom of a pond. The Lamotte grab sampler worked well in the absence of obstacles such as vegetation and stones. Sampling from boat may be advantageous in finding suitable sampling spots for the grab sampler. The stationary bottom trap, tested for more than two years at one of the ponds at the ESS facility, proved functional. To be certain to obtain sufficient sediment during collection period of one year, we recommend using three 5-L buckets per pond. The bottom trap is most likely not suitable for sampling in rivers with flowing water.

For the sample preparation, sieving the sediment in a laboratory was found to be more efficient and more convenient compared to sieving at the sampling site. Freeze-drying was found superior, in terms of efficiency and dried sample texture, to drying the sediment in open air. Measurements of total carbon, total nitrogen, and the carbon to nitrogen ratio proved to have the potential to provide relevant information about the sources of the sediment. The results of gamma-ray spectrometry confirmed sediments as a useful indicator of radionuclides, with activity concentrations above the MDA levels for all reported radionuclides and samples, except for one site. Gamma-ray spectrometry measurements on the samples can provide information on local elevated levels of anthropogenic radionuclides and add information to the sources of the sediment itself.

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C:N ratio	Carbon-to-nitrogen ratio
d.w.	Dry weight
ESS	European Spallation Source
MDA	Minimum Detectable Activity concentration
TC	Total carbon
TN	Total nitrogen
w.w.	Wet weight

1. INTRODUCTION

Man-made radionuclides released and discharged into the environment may accumulate in aquatic bottom sediments. Apart from acting as a sink, the bottom sediments may also become a source from which settled radionuclides re-enter the water and become part of the food chain for various organisms. According to the IAEA's recommendations for environmental monitoring of nuclear and radiation-related facilities [1], the accumulation of radionuclides in sediments should be monitored regularly. The data generated can be used for predicting radionuclide concentrations in food products, and thus in biota, and to understand the site-specific dispersion and radioecology.

The primary objective of this report is to develop a methodology for zero-point assessments of the radiation levels in sediments of relevance for future releases from the European Spallation Source (ESS). Over 1000 different radionuclides will be produced in the ESS tungsten target during operation, and activation of air, instruments, shielding and building materials will occur due to operation of the accelerator and due to the spallation processes. Soil surrounding the facility is also expected to be activated. Three main discharge routes are expected: 1) Airborne releases through the main stack and from the waste building stack; 2) Liquid discharges to the public sewage system; 3) Ground water transport of activation products in soil surrounding the facility. For all these pathways, radionuclides may enter sediments in various surface waters. The atmospheric releases may be deposited over a catchment area or may be directly deposited on the water surface.

This report takes the starting point from the IAEA recommendations [1, 2], ISO 5667-12 [3] , ISO 5667-15 [4] and ISO 5667:19 [5] to implement sampling and analyses of bottom sediments in waters of relevance for the future environmental monitoring of the ESS. The sampling has mainly been designed to fulfil the needs of gamma-spectrometric analysis. Tests for sampling techniques, sample preparation and gamma-spectrometric analysis for sediments are presented. Results for samples collected in 2021 and 2022 are presented in the report.

2. GENERAL RECOMMENDATIONS

The IAEA recommendations [1, 2] include all possible aspects regarding sampling strategy (depending on the aim), sampling frequency, sampling devices, sample preparation and storage, as well as analysis of radionuclides. Some key issues are highlighted in this section.

The sampling strategy can be judgemental, random, or systematic [2]. Regarding sampling frequency, the framework recommendations from the IAEA suggest a sampling frequency for bottom sediments of once a year for normal discharges and weekly following emergencies [1]. In general, the IAEA recommends taking > 5 sub-samples which are pooled into one composite sample, to avoid issues due to heterogeneity. ISO 5667-12 recommends two or more subsamples. The sampled mass required depends on the analytical technique and also on the sediment fraction of interest (1 kg is often sufficient according to [2]). Samples can be collected by a variety of sample devices, including various types of grab samplers and sediment corers [2, 3]. An alternative sampling strategy is the use of sediments traps (see, e.g., [6]), which continuously collect particles settling through the water towards the bottom. In the current report we evaluate and test grab sampling as well as sediment traps.

According to ISO 5667-15, sampling containers for sediments for subsequent radiochemical analysis are preferably made of polyethylene [4]. ISO 5667-15 [4] further recommends a minimum wet weight (w.w.) for various analytes. For gamma spectrometry at least 100 g w.w. is recommended, and wet samples should be stored at 1-5 °C for a maximum of two days. Marine sediments should be frozen immediately after sampling (-20 °C) [5].

Sample preparation for sediment samples includes removal of coarse and foreign material, homogenization, and drying. Samples may be dried, for example, in air at room temperature (slow) or using an oven at a variety of temperatures (e.g., 100 °C). Oven-drying often forms hard aggregates, which can be problematic during the subsequent homogenization. Freeze-drying is an attractive option since aggregation is avoided and the loss of volatile compounds is very low [2]. Typical drying times are a few days. A disadvantage is that the sample capacity of a freeze-drier is often more limited than for a conventional oven.

According to [2], fine-grained sediments often have a higher concentration of contaminants than coarse grains, due to their larger surface area and hence the higher binding capacity. Size fraction may therefore need to be considered to remove effects on the radionuclide activity concentration due to textural variability of the sediment. Examples of size fractions range from [2] are >2 mm, 1-2 mm, 250 µm-1 mm, 125-250 µm, 71-125 µm, 50-71 µm and <50 µm.

3. SELECTION OF SITES

The ESS environmental monitoring programme has so far mainly focussed on the terrestrial environment (see Annual Report 2021 [7]) within a few km of the ESS site. In water bodies we have so far focussed on tritium analysis of ground water, surface water (including Höje river, Kävlinge river, and Lomma bay), tap water, sewage sludge, and seaweed. Sewage sludge and seaweed have also been subjected to gamma-ray spectrometry, and the activity concentration of ^{14}C in seaweeds has also been monitored. In this section we present simplified Gaussian plume modelling to justify the selection of sites for sediment sampling. These results are compared to results published by the ESS consortium.

3.1. Simplified Gaussian plume modelling for atmospheric releases

Appendix 1 presents simple calculations of atmospheric dispersion from the ESS main stack and waste stack using a simple Gaussian plume model, to justify the selection of sampling sites. In the calculations we considered Pasquill stability class D (neutral conditions) and C (slightly unstable) to be the most relevant for the ESS facility. For the main stack of the target building, the maximum long-term ground-level activity concentration in air normalized to a release rate for the main wind direction (WSW) was found at ~1 km from the release point for Pasquill stability class D ($3.3 \cdot 10^{-14}$ Bq m^{-3} per Bq $year^{-1}$) and at ~500 m for category C ($1.7 \cdot 10^{-14}$ Bq m^{-3} per Bq $year^{-1}$). For the waste stack the maximum activity concentrations were most likely to be found between 300 m and 400 m from the stack. The calculations (see also Figure A1- 4) justify that the most intense sampling in the terrestrial environment needs to be within a few km of the ESS stacks.

3.2. Comparison with modelling performed by the ESS consortium

Our simplified Gaussian plume modelling arrives at similar conclusions as dispersion calculations performed by the ESS consortium [8]. The ESS report ESS-0052265 [9] describes the underlying models for radionuclide transport, dose calculations, dose factors for screening purposes of airborne releases from the ESS facility, as well as liquid discharges to the public sewage system. Screening models use generic and conservative assumptions to assess the need for a more detailed analysis [10], hence atmospheric dispersion and groundwater transport models are not covered in ESS-0052265 [9]. ESS-0052265 [9] uses a freshwater body model for streams, lakes and rivers receiving radionuclides deposited from the atmosphere, or from liquid discharges (see Figure 10-1 in [9]). The atmospheric releases may be deposited over a catchment area or may be directly deposited on the water surface. Sediments are divided into top sediment and deep sediment. The top sediment is in direct contact with the water, and suffers from sedimentation as well as resuspension (exchanges between modelled media is shown in Figure 10-2 in [9]). The marine receptor in ESS-0052265 [9] considers deposition from the atmosphere as well as direct liquid discharges (e.g., from a sewage pipe), and divides the sediment into a top and a deep layer. The models account for exchange processes with the water.

