

Discharges of I-131 and Lu-177 from Oslo hospitals before and after installing a decay tank, and levels in seaweed in the Oslofjord

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Abstract

Levels in seaweed at the discharge point in inner
Oslofjord were measurable, even though they were low,
after discharges of I-131 and Lu-177 from two Oslo
hospitals.

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Referanse

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Emneord

Radiofarmaka, sykehus utslipp, I-131, Lu-177,
Oslofjorden, tang.

Resymé

Selv om nivåene i tang ved utslippspunktet i indre
Oslofjord var lave, så var de målbare, etter utslipp av I-
131 og Lu-177 fra to sykehus i Oslo.

Prosjektleder:

Approved:



Ingeborg Mork-Knutsen, Director Radiation and
Environmental Protection Departement

Discharges of I-131 and Lu-177 from Oslo hospitals before and after installing a decay tank, and levels in seaweed in the Oslofjord

Results from 2021-2026 for the DSA collaboration group
TANGSPILL

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Authority (DSA)

Østerås, 2026,
Norway

Innholdsfortegnelse

1	Summary	5
2	Introduction	6
2.1	Radiopharmaceutical applications and discharges	6
2.2	Use of radiopharmaceuticals in Norway	6
2.3	Assessments of impacts to the Oslofjord and IAEA collaboration	8
2.4	Discharges to the Oslofjord and instalment of a decay tank	9
2.5	Oslo sewage system and Oslofjord hydrology	9
2.6	Seaweed uptake and measurable levels of I-131	10
2.7	Aims and objectives	11
3	Methods	12
3.1	Data: administered radioactivity, discharges and seaweed levels	12
3.2	Sampling of seaweed from the Oslofjord	13
3.3	Labwork and analyses	13
4	Results & discussion	16
4.1	Amounts of I-131 and Lu-177 used at the Oslo hospitals	16
4.2	Discharges of I-131 and Lu-177 from the Oslo hospitals	18
4.3	Seaweed levels of I-131 and Lu-177 near the discharge point	19
5	Conclusions	25
6	Acknowledgements	26
7	References	27

1 Summary

As a follow-up to a measured level of I-131 in brown seaweed of the species *Fucus vesiculosus* (bladderwrack) sampled in the inner Oslofjord in connection with marine monitoring, the levels of I-131 and Lu-177 in this seaweed at two locations in the inner Oslofjord were assessed prior to and after the instalment of a decay containment tank for I-131 at the hospital Radiumhospitalet in October 2024. Two hospitals, which are part of Oslo University Hospital, Radiumhospitalet and Rikshospitalet, provided data on daily administrations of I-131 and Lu-177, which were used to estimate daily discharges to the inner Oslofjord. The discharges were estimated taking decay into account, considering time for excretion and transport time in the sewer system. Also, the cumulative activity in Oslofjord was estimated, and its variation was compared with concurrent measured levels in *Fucus vesiculosus*.

We found detectable levels of I-131 in the seaweed both before and after the decay tank was taken into use. In one case, Lu-177 was measurable above measurable detection activity, providing new knowledge and evidence of uptake by seaweed. Discharges of I-131 were significantly reduced after the decay tank was taken into use. The reduction was however not completely reflected in the seaweed levels of I-131. The levels of I-131 in seaweed after the decay tank was taken into use were higher than expected compared to discharge levels. The identified levels of I-131 in the inner Oslofjord seaweed were also much lower than the levels that have been identified by DSA in seaweed near the city of Tromsø after discharges of radiopharmaceuticals there. We identify differences in hydrology, and in tidal currents in particular, as the main reasons for the differences to the Tromsø levels, as well as for the deviation and higher than expected levels in seaweed after the decay tank was installed.

Future studies are recommended when the use of I-131 exceeds the decay tank capacity and to better assess the dynamics of seaweed uptake rates and half-life.

2 Introduction

2.1 Radiopharmaceutical applications and discharges

In nuclear medicine, Norwegian hospitals use and discharge radionuclides to the environment. Permits for discharges of radionuclides are given by the Norwegian Radiation and Nuclear Safety Authority (DSA) and yearly discharges are reported to DSA. Medically applied radionuclides with long enough half-lives to be significantly excreted by patients (Kurth et al. 2018; Cheen Hoe et al. 2018; Demir et al. 2013; Fakhri et al. 2025; Remy et al. 2008), which still may remain in wastewaters that end up in the ocean, are technetium (Tc-99m, $t_{1/2}=6$ h), iodine (I-131, $t_{1/2}=8$ d), and the rare earth element lutetium (Lu-177, $t_{1/2}=6.7$ d).

In nuclear medicine, radiopharmaceuticals are administered to patients for diagnostic examinations and/or treatment purposes. Compared to diagnostic applications, cancer treatments typically involve higher levels of radioactivity. A radiopharmaceutical consists of a radioactive element (radionuclide), often bound to a carrier molecule. In addition to the physical half-life, a radionuclide has a biological half-life that depends upon whether it is bound to a carrier molecule, where it is taken up in the body and the associated excretion time (Remy et al. 2008; Fakhri et al. 2025; Demir et al. 2013; Kurth et al. 2018; Cheen Hoe et al. 2018). Several different radionuclides and carrier molecules are used depending on their properties. Radiopharmaceuticals are administered orally or by injection, and the radionuclides they contain will end up in the sewer system (unless the sewer is contained or excretion time is long compared to the radionuclide half-life). Subsequently, the sewer system discharges to the environment. In Norway, there is a legal requirement that the amount of activity of each radionuclide administered to each patient should be kept in hospital records. Data on daily administrations can, if accounting for decay before excretion from patients and during sewage transport, be used to estimate the amount of activity discharged and reaching the environment. Such data can be used to assess impacts to the environment over time, as well as levels of exposure and whether there is any potential risk to humans and the environment. Therefore, assessment of the use of radiopharmaceuticals in the hospitals, and subsequent discharges to, and levels in the environment are important, especially since the use of radiopharmaceuticals are expected to increase in the future (Ruus et al. 2023).

2.2 Use of radiopharmaceuticals in Norway

In Norway, 19 hospitals perform nuclear medicine diagnostics, and in total, a stable number of examinations, around 46 000, are carried out each year. Tc-99m is the most used radionuclide in nuclear medicine, being applied in 50% of diagnostic examinations. Oslo Hospitals carried out about 3 260 examinations with Tc-99m in 2025. Up to 60% of Tc-99m is excreted through urine from patients, with a rate (Bq d^{-1}) depending on the applied carrier molecule. Most of the patients are outpatients (not staying in the hospital overnight), so the sewer system receives this input at different locations, depending on the home addresses of the patients.

There are 16 hospitals that use radiopharmaceuticals for therapeutic purposes. In such treatments, I-131 and Lu-177 are commonly used. The number of treatments with radiopharmaceuticals vary annually (Figure 1). I-131 is used at all the 16 hospitals in Norway performing therapeutic practices in nuclear

medicine. About 60% of the treatments in nuclear medicine are undertaken with I-131 and around one third of these are cancer treatments. Around 40% of treatments with I-131 are for hyperthyroidism, but these patients are normally not hospitalized (being outpatients) and thus the location of discharge to the sewer system vary. The activity of I-131 used in cancer treatment is 27% of the total administered activity of radionuclides used in therapy.

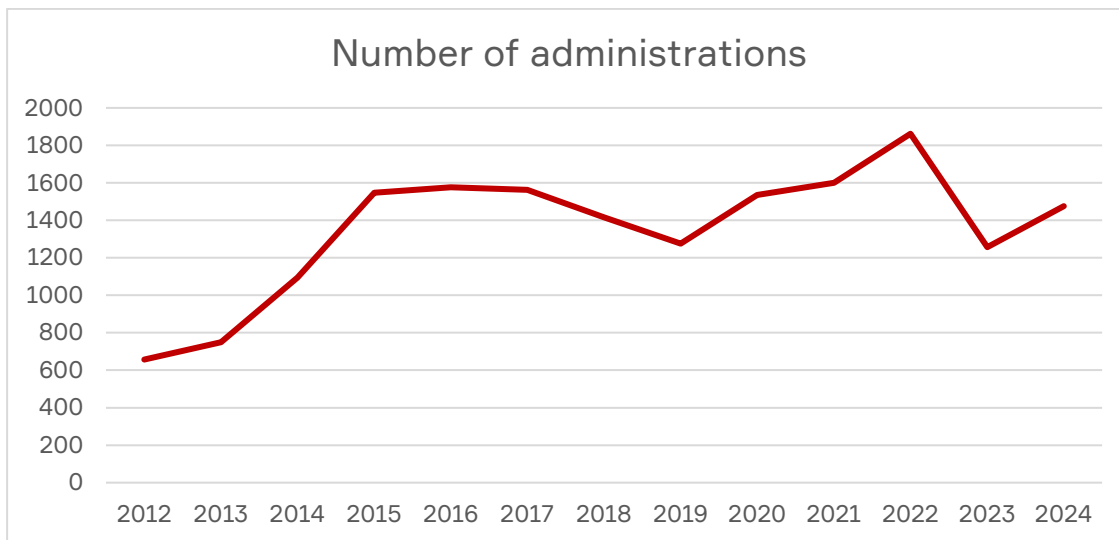


Figure 1 Number of nuclear medicine administrations for therapy in Norway 2012-2024.

