Behaviour of lutetium-177 discharged into UK wastewater systems

Chief Scientist's Group research report

Environment Agency

Date: July 2026

We are the Environment Agency

We're here to protect homes and habitats – not just to safeguard what exists, but to create places of resilience and renewal, where nature returns and futures can take root.

We're regulators and reformers, engineers and ecologists, inspectors and incident responders. Some of us are in labs and offices. Others on riverbanks. Many in boots, hi-vis, or waders.

But wherever you find us, and whatever we're doing, we're one team – all guardians.

Published by:

Environment Agency

Horizon House, Deanery Road, Bristol BS1 5AH

www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue: www.gov.uk/government/publications or our National Customer Contact Centre: 03708 506 506

Email: enquiries@environment-agency.gov.uk

Authors:
David Copplestone (University of Stirling), James Penfold (Qunitessa Ltd), Jasper Hattink (Socotec UK Ltd), Karen Smith (RadEcol Consulting Ltd), Louise Bruffell (Quintessa Ltd), Ishbel Dale (University of Stirling), Rebecca Williams, Christiana Dowds (Environment Agency)

Key words:
monitoring, lutetium-177, wastewater, partitioning coefficient, IRAT2

Research contractors:
University of Stirling, Stirling, FK9 4LA Tel: 01786 473171
SOCOTEC UK, Unit 12 Moorbrook, Southmead Industrial Park, Didcot, OX11 7HP Tel: 01235 750730

Environment Agency's Science Manager:
Christiana Dowds

Citation:
Copplestone, D., Penfold, J., Hattink, J., Smith, K., Bruffell, L., Dale, I., Williams, R., Dowds, C. (2026) Behaviour of lutetium-177 discharged into UK wastewater systems. Environment Agency, Bristol.

Research at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned by the Environment Agency's Chief Regulator's Group.

You can find out more about our current science programmes at https://www.gov.uk/government/organisations/environment-agency/about/research

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Dr Robert Bradburne
Chief Scientist

Contents

Foreword....6

Acknowledgements....7

Executive summary....8

1 Introduction....10

1.1 Background....10

1.2 ^{177}Lu properties....11

1.3 ^{177}Lu radiotherapy treatment....11

1.4 Project aims and objectives....12

1.5 Approach....13

2 Methodology....15

2.1 Sampling methodology....16

2.2 Sampling, sample preparation, and analysis....19

2.3 Literature Review....20

3 Analytical results....23

3.1 WWTW sampling....23

3.2 Environmental sampling....29

4 ^{177}Lu transfer to the freshwater environment....38

5 Determining a ^{177}Lu sewage sludge partitioning factor....41

6 Determining a ^{177}Lu freshwater-sediment distribution coefficient....44

7 IRAT2 modelling and field measurement comparisons....48

7.1 ^{177}Lu source and discharge pathway characteristics....48

7.2 ^{177}Lu concentrations in the Cambridge WWTW....50

7.3 ^{177}Lu river concentrations....52

7.4 Dose assessment....54

7.5 Screening assessment....55

7.6 Site specific assessment 60
7.7 External dose rates.....62
7.8 Dose assessment conclusions 63
8 Conclusions and recommendations.....65
References 68
List of abbreviations and acronyms 73
Glossary.....74
Appendix A: Sample properties 76
Appendix B: Other radionuclides identified 91

Foreword

This document has been prepared for the Environment Agency by a University of Stirling led consortia which included Quintessa Ltd and RadEcol Consulting Ltd. All sampling and analysis were conducted by Socotec UK Ltd. All suppliers involved in the delivery of this project were working under the Environment Agency's Ad Hoc Monitoring and Assessment of Radioactivity in the Environment Contract.

This project builds evidence to aid the radiological assessment of lutetium-177 (^{177}Lu) by providing new insights into the fate and transport of ^{177}Lu in wastewater environments. The Environment Agency (or any of the report's authors) is not giving a regulatory review on the medical (or other) applications of ^{177}Lu. In addition, the selection of samples from and around the Cambridge Wastewater Treatment Works is not a statement of concern by the Environment Agency, or any of the project contributors.

This project is the second of three pieces of research commissioned by the Environment Agency to investigate the solid: solution partitioning behaviour of ^{177}Lu in wastewater environments. The first project is a literature review of the environmental behaviour of 10 radionuclides (including ^{177}Lu) to obtain up-to date environmental transfer parameter values. The review identified knowledge and evidence gaps in the literature regarding the partitioning behaviour of ^{177}Lu in wastewater environments. This project seeks to address those gaps by generating new ^{177}Lu datasets through field monitoring. However, this field investigation is necessarily limited in scope and does not provide a complete dataset, leading to uncertainties in some results. The third project in the series aims to resolve those uncertainties through laboratory experiments that provide important insights into the fundamental behaviour of ^{177}Lu in wastewater environments. The results of the literature review and laboratory study have been discussed in their own standalone reports, which are being published at the same time as this field study report.

Acknowledgements

This project was part funded by Advanced Accelerator Applications Ltd, a Novartis company, and part funded by the Environment Agency. Advanced Accelerator Applications Ltd provided no input or control into the creation, output, or delivery of this project. This included all data analysis, conclusions reached, and recommendations for future work.

The authors would like to thank colleagues at Anglian Water for allowing us to sample wastewater influent, effluent, and sewage sludges at the Cambridge Wastewater Treatment Works in Milton, Cambridgeshire. We would particularly like to thank Karen Gilbert (Anglian Water) for arranging access to and providing information on the Cambridge Wastewater Treatment Works and Daniel Gillett (Cambridge University Hospitals NHS Foundation Trust) for providing information on lutetium-177 treatment dates and patient excretion data. This information enabled the project to proceed. We would also like to thank Adam Lang, Rob Dean, Jane Rowe, and Roger Timmis (Environment Agency) for supporting the design of the project and/or for reviewing the draft report.

Executive summary

Lutetium-177 (^{177}Lu) is being used in novel radiotherapy treatments for several types of cancer. Use of ^{177}Lu for prostate cancer treatments is expected to rise significantly in England, resulting in increased discharges of ^{177}Lu containing liquid waste to the sewer network and then to the wider environment. The presence of ^{177}Lu in the environment has the potential to increase human and wildlife exposures to ionising radiation, and the Environment Agency needs to understand the associated radiological risks. A recent Environment Agency literature review of environmental transfer parameter data revealed that little is currently known about the behaviour of ^{177}Lu in wastewater environments.

The environmental behaviour of medically administered ^{177}Lu has been investigated to improve understanding of the potential public and environmental health impacts arising from expanded use of new ^{177}Lu-based cancer treatments. This project involved sampling at the Cambridge Wastewater Treatment Works (WWTW), near Milton (Cambridgeshire), and in the River Cam, which receives treated effluent from the works. The Addenbrooke's Hospital discharges liquid effluent to the Cambridge WWTW and the study was timed to coincide with one of the hospital's ^{177}Lu radiotherapy treatments. Environmental sampling data was used to determine two transfer parameters for ^{177}Lu; the sewage sludge partitioning factor and the freshwater-sediment distribution coefficient (K_d). The calculated parameter values were compared with those currently used in the Environment Agency's Initial Radiological Assessment Tool (version 2) (IRAT2).

The following parameter values were derived for ^{177}Lu in the environment:

- A sludge partitioning factor of 0.18 was determined, which is lower than the value currently used in IRAT2 (0.5).
- A freshwater-sediment K_d value of 3,000 L kg^{-1} was determined, which is two orders of magnitude lower than the value currently used in IRAT2 (220,000 L kg^{-1}).

Owing to the lack of element specific data, cerium (Ce) is the analogue of choice for ^{177}Lu within the IRAT2 methodology. The inconsistencies between the sludge partitioning factor/ sediment-freshwater K_d values estimated in this project and those currently used in IRAT2 indicate that ^{177}Lu behaves differently from Ce. However, ^{177}Lu behaviour in wastewater systems (WWTW and freshwater environments) was found to be complex and could not be fully explained using the monitoring data. A handful of studies in the literature suggest that the radionuclide chemical form plays a critical role in determining ^{177}Lu environmental behaviour. It is possible that ^{177}Lu bound to radiopharmaceuticals (as used to target specific biological tissues) remains predominantly in solution and is not readily scavenged by particulate matter. This would lead to limited ^{177}Lu uptake to sediment and sewage sludge and would account for the lower transfer parameter values recorded in this project. Further research is required to confirm (or refute) this possible explanation.

A higher ^{177}Lu water solubility (compared to that of Ce) has important implications for environmental dose assessments. Lower levels of radioactivity in sediments should result

in lower external dose rates to people and wildlife. A comparison between analogue-based (Ce) dose calculations and revised dose calculations using the estimated sewage sludge partitioning factor and freshwater K_d from this study supports this conclusion. Major findings from undertaking these comparisons include:

- Initial doses calculated using the IRAT2 screening assumptions exceed the applied 20 μSv y^{-1} screening criterion for key exposure groups, including sewage treatment worker, child in brook, angler, and irrigated food consumers. A nominal discharge of 1 TBq y^{-1} of ^{177}Lu was assumed.

- Doses were significantly lower for all exposure groups, except irrigated food consumer, when the measured sewage sludge partitioning factor and freshwater-sediment K_d values from this project were applied (instead of the analogue values).

- The irrigated food consumer dose was higher because a greater fraction of ^{177}Lu remained in freshwater, which can contaminate the food pathway.

- Initial dose estimates for wildlife exceeded the 1 μGy h^{-1} screening criterion under all assumptions. Doses increased further when the measured K_d and sludge partition factor from this study are used. This is due to greater retention of radioactivity in solution, from which biota doses are calculated.

The elevated doses calculated for some human exposure groups in the initial IRAT2 assessments are largely driven by external doses from riverbed sediments. This report suggests that using ^{177}Lu specific parameter data (i.e. lower sludge partitioning factor and freshwater-sediment K_d) is likely to reduce predicted doses to human and non-human biota by ~2 orders of magnitude. However, doses to wildlife remained well above the screening criterion under both the analogue (Ce) information and the measured ^{177}Lu parameter values from this study. Recalculation of the Dose Per Unit Release values for wildlife may therefore be a useful step in supporting future ^{177}Lu dose assessments.

This project provides new insights into the fate and transport of ^{177}Lu in wastewater environments. The main finding is that ^{177}Lu bound to a radiopharmaceutical appears to be more water soluble than expected (based on analogue Ce data) and may accumulate in freshwater bodies following permitted medical waste discharges. Nevertheless, the field investigation was limited in scope to a single wastewater system and one medical administration of ^{177}Lu. Accordingly, the resulting datasets were incomplete, leading to uncertainties in some of the conclusions. To address these uncertainties, the Environment Agency has since undertaken laboratory scale research into the fundamental behaviour of ^{177}Lu in wastewater systems, including the significance of the initial radionuclide chemical form. The results of the laboratory investigation have been discussed in a separate report.

1 Introduction

1.1 Background

Lutetium-177 (^{177}Lu) is increasingly being utilised in radiotherapy to treat different types of cancer. It is predicted that the use of ^{177}Lu for prostate cancer treatments will increase significantly due to the introduction of novel ^{177}Lu based radiopharmaceuticals such as Lutetium-177 Prostate Specific Membrane Antigen (PSMA) (Delker et al., 2015). The increasing use of ^{177}Lu based radiopharmaceuticals is expected to lead to increased discharges of ^{177}Lu into the sewer network and then into the environment. According to the Pollution Inventory, ^{177}Lu discharges in England is already on the rise, as indicated in Figure 1. Prior to 2020, ^{177}Lu was reported to the Pollution Inventory as part of the 'other beta/gamma' category. For this reason, Figure 1 presents data for 'other beta/gamma' discharges (including ^{177}Lu) from 2013-2022, as well as the individually reported ^{177}Lu discharge data from 2020 onwards.