ESS-0109597 [8] presents the results of radionuclide transport and dose calculations based on the models in ESS-0052265 [9] using the Ecolego[1] software. Kävlinge river is classified as the main freshwater receptor of atmospheric depositions. The liquid discharges to the public sewage system will be transported in downstream surface waters via the Källby waste-water treatment plant into Höje river. Results are also presented for Höje river and for the inner Lomma bay in ESS-0109597 [8]. Since the publication of ESS-0109597 [8] and ESS-0052265 [9] it has decided not to discharge any water from the waste building via Källby waste-water treatment plant (Per Roos personal communication 24 January 2024).

3.3. Catchment areas related to the ESS facility

The city of Lund and the nearby land close to the ESS belong to two main catchment areas [11]: Kävlinge river and Höje river, both entering Öresund in Lomma Bay. The ESS facility itself is located at the border of the Kävlinge river catchment area. The city of Lund belongs to the Höje river catchment area, and the public sewage treatment plant is also connected to this river. The border between these two catchment areas is approximately at MAX IV (in NW-SE direction). Atmospheric releases deposited within a few km of the ESS site may thus end up in either of the two rivers, but due to the main wind direction (WSW, see Appendix 1), Kävlinge river is expected to become the main freshwater receptor of atmospheric depositions from the ESS [9].

The ESS facility is located at the border between three sub-catchment areas, with different pathways to Kävlinge river [11]. According to the map service *Vatten och Miljö* [11], the most important upstream discharge point from surface water from the close vicinity of the ESS facility is at Flyinge Kungsgård (N55.751, E13.337, via Puggängarna, Glomsjön, and Sularpsbäcken: 5.9 km ENE of the ESS main stack). According to [11], another major inflow to Kävlinge river from the land south of the river is at Örtofta (N55.775, E13.249: 4.5 km N of ESS main stack). Several other inflows to Kävlinge river exist.

3.4. Sampling strategy

The sampling strategy for sediments, including selection of sites, has been judgemental (see Table 1 in [2]), taking radionuclide transport and dose calculation models for the ESS into account [8, 9]. Sampling sites for sediment samples during 2021 and 2022 are presented in Table 1 and Figure 1. A reference site was selected in north-eastern Scania, at Helge river (site 88.2 Åhus, Mölleholmen).

[1] www.ecolego.se

Table 1 Sites for collection of sediment samples until 2022.

Area	Site id	Site name	Latitude	Longitude
ESS site	31.6	ESS Pond 4	55.7358N	13.2442E
Kävlinge river	94.1	Kävlinge river, outlet Sularpsbäcken, upstream	55.7504N	13.3379E
	94.2	Kävlinge river, outlet Sularpsbäcken, downstream	55.7514N	13.3367E
	90	Getinge bridge	55.7645N	13.3145E
	92	Örtofta	55.7762N	13.2455E
	93	Kävlinge scoutgård	55.7912N	13.1379E
	91	Pegasus trädgård	55.7625N	13.0544E
Höje river	95	Höje river, Bjällerup	55.6580N	13.2601E
	35.4	Källby, Höje river, Drömbron	55.6980N	13.1552E
	77	Höje river, Lomma kyrka	55.6878N	13.0781E
Waste water treatment plant	35.5	Källby Pond 1, from shore	55.6920N	13.1623E
	35.6	Källby Pond 5	55.6991N	13.1527E
Remote reference site	88.2	Helge river, Åhus, Mölleholmen	55.9148N	14.2838E

Figure 1 Sampling sites for sediments in 2021 (upper image) and 2022 (lower image).

4. SAMPLING AND SAMPLE PREPARATION

4.1. Sampling protocol, storage of data and samples

Documentation of sampling and data storage are based on the procedures described in [12]. Sample id:s for sediment samples are denoted “ESED running number:site”.

4.2. Stationary bottom sediment trap, version 1

The first prototype of a stationary bottom sediment sampling trap for collecting sediments consisted of two 5-L polyethylene buckets (Nordiska Plast, see Figure 2). Stones were placed as ballast in one of the buckets, and the other bucket was placed over the stones in the first bucket. The buckets were fastened to one another using cable ties inserted through two small holes on opposite sides of the buckets, drilled through the rims of the buckets. The handle of the upper bucket was removed. A carbine hook (7 mm x 17 mm AISI 316) was fastened to the handle of the bucket. A 5-10 m long polypropene line (diameter 6 mm) was inserted into the carbine hook. One end of the polypropene line was tied to a marker float (diameter 155 mm). The other end was tied to an anchor (3 kg). A grapnel (Heraco, article number 6526) was tied to the bucket to prevent the bucket from moving on the sediment bottom. The thin rope attached to the grapnel was also used to construct a spare handle for the lower bucket. The spare handle was fastened to the plastic handle using cable ties and secured to the lower bucket by tying the rope around the lower bucket.

Figure 2 The prototype sediment bottom trap.

The first version of the stationary sediment trap was tested at the ESS site (pond 4, site 31.6, N55.74, E13.24), starting 22 June 2020. The water level in the pond was high at the time (see Figure 3). The anchor was placed close to the shore of the pond. A telescopic boathook (length > 4 m) was used to position the bucket and marker float several metres offshore. Sampling personnel wearing waders also entered the pond to be able to position the trap not too close to the shore. The bucket was sunk to the pond bottom by tilting the bucket with the boathook. The stone ballast ensured that the bucket sunk in an upright position.

Figure 3 Pond at the ESS (site 31.6, N55.74, E13.24), 22 June 2020, including boathooks (one of length 1.7 m and one telescopic of length > 4 m) and marker float for the bottom sediment sampling trap.

When retrieving the trapped sediment (10 November 2020, sample ESED_1:31.6), the anchor was located close to the shore, and the polypropene line attached to the anchor was used to carefully pull the bucket in with the line held at chest height. As the other end of the line was fastened to the marker float, the bucket was lifted from the pond bottom when hauled towards the shore. When the bucket was visible, one of the boathooks was used to carefully transport the bucket with its sediment and water content to land.

This first sediment sample (ESED_1:31.6) is shown in Figure 4. About 3 L of the semi-clear upper water in the sediment trap was poured out of the bucket and about 2 L were transferred to a clean 5-L bucket (lower right photo in Figure 4). The sediment trap and the bucket with the 2 L of water were transported to a garage at Timjanvägen 5 in Lund. After 1.5 days of sedimentation (12 November 2020, see Figure 5), the clear water was poured out from the clean bucket. All the wet sediment material from both buckets was transferred to a 200 mL container, which was transported to the Department of Geology at Lund University.

Figure 4 First sediment sample collected between 22 June and 10 November 2020.

Figure 5 The bucket in the lower right photo in Figure 4 after 1.5 days of sedimentation. Clear water is above the sediment at the bottom of the bucket.

The next sediment sample (ESED_2:31.6) was collected with the same equipment from 12 November 2020 to 16 September 2021. Figure 6 shows the sample retrieval. The upper, rather clear, water in the trap was transferred to a 2-L bottle and the wet sediment was transferred to a clean 5-L bucket. These were both transported to the Department of Geology at Lund University.

Figure 6 ESED_2:31:6 collected between 12 November 2020 and 16 September 2021.

The third sediment sample ESED_3:31.6 consists of sediment trapped between 16 September 2021 and 2 May 2022. After retrieval from the pond bottom, the sediment trap bucket was let standing for about 20 h, to allow settling of particles in the water. The clear water was poured out of the bucket. The rest, about 2 L, was transferred to a 2-L bottle. Figure 7 (right) shows the sediment remaining after transferring the muddy water to the 2-L container (left). This sediment material was also transferred to the 2-L container. The 2-L container was transported to the Department of Geology, Lund University.

Figure 7 ESED_3:31:6 collected between 16 September 2021 and 2 May 2022. The plastic spoon and scraper were used to transfer the sediment from the 5-L bucket to the 2-L container.