Only four Norwegian hospitals use Lu-177. However, the use of Lu-177 is expected to increase drastically in future years due to good clinical results and increased applications in other countries (from the time of writing this report in 2026). About 16% of the treatments were done with Lu-177 in 2024, but the contribution to the total administered activity per year in nuclear medicine therapy was 58%.

Considering all radiopharmaceuticals, about 1 200 GBq of I-131 and 1 700 GBq of Lu-177 was used by Norwegian hospitals to treat patients in nuclear medicine therapy in 2024. The total radioactivity of radiopharmaceuticals used per year has decreased over the last couple of years, contrary to expectations (Figure 2).

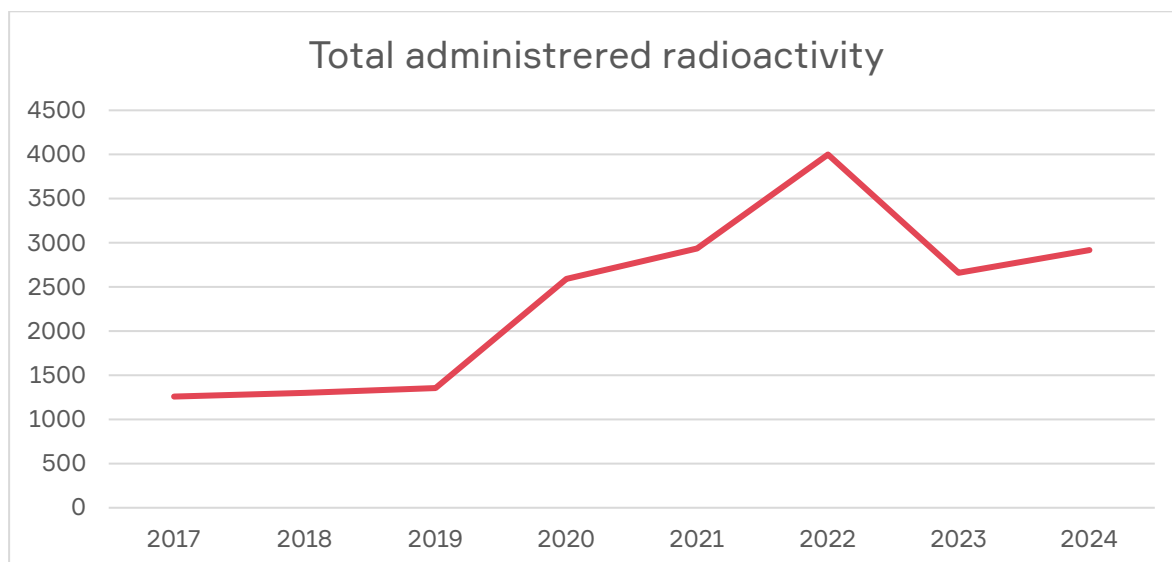


Figure 2 Total administered activity (GBq) administered to patients in nuclear medicine therapy pr year from 2017 to 2025

2.3 Assessments of impacts to the Oslofjord and IAEA collaboration

In 2020, DSA announced a tender for an assessment of levels and risk of radionuclides in radiopharmaceuticals to the environment and biota in the inner Oslofjord. In 2023, a thorough assessment was reported, showing that the discharges of radionuclides I-131 and Lu-177 did not have any significant impact in the inner Oslofjord (Ruus et al. 2023). In this report, no measurements above the minimum detectable activities of I-131 were reported for the brown seaweed *Fucus vesiculosus*. In contrast, as part of DSA's program for monitoring of radioactivity in the marine environment (RAME), a *Fucus vesiculosus* sample from the inner Oslofjord taken during the autumn 2023 contained a measurable level of I-131. This observation provided arguments for continued sampling of seaweed, and a new project was initiated in 2024, constituting the project behind the present report. Moreover, due to the comprehensive amount of data in the earlier report (Ruus et al. 2023) and the known poor ecological status of the system (Ruus et al. 2025; Ruus et al. 2022), the Oslofjord was suggested and chosen as a candidate for assessment and modelling of dispersal, impact, exposure and risk to humans and biota in one of the working groups of the MEREIA program at the International Atomic Energy Agency (IAEA).

The IAEA MEREIA program is the latest in a series of IAEA initiatives to assist countries in applying assessment approaches, conceptual models, mathematical models and data within the context of radiological environmental impact assessment (REIA). The Oslofjord project "Multi stressors in a fjord" was selected in one of the MEREIA working groups (WG5) to assess the effects of ionizing radiation in a multi-stressor scenario, in which radionuclides and other pollutants are discharged into the same environment. Among tasks in this working group was modelling of dispersion in the Oslofjord, assessing risk and uptake, as well as to assess effects from radiopharmaceutical radionuclides in conjunction with other pollutants. DSA has previously provided for MEREIA both data on I-131 measured at the sewer treatment facility Vestfjorden Avløpsselskap (VEAS) in 2006 and 2022 (unpublished data from DSA), as well as data from other Norwegian institutions on the discharges of other pollutants. The present work and forthcoming technical IAEA reports and other peer reviewed papers (in a forthcoming special issue

of Journal of Environmental Radioactivity), use previous data as well as the new hospital data on administered radioactivity of I-131 and Lu-177 and seaweed data used in the present study. For a citation of the radionuclide data presented in the present study, the present report can be cited.

2.4 Discharges to the Oslofjord and instalment of a decay tank

Many pollutants have, over a long time, been discharged into and had a large impact on Oslofjord. Due to subsequent levels in seawater, sediments and biota, Oslofjord has over time been in a poor ecological state (Ruus et al. 2025). As pointed out in the previous chapter, this was the reason for the initiative with the MEREIA programme. The MEREIA studies show that, compared to I-131, the levels of heavy metals like chromium (Cr) and mercury (Hg) in the Oslofjord have higher impacts and effects in people and biota, respectively (Blanchardon et al. 2026; Vives i Batlle et al. 2026b; Vives i Batlle et al. 2026a).

In the national regulations of radionuclides, there is a legal requirement to use the best available technology (BAT) to minimise discharges. Thus, in addition to the focus on assessment of discharges of radiopharmaceuticals, there has also been a focus on how to reduce these discharges. In collaboration with DSA, Oslo University hospital (OUS) therefore planned, in connection with the building of a new clinic at Radiumhospitalet, a containment decay tank as a sewage receptacle for I-131. The decay tank was taken into use the first week of October in 2024. The result was that radiopharmaceuticals that previously discharged directly into the sewer were instead retained in this decay tank to reduce radioactivity in the wastewater before being discharged into the sewer. The decay tank has three compartments. The first one is filled and its radioactivity decays while the second chamber fills up. When the third chamber is filling, the first chamber needs to be emptied. In 2025, the use of this decay tank involved practically zero activity being discharged from Radiumhospitalet (first emptied 28/5 2025). We have assessed the amounts of radioactivity administered at the Oslo hospitals over the last five years (2021-2025), and have estimated the subsequent discharges of I-131 and Lu-177 and their cumulative levels at the discharge point in the inner Oslofjord, as well as measuring the actual levels of these radionuclides in *Fucus vesiculosus*, both before and after the decay tank was taken into use. In the discharge estimates, the administrations at Radiumhospitalet, after the decay tank was taken into use, are not included (i.e. after October 2024).