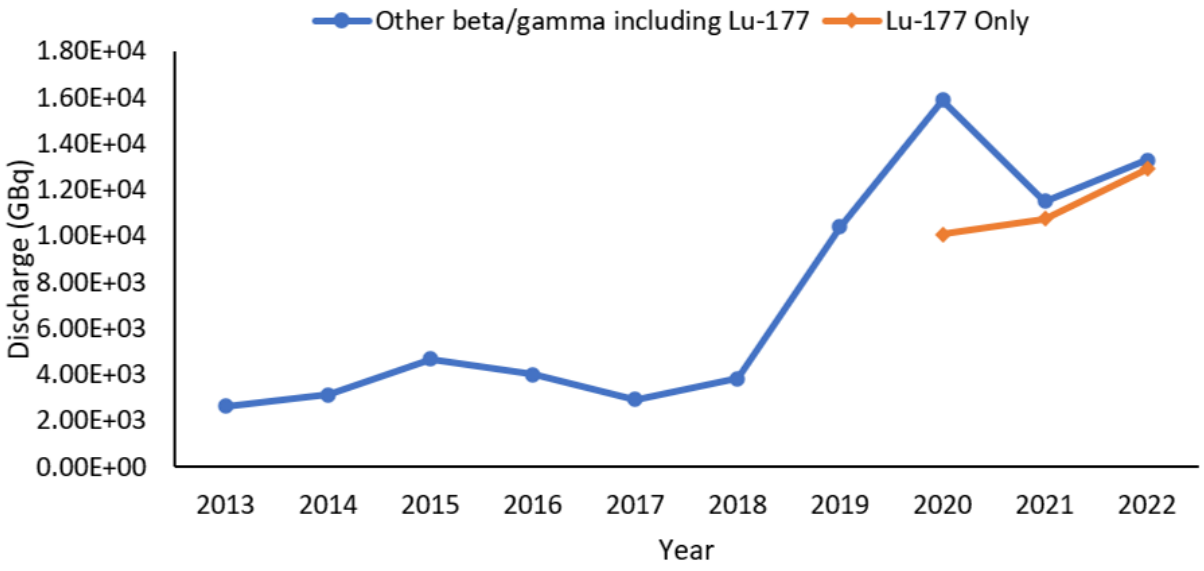


Figure 1: 'Other beta/gamma radionuclide' (including ^{177}Lu) and ^{177}Lu specific discharges from non-nuclear facilities into aqueous wastewaters in England (data sourced from Environment Agency, 2026). ^{177}Lu was only reported individually in the Pollution Inventory from 2020 onwards.

Patients typically receive 4-5 doses of 6,300-7,400 MBq ^{177}Lu as treatment (Kurth et al., 2018). At the beginning of this project, estimates provided to the Environment Agency by Advanced Accelerator Applications Ltd, indicated the number of patients to be treated with Lu-PMSA could reach upwards of 550 patients per year by 2025 with the potential for this number to continue to increase. This equates to annual administration of 20 TBq of ^{177}Lu nationally by 2025. No recent data could be found in the published literature to determine if these earlier predictions were accurate. Regardless, the potential advantage of Lu-PSMA is that the ^{177}Lu is bound to the protein PSMA. Of note, PSMA is found in the membranes of prostate cells and people with prostate cancer have high PSA levels and PSMA

expression. This means that ^{177}Lu can be carried to the sites of interest for the radiation therapy and then binds to the PSMA receptors on metastasised prostate cancer cells. Lutetium emits both beta and gamma radiation, and since the ^{177}Lu is PSMA-bound to the tumour, the radiation can damage the cancer cells (Kurth et al., 2018). Surrounding healthy tissue is spared during this process.

1.2 ^{177}Lu properties

Lutetium-177 is a radioisotope of the metal Lu, the last element in the lanthanide series in the periodic table. Lutetium-177 is a beta emitter with a half-life of 6.65 days and emits 3 major beta particles with a maximum energy of 498.3 keV (79.3%), 385.4 keV (9.10%), and 177.0 keV (11.6%), respectively (Schötzig et al., 2001). The maximum penetration of the beta-particles is 2.2 mm in tissue and water, with an average penetration range of 0.67 mm (Hennrich and Kopka, 2019). Lutetium-177 also emits gamma rays, mainly at 208.4 keV (10.4%) and 113.0 keV (6.20%), and decays to stable hafnium-177 (Shirley et al, 1978; Helmer et al., 2002; Dash et al., 2015).

As a lanthanide element, Lu is often grouped with scandium, yttrium, and cerium (Ce) due to their similar chemical properties. Indeed, Ce is frequently used as the analogue radionuclide for ^{177}Lu dose assessments where element specific data are unavailable. The environmental behaviour of Ce has been studied more widely than that of Lu as Ce isotopes are routinely produced in small amounts in nuclear reactors before being released into the environment (unlike Lu). In general, Lu and other lanthanide elements would be expected to be scavenged from the water column by any particulate material and/or deposited in sediments (Sholkovits, 1995; Weltje et al., 2002; Piper and Bau, 2013). However, Lu may behave differently when chemically bound to a radiopharmaceutical and could remain to a greater extent in the water column (Turcotte et al., 2022). This would result in greater dispersion of Lu throughout aquatic environments.

1.3 ^{177}Lu radiotherapy treatment

Lutetium-177 can be complexed with several different chelators to treat different types of cancer, but most notably prostate cancer. Lutetium-177 is often complexed with the DOTA (1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid) chelator, which is then coupled to the target molecule. The resulting substance has a strong affinity for the somatostatin receptors or specific proteins. Common ^{177}Lu-DOTA chemical forms used in radiotherapy treatments include ^{177}Lu-DOTATATE (Lutathera®), ^{177}Lu-DOTA-PSMA-GUL (^{177}Lu PSMA), and ^{177}Lu- NeoRay®. The different chemical forms of ^{177}Lu can target different biological receptors within the body and are therefore effective at treating different cancerous cells.

Lutetium-177 radiotherapy treatment can be administered as an outpatient treatment, or with an overnight stay. A patient may only spend 6-8 hours in the hospital following an outpatient treatment before being discharged. Consequently, outpatients may excrete some of the ^{177}Lu in the hospital with the remainder later excreted at home. Under these circumstances, ^{177}Lu may be routed to different sewage collection systems and then

discharged to one or more WWTWs. This would make the ^{177}Lu discharge more disperse in the environment and likely reduce the radiological impacts on people and wildlife. Researchers have found that 36% of the administered ^{177}Lu-DOTATATE is retained by the patient during an outpatient treatment (Levart et al., 2019). In contrast, patients kept in overnight may only retain 16% of ^{177}Lu-DOTATATE during their hospital visit (Gillett, 2024). It is interesting to note that 50% and 70% of ^{177}Lu-PMSA is cleared from the body after 4 hours and 12 hours, respectively (Kurth et al., 2018). These differences show that different chemical forms of ^{177}Lu possess non-identical biochemical properties, implying that the environmental behaviour of different ^{177}Lu radiopharmaceuticals might also vary.

Hospitals are beginning to apply for variations to their permits to increase their discharge limits for ^{177}Lu. The Environment Agency uses their Initial Radiological Assessment Tool (version 2) (IRAT2) to assess the impact of requested discharge limits. When assessing the impact of ^{177}Lu discharges using IRAT2, the Environment Agency has found that some assessments predict elevated doses to some exposure groups from ^{177}Lu. These elevated predicted doses are largely attributed to high external doses from contaminated sediment. However, some of the environmental transfer parameters used in these calculations, particularly the freshwater-sediment distribution coefficient (K_d) and sludge partitioning factor, are uncertain. The 2 parameters are based on radionuclide analogues as there is limited data available for ^{177}Lu (Mobbs et al., 2026). This is particularly the case for ^{177}Lu chelated (chemically bound) to different radiopharmaceuticals. Such a paucity of information likely reflects the relative novelty of ^{177}Lu in medical applications. Hence, there is currently an absence of studies into this radionuclide's behaviour in the environment.

The freshwater-sediment K_d value describes the distribution of ^{177}Lu between the water and sediment phases in the freshwater environment. In contrast, the sludge partitioning factor describes the partitioning of ^{177}Lu between solid and liquid phases in the WWTW, specifically the amount of ^{177}Lu accumulating in the solid sludge. Both transfer parameters for ^{177}Lu in IRAT2 are currently based on the values of the analogue cerium (Ce), another lanthanide element. This project investigates the environmental behaviour of medically administered ^{177}Lu in wastewater environments. and compares the results with the IRAT2 predictions of ^{177}Lu behaviour using the Ce analogue. This work has been done to better understand whether there may be any public and environmental consequences from more widespread use of ^{177}Lu which are not apparent from previous analogue-based estimates.

1.4 Project aims and objectives

The overall aim of this project is to explore the partitioning behaviour of ^{177}Lu in UK wastewater systems and to examine the implications for radiological dose assessment methodologies. A wastewater treatment works (WWTW) and a freshwater environment that receives treated effluent from the WWTW have been selected for this investigation. The objectives of this project are to:

- Evaluate ^{177}Lu activity concentrations in liquid waste streams arriving at the WWTW and being discharged from the WWTW into a freshwater environment.

- Compare measured ^{177}Lu activity concentrations in the environment against known hospital treatment amounts to determine the percentage of administered ^{177}Lu that may reach the freshwater environment (for an in-patient treatment of ^{177}Lu).
- Characterise the distribution of ^{177}Lu in waste streams arising at WWTWs (treated effluent and treated solids) to determine a sludge partitioning factor.
- Characterise the distribution of ^{177}Lu between freshwater sediments and water in brooks and/or rivers to determine a freshwater-sediment K_d.
- Compare measured ^{177}Lu activity concentrations in a freshwater environment (water and sediment) with those predicted using the IRAT2 methodology.
- Evaluate the suitability of Ce as an analogue for Lu in IRAT2.

This field study is the second of three research projects recently commissioned by the Environment Agency to investigate the solid: solution partitioning behaviour of medical radionuclides in wastewater environments. The first project is a scientific literature review of the environmental behaviour of 10 radionuclides (including ^{177}Lu) to obtain up-to-date environmental transfer parameter values (Mobbs et al., 2026). These values are a crucial component of the IRAT2 methodology. The literature review revealed significant knowledge gaps regarding the partitioning behaviour of ^{177}Lu in wastewater systems. To address this issue, the Environment Agency has undertaken a second project to measure ^{177}Lu activity concentrations in wastewater systems. The major findings of the field study are described in this report. The third Environment Agency project entails laboratory experiments to better understand the fundamental behaviour of ^{177}Lu and iodine-131 (another medical radionuclide) in wastewater environments (Lang et al., 2026).

1.5 Approach

This project involved sampling at a WWTW and the receiving river following administration of ^{177}Lu at a local hospital. Using the collected environmental sampling data, key transfer parameters such as the sludge partitioning factor and freshwater-sediment K_d were determined. These field derived values were then used to predict doses to the exposure groups used in IRAT2. The assumed discharge routes of ^{177}Lu following treatment as shown in Figure 2 to illustrate the potential exposure pathways to the public.

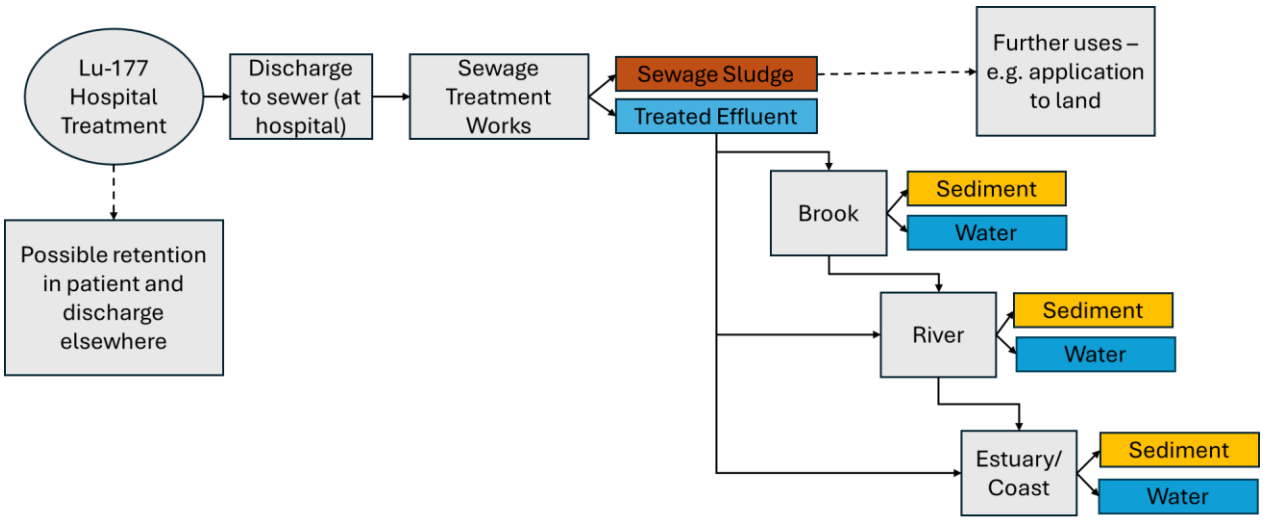


Figure 2: Possible discharge pathways of ^{177}Lu following a medical administration to a patient at hospital. Colour coding is used to show the partitioning between solid and liquid phases, blue is used for liquid phases and yellow, and orange are used for solid phases.