4.3. Stationary bottom sediment trap, version 2

The second prototype (see Figure 8) was made in three copies (labelled 2, 3 and 4 on the marker float and on the bucket). A hole was drilled in the middle of the lower bucket to allow water to flow in and out from the bucket, i.e. in when placed at the site and out at the end of sampling. Four instead of two holes (see Section 4.2) were used to fasten the two buckets to each other.

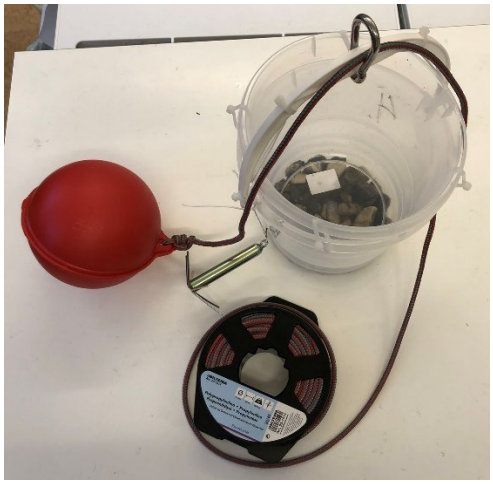

Figure 8 Second version of the bottom trap.

The three second-version stationary sediment traps were placed at the ESS pond 4 (site 31.6) 2 May 2022 (as shown in Figure 9). The water level in the pond was low at the time (the stones in Figure 9 are not visible in Figure 3). These samples have been retrieved in May 2023. The results will be reported later. Using three traps instead of one aims to guarantee that the sampled mass of sediment is sufficient for gamma-ray spectrometric analysis, and possible other, more detailed, radiometric analysis. In this way, sampling can also be more representative by placing the buckets in different places in the pond.

Figure 9 The three copies of the second prototype in the ESS pond 4 (site 31.6) 2 May 2022.

4.4. Lamotte bottom sampling dredge

The Lamotte bottom sampling dredge (stainless steel, Heraco AB) is of the scissor grab type. It has hinged buckets shutting together when reaching the sediment surface (see Figure 10). The maximum sampled volume is approximately 1.2 L (19 cm x 8 cm x 8 cm).

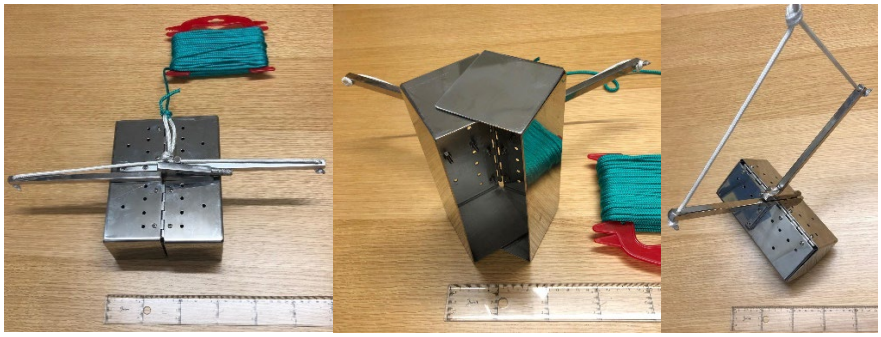

Figure 10 The Lamotte bottom sampling dredge.

A first test of the Lamotte bottom sampling dredge was performed 2 May 2022 at ESS pond 4 (site 31.6). One person, wearing waders, entered the pond and one sample was collected at a water depth a few tens of centimetres. The sample (ESED_4:31.6, see Figure 11) was released into a 5-L bucket, sealed with a lid and transported to the Department of Geology, Lund University.

Figure 11 Sediment sample collected with the Lamotte bottom sampling dredge, 2 May 2022.

Tests using the Lamotte sampler were performed in May, June, August and September 2022. The first tests (May 2022) at various sites at Kävlinge river (bridge in Flyinge, jetty at Gårdstånga church, Getinge bridge) demonstrated that sampling from land may be both inflexible and difficult. Stones, roots, and vegetation material may prevent the sampler from closing at the bottom, resulting in unsuccessful sampling. Sampling was only successful at Getinge bridge, and only towards the shores on either side of the bridge. No sample could be retrieved in attempts to sample from the middle of the bridge. Additionally, runoff holes in the

bridge, transporting material from the road into the river, may have provided unrepresentative results.

To increase the flexibility of sampling from land, the range of the Lamotte sampler was extended by using a boathook (see Figure 12). This strategy proved successful at some sites, provided that no obstacles on the bottom prevented the Lamotte sampler from enclosing the sediment sample. Sampling from boat (inflatable Zodiak Cadet) was tested and proved more flexible. However, the problem of vegetation preventing the Lamotte sampler from closing was frequently prevailing.

Figure 12 The Lamotte sampler with extended range.

Details of sampling and comments for specific sites are provided in Table 2. Dry weights (d.w.) of the sediment samples collected with the bucket bottom-trap tested at ESS pond 4 (site 31.6) are provided. ESED_1 provided 24.1 g (d.w.) during almost five months of collection, whereas ESED_2 collected only 11.7 g (d.w.) during ten months, and ESED_3 resulted in 82.7 g (d.w.) from almost eight months of sampling. The high variability in sampled weight led to the decision to use three traps instead of a single trap for the next sampling at ESS Pond 4.

The Lamotte sampler worked well only in absence of stones and vegetation. At ideal sampling spots, gas bubbles appeared at the water surface when the sampler sank into the sediment. The sampler was lifted from the bottom after the bubbles ceased to appear.

Table 2 Details on sampling tests. SBST: Stationary bottom sediment trap. LBD: Lamotte bottom dredge.

ID ESED_	Site	Sampling date	Sampling method	Comments sampling
1	31.6. ESS Pond 4	2020-06-22 -- 2020-11-10	SBST	Single trap. Version 1, d.w. 24.1 g.
2	31.6. ESS Pond 4	2020-11-12 -- 2021-09-16	SBST	Single trap. Version 1, d.w. 11.7 g.
3	31.6. ESS Pond 4	2021-09-16 -- 2022-05-02	SBST	Single trap. Version 1, d.w. 72.7 g.
4	31.6. ESS Pond 4	2022-05-02	LBD	Collected using waders. One grab sample (scoop) enough, easy collection.
5	90. Getinge bridge	2022-05-10	LBD	Difficult to sample from bridge, samples did not close due to stones and vegetation. Sample collection successful at east side of the bridge, close to shore. Runoff holes in bridge close to sample collection. Plant material and some small animals in the sample.
6	90. Getinge bridge	2022-05-10	LBD	Same as above but on west side of the bridge.
7	91. Pegasus trädgård	2022-06-08	LBD	No success sampling from boat, due to too much vegetation. Success collection using waders. Lots of sand in the sample. Unsuitable site.
8	92. Örtofta	2022-06-08	Extended LBD	From jetty, two scoops. Fine sediment, bubbles released from bottom. Suitable sampling site.
9	93. Kävlinge scoutgård	2022-06-08	Extended LBD	Unsuccessful sampling from the jetty (roots and vegetation). Sampling successful to the left of the jetty (three scoops).
10	94.1. Kävlinge river, outlet Sularpsbäcken, upstream	2022-08-17	LBD	From boat. Sampling difficult due to vegetation. Sampling successful close to shore at the location of entering the water with the boat.
11	94.2. Kävlinge river, outlet Sularpsbäcken, downstream	2022-08-17	LBD	From boat. Difficult to sample due to vegetation. Successful sampling close to the reedbed. Sampler was pushed down into the bottom sediment using a boathook.
12	77. Höje river, Lomma church	2022-08-24	Extended LBD	Three scoops from river edge, two scoops from bride. Suitable site.
13	95. Höje river, Bjällerup	2022-08-24	Extended LBD	From bridge, sandy bottom. Several scoops. Lots of sand in sample. Not ideal site (sandy, stony).
14	35.4. Källby, Höje river, Drömbron	2022-09-09	Extended LBD	From bridge. Many scoops needed. Not ideal, due to vegetation.
15	35.5. Källby Pond 1, from shore	2022-09-09	Extended LBD	From land. Easy sampling.
16	35.6. Källby Pond 5	2022-09-09	Extended LBD	From metal jetty. Easy sampling.
17	88.2. Helge river, Åhus, Mölleholmen	2022-09-10	LBD	From boat, several scoops over an extended area. Some problems with bottom vegetation.