2.5 Oslo sewage system and Oslofjord hydrology

The capital of Norway, Oslo, is a municipality, that had 760 000 inhabitants in 2025. Adjacent areas around the inner Oslofjord, called "The Greater Oslo region" consists of 31 municipalities, are rich in settlements and infrastructure, and had around 1.75 million inhabitants in 2025. VEAS is Norway's largest wastewater treatment plant and treats sewage water originating from Oslo, and nearby municipalities. This wastewater corresponds to about 900 000 person equivalents and includes wastewater from the two assessed hospitals. Annually, the plant produces approximately 110 million m³ of treated sewage water (www.veas.no). In 2024, VEAS received from 2 300 to 2 700 L s⁻¹ in periods with no precipitation. It takes around 8 hours for the wastewater from the two assessed hospitals to reach and go through VEAS before being discharged in the inner Oslofjord (Ruus et al. 2023). The VEAS discharge point (59.79287N, 10.515976E) consists of diffuser tubes that are 75 meters long with 153 holes, which are situated at the bottom from 23 to 55 meters depth around 800 meters from shore

(Staalstrom et al. 2024). The seaweed sampling points used in the present study were set north and south of the discharge point (Figure 3). The sewer system to VEAS also has a couple of excess drain pipes for flooding situations, one of which discharges at 25 meters depth at the most inner part of the Oslofjord, and, when water escapes through this pipe, discharges disperse as a large volume plume all the way to the surface (Staalstrom et al. 2024).

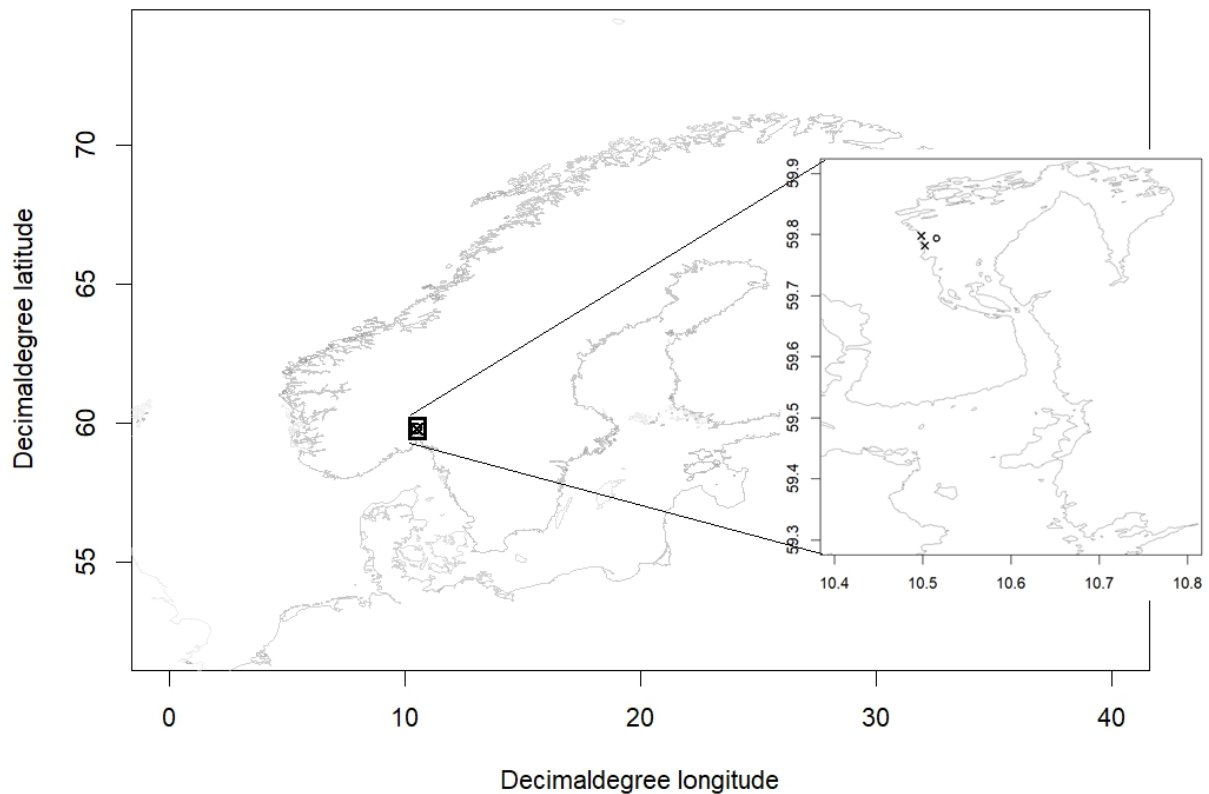


Figure 3 Study area, with discharge point (circle) and sampling points (x) of the brown seaweed *Fucus vesiculosus* in the inner Oslofjord.

The Oslofjord is an estuary with several basins and a shallow sill at Drøbakssundet (Staalstrom et al. 2023a). Circulation is complex and mainly driven by freshwater riverine run-off affected by tidal action. Exchange of seawater across the sill is limited and bottom waters are poor in oxygen (Staalstrom et al. 2023b). This has led to moderate to poor ecological conditions (Staalstrom et al. 2023a).

2.6 Seaweed uptake and measurable levels of I-131

For I-131, brown seaweed of the genus *Fucus* has a fast uptake of iodine with excretion and a biological half-life of around 5 days (Fievet et al. 2023). The uptake rate increases with seawater radionuclide content in a hyperbolic fashion (Nitschke et al. 2018). *Fucus vesiculosus*, called bladder wrack, is easily accessible in the tidal zone and an excellent indicator of pollutants like I-131 taken up by the seaweed. For example, after the Chernobyl accident, levels up to 5 Bq kg⁻¹ wet weight (ww) of I-131 were measured

in *Fucus sp.* in the US and Canada while levels as high as 30 Bq kg⁻¹ ww were measured in Sweden (Druehl et al. 1988). In a recent study on the marine impact of radiopharmaceuticals in northern Norway, near the University hospital of Northern Norway (UNN) in Tromsø, levels of I-131 in *Fucus vesiculosus* ranged from a few to almost 400 Bq kg⁻¹ ww, which with 80% water content would correspond to up to 2 000 Bq per kilogram dry weight (dw). These levels were ascribed to and co-varied with the discharges from the hospital and with magnitudes probably varying according to tidal cycle and stream direction (Gwynn and Jensen 2019). In other areas, such as Swedish waters, I-131 is only occasionally measurable in *Fucus vesiculosus*, and then ranging from 0.5 to 5 Bq kg⁻¹ dw (Mattsson et al. 2022). Levels in other species of seaweed, have, after uptake of I-131 discharged from hospitals in Australia, been recorded to be 0.5 to 38 Bq kg⁻¹ ww for the genus *Ulva* and 5 to 70 Bq kg⁻¹ ww for kelp (Veliscek Carolan et al. 2011).

It has been documented that rare earth elements (REE), such as lutetium, are taken up from seawater by algae and, in particular, by brown seaweed (Ryabushko et al. 2022), leading to the suggestion that they may be used as indicators for REE (Squadrone et al. 2017). Any studies on uptake of Lu-177 are not known to us, and we therefore have included analyses of this radionuclide in *Fucus vesiculosus* in the present study.

The amount of stable iodine can be high in brown seaweed like *Fucus vesiculosus*, and like I-131, it may pose a risk with consumption of brown seaweed. In Europe and the Nordic countries, the consumption of seaweed is limited compared to in Asia, even though there is little data available (Hogstad et al. 2022). However, in northern Norway, one assessment shows that some people often consume brown seaweed (Hustad 2022). Also, in France consumption of brown seaweed is high in some places, and due to toxicity from uptake of pollutants, risks from that consumption have been assessed (Ficheux et al. 2022).

2.7 Aims and objectives

In this study, we assess I-131 administered to patients at two hospitals in Oslo, and Lu-177 administered at one of these. We estimate the activity of the associated discharges from these hospitals to the sewer system and the VEAS treatment plant, before and after the installation of a decay containment tank at one of the hospitals in the autumn of 2024. We received data on the radioactivity of daily administered I-131 and Lu-177 over a period of five years, and by accounting for decay before excretion and during time in the sewer system, we estimate the activity of discharges from these hospitals and the subsequent cumulative level of radioactivity at the discharge point, accounting also for decay after the discharge. We address whether these cumulative levels result in any measurable levels in the brown intertidal seaweed, *Fucus vesiculosus*, to assess the impact of these discharges to the inner Oslofjord. We assess seaweed at two locations close to the VEAS discharge point in the inner Oslofjord, before and after the decay containment tank was taken into use. We initially assumed that the introduction of the decay tank would lead to levels that were not measurable in seaweed, but here we present surprising results in this regard.