The exposure groups considered within this report are:

- Sewage treatment works worker.
- Child playing in a brook.
- Angler.
- Irrigated food consumer (river).
- Fishing family (for estuary/coastal assessments).
- Farming family (sewage sludge to land).
- Non-human biota in the freshwater environment.

2 Methodology

Addenbrookes hospital in Cambridge and the Cambridge WWTW (near Milton) was the focus of this project for environmental sample collection. Addenbrookes hospital routinely discharges liquid waste into the Cambridge WWTW, which then treats the wastewater and discharges it into the nearby River Cam. Addenbrookes hospital is regularly using ^{177}Lu based radiotherapy treatments and is the only site permitted to discharge ^{177}Lu into the Cambridge WWTW. For this project, environmental sampling was conducted at the Cambridge WWTW and in the River Cam before and then for up to two weeks after a targeted treatment of 9.2 GBq ^{177}Lu NeoRay®. Sampling was conducted before to gather background data on residual ^{177}Lu levels from previous treatments. The targeted treatment was applied on Tuesday 2 July 2024 10:58 am with the patient being kept in the hospital overnight. This was the only ^{177}Lu based radiotherapy treatment performed in the hospital during the week targeted for sampling. However, it is understood that multiple ^{177}Lu treatments were administered in the weeks before this project's targeted treatment (Gillett, 2024). Fractions of ^{177}Lu from these earlier treatments might have been present in the Cambridge WWTW at the time of the main environmental sampling, especially in sewage sludges and river sediments. This was investigated using the background surveying data.

A flow diagram illustrating the flow of the wastewater and associated treatments taking place at the Cambridge WWTW is shown in Figure 3. The catchment sewage and discharges from residential properties and businesses (including Addenbrookes hospital) are continuously received by the Cambridge WWTW. Coarse material in the influent is removed by a screen before the influent reaches the primary settlement. In the primary settlement tank, sludge and debris are allowed to settle out while the supernatant passes to the biological treatment (where secondary sludge can be produced). After a delay, the treated sewage is clarified with the supernatant and discharged as final effluent to the River Cam. Sludge produced during this process is passed back to biological treatment.

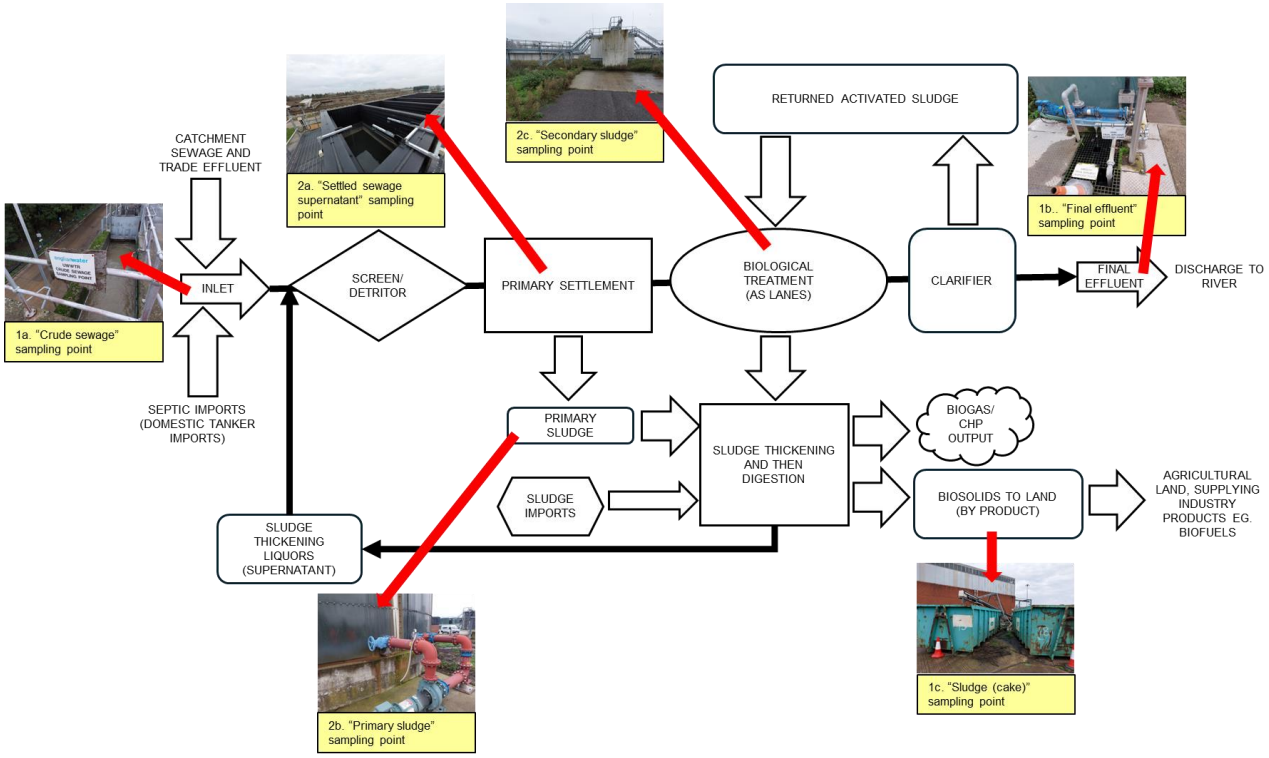


Figure 3: Simplified flow diagram of the process and water flow through Cambridge WWTW (reproduced from Gilbert, 2024). Pictures show the sampling points.

The primary sludge might reside in the primary settlement tanks for some time before it is moved and combined with the secondary sludge and off-site produced sludge. This combined sludge is thickened by the removal of water and then digested in an anaerobic digestor to form biogas (often used for energy production) and biosolids (often used as a fertiliser). Any remaining sludge liquors or supernatant can be returned to the inlet and cycled through the sewage works. Sludge thickening and the production of the biosolids can take from as little as 1-2 days to weeks to form. Six points in the Cambridge WWTW were monitored or sampled for ^{177}Lu (1a-1c and 2a-2c), as shown in Figure 3.

2.1 Sampling methodology

A total of 9 sampling points were used for this project. Three of the points covered inputs to and outputs from the WWTW (shown as 1a-c in Figure 3 and A,B and C in Figure 4) and 3 covered key processes within the WWTW (shown as 2a-c in Figure 3 and D,E and F in Figure 4). The remaining 3 environmental sampling points were in the River Cam. The sampling points were chosen to provide data to address the project objectives as follows. Three sampling points were used to obtain data on ^{177}Lu behaviour in the WWTW and to allow determination of the percentage of ^{177}Lu administered that might reach the freshwater environment. Furthermore, the sampling conducted aimed to allow determination of the fraction of the ^{177}Lu in the sewage works that remains in the liquid phase and the fraction that becomes bound to the sludge produced in the WWTW. The environmental sampling locations in the River Cam were selected to enable assessment of the fractions of ^{177}Lu associated with the water and sediment. By collecting samples over a period of 5 days, observation of ^{177}Lu passing through the WWTW became possible. This

sampling plan allowed the first three project objectives to be addressed i.e., evaluate the ^{177}Lu levels in effluent waste streams arriving at, and being discharged, from a WWTW.

The 6 WWTW sampling points included 3 points to cover inputs to and outputs from the WWTW (shown as 1a-c in Figure 3 and A,B and C in Figure 4):

- “Crude sewage sampling point,” shown as “inlet” in Figure 3 and photograph A in Figure 4. Auto-samplers which can collect liquid samples to any required frequency were used to collect two 12-h bulk samples every 24 hours providing one “day” and one “night” sample.

- “Final effluent sampling point,” shown as “final effluent” in Figure 3 and photograph B in Figure 4, using autosamplers to collect two 12-h bulk samples every 24 hours providing one “day” and one “night” sample.

- “Sludge (cake) sampling point,” shown as “Biosolids to land (byproduct)” in Figure 3 and photograph C in Figure 4, which was sampled using a daily grab sample.

The WWTW sampling points also included points to cover the processes within the Cambridge WWTW to provide information on the distribution of ^{177}Lu in the WWTW (i.e. the treated effluent and sludge samples), this is to enable the determination of a sludge partitioning factor for the chemical form of ^{177}Lu used in the radiotherapy. These included (shown as 2a-c in Figure 3 and images D, E, and F in Figure 4):

- “Settled sewage supernatant sampling point,” shown as “primary settlement” in Figure 3 and photograph D in Figure 4, which used auto-samplers to collect two 12-h bulk samples per 24 hours providing one “day” and one “night” sample.

- “Primary sludge sampling point,” shown as “primary sludge” in Figure 3 and photograph E in Figure 4, using daily grab sampling.

- “Secondary sludge sampling point,” shown as “biological treatment (AS lanes)” in Figure 3 and photograph F in Figure 4, using autosamplers to collect two 12-h bulk samples per 24 hours providing one “day” and one “night” sample.

Figure 4: Sampling points at the Cambridge WWTW. A) crude sewage (influent) sampling point, B) final effluent sampling point, C) sludge (cake) sampling point D) settled sewage supernatant point, E) primary sludge sampling point and F) secondary sludge sampling point. Autosamplers were set up at points A, B, D and F. Daily grab sampling was performed at points C and E.

Three sampling points within the River Cam were sampled for water and sediment to provide information on the distribution of ^{177}Lu in the freshwater environment to enable freshwater-sediment K_d to be determined. This allows comparison of predicted activity concentrations derived from the IRAT2 dose assessment tool with actual discharge measurements. The River Cam sampling points were as follows.

- The point of discharge where daily grab samples for water and sediment were collected.
- 500 m downstream from the discharge point where daily grab samples for water and sediment were collected.
- One kilometre downstream from the discharge point where daily grab samples for water and sediment were collected.

2.2 Sampling, sample preparation, and analysis

All environmental sampling, sample preparation and analysis was undertaken to ISO 17025 standard by the UKAS accredited analytical laboratory 1252 SOCOTEC UK. Sampling was performed following SOCOTEC UK's existing internal sampling procedure procedures for radioactivity in the environment adapted with instructions to operate the autosamplers. Briefly, 4 ISCO 3700/6712/GLS automatic water samplers were set to sample 100 mL at 72-min intervals to produce a bulk sample of 1 L every 12 hours. This was performed continuously over 5 days: from Monday 1 July 2024 08:00 to Friday 5 July 2024. It was necessary to assign a time to each 12-h bulk sample, and the mid-point of the 12-h period (i.e., midnight and noon) was used for this purpose. Sludge samples were collected using grab samplers once every 24 hours during the same time-period. Sediment and water samples from the River Cam were taken using a long-handled dipper and the sediment was scraped to ~1 cm deep. Water samples were collected from the surface.

All samples were sent to the laboratory for analysis within 24-hours of collection. Liquid samples from crude sewage, final effluent, settled supernatant, primary sludge, secondary sludge, and surface water were pasteurised at 80 °C for 1 hour. Sludge cake samples and sediment samples were dried at 105 °C overnight and ground below 2 mm. The moisture content was recorded. When ^{177}Lu was detected in the surface water samples, 4-5 L were filtered through a 0.45 µm nylon membrane filter using a vacuum filtration system to separate the particulate and dissolved ^{177}Lu fractions from one another.

Gamma spectrometry was used as described in SOCOTEC UK's internal procedure. Briefly, test portions of 1 L from the liquid samples of crude sewage, final effluent, settled supernatant, primary sludge, secondary sludge, and surface water were analysed for ^{177}Lu (unfiltered and filtered). A count time of up to 18,000 seconds (5 hours) was applied to the liquid sample test portions. For sludge cake samples and sediment samples, a count time of up to 250,000 seconds (~3 days) was applied to the solid samples, depending on the volume available.