4.5. Sample preparation

Obvious foreign matter was removed from the sediment sample before sieving, using multiple sizes (5.6 and 4.0 mm) depending on the nature of each specific sample (see Figure 13). Final sieving was done using a 2.0 mm sieve.

The first sediment samples that were collected were sieved directly after sampling near the sampling location. This was both time-consuming and inconvenient. Instead, bringing the samples to a laboratory and sieving the sediment there proved to be easier and more efficient. After sieving, the samples were allowed to settle so that excess water could be removed.

Figure 13 Sieving of sediment samples. The two upper photos demonstrate the sieving procedure. The bottom photo shows the sinks with sediment traps at the sediment lab at the Department of Geology, Lund University.

All samples except one were freeze-dried. The sample that was not freeze-dried was poured into a plastic bucket for sedimentation for 24 h. The excess water was removed, and the sediment was moved to a smaller container and allowed to settle for four days. The excess water was removed, and the sample was allowed to dry both at air temperature and in an oven at 70 °C for a total of 16 days until completely dry.

The samples that were freeze dried were divided into subsamples in 200 mL plastic jars (Cerbo) containing approximately 150 g of sediment in each. The samples were stored in a freezer at -22 °C until freeze-drying.

Figure 14 Sediment samples prior to drying (right) and after drying (right).

The subsamples were freeze-dried in a Hypercool HC3055 at -55 °C for up to 90 h depending on the sample load. Large sediment samples were freeze-dried in batches to not overload the freeze-dryer (see Figure 14). Freeze drying produced a porous sample material that was easily homogenized, whereas drying in air resulted in a solid and hard material, that was not easily homogenized (see Figure 15).

Figure 15 ***Left:*** **ESED_1:1.6 and after freeze-drying.** ***Right:*** **ESED_2:13.6 after oven-drying.**

The dried subsamples were homogenized in its plastic jars with a pestle and then combined in a resealable plastic bag (see Figure 16) for storage until preparation for gamma-ray spectrometry measurements. For the gamma-ray spectrometry measurements the samples were transferred to 200-mL plastic jars (see Figure 16)) and compacted with a pestle.

Figure 16 ***Left:*** **Homogenized, dried, and homogenized sediment samples.** ***Right:*** **200-mL sample jars with dried and homogenized sediment samples for gamma-ray spectrometry.**

Table 3 List of sediment samples, collection and drying methods, sampling dates and dry weights.

ID ESED_	Site	Sampling date	Comments sample preparation	Wet weight (g)	Dry weight (g)	Dry weight (%)
1	31.6. ESS Pond 4	2020-06-22 - - 2020-11-10	Stored in freezer until Oct-21. Freeze-dried		24.1	
2	31.6. ESS Pond 4	2020-11-12 - - 2021-09-16	Dried in air and in oven (70 °C).		11.7	
3	31.6. ESS Pond 4	2021-09-16 - - 2022-05-02	Freeze-dried	356.7	72.7	20%
4	31.6. ESS Pond 4	2022-05-02	Freeze-dried	1216.8	262.9	22%
5	90. Getinge bridge	2022-05-10	Freeze-dried	1591.1	234.1	15%
6	90. Getinge bridge	2022-05-10	Freeze-dried	1205.2	163.9	14%
7	91. Pegasus trädgård	2022-06-08	Freeze-dried	1503.9	898.4	60%
8	92. Örtofta	2022-06-08	Freeze-dried	1247.8	194.5	16%
9	93. Kävlinge scoutgård	2022-06-08	Freeze-dried	1632.2	406.2	25%
10	94.1. Kävlinge river, outlet Sularpsbäcken, upstream	2022-08-17	Freeze-dried	1398.9	365.1	26%
11	94.2. Kävlinge river, outlet Sularpsbäcken, downstram	2022-08-17	Freeze-dried	1562.9	792.0	51%
12	77. Höje river, Lomma church	2022-08-24	Freeze-dried	1867.0	568.0	30%
13	95. Höje river, Bjällerup	2022-08-24	Freeze-dried	1425.9	1037.2	73%
14	35.4. Källby, Höje river, Drömbron	2022-09-09	Freeze-dried	1752.2	472.2	27%
15	35.5. Källby Pond 1, from shore	2022-09-09	Freeze-dried	2231.2	117.7	5%
16	35.6. Källby Pond 5	2022-09-09	Freeze-dried	1738.0	163.00	9%
17	88.2. Åhus, Helge river, Mölleholmen	2022-09-10	Freeze-dried	2601.0	280.40	11%

5. ANALYTICAL METHODS

5.1. C:N analysis

The C:N atomic ratios, the atomic % C and N, were determined in all samples except ESED_1 and ESED_2. The C:N atomic ratios may aid in assessing the relative contribution of land-plant and algal origin, as algae typically have lower C:N ratios (typically 4-10) than land-based plants (typical C:N ratios of >20) [13].

The elemental analysis "C/N analysis in solids" was performed for 15 sediment samples at the Instrumental Chemistry Laboratory, Department of Biology, Lund University. For the elemental analysis a vario MAX CN, an elemental analyser with TCD detector, was used. At least 200 mg (d.w.) per sample was required for analysis. The sediment samples submitted for analysis ranged from 426 mg to 1825 mg (d.w.) in size. Generally, elemental analysers have high precision (≤ 0.5 % for test substances according to product specifications from the manufacturer Elementar Analysensysteme GmbH[2]; for samples usually less than single %, see, e.g., [14]).

5.2. Gamma-ray spectrometry

Gamma-ray spectrometry was performed in the laboratory in Malmö as described in [15].

[2] http://www.vertex.es/portal/docs/elementar/C_Elementar_vario_MAX.pdf, accessed 26 May 2023.

6. RESULTS AND DISCUSSION

6.1. C:N analysis

The results from the C:N analysis are presented in Table 4, Figure 17 and Figure 18. For Kävlinge river as well as Höje river, the sites are arranged from furthest upstream to furthest downstream. The higher the C:N ratio, the more influence from land-based plants over aquatic algae according to [13]. Furthermore, Nasir *et al.* [16] state: "generally the value of C:N ratio for organic matter of sea is 7, organic matter of soil 8–20, and the ratio bigger than 20 is for organic matter of terrigenous".

The Källby ponds display the lowest C:N ratios of the samples analysed (C:N ratio 7-8), indicating that these ponds have higher contribution from aquatic algae to the bottom sediment than the other sites. The carbon and nitrogen content of these ponds are the highest of all samples analysed.

The sample with the highest C:N value (ESED_13, site 95, Höje river, Bjällerup) had very little organic content (sandy sample, see Table 2; only 0.48% TC and 0.02% TN), and with a C:N ratio of over 20, the organic content of this sample is predominantly from land-based vegetation.

Table 4 Percentage of carbon and nitrogen in the samples, as well as atomic C:N ratios. For Kävlinge river as well as Höje river sites are arranged from furthest upstream to furthest downstream.