To carry out this study, DSA organized a project. The project is called TANGSPILL and has had a dual role to improve the practice of nuclear safety preparedness at DSA through planning, taking and analysing samples of seaweed for radionuclides otherwise not monitored, as well as through increasing collaboration and interactions among different sections at DSA.

3 Methods

3.1 Data: administered radioactivity, discharges and seaweed levels

To assess the discharges from the hospitals in the Oslo region we assessed I-131 from Radiumhospitalet (59.930584N, 10.662284E) and I-131 and Lu-177 from Rikshospitalet (59.947780N, 10.715340E)(also part of Oslo University Hospital), using data on daily administered radioactivity kindly provided by these hospitals. The data was provided to address impact to the inner Oslofjord and be able to assess exposure and risk to the public and biota, in order to achieve an optimised and knowledge-based management. Since the discharges go into the sewer system, we have also sampled seaweed at two locations near the sewer discharge point from the VEAS treatment plant to assess whether the activity concentrations in the sea from the discharges are high enough to be detected after seaweed uptake. Data on Tc-99m were requested but could not be provided, as such data are not stored in a digitally accessible format that allows practical extraction at daily resolution over many years. Tc-99m administration and estimated discharges are therefore not a part of this report.

For I-131 and Lu-177, the radioactivity administered to patients was, for each of these radionuclides, summed per treatment day per hospital. To estimate the discharge to the sewer system of each radionuclide at each hospital, we accounted for residence time and decay within the human body until excretion. For radioiodine (RAI), humans excrete around half of the administered I-131 activity the first day and around 90 % of the remaining I-131 activity the second day (Cheen Hoe et al. 2018; Demir et al. 2013; Remy et al. 2008). For simplicity in calculations, we assume half is excreted when passing 24 hours and all is excreted when passing 48 hours. For Lu-177 bound to the carrier molecule PSMA-617, it has been shown that approximately half of the administered activity is excreted from the human body within 4 hours (Kurth et al. 2018). This carrier molecule (PSMA) is used in Lu-177 treatments in Norway, even though another carrier molecule (dotatate) is more commonly used in Norway. Not having information about the excretion of that carrier molecule, we assume that half of Lu-177 is excreted after 4 hours and all is excreted when passing 8 hours. To estimate the amount of activity that is discharged at the discharge point of each of the radionuclides, we accounted also for decay during the transport time for wastewater from the hospital sewer through the sewer system to VEAS, which is around 8 hours (Ruus et al. 2023), and summed discharges each calendar day. The estimated cumulative activity of each radionuclide at the discharge point was found by summing the estimated activity of daily discharges to the discharge point from each hospital over days while accounting for decay. For Lu-177, this was only done for Rikshospitalet (which is the only one of these hospitals using Lu-177). Note also, that in the estimated cumulative activity at the discharge point, discharges from Radiumhospitalet are not included from October 2024 when the containment decay tank was taken into use. Dilution at the discharge point is probably complex, but unknown, and therefore uptake rates of seaweed are not calculated. We do however compare the estimated cumulative levels in seawater at the discharge point with the measured levels in the sampled *Fucus vesiculosus* for each day that seaweed was sampled. In addition, we also assess the same ratio using the eight and 16 days rolling averages for the estimated cumulative I-131 activity at the discharge point to account for uptake over a longer period than just that day.

3.2 Sampling of seaweed from the Oslofjord

The brown seaweed *Fucus vesiculosus* was sampled in 2023, 2024 and 2025. The first sample was taken at the location Sjøstrand in October 2023 without any knowledge about timing and magnitude of discharges. The 2023 sampling was conducted as part of the Norwegian monitoring program of radioactivity in the marine environment (RAME), but I-131 was also assessed to verify the non-measurable levels reported for the inner Oslofjord and to double-check whether I-131 was measurable at a random time (above measurable detection level, MDA). Since the I-131 level in our 2023 seaweed sample actually was measurable, we performed seaweed sampling in 2024 and 2025 at two locations. A map to show this was made in R (R Core Team 2016) using package SF (Pebesma and Bivand 2023) on downloaded map data for world coastlines (ne-coastlines-10m/ne_10m_coastline from github) and EU coastlines (ETRS89 in the EPSG: 3035 from <https://epsg.io/3035>). These locations were Sjøstrand (the same as in 2023) and Slemmestad (Figure 3). Sjøstrand (59.7975N, 10.4983E) is located just north of VEAS' discharge point in Asker municipality (59.79287N, 10.515976E), and Slemmestad (59.7813N, 10.5023E) just south of the discharge point. For each sampling day in 2024 and 2025, both locations were sampled subsequently, during the best available low tide during working hours. In 2024, sampling dates were March 4th, 6th, 11th, 13th, 18th, 20th and 25th. In 2025, sampling dates were June 3rd, 4th and 5th. We planned sampling in 2024 and 2025 according to information from the hospitals about the timing and magnitude of planned treatments and discharges. Lu-177 is administered on Tuesdays and Thursdays, but since it was I-131 that was detected in the monitoring sample, we designed sampling for I-131. With I-131 treatment of patients often occurring on Fridays and due to the need of immediate gamma spectrometry that involves at least one day with follow-up, sampling of seaweed was mostly undertaken on Mondays and Wednesdays. The 2024 sampling campaign was performed to assess impact from discharges before instalment of the decay tank, while the 2025 sampling campaign was performed to show the anticipated zero impact expected after instalment of the decay containment tank at the new facility at Radiumhospitalet (assuming all patients would be treated at that same facility).

Sampling of seaweed was performed at hours during or close to low tide, to be able to have an easy access to the seaweed. Seaweed of the species *Fucus vesiculosus* was sampled in all cases. Sampling was performed in the lower part of the tidal zone of seaweed preferably submerged in seawater. This was done to approximate a similar content of water in the seaweed. Seaweed loses water rapidly and including samples from high in the tidal zone may therefore involve large variation in water content among samples. Since *Fucus vesiculosus* consists of about 75-80% H₂O, we collected around 1 000 – 2 000 grams (wet weight) for each sample. Such large samples were taken to increase the chances of being able to detect I-131 and Lu-177 in the samples, aiming to attain dry weight samples of 100-200 grams. Samples were kept in low-density polyethylene plastic bags. When the bags were full, the samplers would turn the bag upside down for a few seconds to empty excess water following the sample. Wet weight was registered immediately upon return to the laboratory at DSA.

3.3 Labwork and analyses

To be able to perform analyses before too much I-131 had decayed, all samples were treated at the laboratory at DSA location Østerås immediately after returning the same day as sampling was performed. Initially in the project, one wet sample was analysed on the largest box (geometry) available

for gamma spectrometry and another seaweed sample was dried, weighed and then measured. It turned out that the up-concentration of I-131 activity concentration by loss of water from the dried sample involved a higher and more accurately detectable activity concentration than the measured activity concentration in the wet sample. However, it should be noted that loss of I-131 during a drying process has been proposed (Gwynn and Jensen 2019). The wet sample had an activity of 0.08 Bq per kg of wet weight seaweed and the dry sample, after accounting for decay, had an activity of 0.4 Bq per kg dry weight seaweed, which is approximately the ratio between wet and dry that is expected. Therefore, all subsequently taken seaweed samples were dried before gamma spectrometry. The seaweed samples were dried at 80 °C for 24 hours in a Termaks TS9430 before the samples were milled and homogenized using a Retsch Grindomix Gm200 220-240V.

Immediately after the 24h drying process and the subsequent milling for homogenisation of each sample, the material was transferred to and weighed in a W2-geometry, produced by the Leomuovi Group in Finland. The diameter of this geometry is 7.2 cm and the height is 2.6 cm, giving a total volume of 110.3 cm³. The scales that were used for weighing were Mettler BB2440 Deltarange and Sartorius ED4202S-CW. These scales were both calibrated 31st of January 2024 by Mettler Toledo, and the performance of the accuracy of these scales have been re-verified and recorded each of the following days when the scales have been used.

Gamma spectrometry was used to assess seaweed levels of I-131 and Lu-177, using High Purity Germanium-detectors (HPGe), which provide high resolution spectra of gamma-emitting radionuclides. All the detectors are equipped with a shield of 5 cm thick layer of aged lead (Pb). The detectors are situated in a separate and isolated room with 0.5 meters thick concrete to ensure a low background radioactivity from natural radioactivity. The samples were measured for approximately 24 hours in this low-background gamma spectrometry laboratory at DSA location Østerås. These HPGe detectors are calibrated regarding efficiency with a multi-nuclide standard solution from National Physical Laboratory (NPL).