High purity germanium (HPGe) detectors coupled to an Ortec gamma ray spectroscopy system were used to analyse ^{177}Lu activity concentrations in samples. The identification and quantification of the photopeaks in the measured gamma ray spectra were performed using the Fitzpeaks software programme (Fitzgerald, 2002). The detectors were calibrated for efficiency using a mixed radionuclide standard that covered an energy range of 30-2,000 keV. Detector calibrations were based on homogeneous standard solutions. While

some of the samples might have contained particulate material (e.g., the influent samples), it was assumed for the purposes of quantification that they were homogeneous. This was considered a reasonable assumption where the bulk ^{177}Lu activity concentration in the sample is of primary interest. Self-attenuation was corrected for by calculating the average mass attenuation coefficient for sediment or bio-solids, or sludge (cake), and the bulk density of the sample using the GAMATOOL program (Debertin and Jianping, 1989). All results were corrected for radioactive decay between the date of sampling and the date of analysis. Hence, all results provided in this report relate to the sampling date.

2.3 Literature Review

A systematic review of the scientific literature on ^{177}Lu was also conducted within this project to enable a comparison of this monitoring study with similar studies undertaken by other researchers. It focused on information related to:

- Lutetium levels in effluent waste streams arriving at, and being discharged from, WWTW and quantify levels against known treatment amounts. This is to determine the percentage of ^{177}Lu administered which may reach the freshwater environment.
- Lutetium distribution between the waste streams arising at WWTWs (e.g., treated effluent and treated solids). This is to determine a sludge partitioning factor.
- Lutetium distribution between freshwater sediments and water in brooks and/or rivers receiving ^{177}Lu discharges. This is to determine a freshwater-sediment K_d.

The systematic review of the scientific literature on ^{177}Lu was conducted by entering key word combinations in Scopus. A series of keywords were identified and subsequently modified after examining the search findings.

Full details of each publication were downloaded into Refworks®, including the authors, publication title, year, journal, or book title, abstract, and keywords. A review for duplicate references found via different searches was then undertaken with duplicate references removed. At this stage, all remaining references were reviewed (with a focus on the title, keywords and abstract) to determine whether the article may provide additional information for any other tasks associated with this project. All references that might contain useful information were then downloaded in full and each reference was read in detail with any useful information extracted and reported within the main body of this report.

Overall, 1,475 references were initially identified during the extensive literature search. Of these, 310 unique papers were extracted for initial review (i.e., abstract, title). Thereafter, 58 papers within this set of 310 were selected for full review. Unfortunately, relevant data appeared to be limited during the full review. A significant number of papers on ^{177}Lu were mainly related to its medical application, and not its environmental fate and transport. The number of publications found are listed in Table 1 below.

Table 1: Keywords and combinations searched in Scopus and the number of references found.

Keywords	Modifiers	Papers found	Comments
Lutetium-177		3,394	Mostly medical, not downloaded, modifiers used instead
Lutetium-177	Environment	32	
Lutetium-177	Waste Water Treatment Works	1	
Lutetium-177	WWTW	0	
Lutetium-177	Sewage	5	
Lutetium-177	K_d	44	But mostly medical still and about partitioning within the body
Lutetium-177	Freshwater	0	
^{177}Lu-DOTA-TATE		20	
^{177}Lu-Dotatate		858	
^{177}Lu-Dotatate	Environment	6	
Dota Octreotate	Environment	0	666 without environment
Vipivotide tetraxetan	Environment	3	Only 1 was relevant
^{177}Lu PSMA	Environment	6	
^{177}Lu PSMA	K_d	7	
NeoBOMB1		17	

Keywords	Modifiers	Papers found	Comments
Lutathera		187	
Lutathera	Environment	1	
Lutathera	K_d	0	
Liquid radioactive waste	Lutetium	13	
Waste water	Lutetium	53	
Sewer	Lutetium	5	
Radioactive waste management	Lutetium	15	
Waste disposal	Lutetium	28	
Environmental monitoring	Lutetium	121	
Environmental radioactivity	Lutetium	23	
Lanthanide	Wastewater + partition	10	

3 Analytical results

3.1 WWTW sampling

Sections 3.1 and 3.2 provide the results for ^{177}Lu measured in the Cambridge WWTW:

- The results for influent, effluent, and final sludge cake samples are shown in in Table 2 and Figure 5.
- The results for the settled sewage supernatant, primary and secondary sludge samples are shown in Table 3 and Figure 5.
- The results for the environmental freshwater and sediment samples are shown in Table 4 and Figures 7 and 8 in Section 3.2.

All other analytical results are provided in Appendix A (i.e., sample ID numbers and sample properties) and Appendix B (i.e., other gamma emitting radionuclides detected in the samples).

Table 2: ^{177}Lu activity at 1a the "crude sewage sampling point", at 1b "final effluent sampling point" and 1c in the "final sludge (cake)". Results are decay corrected to the sampling date. Uncertainties are quoted at 2 standard deviations based on a total uncertainty budget.

	Sampling point 1a, Figure 4A Crude sewage sampling point	Sampling point 1a, Figure 4A Crude sewage sampling point	Sampling point 1b, Figure 4B final effluent sampling point	Sampling point 1b, Figure 4B final effluent sampling point	Sampling point 1c, Figure 4C Final sludge (cake) sampling point	Sampling point 1c, Figure 4C Final sludge (cake) sampling point
Sampling method	Auto sampler, 12-hour bulk samples	Auto sampler, 12-hour bulk samples	Auto sampler, 12-hour bulk samples	Auto sampler, 12-hour bulk samples	Daily grab sample	Daily grab sample
Matrix	Influent	Influent	Effluent	Effluent	Sludge (cake)	Sludge (cake)

	Sampling point 1a, Figure 4A Crude sewage sampling point	Sampling point 1a, Figure 4A Crude sewage sampling point	Sampling point 1b, Figure 4B final effluent sampling point	Sampling point 1b, Figure 4B final effluent sampling point	Sampling point 1c, Figure 4C Final sludge (cake) sampling point	Sampling point 1c, Figure 4C Final sludge (cake) sampling point
Sample collection time	AM	PM	AM	PM	N/A	N/A
	^{177}Lu activity (Bq L^{-1})	^{177}Lu activity (Bq L^{-1})	^{177}Lu activity (Bq L^{-1})	^{177}Lu activity (Bq L^{-1})	^{177}Lu activity (Bq/ kg) dry weight	Moisture content (%)
Friday 28/06/2024	Not sampled	Not sampled	Not sampled	Not sampled	185 ± 23	73%
Monday 01/07/2024	<2.3	<3.6	<2	<2	Not sampled	Not sampled
Tuesday 02/07/2024*	188 ± 17	18.6 ± 2.1	<0.94	18.8 ± 1.9	327 ± 35	74%
Wednesday 03/07/2024	220 ± 20	12.8 ± 2.1	69.4 ± 7.1	123 ± 13	263 ± 29	66%
Thursday 04/07/2024	25.6 ± 2.9	<2.8	74.8 ± 7.3	74.4 ± 7.7	129 ± 15	79%
Friday 05/07/2024	<2.1	<1.3	14.6 ± 1.8	5.6 ± 1.4	253 ± 29	72%

*Date of targeted ^{177}Lu treatment.

The results in Table 2 (and shown graphically in Figure 5A) show that the concentration of ^{177}Lu in the crude sewage influent peaks at 188 Bq L^{-1} during the daytime of the treatment day (2 July). During the first night, ^{177}Lu activity concentrations decrease to ~10% of the peak loading, potentially due to the patient sleeping (and hence generating less excrement waste). Thereafter, ^{177}Lu activity concentrations increase again during the day on 3 July

(220 Bq L^{-1}) before reducing during the night and the next day. After 2.5 days, no ^{177}Lu can be detected in the crude sewage influent.

Lutetium is first seen in the final effluent after ~12 hours, as shown in Figure 5A. Here, ^{177}Lu activity concentrations increase to a peak 2-2.5 days after treatment before it then starts to decrease. The final effluent is discharged into the River Cam. This produces a relatively broad peak of ^{177}Lu activity that can be observed between Wednesday 3 July and Thursday 4 July, reaching its peak in the night of Wednesday 3 July (123 Bq L^{-1}). On Friday 5 July, ^{177}Lu levels rapidly drop to just above the limit of the detection (5.6 Bq L^{-1}).

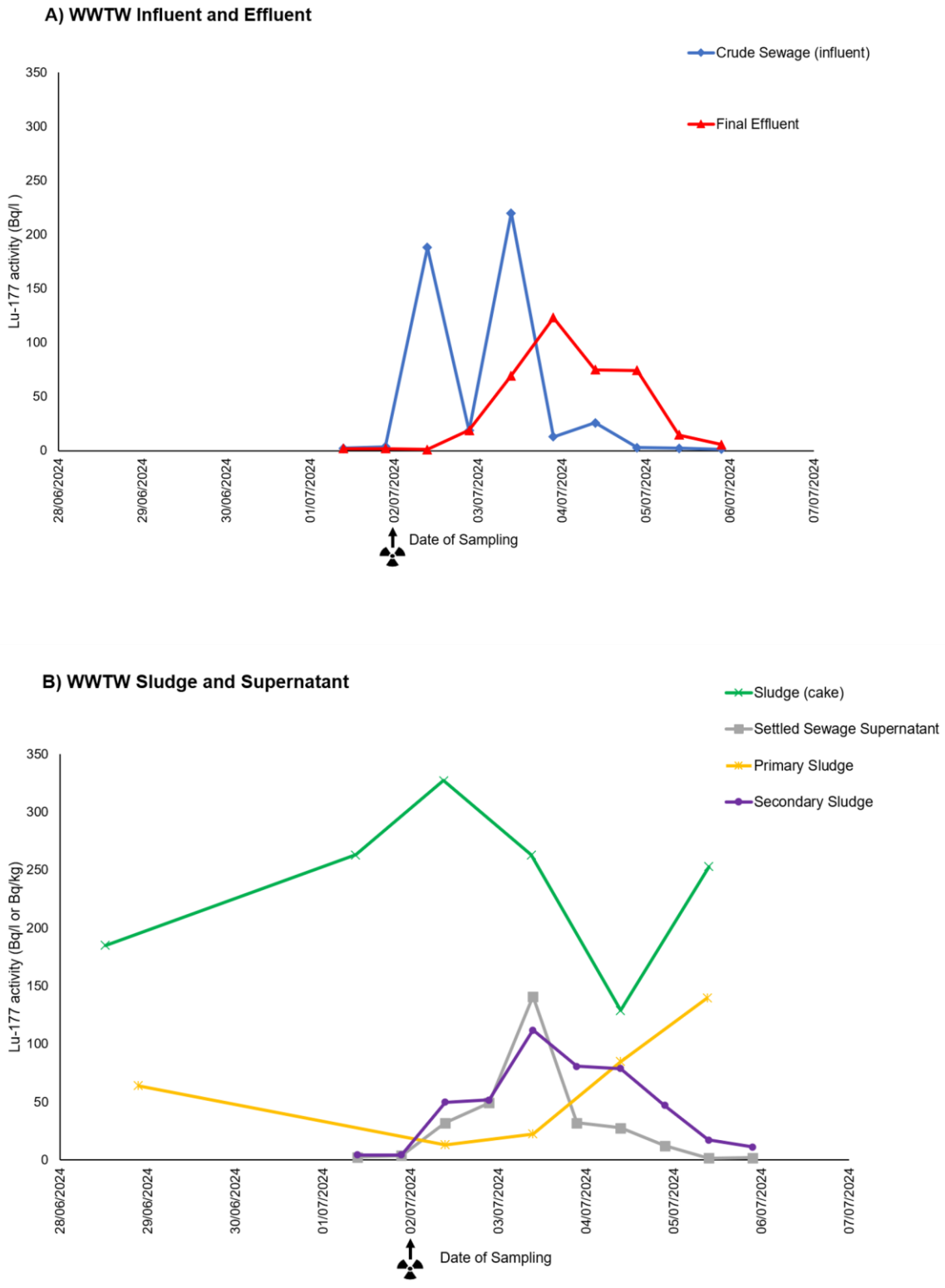


Figure 5: Cambridge WWTW sampling showing ^{177}Lu activity concentrations in A) crude sewage (influent) and final effluent and B) settled sewage supernatant, primary sludge, secondary sludge, and sludge (cake). The trefoil on the horizontal axis indicates the date of the administered ^{177}Lu NeoRay® treatment. Results below the limit of detection (<LoD) are displayed as the LoD value.