River	Site	Sample ID	Site	TC (%)	TN (%)	C:N
ESS Pond 4	31.6	ESED_3	31.6	6.76	0.62	10.9
	31.6	ESED_4	31.6	5.74	0.45	12.7
Kävlinge river	94.2	ESED_11	94.2	2.10	0.15	14.5
	94.1	ESED_10	94.1	9.11	0.85	10.7
	90	ESED_5	90	10.25	1.00	10.3
	90	ESED_6	90	10.67	1.01	10.5
	92	ESED_8	92	10.86	1.04	10.4
	93	ESED_9	93	7.30	0.61	11.9
	91	ESED_7	91	1.02	0.07	15.4
Höje river	95	ESED_13	95	0.48	0.02	22.9
	35.4	ESED_14	35.4	5.21	0.41	12.6
	77	ESED_12	77	5.82	0.52	11.2
Källby ponds	35.5	ESED_15	35.5	21.54	2.88	7.5
	35.6	ESED_16	35.6	13.07	1.66	7.9
Helge river	88.2	ESED_17	88.2	14.94	1.50	10.0

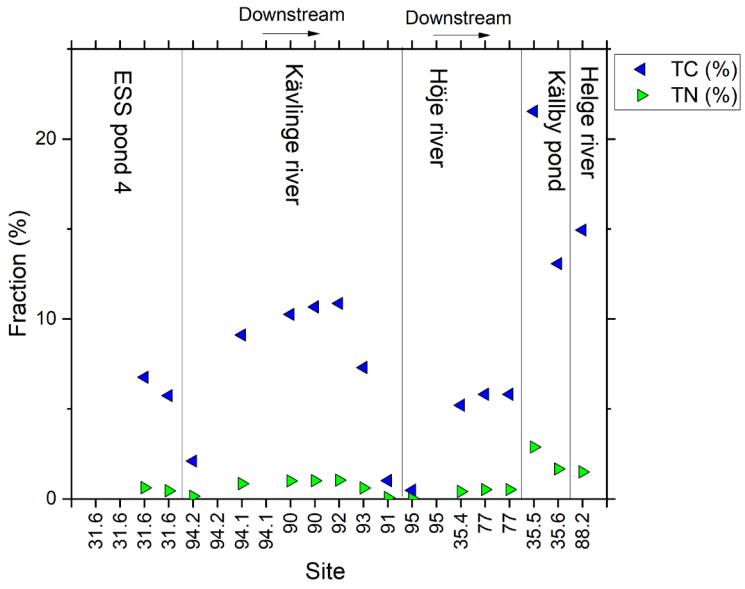

Figure 17 Total carbon (TC) and total nitrogen (TN) for the sediment samples from the sites investigated.

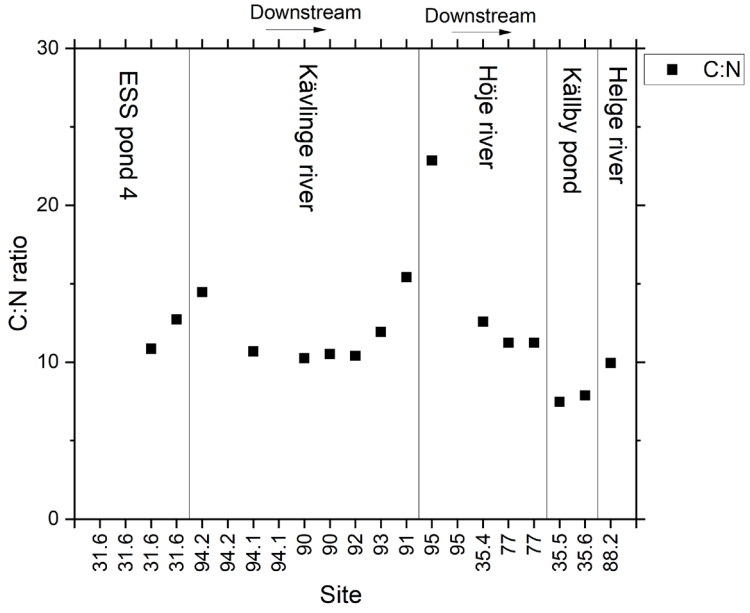

Figure 18 Carbon to nitrogen ratio (C:N) for the sediment samples from the sites investigated.

6.2. Gamma-ray spectrometry

The results of the gamma-ray spectrometric analysis are presented in Table 5, Figure 19 (^{214}Bi from the uranium series starting with ^{238}U, anthropogenic ^{137}Cs mainly from the Chernobyl accident, and ^{228}Ac from the thorium series starting with ^{232}Th) and Figure 20 (natural ^{40}K).

Table 5 Activity concentration, A_c, (Bq kg^{-1}) and minimum detectable activity, MDA, (Bq kg^{-1}) of gamma emitting radionuclides in sediment. The uncertainty refers to one standard deviation (k=1).

					^{214}Bi		^{137}Cs		^{228}Ac		^{40}K	
Sample	**Site**	**Reference date**	**Mass d.w. (g)**	**ID****	**A_c**	**MDA**	**A_c**	**MDA**	**A_c**	**MDA**	**A_c**	**MDA**
ESED_1:31.6*	31.6	2020-06-22 to 2020-11-10	24.1	E730	79±12	46	<MDA	3.0	94±6	8.1	552±19	47
ESED_2:31.6*	31.6	2020-11-12 to 2021-09-16	11.7									
ESED_3:31.6*	31.6	2021-09-16 to 2022-05-02	28.1	E744	38±2	1.6	5.9±0.5	1.8	108±6	4.9	720±23	31
ESED_4:31.6	31.6	2022-05-25	118.4	E742	51±3	1.0	3.1±0.3	1.1	93±5	3.0	795±22	22
ESED_5:90	90	2022-05-11	89.9	E751	67±4	0.8	10.0±0.4	0.9	88±5	1.1	487±14	15
ESED_6:90	90	2022-05-11	91.5	E753	56±3	1.8	11.0±0.6	1.9	76±5	2.6	497±16	30
ESED_7:91	91	2022-06-08	285.8	E755	12±1	0.4	1.2±0.1	0.4	15±1	2.5	545±15	6.6
ESED_8:92	92	2022-06-08	85.7	E757	55±3	2.3	10±1	2.3	51±4	2.2	465±16	39
ESED_9:93	93	2022-06-08	126.4	E759	31±2	1.3	11±1	1.5	44±3	8.9	559±17	23
ESED_12:77	77	2022-08-24	131.5	E791	24±1	0.9	21±1	1.0	37±2	10	613±17	16
ESED_12:77	77	2022-08-24	136.6	E792	23±1	1.7	20±1	1.7	32±2	5.0	599±17	29
ESED_10:94.1	94.1	2022-08-17	106.4	E793	56±3	1.3	8.1±0.4	1.4	46±3	18	471±14	22
ESED_10:94.1	94.1	2022-08-17	114.7	E794	53±3	0.8	7.8±0.3	0.9	44±3	5.9	451±13	14
ESED_11:94.2	94.2	2022-08-17	205.6	E795	3.6±0.5	1.4	3.3±0.3	1.3	11±1	3.8	494±14	23
ESED_11:94.2	94.2	2022-08-17	213.3	E796	26±2	1.3	3.6±0.3	1.3	27±2	5.9	528±14	22
ESED_13:95	95	2022-08-24	308.4	E797	7.6±0.5	0.6	<MDA	0.6	8.4±0.7	4.7	399±10	10
ESED_13:95	95	2022-08-24	342.8	E798	<MDA	1.4	<MDA	1.4	<MDA	3.5	424±12	24
ESED_14:35.4	35.4	2022-09-09	126.7	E799	47±3	1.3	11±1	1.5	59±4	1.6	611±18	23
ESED_17:88.2	88.2	2022-09-10	72.2	E800	15±1	3.4	165±4	3.3	30±3	9.3	495±20	9.3
ESED_15:35.5	35.5	2022-09-09	109.0	E801	14±1	3.0	9.6±0.7	3.0	27±3	3.9	191±14	51
ESED_16:35.6	35.6	2022-09-09	84.3	E802	17±2	4.0	11±1	4.0	22±4	9.3	278±19	68

*Sampled with Bottom trap. The rest of the samples were sampled with a Lamotte bottom dredge.