Gamma photons with energies from 40 to 3000 keV that collide with the detector crystal are counted. The photons from the analyte constitute the basis of the calculated activity, which is found by accounting also for background radiation photons. These gamma spectra from the HPGe analyses were collected with Ortec Maestro and analysed using an in-house analysis software called Gamma 10. The script automatically searches for peaks in the energy spectrum, uses the integral of counts in the peak area, and subtracts the background from the integral. The script then searches in the library to check whether any radionuclides can be identified to fit each peak, and examines whether several peaks originate from the same nuclide. For radionuclides with several peaks, the integrals of several peaks are in some instances used in a weighting method between peaks to account for different contributions to the activity concentration of the associated radionuclide.

The laboratory at DSA location Østerås is accredited after ISO 17025:2017 organised by the Norwegian Accreditation institution for analysing samples with HPGe in matrices between 0.5-2.0 g/cm³ for gamma emitting radionuclides with photo peaks with energies between 100 – 1 800 keV. The by far most prominent gamma line of I-131 is 364.5 keV, with 81.5% intensity. The most prominent gamma line of Lu-177 is 208.3 keV. Each analysis of I-131 was accredited if the sample mass was between 55.15 and 220.60

grams. Due to significance in counting numbers of only two Lu-177 samples, we included both these in the results, even though one of these was slightly below MDA.

Based on the net count rate in the respective gamma emission-lines of the analytes, the efficiency calibration, the density and the mass of the sample, the activity of the nuclides are calculated. The uncertainty of the analysis is calculated in the software Gamma 10, which uses the GUM methodology to combine the different sources of uncertainty. The dominant sources to the combined uncertainty in the analysis are the counting statistics in the detector, coincidence summing corrections, efficiency calibration, the fill-height corrections and the peak fitting. Reported uncertainties from gamma spectroscopy represent combined standard uncertainties with a coverage factor of $k=2$ (two standard deviations).

4 Results & discussion

4.1 Amounts of I-131 and Lu-177 used at the Oslo hospitals

The data on the use of radiopharmaceuticals in this report are from January 2021 until March 6 in 2026. For this period, 583 administrations of I-131 were performed at Radiumhospitalet and 499 administrations of I-131 and 529 administrations of Lu-177 at Rikshospitalet. These administrations were for Radiumhospitalet given on 254 of the days in this period and at Rikshospitalet on 328 and 306 days in this period for I-131 and Lu-177, respectively. Combined for both hospitals, administrations of I-131 were given on 424 days in the whole period, or around 1/5 of the days in the period.

Among days with administrations to patients, the daily sum of radioactivity from I-131 at Radiumhospitalet ranged from 1 000 to 27 700 MBq (mean: 9 100, median: 10 600, SD: 5 000). The corresponding daily sum of I-131 administered at Rikshospitalet in the same period ranged from 210 to 7 100 MBq (mean: 2 200, median: 1 100, SD: 1 800). By comparison, during the seaweed campaign in Northern Norway to assess radiopharmaceutical marine impact, the daily discharge levels prior to seaweed sampling were comparable to lower in activity (4 000 and 6000 MBq). Comparing yearly discharges, the discharge from UNN in Tromsø in 2017 was 106 GBq of I-131 (Gwynn and Jensen 2019), which is around one fifth of the yearly sum of I-131 at the two Oslo hospitals from 2021 to 2025 (Table 1). Between the two Oslo hospitals, the monthly sums of administered radioactivity were higher and often more than twice as large at Radiumhospitalet compared to those at Rikshospitalet (Figure 4). The reason is related to these hospitals having different numbers and types of patients, perform different kinds of cancer treatments, leading to different administered activities. Contrary to the expectation of an increasing use of radiopharmaceuticals, the use of I-131 over months and years was decreasing at both hospitals (Figure 4, Table 1).

Table 1 Yearly sum of radioactivity (MBq) of administered I-131 at the two hospitals.

Hospital/Year	2021	2022	2023	2024	2025
Radiumhospitalet	511 400	482 500	493 000	396 900	362 100
Rikshospitalet	188 700	138 100	134 700	150 100	108 600

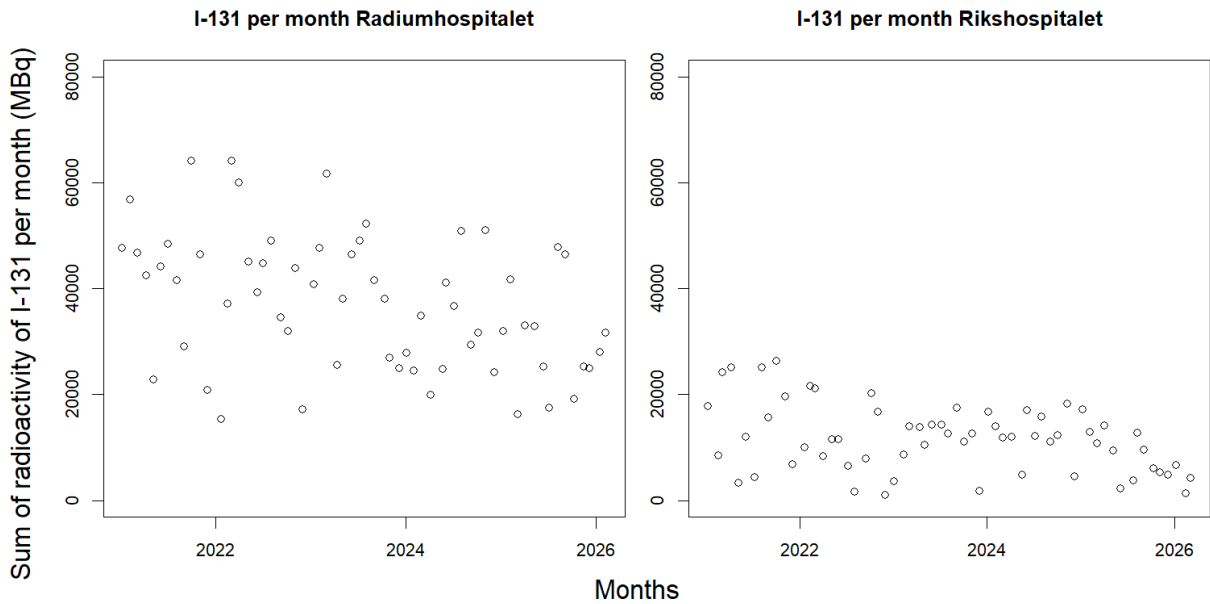


Figure 4 Sum of radioactivity of I-131 (MBq per month) administered to patients.

Among days with administration to patients, the daily sum of radioactivity from Lu-177 from 2021 to February 2026 at Rikshospitalet ranged from 4 500 to 15 500 MBq (mean: 12 600, median: 14 600, SD: 3 300). Contrary to I-131, the use of Lu-177 at Rikshospitalet has been relatively stable (Figure 5), with some yearly variation (Table 2). Note that these discharges are not affected by the decay containment tank (at Radiumhospitalet).

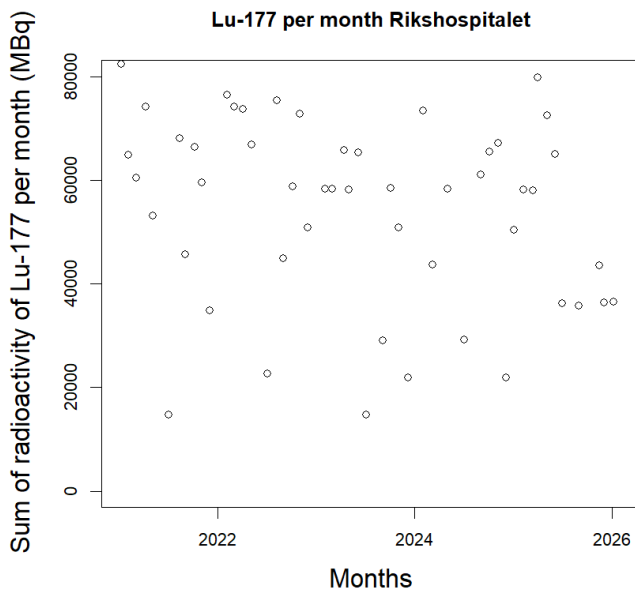


Figure 5 Sum of radioactivity of Lu-177 (MBq per month) administered to patients.