Lutetium activities in the sludge (cake) and biosolids do not show a clear correlation with the radiotherapy treatment administration on 2 July. The ^{177}Lu level before the treatment is 185 Bq kg^{-1} dry material, which increases to 327 Bq kg^{-1} (dry) on the day of the treatment. It then fluctuates over the next few days. This behaviour may be attributed to the gradual formation of the sludge cake over time enabling measured ^{177}Lu to have accumulated from multiple treatments prior to the sampling dates. It is known that that treatments took place at Addenbrookes hospital on 24 June (9.7 GBq ^{177}Lu NeoRay®) and 25 June (8.6 GBq ^{177}Lu NeoRay®) (Gillett, 2024). The timeline for the administration of ^{177}Lu treatments, alongside the environmental and Cambridge WWTW sampling dates, are shown in Figure 6.

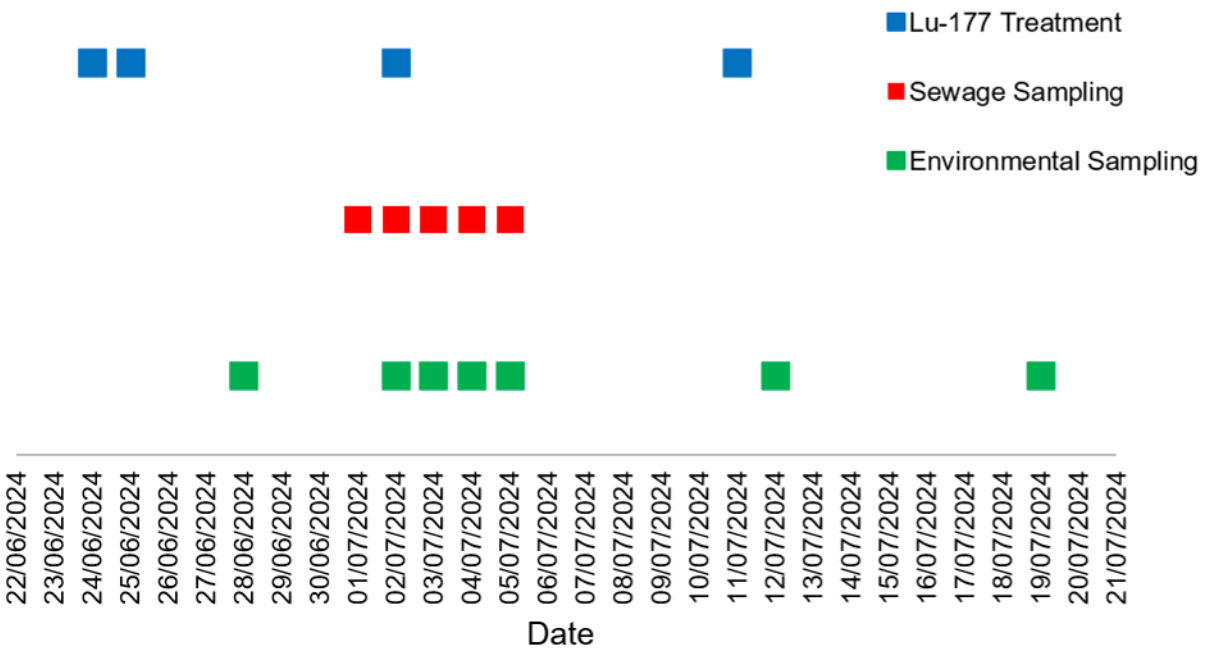


Figure 6: The timeline for the medical ^{177}Lu treatments at Addenbrookes hospital shown alongside the dates of environmental and Cambridge WWTW sampling.

Once the crude sewage influent has passed through a screen to remove large artefacts, it is pumped into the settling tanks where the primary sludge settled. As per Table 2 and Figure 5, the settled sewage supernatant starts to receive ^{177}Lu on the treatment day. The ^{177}Lu activity concentration then slowly builds up to a maximum of 141 Bq L^{-1} one day after the treatment. Over the next 1-2 days, ^{177}Lu activity concentrations decrease again until they are below the limits of detection by Friday 5 July i.e., 3 days post patient treatment.

The supernatant from the primary sludge settling tanks is pumped to the biological treatment tanks, where the secondary sludge is produced. Lutetium accumulation in the secondary sludge showed a similar pattern to the recorded ^{177}Lu levels in the settled sewage supernatant; increasing on the day of the treatment and peaking at 112 Bq L^{-1} one day after treatment before starting to fall. The ^{177}Lu activity is ~80 Bq L^{-1} on Wednesday 3 July night and Thursday 4 July during the day i.e., over a total period of ~24 hours. It then slowly decreases further on Friday 5 July i.e., 3 days post patient treatment.

The primary sludge had a background ^{177}Lu level of 64 Bq L^{-1}, as measured on the Friday before the treatment started. This likely reflects the accumulation of ^{177}Lu in the primary sludge from treatments administered at the hospital prior to the targeted treatment on 2 July (see Figure 5, graph D). Lutetium levels in the primary sludge were lower at 13 Bq L^{-1} and 22 Bq L^{-1} on the treatment day. On the following day, ^{177}Lu levels increase to the highest concentration of 140 Bq L^{-1} measured on Friday 5 July, 3 days post patient treatment. This is reflective of the gradual accumulation of primary sludge which consists of material from before and after the targeted treatment administered on 2 July 2024.

Table 3: ^{177}Lu activity concentrations measured at A) "settled sewage supernatant sampling point", B) "primary sludge sampling point" and C) "secondary sludge sampling point". Results are decay corrected to the sampling date. Uncertainties are quoted at 2 standard deviations based on a total uncertainty budget.

	Sampling point 2a, Figure 4D settled sewage supernatant sampling point	**Sampling point 2a, Figure 4D settled sewage supernatant sampling point**	**Sampling point 2b, Figure 4E Primary sludge sampling point**	**Sampling point 2c, Figure 4F Secondary sludge sampling point**	**Sampling point 2c, Figure 4F Secondary sludge sampling point**
Sampling method	Auto sampler, 12-hour bulk samples	Auto sampler, 12-hour bulk samples	Daily grab sample	Auto sampler, 12-hour bulk samples	Auto sampler, 12-hour bulk samples
Matrix	Supernatant after initial screening	Supernatant after initial screening	Primary sludge	Sewage sludge (secondary)	Sewage sludge (secondary)
Sample collection time	AM	PM	N/A	AM	PM
	^{177}Lu activity (Bq L^{-1})	**^{177}Lu activity (Bq L^{-1})**	**^{177}Lu activity (Bq L^{-1})**	**^{177}Lu (Bq kg^{-1}) dry weight**	**^{177}Lu (Bq kg^{-1}) dry weight**
Friday 28/06/2024	Not sampled	Not sampled	64.1 ± 7	Not sampled	Not sampled

	Sampling point 2a, Figure 4D settled sewage supernatant sampling point	Sampling point 2a, Figure 4D settled sewage supernatant sampling point	Sampling point 2b, Figure 4E Primary sludge sampling point	Sampling point 2c, Figure 4F Secondary sludge sampling point	Sampling point 2c, Figure 4F Secondary sludge sampling point
Monday 01/07/2024	<2.5	<3.9	Not sampled	<4.3	<4.5
Tuesday 02/07/2024*	32.1 ± 3.4	49.4 ± 4.8	13.2 ± 1.6	49.7 ± 5.1	51.8 ± 6.2
Wednesday 03/07/2024	141 ± 15	32.0 ± 3.9	22.6 ± 2.4	112 ± 13	80.8 ± 8.1
Thursday 04/07/2024	27.8 ± 4.0	12.4 ± 3.0	84.9 ± 8.0	78.8 ± 9.3	47.2 ± 6.5
Friday 05/07/2024	<1.7	<1.9	140 ± 13	17.2 ± 2.4	11.3 ± 2.1

*Date of targeted ^{177}Lu treatment.

3.2 Environmental sampling

Two sets of baseline environmental monitoring were conducted during this project. The first took place on 5 March 2024, ~2 months before the targeted treatment date (2 July 2024), and the second took place on 28 June 2024, 4 days before the targeted treatment date. The baseline monitoring locations were the same, as explained in Section 2.1.

The first baseline environmental monitoring on 5 March 2024 established background levels of ^{177}Lu in the environment and the Cambridge WWTW (Table 4 and Figure 7). No ^{177}Lu treatments were administered in the week prior to 5 March, but a series of 3 treatments occurred in January and February (Gillett, 2024):

- 30 January 9.6 GBq [^{177}Lu]-NeoRay®
- 8 February 7.4 GBq [^{177}Lu]-DOTATATE
- 22 February 7.4 GBq [^{177}Lu]-DOTATATE

Accordingly, the first baseline environmental monitoring took place when 2-9 half-lives of ^{177}Lu had passed (depending on which of the three earlier treatments is being considered). This resulted in the decay of between 71% and 99.8% of the earlier ^{177}Lu sources. Of note, a treatment of 9.6 GBq [^{177}Lu]-NeoRay® was administered to a patient on the day of the first baseline environmental monitoring (5 March). However, this treatment was administered in the afternoon, and excreted activity would not yet have reached the Cambridge WWTW at the time of sampling. On this day, no ^{177}Lu was detected in river water samples. Only 3.5 Bq kg^{-1} (dry weight) of ^{177}Lu was detected in the sediment at the discharge point. In addition, no ^{177}Lu was detected in the sediment further downstream.

The second baseline environmental monitoring took place on Friday 28 June i.e., 4 days before the targeted treatment date. Multiple ^{177}Lu treatments were carried out in the weeks before the second baseline environmental monitoring (Gillett, 2024):

- 6 June 7.4 GBq [^{177}Lu]-DOTATATE
- 10 June 9.3 GBq [^{177}Lu]-NeoRay®
- 24 June 9.8 GBq [^{177}Lu]-NeoRay®
- 25 June 8.6 GBq [^{177}Lu]-NeoRay®

During the second baseline environmental monitoring, the ^{177}Lu activity concentration was 20 Bq L^{-1} in the water at the discharge point. Further downstream, a ^{177}Lu concentration of ~5 Bq L^{-1} was measured at both the 500 and 1,000 m sampling points. No ^{177}Lu was associated with the particulate phase in these samples, with the bulk of the activity present in the dissolved phase. The sediment at the discharge point contained no ^{177}Lu, although 46-48 Bq kg^{-1} (dry weight) was detected in the sediment at 500 m and 1,000 m from the discharge point.

Lutetium was detected in the final (treated) effluent 1-1.5 days after the targeted treatment on Tuesday 2 July. A similar delay was observed for the river water (Table 4 and Figure 7). Here, ^{177}Lu activity concentrations in the river water peaked 1-2 days after the treatment, indicating passage through the Cambridge WWTW. Measured ^{177}Lu concentrations at the discharge point were ~25% and 30% of the final effluent concentration, at 26 Bq L^{-1} and 39 Bq L^{-1}, respectively. While ^{177}Lu was diluted further downstream, the same time dependency of activity concentrations was apparent. After 1-2 days, the ^{177}Lu concentration in the water peaked and then decreased by ~50% on Friday 5 July (i.e., 3 days post treatment). All ^{177}Lu was present in a dissolved chemical form, and no ^{177}Lu was detected in the particulate phase.