**Gamma-ray spectrometry ID.

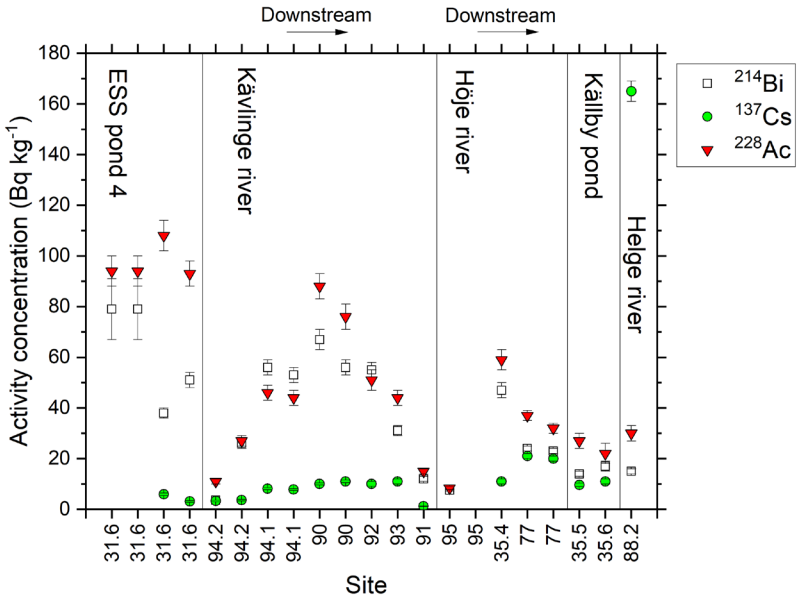

Figure 19 Activity concentrations of ^{214}Bi, ^{137}Cs, and ^{228}Ac in the sediment samples from the sites investigated.

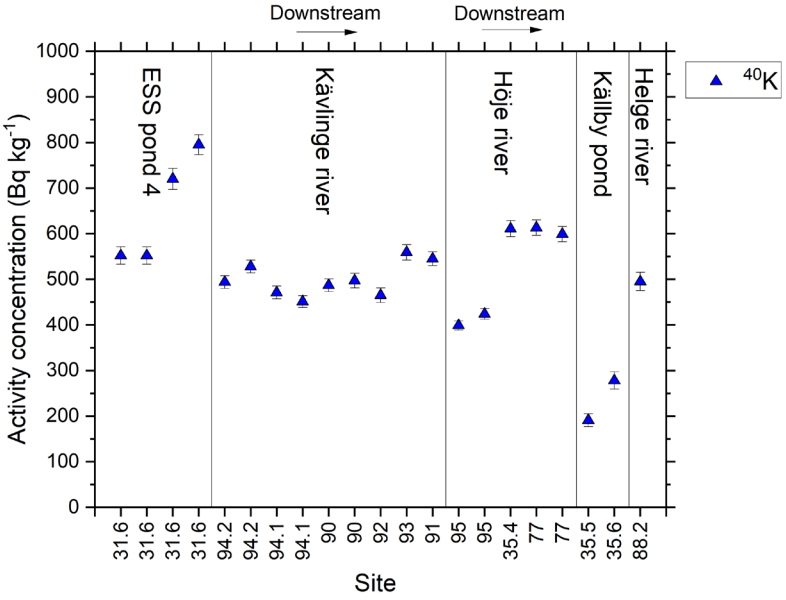

Figure 20 Activity concentrations of ^{40}K in the sediment samples from the sites investigated.

All measured activity concentrations were above the MDA for the reported radionuclides except for the two samples from site 95 (ESED_13:95). The reason the levels are below the MDA for ^{214}Bi and ^{228}Ac for one of these samples, although the MDA is relatively low, is unclear. An explanation could be that one of the samples from this particular site mainly contained sand. Among the sediment

samples it is also observed that the ^{137}Cs concentration is typically in the range from 0.3-21 Bq kg^{-1} (on average 8.7 Bq kg^{-1}), with an exceptionally higher value for sample E800 that had a ^{137}Cs activity concentration of 165±4 Bq kg^{-1}. The high value was confirmed by a second measurement of the same sample. The sample was collected at Site 72.2, in Helge river near Åhus on the east coast of Scania. It is known that the activity concentration of ^{137}Cs is about one order of magnitude higher in bioindicators collected at the east coast of Scania (Baltic Sea) than on the west coast (Öresund) as shown by Eriksson Stenström and Mattsson [17]. Thus, it is expected to find higher activity concentrations in sediment samples from the east coast than in samples from the west coast. Additionally, for sampling site 31.6 two different sample collection methods were used, bottom trap and Lamotte bottom dredge, respectively. Although the sampling method and periods differ the activity concentration of the radionuclides reported are comparable. Hence, the choice of sampling method and period can be interchanged depending on the purpose of the study, for example, when studying site 72.2 in more detail.

The expanded survey of sediments confirmed it as a useful indicator of radionuclides with activity concentrations above the MDA levels for all reported radionuclides and samples, except for site 95.

6.3. Statistical analysis

A Pearson correlation analysis was performed for the measured parameters using the software OriginPro 2023b. Pearson correlation analysis requires normally distributed data. The data for TC, ^{214}Bi, ^{228}Ac, and ^{40}K was normally distributed. Furthermore, Grubb's test identified the following outliers:

- TN: 2.88% (site 35.5, Källby pond, highest TN value);
- C:N: 22.86 (site 95 in Höje river, sandy sample with lowest TC and TN);
- ^{137}Cs: 165 Bq kg^{-1} (site 88.2, the only sample in this study from Helge river, connected to the Baltic Sea).

After removing these outliers the data for TN, C:N, and ^{137}Cs became normally distributed. The results of the Pearson correlation analysis that followed (Table 6) show a very high positive linear correlation between TC and TN, and a significant linear correlation between C:N and TC, as well as C:N and TN. The correlation between ^{214}Bi and ^{228}Ac may be interpreted as little variation in the ratio between ^{238}U and ^{232}Th in the local bedrock. Other significant correlations can be seen between ^{40}K and TC as well as ^{40}K and ^{228}Ac.

Table 6 Pearson correlation matrix of all samples. Significant correlations ($p<0.05$) are highlighted.

		TC (%)	TN (%)	C:N	^{214}Bi	^{137}Cs	^{228}Ac	^{40}K
TC (%)	**Pearson Corr.**	1	**0.98**	**-0.90**	0.14	0.20	0.094	**-0.56**
	p-value		**<0.0001**	**<0.0001**	0.61	0.50	0.73	**0.022**
TN (%)	**Pearson Corr.**		1	**-0.91**	0.29	0.27	0.17	-0.42
	p-value			**<0.0001**	0.30	0.37	0.54	0.12
C:N	**Pearson Corr.**			1	-0.12	-0.42	-0.081	**0.61**
	p-value				0.67	0.13	0.78	**0.015**
^{214}Bi	**Pearson Corr.**				1	0.036	**0.77**	0.29
	p-value					0.90	**<0.001**	0.24
^{137}Cs	**Pearson Corr.**					1	-0.053	-0.064
	p-value						0.85	0.81
^{228}Ac	**Pearson Corr.**						1	**0.57**
	p-value							**0.014**
^{40}K	**Pearson Corr.**							1
	p-value							

7. SUMMARY AND CONCLUSIONS

The experience of using stationary bottom sediment traps for annual integrated sampling in the ponds at the ESS indicates that this sampling strategy is suitable and simple. The robustness of concept will be further tested and evaluated. Positioning of the sediment samplers in the ponds and retrieving the samplers from the ponds could possibly benefit from using a boat (an inflatable boat is available). We recommend using three 5-L buckets per pond during a collection period of one year to be certain to obtain enough sediment for gamma-ray spectrometry.

The Lamotte bottom dredge with extended range works well in ponds, when the sediment layer is thick and without vegetation parts or stones. However, it is not seldom difficult to use the Lamotte bottom dredge from land to sample sediments in rivers, in particular when the bottom has obstacles, such as vegetation and stones, preventing the sampler from closing and retrieving the sediment sample. Sampling with the Lamotte bottom dredge from boat may be more suitable at some sites, but not all. We therefore propose future investigations of testing other types of bottom sediment sampling devices for rivers, such as sediment corers, or so called Russian sediment samplers. Furthermore, annual sampling of sediments is suggested to be performed in early spring to minimize problems related to vegetation.

It is important to note that the two types of sediment samplers tested so far, provide different information. The stationary bottom sediment trap collects only material that has sunk to the bottom from the water column over the sampler during several months. The other type of sampler tested in this report, the Lamotte bottom dredge, provides instant grab samples of sediment with thicknesses up to ~8 cm, containing material accumulated during an unknown, site-specific number of years.

In the sample preparation, freeze-drying was found superior to air and oven drying. Sieving the sediment in a laboratory was found to be more efficient and more convenient compared to sieving at the sampling site.