Table 2 Yearly sum of radioactivity of administered Lu-177 at Rikshospitalet.

Hospital/Year	2021	2022	2023	2024	2025
Rikshospitalet	714 400	804 000	668 900	813 300	723 300

4.2 Discharges of I-131 and Lu-177 from the Oslo hospitals

Accounting for decay before excretion and during transport through the sewer system, the estimated activity of daily discharges of I-131 (on days with a discharge, summed for both hospitals) to the Oslofjord ranged from 120 to 13 700 MBq d⁻¹ (mean: 3 300, median: 2 200, SD: 2 900) during the period January 2021 to February 2026. Note that discharges from Radiumhospitalet are not included in these discharge estimates after the first week of October 2024 when the containment decay tank was taken into use, since no discharges from Radiumhospitalet, after this time, went directly to the sewer (having been retained in the tank). The subsequent cumulative radioactivity of I-131 over time at the discharge point ranged from 89 to 37 900 MBq (mean: 13 700, median: 14 600, SD: 8 600, Figure 6) when accounting for decay at the discharge point. We have not considered activity concentrations or further fate of radionuclides due to lack of knowledge about dilution in seawater or transport with ocean currents. Due to the short half-life of I-131, the estimated cumulative activity oscillates from high levels rapidly towards low levels until the next discharge. Also, a decreasing trend in cumulative radioactivity of I-131 is apparent in this plot prior to autumn 2024 but the main downward break in the plot is after the decay containment tank came into use, during the first week of October 2024, and I-131 discharges from the Radiumhospitalet came to a stop.

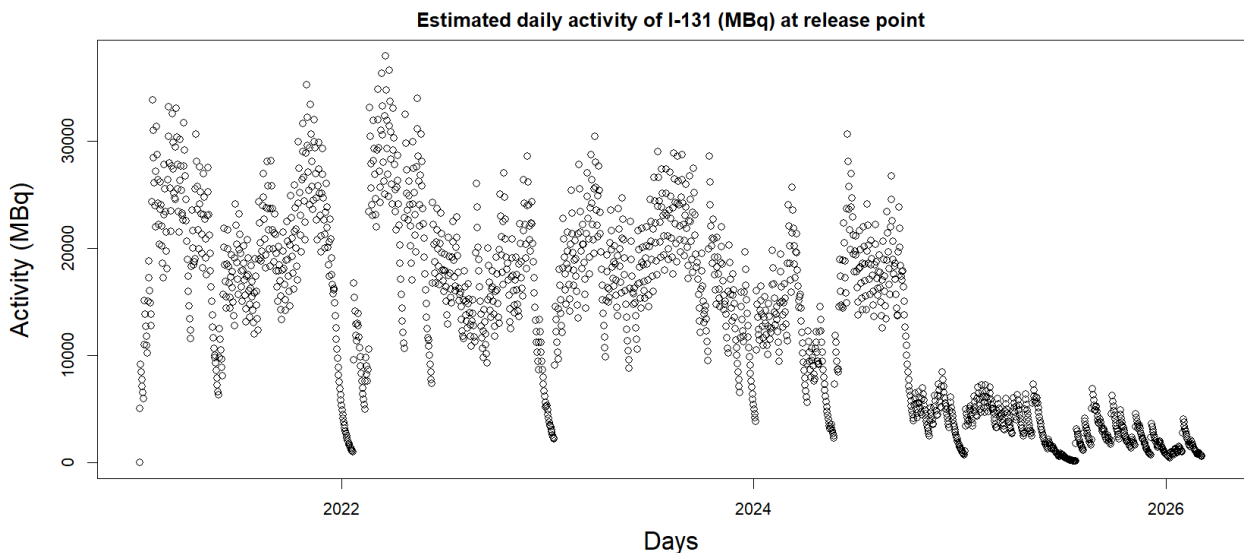


Figure 6 Estimated daily cumulative activity (MBq) of I-131 accounting for decay at discharge point in the inner Oslofjord, from both hospitals. NOTE that discharges from Radiumhospitalet are not included after first week of October 2024 when containment decay tank was taken into use.

For Lu-177, when accounting for decay before excretion and during sewer transport, the estimated daily discharges at the discharge point (on days with a discharge) to the Oslofjord during the assessed period ranged from 2 100 to 14 400 MBq d⁻¹ (mean: 6 000, median: 6 900, SD: 1 700). The estimated cumulative activity at the discharge point ranged from 390 to 43 100 MBq (mean: 18 500, median: 18 400, SD: 8 700), when accounting for decay over time. The level of cumulative activity of Lu-177 is also oscillating due to the short half-life but without any other apparent trend over time (Figure 7). Maximum levels are somewhat higher than for I-131 (Figure 6), and especially higher than I-131 after the decay tank became operational (since Lu-177 is discharged only from Rikshospitalet and not held back by the decay tank).

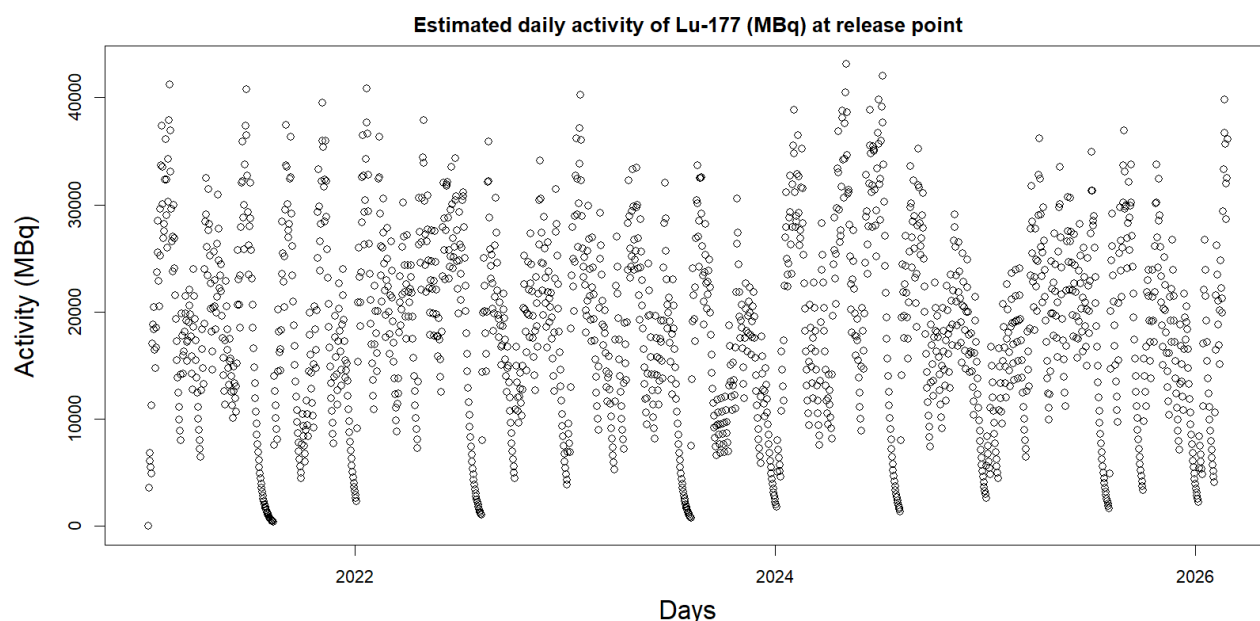


Figure 7 Estimated daily cumulative activity (MBq) of Lu-177 at discharge point in the inner Oslofjord, from Rikshospitalet only, accounting for decay from the time when the radiopharmaceutical was administered to patient to when radionuclides enter the sewer, and accounting for decay during time in sewer system and when accumulating at discharge point.

4.3 Seaweed levels of I-131 and Lu-177 near the discharge point

Among the assessed seaweed samples from the inner Oslofjord, we found low but detectable levels of radionuclides from radiopharmaceuticals in *Fucus vesiculosus* with up to 9 Bq kg⁻¹ dry weight of I-131 and up to 1.9 Bq kg⁻¹ dry weight of Lu-177 (Table 3). These findings comprise new information on measurability and magnitude of seaweed levels compared to the non-detectable levels previously reported for these radionuclides in seaweed in this area of the inner Oslofjord (Ruus et al. 2023). For Lu-177, this is the first recorded seaweed uptake that we know of.