Lutetium was not observed in the sediment sampled at the discharge point (Table 4 and Figure 7). However, sediment started to accumulate ^{177}Lu at 500 m downstream, which became apparent 1-2 days after treatment. Lutetium concentrations of 48 Bq kg-^{1} and 30 Bq kg^{-1} dry weight was measured for Friday 28 June (i.e., 4 days before the treatment) and Tuesday 2 July (targeted treatment day), respectively. Afterwards, ^{177}Lu activity concentrations increased to ~59 Bq kg^{-1}, 312 Bq kg^{-1}, and 620 Bq kg^{-1} dry weight on

Wednesday 3 July (1 day post treatment), Thursday 4 July (2 days post treatment) and Friday 5 July (3 days post treatment), respectively. For the sampling point located 1,000 m from the discharge point, a similar pattern in ^{177}Lu activity concentrations in the sediment occurred, with an apparent 1-day delay. Here, relatively constant ^{177}Lu concentrations of 46 Bq kg-^{1} and 53 Bq kg-^{1} dry weight was recorded on Tuesday 2 July (treatment day) and Friday 28 June (4 days before the treatment), respectively. Of note, ^{177}Lu was below the limit of detection (LoD) on Wednesday 3 July (1 day post treatment). The activity concentrations then increased to 59 Bq kg^{-1} and 143 Bq kg^{-1} dry weight on Thursday 4 July (2 days post treatment) and Friday 5 July (3 days post treatment), respectively. That is, sediment started to accumulate ^{177}Lu only 2-3 days after the hospital treatment. It should be noted that the 1,000 m sampling point was located just before a weir in the river which could have affected the water flow and/or sedimentation processes. This may have influenced ^{177}Lu partitioning behaviour observed.

Environmental monitoring was undertaken twice more on Fridays for the following two weeks. On Friday 12 July (i.e., 10 days post the monitored treatment on 2 July), ^{177}Lu river water concentrations were at a similar level as recorded on Friday 5 July, 3 days post treatment. Again, no ^{177}Lu was detected in the particulate phase, and was only present in a dissolved form. It should be noted that the measurement on 12 July was 1 day after a new ^{177}Lu treatment (7.3 GBq [^{177}Lu] DOTATATE administered on 11 July). Lutetium was not detected in sediment at any of the 3 sampling points on 12 July. This is consistent with ^{177}Lu (from the targeted treatment date on 2 July) having passed through the environment.

On Friday 19 July, ^{177}Lu was not detected in water at any of the three sampling points or in sediment at the discharge point. This was 17 days after the targeted treatment on 2 July. Lutetium was found in sediment 500 m downstream from the discharge point, specifically at a concentration of 31.5 Bq kg^{-1} dry weight. In contrast, ^{177}Lu was not detected in the sediment 1,000 m downstream. These data collectively highlight the temporal and spatial variations of the environmental monitoring data.

Table 4A: ^{177}Lu activity in freshwater (total, particulate, and dissolved) and sediment at the discharge point to the River Cam. Data are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Matrix	Water – total / Bq L^{-1}	Water – particulate / Bq L^{-1}	Water – soluble / Bq L^{-1}	^{177}Lu in sediment / Bq kg^{-1}	Sediment moisture / %
Tuesday 05/03/2024	<0.84	Not detected	Not detected	3.5±1.3	63%
Friday 28/06/2024	20.2 ± 2.2	<0.39	20.6 ± 2.6	<3.5	51%

Matrix	Water – total / Bq L^{-1}	Water – particulate / Bq L^{-1}	Water – soluble / Bq L^{-1}	^{177}Lu in sediment / Bq kg^{-1}	Sediment moisture / %
Tuesday 02/07/2024*	<1.1	Not detected	Not detected	<2.8	55%
Wednesday 03/07/2024	25.8 ± 2.6	<0.14	24.4 ± 2.6	<15	70%
Thursday 04/07/2024	30.1 ± 3.0	<0.13	30.0 ± 3.1	<9.2	69%
Friday 05/07/2024	14.2 ± 1.7	<0.14	11.7 ± 1.5	<5.3	61%
Friday 12/07/2024	10.5 ± 1.2	<0.13	11.2 ± 1.5	<13	67%
Friday 19/07/2024	<0.9	Not detected	Not detected	<13	69%

*Date of targeted ^{177}Lu treatment.

Table 4B: ^{177}Lu activity in freshwater (total, particulate and soluble) and sediment 500m downstream of the discharge point. Data are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Matrix	Water – total / Bq L^{-1}	Water – particulate Bq L^{-1}	Water – soluble Bq L^{-1}	^{177}Lu in sediment Bq kg^{-1}	Sediment moisture / %
Tuesday 05/03/2024	<0.82	Not detected	Not detected	<2.2	56%
Friday 28/06/2024	5.8 ± 1.1	<0.38	5.8 ± 1.2	48.4 ± 5.6	23%
Tuesday 02/07/2024*	<1.1	Not detected	Not detected	29.6 ± 3.5	28%
Wednesday 03/07/2024	9.1 ± 1.2	<0.13	9.4 ± 1.4	58.9 ± 9.6	54%

Matrix	Water – total / Bq L^{-1}	Water – particulate Bq L^{-1}	Water – soluble Bq L^{-1}	^{177}Lu in sediment Bq kg^{-1}	Sediment moisture / %
Thursday 04/07/2024	8.9 ± 1.2	<0.13	8.8 ± 1.4	312 ± 31	72%
Friday 05/07/2024	4.04 ± 0.87	<0.13	3.4 ± 1.0	620 ± 68	82%
Friday 12/07/2024	4.35 ± 0.72	<0.12	4.12 ± 0.89	<12	37%
Friday 19/07/2024	<0.95	Not detected	Not detected	31.5 ± 7.3	68%

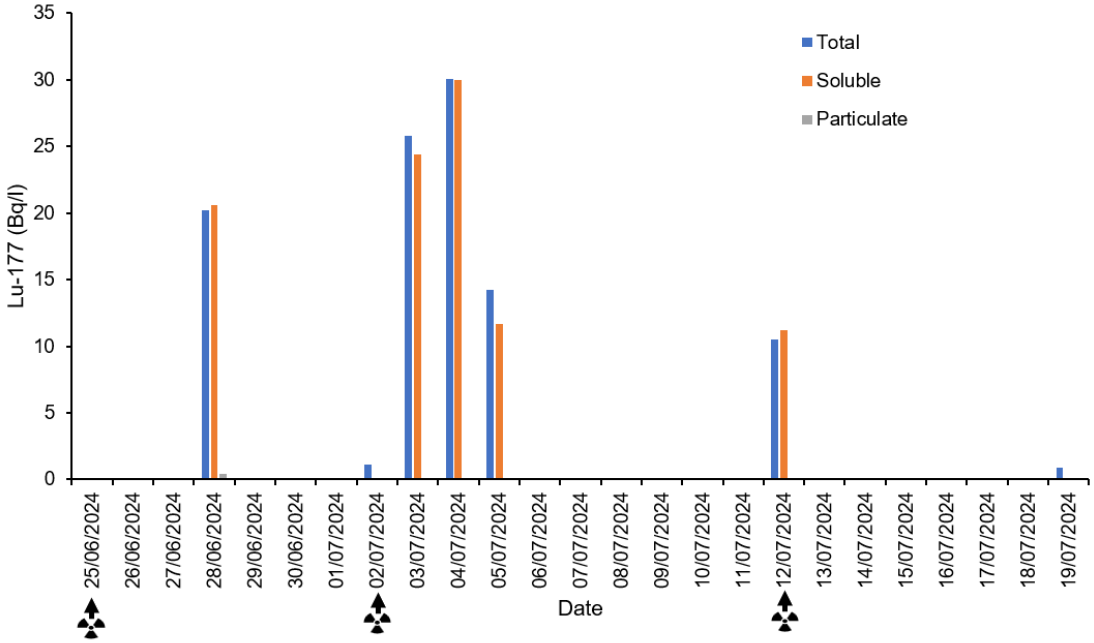
*Date of targeted ^{177}Lu treatment.

Table 4C: ^{177}Lu activity in freshwater (total, particulate and soluble) and sediment 1,000 m downstream of the discharge point. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

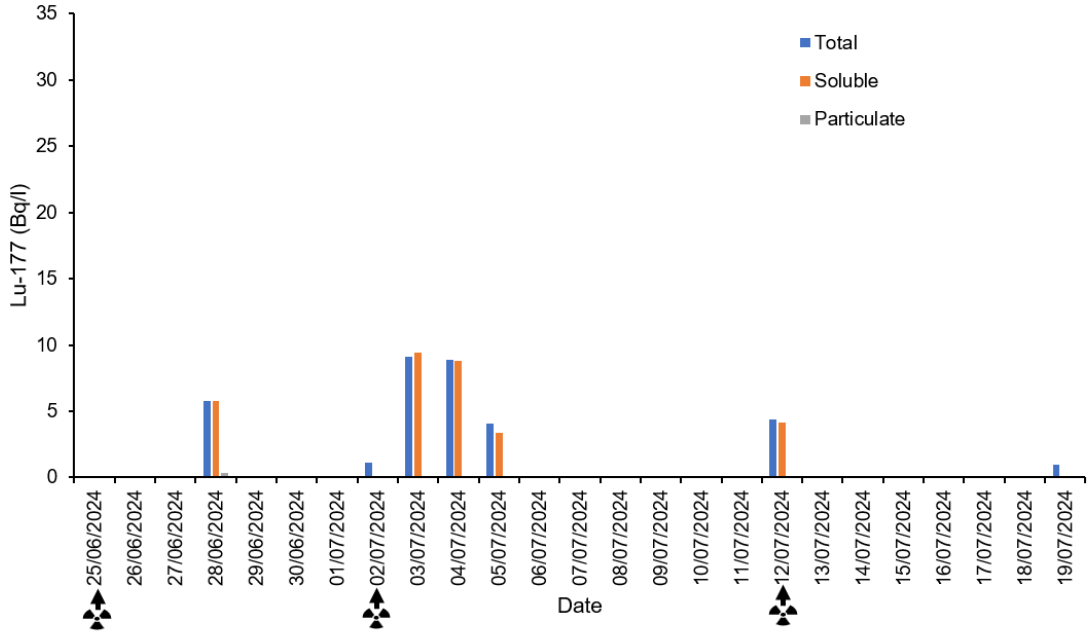
Matrix	Water – total / Bq L^{-1}	Water – particulate / Bq L^{-1}	Water – soluble / Bq L^{-1}	^{177}Lu in sediment / Bq kg^{-1}	Sediment moisture / %
Tuesday 05/03/2024	<0.98	Not detected	Not detected	<2.6	61%
Friday 28/06/2024	4.8 ± 1.1	<0.42	5.0 ± 1.1	46.3 ± 9.7	68%
Tuesday 02/07/2024*	<1.1	Not detected	Not detected	53 ± 12	71%
Wednesday 03/07/2024	5.29 ± 0.96	<0.14	4.6 ± 1.3	<15	79%
Thursday 04/07/2024	6.3 ± 1.0	<0.14	6.6 ± 1.1	59 ± 13	67%
Friday 05/07/2024	2.71 ± 0.89	<0.13	3.35 ± 0.99	143 ± 21	73%
Friday 12/07/2024	2.85 ± 0.65	<0.13	2.81 ± 1	<14	79%
Friday 19/07/2024	<0.79	Not detected	Not detected	<13	79%

*Date of targeted ^{177}Lu treatment.

A) water at discharge point



B) water 500m from discharge point



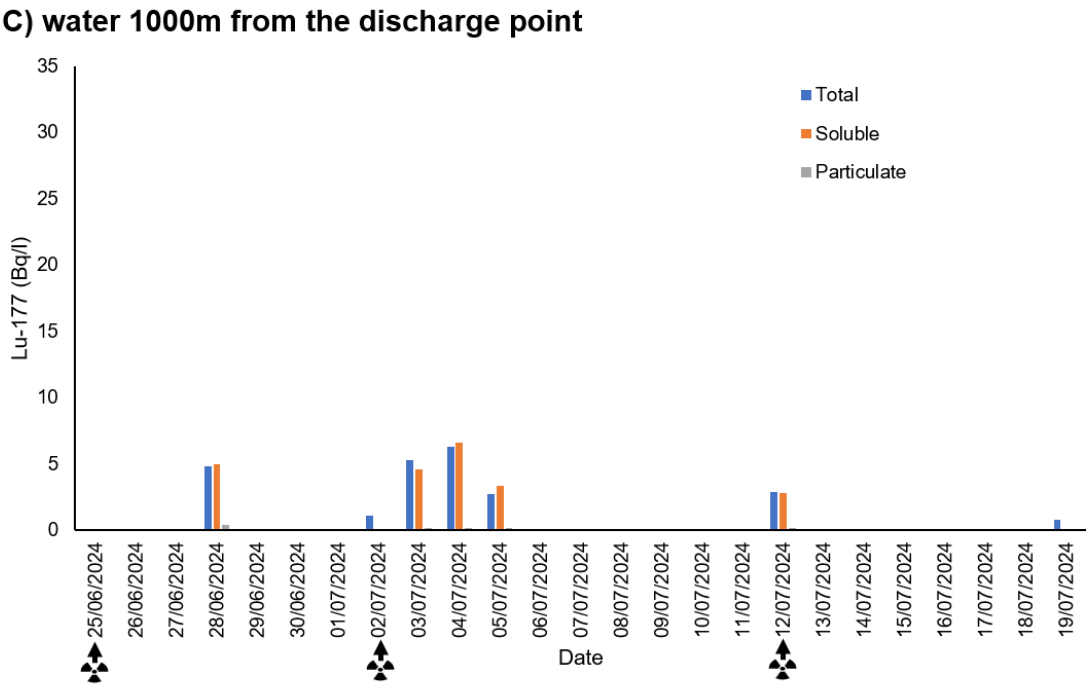


Figure 7: ^{177}Lu activity concentrations measured in water samples from A) the point of discharge, B) 500 m downstream, and C) 1,000 m downstream. The trefoil on the horizontal axis indicates the date of the administered ^{177}Lu NeoRay® treatment. Results below the limit of detection (<LoD) are displayed as the LoD value.