Measurements of TC, TN, and the C:N ratio proved to have the potential to provide useful information about the sources of the sediment. Similarly, gamma-ray spectrometry of the samples can add information about the sources of the sediment (^{40}K) and identify anthropogenic radionuclides. The half-lives of the studied radionuclides need to be considered when selecting the sampling method.

Analysis of radionuclides that are not gamma emitters may require adaption of the sampling strategy, for instance, larger samples. Furthermore, sample preparation techniques for non-gamma emitters are often nuclide- and technique-specific.

8. ACKNOWLEDGMENT

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We also thank research engineer Sofia Mebratu Wisén at the Instrumental Chemistry Lab (Department of Biology, Lund University) for performing the “C/N in solids” elemental analysis.

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APPENDIX 1. GAUSSIAN PLUME MODELLING PERFORMED BY LUND UNIVERSITY

This appendix presents calculations performed by Lund University for the estimation of the long-term activity concentration in air around the ESS. The calculations are very basic, and do not include effects caused by, for example, influence on the wind pattern from large buildings or from surface roughness. The aim of these calculations is to justify the choice of sampling sites only.

1. METHODS

The version of the Gaussian plume model used for the calculations assumes that the long-term average concentration C_{av} at a distance x in a specific sector n_i from a point source releasing airborne radionuclides can be approximated by [1]:

$$C_{av} = \sqrt{\frac{2}{\pi}} \frac{\left(\frac{f}{100}\right) Q}{\left(\frac{2\,\pi\,x}{n}\right) \sigma_z u} \cdot e^{-\frac{H_e{}^2}{2\sigma_z{}^2}} \qquad \text{(A1.1)}$$

where

C_{av}	average long-term concentration (Bq/m^3)
f	frequency of wind directions into the wind sector
σ_z	vertical standard deviation of the concentration distribution (m)
n	number of wind sectors
Q	average long-term release rate (Bq/s)
x	distance from source (m)
H_e	effective stack height (m)
u	mean horizontal air velocity (m/s)

The effective stack height may be approximated by [2]:

$$H_e = h + d \cdot \left(\frac{v}{u}\right)^{1.4} \cdot \left(1 + \frac{\Delta T}{T}\right) \qquad \text{(A1.2)}$$

where

H_e	effective stack height (m)
h	physical stack height (m)
d	chimney outlet diameter (m)
v	exit velocity of effluent (m/s)
u	mean horizontal air velocity (m/s)
T	temperature of effluent gas (K)
ΔT	difference between effluent and ambient temperature (K)

The vertical standard deviation of the concentration distribution (σ_z) depends on atmospheric conditions which usually are categorized by atmospheric stability classes (Pasquill stability classes), as shown in Table A1- 1 and Table A1- 2.

Table A1- 1 Pasquill stability classes.

Stability class	Conditions
A	Extremely unstable conditions
B	Moderately unstable conditions
C	Slightly unstable conditions
D	Neutral conditions
E	Slightly stable conditions
F	Moderately stable conditions
G	Extremely Stable

Table A1- 2 Meteorological conditions defining Pasquill stability classes, from https://www.ready.noaa.gov/READYpgclass.php. Strong insolation refers to sunny midday in summer; slight insolation to sunny midday in winter. The neutral category D is used for overcast conditions during day or night for all wind speeds. Category D is also for one hour at sunrise and one hour at sunset.

	Daytime insolation			Night-time conditions	
Surface wind speed (m/s)	**Strong**	**Moderate**	**Slight**	**Thin overcast or > 4/8 low cloud**	**<= 4/8 cloudiness**
< 2	A	A - B	B	E	F
2 - 3	A - B	B	C	E	F
3 - 5	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

The vertical standard deviation of the concentration distribution σ_z (m) can be estimated from [3] and references therein:

$$\sigma_z = \frac{k_4 x}{\left(1 + \frac{x}{k_2}\right)^{k_5}} \qquad \text{(A1.3)}$$

with constants k_2, k_4, and k_5 listed in Table A1- 3. Figure A1- 1 presents σ_z as a function of distance x for various Pasquill stability classes.

Table A1- 3 Constants for calculation of vertical standard deviation of the concentration distribution σ_z (and other parameters). From [3] and references therein.

Stability class	k_1	k_2	k_3	k_4	k_5
A	0.250	927	0.189	0.1020	-1.918
B	0.202	370	0.162	0.0962	-0.101
C	0.134	283	0.134	0.0722	0.102
D	0.0787	707	0.135	0.0475	0.465
E	0.0566	1070	0.137	0.0335	0.624
F	0.0370	1170	0.134	0.0220	0.700

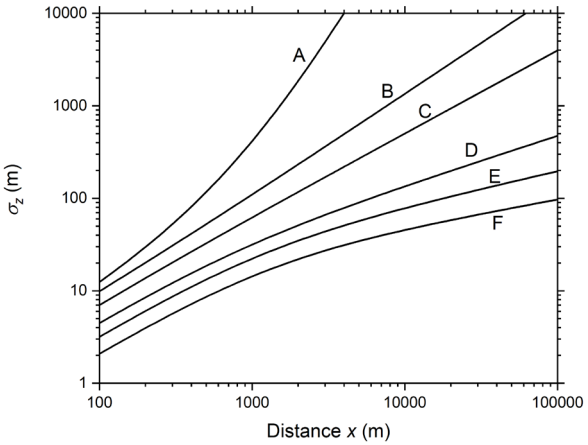

Figure A1- 1 Vertical standard deviation of the concentration distribution (σ_z) as a function of distance to source for various Pasquill stability classes, according to Eq (A1-3).

2. INPUT DATA

Data from Malmö-Sturup Airport (26 km south-east of the ESS) for the years 2006-2012 shows that the predominant winds in the region were westerly (on average 20% of the time) and south-westerly (17% of the time) [4] (see Figure A1- 2, left). More detailed wind data for the ESS site for 2019 has been reported in [5] and are shown in Figure A1- 2 (right). The most dominant wind directions were: WSW (12.3% of the time, average wind speed 4.2 m/s), ESE (12.2%, 3.8 m/s), W (11.6%, 3.8 m/s) and SW (11.3%, 5.2 m/s). The overall annual average wind speed was 3.7 m/s. All wind data for 2019 are shown in Table A1-4. The annual average outdoor temperature in 2019 was 9.8 °C (T_{av} = 10°C = 283 K used in the calculations).

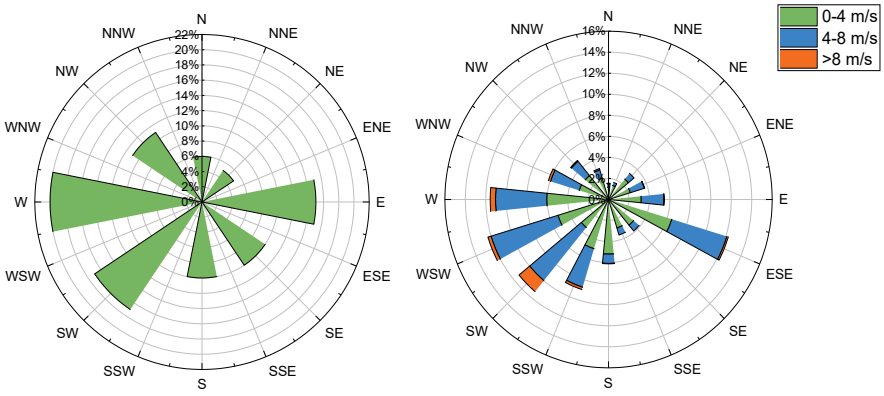

Figure A1- 2 *Left:* Windrose for Malmö-Sturup airport for years 2006-2012, data taken from Ref [4]. *Right:* Windrose representative for the location of the ESS facility for year 2019, obtained from hourly measurements with a Davies Vantage Pro weather station located at the ESS.

Table A1- 4 Wind data for 2019 obtained with a Davies Vantage Pro weather station located at the ESS. The wind directions are divided into n = 16 sectors. The four most frequent wind directions are marked in bold.