Table 3 Ranges (min-max), mean, median and standard deviation (SD) of the level (Bq kg⁻¹ dw) of radionuclides (Nuclide) in seaweed samples (n=number of samples) from the inner part of the Oslofjord.

Nuclide	n	Min	Max	Mean	Median
I-131	21	0.42	9.0	4.8	4.9
Lu-177	2	1.7*	1.9		

* slightly below MDA

Prior to the project, after having found a measurable amount of I-131 in the seaweed sample from the marine monitoring program (RAME), we planned and executed the assessment of the present study to verify and quantify the measurability of I-131 (and Lu-177) in *Fucus vesiculosus* at the two locations near the discharge point in the Oslofjord before and after instalment of the decay containment tank. The level of I-131 was measurable in all the subsequently sampled seaweed (Table 2), surprisingly so also after the decay containment tank was taken into use. During the design of the project, we originally expected all patients treated with I-131 to occupy the new isolation unit at Radiumhospitalet where the decay containment tank came into use in October 2024, and thus we originally expected zero levels in seaweed in 2025. However, with continued discharges of I-131 (and Lu-177) from Rikshospitalet, there was still measurable levels in seaweed in June 2025. The levels of I-131 in seaweed in 2025 were, though, in a Student t-test, significantly lower ($t=5.5$, $df=18$, $p<0.001$) than in the 2024 seaweed (Figure 8). The project has thus been able to show that using a decay containment tank at Radiumhospitalet resulted in lower levels of I-131 in the seaweed *Fucus vesiculosus* near the discharge point in the Oslofjord. By comparison, the level in the seaweed recorded in 2023 was much lower (Figure 8). The highest level was measured at the location Slemmestad in 2024 (outlier value), but there was no statistically significant difference between the two sampled locations in a pairwise t-test by date in the level of I-131 in seaweed ($t< -0.96$, $df = 9$, $p> 0.36$).

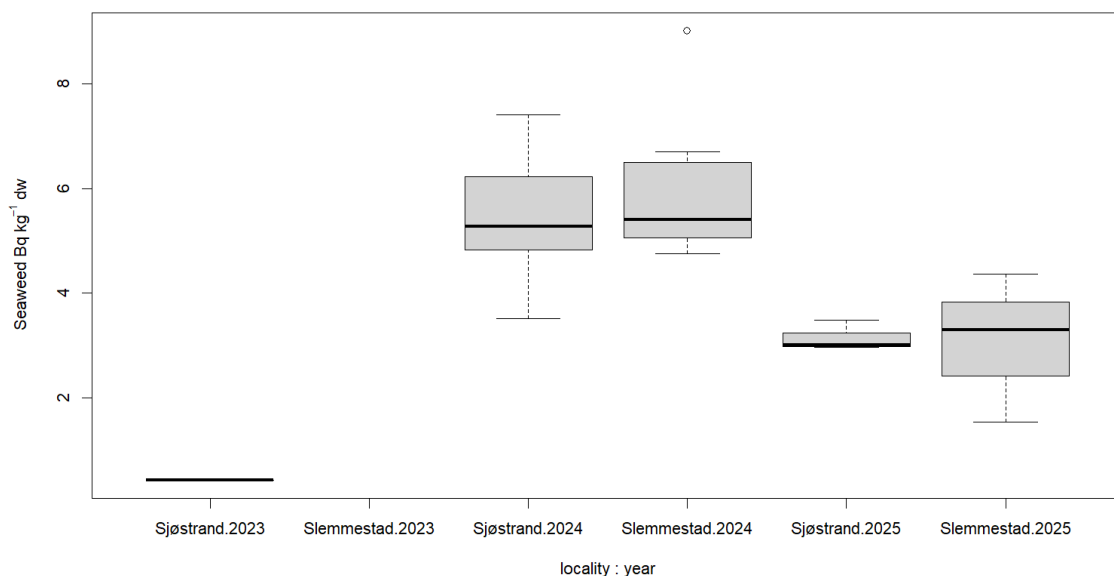


Figure 8 Levels of I-131 in seaweed sampled at two locations nearby the discharge point by year.

If the seaweed levels of I-131 are compared with the estimated cumulative activity at the discharge point, reductions in both estimated cumulative activity and seaweed levels of I-131 at the discharge point from spring 2024 to summer 2025 are obvious (Figure 9). However, the magnitude of difference between spring 2024 and summer 2025 is larger for the estimated cumulative discharged activity than the magnitude of the difference in seaweed I-131 levels between these periods. A comparison of the ratio between estimated cumulative activity and measured seaweed levels on the sampling days, shows that the ratio in 2024 ranged from being 2 100 to 5 800 times higher for cumulative activity versus seaweed

(mean: 3500, median: 3400, SD: 950) while in 2025 the ratio ranged from 290 to 550 (mean: 440, median: 460, SD: 93). This ratio is in a t-test significantly higher in 2024 than in 2025 ($t=12$, $df=14$, $p<0.001$), suggesting that the *Fucus vesiculosus* seaweed levels in 2025 were much higher compared to the estimated cumulative activity than it was in 2024. Applying an eight-day or 16-day rolling average of the estimated cumulative activity of I-131 at the discharge point involve somewhat higher ratios for 2025 (400-1 100), but these are still lower than when the corresponding ratios are calculated for 2024 (1 800-5 800). Therefore, there is a higher proportion of I-131 activity in the seaweed in 2025 than in 2024 when comparing with these estimates of cumulative I-131 activity at the discharge point.

Moreover, the ratio is even higher in 2023, ranging from 2100 to 62 000 times higher estimated cumulative activity than compared to what was measured for seaweed as $Bq\ kg^{-1}\ dw$ (Figure 9). We must however highlight that these ratios are no measures of uptake, since the cumulative value is estimated at the discharge point with no dilution and without accounting for currents directions and velocities.

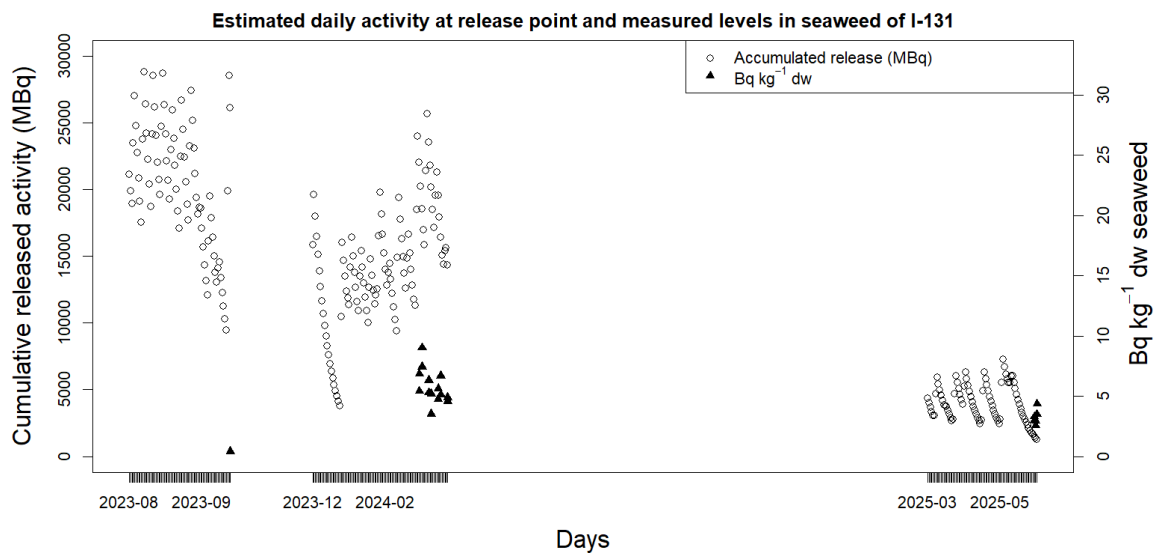


Figure 9 Plot of cumulative daily activity of I-131 at the discharge point after correcting for decay (left y-axis) in periods prior to and during sampling of seaweed (ten half-lives ahead) and seaweed levels of I-131 near the discharge point ($Bq\ kg^{-1}\ dw$ on secondary y-axis). Note that the third period in 2025 exclusively pertains to discharges from Rikshospitalet.