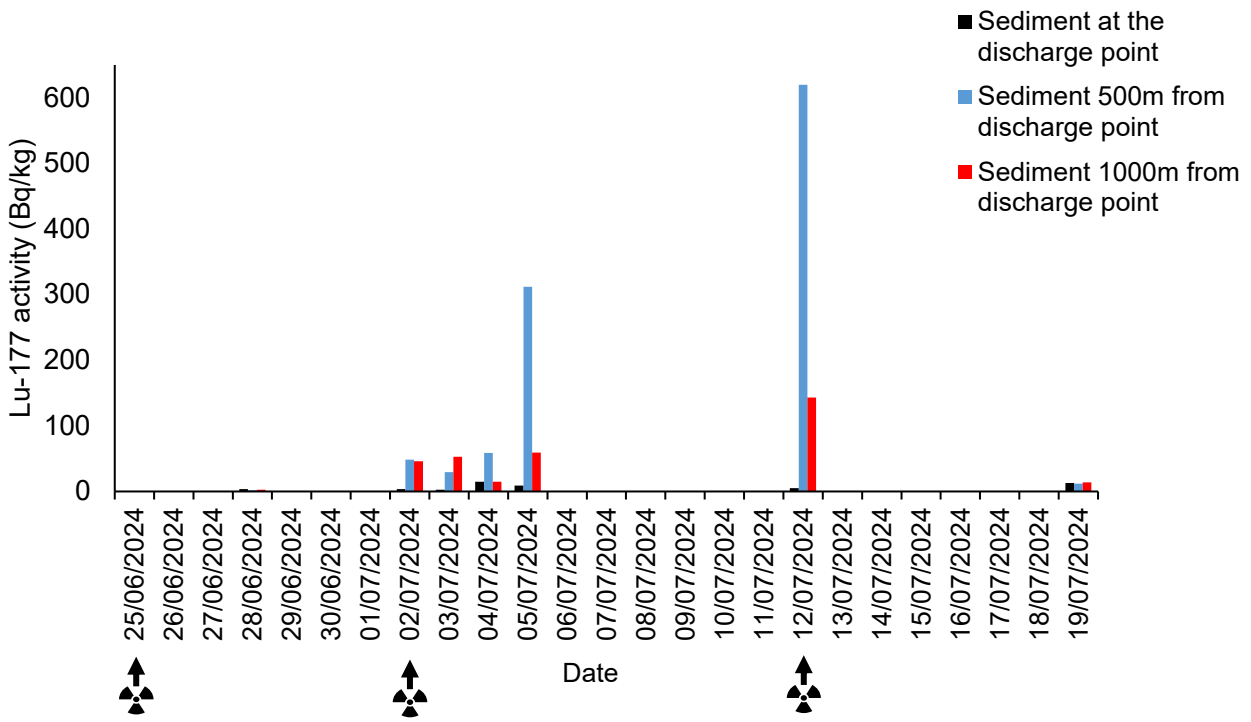


Figure 8: ^{177}Lu activity concentrations measured in sediment at the point of discharge, 500 m downstream and sediment 1,000 m downstream. The trefoil on the horizontal axis indicates the date of the administered ^{177}Lu NeoRay® treatment. Results below the limit of detection (<LoD) are displayed as the LoD value.

4 ^{177}Lu transfer to the freshwater environment

This section describes the calculations performed to determine the percentage of ^{177}Lu administered which reached the freshwater environment in the River Cam (following passage through the Cambridge WWTW).

A single patient was administered with 9.2 GBq ^{177}Lu (NeoRay® form) at Addenbrookes Hospital on the morning of 2 July and was kept in hospital overnight. 8.97 GBq (97%) of the treatment administered had been excreted by the patient before leaving hospital on 3 July. This value was calculated using dose rate measurements taken by hospital staff immediately after the therapy and then before the patient left the hospital. This gives an 'excretion factor' of 0.97 over 24 hours, which is higher than the recommended factor used by the Environment Agency of 0.90 (IPEM, 2018). The slight difference in excretion factors may relate to the chemical form of ^{177}Lu administered to patients. For example, one study reported an 80% excretion rate of ^{177}Lu following patient treatment with ^{177}Lu-DOTATATE (Barquero et al., 2022). In contrast, ~50% of ^{177}Lu has been found to be excreted in the first 4-hours following treatment with ^{177}Lu PSMA (Chipiga et al., 2023). Excretion after the first 4-hours post-treatment was not reported in this investigation. Collectively, these data suggest that ^{177}Lu the excretion factors can vary widely, depending on the specific type of radiotherapy treatment administered.

The monitoring results for ^{177}Lu in the final effluent from the Cambridge WWTW are reported in Table 2. The results relate to 12-hour bulk samples, corresponding to one day (8 am to 8 pm) and night (8 pm to 8 am) samples, such that midpoints of samples corresponded to noon and midnight. Lutetium was first detected in final effluent in the second 12-h bulk sample on 2 July (targeted treatment date). Activity concentrations then remained above detection limits for the remainder of the sampling period (Figure 5).

An initial pulse of ^{177}Lu was detected in the first 12-hour bulk sample, corresponding to the morning of patient administration, as shown in Figure 9. This finding indicates rapid transport of effluent from the hospital to the Cambridge WWTW, ruling out any notable loss due to radioactive decay from the point of administration prior to arrival at the WWTW. The first measurable ^{177}Lu in final effluent occurred in the second 12-hour bulk sample taken on 2 July, implying relatively fast transport of ^{177}Lu through the Cambridge WWTW to final effluent. Finer resolution of the effluent residence time was not possible from the data due to the aggregation of influent and effluent samples over 12-hour intervals.

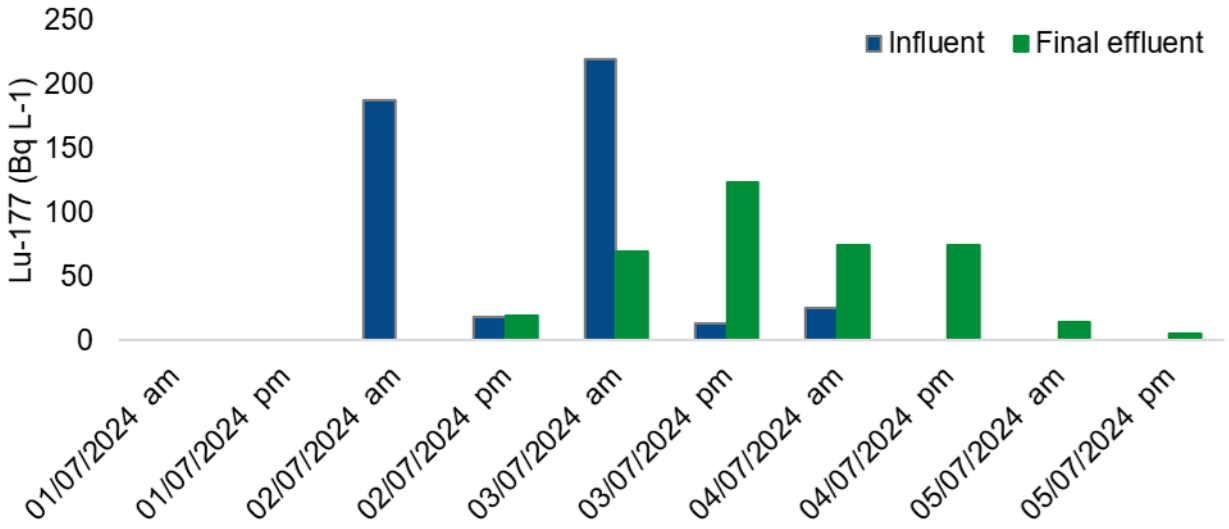


Figure 9: ^{177}Lu activity concentrations in 12-hour bulk samples of unfiltered crude sewage (influent) and final effluent collected from the Cambridge WWTW.

Daily volumetric flow rates through the Cambridge WWTW corresponding to the sampling period were not available. Consequently, it was necessary to apply an estimated site-specific flow rate to calculate the total amount of ^{177}Lu transported through the Cambridge WWTW to the final effluent (based on measured activity concentrations in the final effluent samples). The volumetric flow rates used were based on daily measurements at the Cambridge WWTW in 2022. Here, the average volumetric flow rate was 50,000 m^3 d^{-1}, with lower and upper flow rates of 37,000 m^3 d^{-1} and 77,000 m^3 d^{-1}, respectively. Of these, only the lower flow rate of 37,000 m^3 d^{-1} is consistent with the measured radionuclide concentrations at the Cambridge WWTW in this project and the total activity that was excreted following a single treatment. Using higher flow rates would imply that more radioactivity was present in the WWTW than was known to have been administered at the hospital. Furthermore, there was minimal precipitation in the month prior to the sampling suggesting that it is reasonable to apply the minimum flow rate value (University of Cambridge, 2024). The default IRAT2 site specific volumetric flow rate for the Cambridge WWTW is 36,000 m^3 d^{-1}, which is consistent with the reported minimum value.

The average ^{177}Lu concentration in final effluents, corresponding to the seven 12-hour bulk samples (equivalent to 3.5 days of sampling), was 54.4 Bq L^{-1}. The range of the measured values was 5.6-123 Bq L^{-1}, where measurements below the limits of detection were excluded from these calculations. The total ^{177}Lu activity (Bq) in the final effluent (A_{eff}) was then calculated according to the following equation:

$$A_{eff} = C_{eff} F T_{eff}$$

where C_{eff} is the average concentration in the final effluent (Bq L^{-1}), F is the flow rate through the WWTW (L d^{-1}), and T_{eff} is the time (days) over which ^{177}Lu is detected in the final effluent. Adopting a minimum volumetric flow rate of 37,000,000 L d^{-1} (corresponding to the low volumetric flow rate of 37,000 m^3 d^{-1}) over 3.5 days, yields a total ^{177}Lu activity

of ~7 GBq in final effluent discharged to the River Cam. The percentage of administered ^{177}Lu activity reaching the freshwater environment (E) is then calculated as:

$$E = \frac{A_{eff}}{A_{adm}}\%$$

where A_{adm} is the amount of ^{177}Lu administered (Bq). Reflecting that 9.2 GBq had been administered to the patient, 76% of this was determined to have reached the freshwater environment. For comparison, use of default IRAT2 site specific volumetric flow rate for the Cambridge WWTW gives a comparable 74% of administered activity reaching freshwater. This is perhaps not surprising given that the default IRAT2 volumetric flow rate closely matches the measured volumetric flow rate used in the calculation.

5 Determining a ^{177}Lu sewage sludge partitioning factor

This section describes the calculations performed to determine a sludge partitioning factor for ^{177}Lu in the Cambridge WWTW. As previously noted, a sludge partitioning factor value refers to the distribution of radionuclides between different phases or components of a sewage sludge management system. For this project, it is the distribution between liquid and sludge phases within the Cambridge WWTW. That is, the sludge partitioning factor aids understanding of how ^{177}Lu is partitioned during the treatment and disposal of sewage sludge. Such a factor provides important information on the inputs for IRAT2, as used to assess doses for different exposure groups (e.g., an angler or farming family where sewage sludge is applied to land for crop production).