Wind direction	Frequency f (%)	Average wind speed u (m/s)
N	1.6	2.8
NNE	1.7	2.3
NE	3.2	2.5
ENE	3.7	3.4
E	5.5	3.6
ESE	**12.2**	**3.8**
SE	3.9	2.6
SSE	3.5	2.6
S	6.1	2.4
SSW	8.9	3.8
SW	**11.3**	**5.2**
WSW	**12.3**	**4.2**
W	**11.6**	**3.8**
WNW	6.2	3.8
NW	4.8	3.2
NNW	3.1	3.1
Average wind speed u_{av} (m/s)		3.7

The parameters for the airborne discharges from the main stack and from the waste facility stack are presented in Table A1- 5 [4].

Table A1- 5 Parameters for airborne discharges from the main stack and from the waste facility building [4] and Per Roos (ESS) personal communication (2020-03-12).

Parameter	Abbreviation	Main stack	Waste facility stack	Reference
Release type		Continuous and short-time (hot cells)	Short-time	**[4]**
Stack height above ground (m)	h	45	25	**[4]**
Stack inner diameter (m)	d	1.7	0.787	**[4]**
Discharge speed (m/s)	v	10 (max 16 m/s)	8-14 (11)	**[4]**
Temperature of effluents (K)	T	296 K	297 K	**[4]**
Difference between effluent and ambient temperature (K)	$\Delta T = T - T_{av}$	296 - 283 = 13	297 - 283 = 14	Davis weather station

The software Origin Pro was used to calculate the long-term average concentration C_{av} (see above) resulting from dispersion of the effluents from the main stack and from the waste stack including all stability classes. Pasquill stability classes D (neutral) and C (slightly unstable) may be considered as most relevant for the meteorological conditions at the ESS based on the local average meteorological conditions (Figure A1-2) and data in Table A1- 2.

3. RESULTS

3.1. Main stack

Figure A1- 4 shows the normalised C_{av} (Bq m^{-3} in air per released Bq year^{-1}) for the main wind direction, WSW, for dispersion from the main stack. The average wind speed into that sector (in total n = 16 sectors) was used in the calculations. Pasquill stability class D (neutral conditions) and C (slightly unstable) are considered most relevant for the ESS facility. The maximum activity concentration can be found at ~1 km from the release point for Pasquill stability class D and at ~500 m for category C.

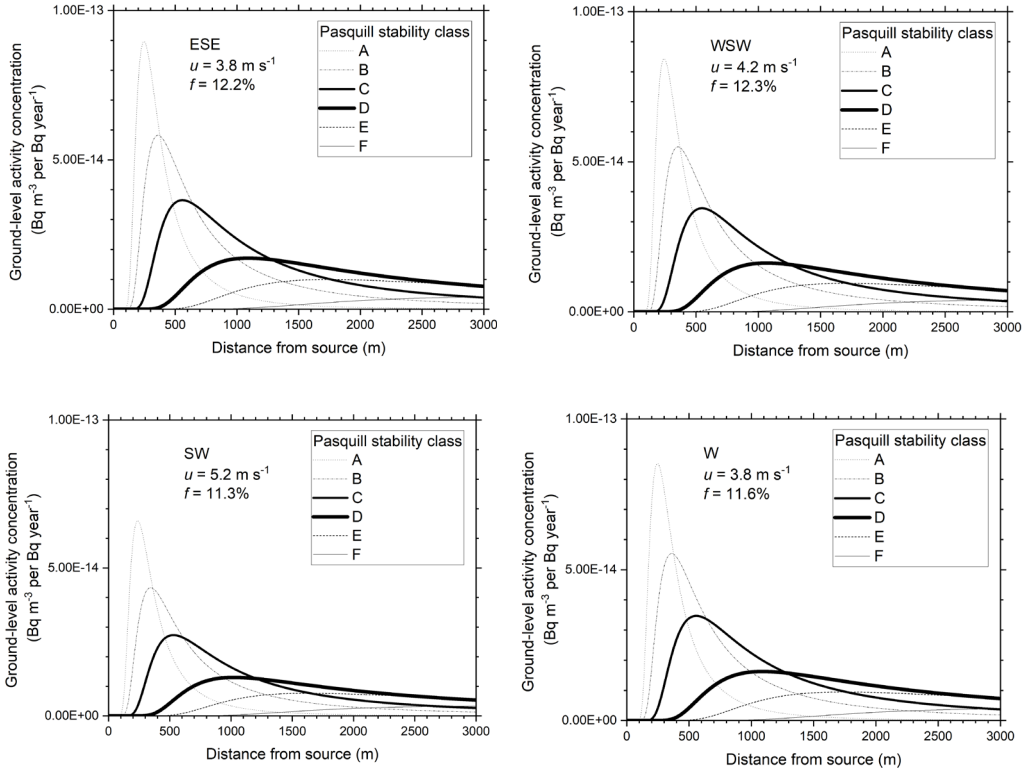

Figure A1- 3 Ground-level activity concentration in air normalized to a release rate (Bq m^{-3} per Bq year^{-1}) as a function of distance from the source of the release for the ESS main stack for winds blowing from the four main wind directions ESE, WSW, SW, and W.

3.1.1. Waste stack

Due to the shorter stack height compared to the main stack, the maximum activity at receptor level is higher than for the main stack (typically by a factor of 3) and the distance from the point of release is shorter (typically 300-400 m from the release point for weather category C or D, i.e., at about half the distance for the main stack releases). Main areas of interest for the waste stack are shown in Figure A1- 4.

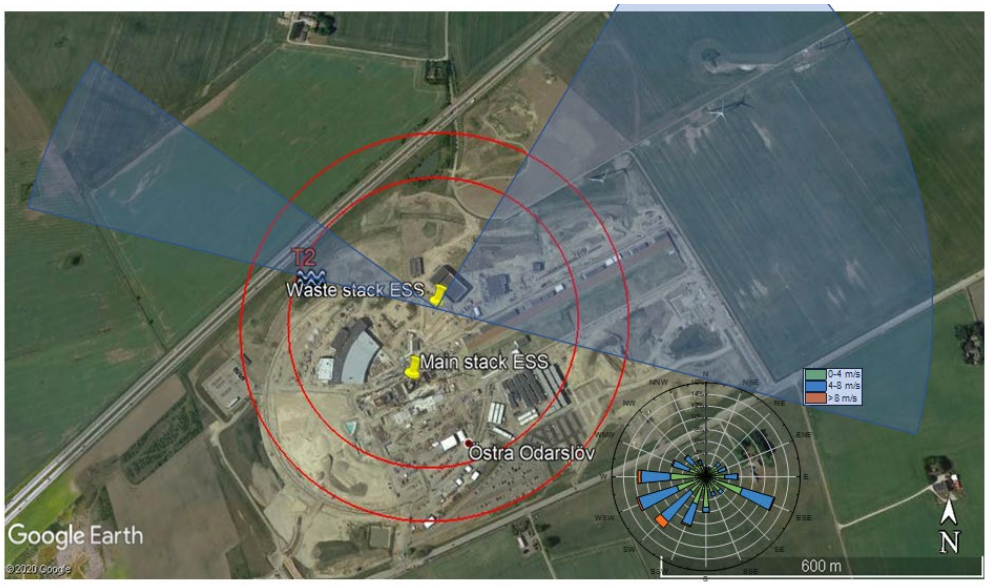

Figure A1- 4 Main areas of interest for releases from the waste stack are in the blue sectors between the red circles (300 and 400 m).

4. SUMMARY

In the calculations we considered Pasquill stability class D (neutral conditions) and C (slightly unstable) to be relevant for the weather conditions at the ESS facility. For the main stack of the target building, the maximum long-term ground-level activity concentration in air normalized to a release rate for the main wind direction (WSW) was found at ~1 km from the release point for Pasquill stability class D ($3.3 \cdot 10^{-14}$ Bq m^{-3} per Bq year^{-1}) and at ~500 m for category C ($1.7 \cdot 10^{-14}$ Bq m^{-3} per Bq year^{-1}). For the waste stack the maximum activity concentrations were most likely to be found at distances between 300 m and 400 m from the stack.

5. REFERENCES

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