For Lu-177, all except one ($n=19$) of the measurements of Lu-177 were below a measurable minimum detectable activity (MDA). The MDA ranged from 1.3 to 2.8 $Bq\ kg^{-1}\ dw$, and we included a result of 1.7 $Bq\ kg^{-1}\ dw$ for one sample with significant counting numbers that was slightly below the MDA of 1.8 $Bq\ kg^{-1}\ dw$. The only sample above MDA was for Lu-177 at 1.9 $Bq\ kg^{-1}\ dw$. It does however constitute the only reported case of seaweed uptake of Lu-177 that we know of. Both reported samples (one above MDA and the other below) are from Slemmestad on March 11th and 18th in 2024. It is conspicuous that detectability of Lu-177 occurred the same year as we found the highest I-131 levels in seaweed. The ratio between estimated cumulative activity at the discharge point and the level in seaweed was either 5 000 or 9 500 times higher when using the estimate of cumulative activity from the seaweed sampling day, and using rolling averages increased the lower and reduced the higher estimate.

There are various possible reasons for the differences in seaweed levels between the sampled years in this project. Hydrological explanations seem most probable. First, during a tidal cycle, the tidal wave in the northern hemisphere due to the Coriolis effect, travels along the right side of an estuary (Mann and Lazier 2005), the Oslofjord in this case. During the rise and fall of the tide, currents often vary in velocity and direction. Such variations may have affected the transport from the discharge point to the sampling locations differently between the three different campaigns and this may have led to differences in the levels of I-131 in the seawater at these locations compared to what was discharged at the discharge point.

For example, if currents ran a different way or at slower velocities during one campaign, obviously the levels at the sampling localities would turn out different, even with the same discharge at the discharge point. This may again explain the differences in the seaweed between campaigns. With a biological half-life of five days of I-131 (Fiévet et al. 2021), the seaweed level of I-131 will result from uptake over several tidal cycles. In 2023, seaweed was only sampled at one point on one day. However, in 2024, we had sampling of seaweed on seven days across three weeks, which should incorporate any variation within tidal cycles and across a whole tidal moon cycle. For the three subsequent days in 2025, this may not be the case.

The tidal cycle only shifts by 50 minutes in periodicity per day and the variability in current velocities and directions may be different during a three-day window compared to other parts of a whole tidal moon cycle (around one month). Thus, any differences in currents during the whole tidal moon cycle may involve water from the discharge point ending up at different locations. The three subsequent days of seaweed sampling in 2025 may therefore not be representative of the whole tidal moon cycle. We believe that different tidal actions on hydrology constitute the best possible explanation for the higher-than-expected seaweed levels of I-131 in 2025 compared to the two other years. Similarly for 2023, oceanographic conditions in advance of the single sampling may involve differences compared to during other parts of a tidal cycle, while 2024 seaweed, with all its sampling days, probably gives the best integrative level in seaweed.

Another possible hydrological explanation is that the three sampling campaigns were done during different seasons and that variability in our data is due to seasonal differences. For example, from different degrees of ocean stratification, different degrees of precipitation and runoff or other varying atmospheric influences. For ocean stratification, this occurs in the sea during spring, from march and onwards, when a warmer and less saline surface layer with less density creates a vertical stratification where the spring bloom of phytoplankton typically occurs (Mann and Lazier 2005). Such stratification could affect vertical transport from the discharge point towards the surface (where seaweed is located). However, in such a case, the pattern of seaweed levels of I-131 should have been the opposite compared to what was observed among the sampled years (October in 2023, march in 2024 and June in 2025). Considering seasonal differences in amounts of precipitation and runoff, the differences in seaweed levels could have been explained by estuarine runoff. In an estuary, riverine input typically creates a fresher and less dense surface layer that flows outwards along the estuary (Mann and Lazier 2005). With expectations of more precipitation and runoff in the autumn, that could have been a good explanation, had it not been for the especially dry October in 2023 with only 1/3 of the amount of precipitation that was seen most of the years 2021-2026, and which was half of March 2024 and June 2025 precipitation, the two being similar (<https://seklima.met.no/observations/>).

Another factor that may have contributed to the differences in seaweed levels is if sampling of seaweed was done at different times or places in the tidal zone. We consistently tried to time our sampling with the low tide of the sampling day, so that should not be an affecting factor. However, among the samplers, there might be a bias in where in the tidal zone samples were taken. An argument against this having an effect, is that there was no systematic bias in who did sampling among the different sampling campaigns, even though we cannot disregard the contention that there may be some effect of this factor.

Other factors that may contribute are uncertainties in the measurement. However, given the large differences in both estimated cumulative activity and the differences in seaweed I-131 activities, this seems unlikely to be the most important reason.

Compared to levels of I-131 in *Fucus vesiculosus* elsewhere, the levels found in the inner Oslofjord are relatively low. The seaweed campaign in Tromsø had *Fucus vesiculosus* levels ranging from a few to almost 400 Bq per kilo wet weight (Gwynn and Jensen 2019), which, with 80% water content, would correspond to up to 2 000 Bq per kilo dry weight. These levels are much higher than the levels found in the present study.

Moreover, the highest of the Tromsø seaweed levels are more than ten times higher than recorded in Swedish waters right after the Chernobyl accident (Druehl et al. 1988). By comparison, after the Fukushima accident, levels in Canada ranged from 10 to 40 Bq/kg dw in another brown seaweed (*Ascophyllum nodosum*) and 50 – 300 Bq/kg dw in kelp (*Saccharina latissima*) (Kelly et al. 2014).

The Tromsø seaweed levels were ascribed to and co-varied with the discharges from the hospital, and both the levels and the far-reaching impact on seaweed was explained by the shallow discharge point at 17 meters depth and the high degree of mixing due to strong tidal currents, with the direction of the current explaining the large differences in levels (Gwynn and Jensen 2019). However, this argument also has a caveat, as the very strong tidal currents around the Tromsø area also involve a very fast exchange and replacement of large fractions of the water masses around Tromsø Island during each tidal cycle (i.e., twice a day), leading to an enormous dilution effect that effectively removes pollutants from this area (McClimans 1973). This should lead to a fast dilution of I-131 rather than high levels due to cumulative buildup.

The high levels of I-131 recorded in Tromsø must therefore be explained by uptake during the time when currents containing the discharge pass by. Brown seaweed like *Fucus vesiculosus* are known for its high and rapid capacity for uptake of iodine isotopes (Fievet et al. 2023) and it is therefore probably the “delivery” of I-131 to the seaweed by tidal currents from the discharge point that explain the high levels in Tromsø seaweed compared to the Oslofjord seaweed. This suggests the hydrological factors as the most important reason for Oslofjord (and Tromsø) seaweed variation in radionuclide levels, and especially from tidal variations.

Since the dynamics of seaweed uptake are affected by short term variations in hydrology and the five days biological half-life of I-131 involves seaweed levels integrating over longer time, it seems clear that more studies on these dynamics are needed. For Lu-177, the only two reported seaweed levels suggest a lower uptake, which should be more rigorously assessed in the future. Moreover, future studies may

become relevant if the volumes of wastewater with radiopharmaceuticals increase so that the decay containment tank must be emptied at shorter intervals, leading to less decay and possibly increased discharge activities from the tank. The situation is followed by the DSA. Interestingly, there are plans for kelp agriculture from autumn 2026 at one of the two assessed localities, Slemmestad, where the kelp will be used to capture CO₂ and pollutants from the Oslofjord (<https://bellona.no/project/Oslofjord-tarepark>). How that might be affected by the assessed discharges and how the kelp may affect ocean activity concentrations may also be a topic of future studies.

5 Conclusions

The main finding of this study is the reduction of I-131 in seaweed *Fucus vesiculosus* near the sewer discharge point in the inner Oslofjord after a decay containment tank for wastewaters was taken into use in October 2024 at a new treatment facility at Radiumhospitalet. This shows that preventive actions can have a reducing effect on impacts like uptake of radionuclides by seaweed. However, discharges of I-131 and Lu-177 from Rikshospitalet are still ongoing and result in measurable levels of I-131 in seaweed. Any future increase in the use of radiopharmaceuticals, will reduce the residence time in the decay tank, hence leading to higher activities in the effluent water going to the sewer system. For such a scenario, we recommend a new assessment of impacts to the inner Oslofjord and seaweed. However, there has been a decreasing trend in the use of I-131 during the assessed years, contrary to the expectation of an increased use. In comparison, the use of Lu-177 was more stable. Daily Tc-99m records were not accessible and were therefore not included in this study.

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