The sludge partitioning factor was estimated based on decay-corrected measured ^{177}Lu activity concentrations in the influent and effluent passing through the Cambridge WWTW. The average ^{177}Lu concentration in the unfiltered raw sewage influent to the WWTW was 93 Bq L^{-1}. This value is based on the results presented in Table 2 for the five 12-h bulk samples for which ^{177}Lu levels were above the LoD. The following equation was used to determine the total ^{177}Lu activity in the unfiltered raw sewage influent (A_{raw}) which is consistent with the equation to calculate the ^{177}Lu activity in the final effluent:

$$A_{raw} = C_{raw} V T_{inf}$$

where C_{raw} is the average ^{177}Lu concentration (Bq L^{-1}) in raw sewage influent, V is the flow rate through the WWTW (L d^{-1}) and T_{inf} is the time (days) over which ^{177}Lu is detected in the raw sewage influent. Assuming a consistent flow rate (37,000,000 L d^{-1}) through the WWTW and a period of 2.5 days (corresponding to the five 12-hour bulk samples in which ^{177}Lu activity concentrations were above the (LoD)), the total activity entering the WWTW in raw sewage is calculated as 8.5 GBq. For comparison, a comparable total ^{177}Lu activity in the raw sewage influent of 8.4 GBq is calculated if the IRAT2 site-specific volumetric flow rate of 36,000 m^3 d^{-1} (36,000,000 L d^{-1}) is applied for the Cambridge WWTW.

Of the 8.5 GBq activity entering the Cambridge WWTW, 7 GBq was calculated to reach the final effluent. The ^{177}Lu partitioning factors to final effluent (F_{eff}) and to sludge (F_{slu}) (both unitless) are then calculated according to the following two equations:

$$F_{eff} = \frac{A_{eff}}{A_{raw}}$$

$$F_{slu} = 1 - F_{eff}$$

The calculated ^{177}Lu partitioning values are shown in the table below.

Table 5: Calculated ^{177}Lu partitioning factors for final effluent and sludge.

	Partitioning factor (no unit)
Effluent	0.82
Sludge	0.18

The calculated sludge partitioning factor is lower than the default value (0.5) currently applied in IRAT2, for which Ce is the typical analogue of choice for Lu (see Section 8 in Mobbs et al., 2026). No ^{177}Lu specific partitioning factors (or data to support their calculation) were identified during the Environment Agency transfer parameter review. However, a previous study reported total and dissolved lanthanide element concentrations (including both Lu and Ce) in both inflow and outflow from 6 municipal WWTWs in Canada (Turcotte et al., 2022). The results from this Canadian study indicated that WWTWs were more effective at removing Lu (and Ce) from the particulate phase than from the dissolved phase. This information is reproduced in the table below.

Table 6: Removal efficiency of total and dissolved Lu and Ce by 6 WWTWs, as defined as the effluent: influent concentrations (from Turcotte et al., 2022).

Element	Matrix	Average effluent removal factor	Range
Lu	**Total**	0.3	0.2-0.5
Lu	**Dissolved**	0.9	0.8-1.0
Ce	**Total**	0.04	0.02-0.1
Ce	**Dissolved**	0.4	0.1-0.9

Comparison of the calculated effluent removal factors for Lu with those for Ce show that retention of Ce within the WWTW was considerably more effective than for Lu. This was the case for both total and dissolved phases. These findings are supported by other publications on the behaviour of the lanthanide elements, where the heavy lanthanide elements (i.e., Lu) were found to be less particle reactive than light lanthanide elements (i.e., Ce) (Sholkovitz, 1995; Piper et al., 2013). Accordingly, Lu remains in the dissolved fraction to a greater extent than the other lanthanides. The literature evidence suggests that Lu may behave differently from its IRAT2 assumed analogue, Ce (and other lanthanides), in wastewater environments. However, the impact of the Lu chemical form on its behaviour and associated removal efficiencies requires further investigation.

No data were identified from available literature from which further analysis could be undertaken on the quantities of ^{177}Lu administered to patients that ultimately reached

freshwater. Nonetheless, some evidence is available that supports the finding that ^{177}Lu excreted from the patient, largely remains in dissolved form in wastewater and is transported through a WWTW to freshwater. As further detailed in Section 4, only a small fraction of the discharged radioactivity is retained in sludges in the WWTW. An investigation into the partitioning behaviour of the 14 lanthanide elements at multiple Canadian WWTWs found that Lu had the lowest affinity for solid phases (Turcotte et al., 2022). A general trend was also observed where a notable decrease in the solid phase concentration occurred from the lightest (e.g., Ce) to the heaviest (Lu) lanthanide elements (Turcotte et al., 2022). Other studies have also reported that Lu exists predominantly in the dissolved form in rivers (Sholkovits, 1995; Chudaev et al., 2016). In contrast, Ce readily binds to organic matter, particulates, and river colloids. It should be noted that these studies examined the behaviour of lanthanide elements in chemical forms that were distinct from those associated with ^{177}Lu in radiopharmaceuticals. Caution is therefore required when using these literature data to explain the monitoring results of this project.

6 Determining a ^{177}Lu freshwater-sediment distribution coefficient

This section describes the calculations performed to determine the distribution of ^{177}Lu between freshwater sediments and water in brooks and/or rivers receiving ^{177}Lu discharges. This information has been used to derive a freshwater-sediment K_d value.

In general, a sediment K_d value can be used to describe how radionuclides may partition between water and suspended matter. It is expressed as the concentration ratio of the radionuclide in the particulate phase to that in the dissolved phase under equilibrium conditions (usually in Bq kg^{-1} of suspended particulate matter per Bq L^{-1}) (IAEA, 1994; 2010). For dose assessment, this parameter is important as it can predict the activity concentration present in the water (for internal exposure from consumption of drinking water and uptake into fish and other aquatic species which may also be consumed by people) and sediment (for external exposure to people and non-human biota).

Lutetium analysis is not routinely undertaken in environmental monitoring programmes. The Environment Agency therefore undertook limited sampling and analysis in 2021/22 to determine if ^{177}Lu could be detected in the environment and to obtain indicative values of ^{177}Lu activity concentrations (in water and sediment) following treatment administration. In this early study, sediment and water samples were collected in 2 separate campaigns at a location in London to target multiple hospital treatment days and this provided temporal information on ^{177}Lu distribution over a localised area. Lutetium was detected in both water and sediment, where measured concentrations in the latter ranged from 6.2 – 51.8 Bq kg^{-1}.

A comparison of ^{177}Lu activity concentrations in bulk water and sediment from the same location indicated a markedly different behaviour than predicted by a K_d value of 220,000 L kg^{-1}, as currently used in IRAT2. In contrast with the London study, this project focused on a single hospital discharge (Addenbrookes hospital) and the Cambridge WWTW, with environmental samples of freshwater and sediment collected systematically to evaluate the fate and behaviour of ^{177}Lu in the freshwater environment. The freshwater samples were measured for total, particulate, and soluble components for ^{177}Lu activities.

The freshwater-sediment K_d (L kg^{-1}) value was determined from the measured suspended particulate and soluble ^{177}Lu activity concentrations (in units of Bq L^{-1}) in water samples. Here, samples were collected from the point of discharge from Cambridge WWTW into the River Cam, and at distances of 500 m and 1,000 m downstream, using the equation below:

$$K_d = \frac{C_{part}}{C_{filt}}$$

where $C_{part}$is the ^{177}Lu activity associated with suspended particulates (Bq kg^{-1}) and C_{filt} is the ^{177}Lu activity concentration in filtered water (Bq L^{-1}). The term C_{part} (Bq kg^{-1}) was

calculated from the ^{177}Lu activity associated with filtered particulates (C_{filt}, Bq L^{-1}) and suspended sediment load S (kg L ^{1}) according to the following equation:

$$C_{part} = \frac{C_{fp}}{S} \times 10^6$$

where C_{fp} is the ^{177}Lu activity concentration on filtered particulates (Bq L^{-1}) and S is the suspended sediment load (mg L^{-1}).

It should be noted though that ^{177}Lu activities associated with the filtered particulate fraction (C_{fp}) were below the LoD for all samples. Moreover, no ^{177}Lu was detected in either water or filtered particulate for two samples (2 July and 19 July). For samples where ^{177}Lu was detected in water but below the LoD in filtered particulate, it was assumed that filtered particulate ^{177}Lu concentrations were equal to the LoD. This was done to allow a freshwater-sediment K_d to be estimated. However, this is a precautionary assumption as the actual ^{177}Lu concentration in suspended particulates will be lower than the LoD. A less precautionary assumption was also applied in the K_d calculations whereby the suspended particulate concentrations were assumed to be half of the LoD (i.e., 0.5 LoD).

The suspended sediment load in river water (S) was measured in three 2 L river water samples (one at each sampling location). The results are shown in the table below.

Table 7: Measured suspended sediment load in River Cam water samples.

Location	Suspended sediment load (mg L^{-1})
Point of treated effluent discharge from the WWTW	9.0
500 m downstream	0.3
1,000 m downstream	9.3

The data show that the suspended sediment loads are consistent at the point of discharge and 1,000 m downstream (~9 mg L^{-1}). In contrast, the mid-point sample was almost devoid of particulates. A suspended sediment load of 9 mg L^{-1} was therefore used as the basis for the estimation of ^{177}Lu activity (Bq kg^{-1}) associated with suspended particulate sediment (C_{part}) at each sample location. Upper and lower bounds were also calculated, assuming suspended sediment loads of 5 and 20 mg L^{-1}, respectively. Such loads are judged to be appropriate for clear river water and are consistent with a measured suspended sediment load of 9 mg L^{-1}. The values come from expert judgement of the project contributors based on previous studies of a similar nature to determine freshwater-sediment K_d values.

For this project, freshwater-sediment K_d values were derived as the best estimate, lower and upper suspended sediment loads at each sampling location, and for both LoD and 0.5 LoD filtered particulate ^{177}Lu activity concentrations. Results were obtained for 3

locations (0 m, 500 m, and 1,000 m from the discharge point) and are presented in Table 8A and 8B.

Table 8A: Calculated best estimate, upper and lower bound ^{177}Lu freshwater-sediment K_d values from River Cam water samples. Calculations are based on 3 assumed suspended sediment loads to provide the range of K_d values. It is assumed that the suspended particulate concentration is equal to LoD.

Sampling location	K_d (L kg^{-1}) assuming 5 mg L^{-1} (lower bound)	K_d (L kg^{-1}) assuming 9 mg L^{-1} (best estimate)	K_d (L kg^{-1}) assuming 20 mg L^{-1} (upper bound)
Point of discharge	2,100	1,170	526
500 m downstream	6,460	3,590	1,610
1,000 m downstream	8,830	4,900	2,210

Table 8B: Calculated best estimate, upper and lower bound ^{177}Lu freshwater-sediment K_d values from River Cam water samples. Calculations are based on 3 assumed suspended sediment loads to provide the range of K_d values. It is assumed that the suspended particulate concentration is equal to 0.5 LoD.

Sampling location	K_d (L kg^{-1}) assuming 5 mg L^{-1} (lower bound)	K_d (L kg^{-1}) assuming 9 mg L^{-1} (best estimate)	K_d (L kg^{1}) assuming 20 mg L^{1} (upper bound)
Point of discharge	1,050	526	263
500 m downstream	3,230	1,610	807
1,000 m downstream	4,410	2,210	1,100

As the actual ^{177}Lu concentrations in filtered particulate were lower than the LoD, it can be concluded that the freshwater-sediment K_d value is likely to lower than this study's calculated range. Furthermore, downstream values are likely to be more representative of the actual K_d value as these better account for mixing and adsorption processes. Giving more weight to results from the downstream samples, a best estimate freshwater-sediment K_d value of 3,000 L kg^{-1} is proposed. The lower and upper range is 1,000 and 5,000 L kg^{-1}, respectively. The best estimate is ~2 orders of magnitude lower than the IRAT2 default value (220,000 L kg^{-1}), which is based on Ce as a chemical analogue for Lu. This result suggests that Ce may not be an appropriate analogue for Lu for environment dose

assessments. This possibility is explored further in Section 7. The suitability of the current IRAT2 methodology for ^{177}Lu dose assessments is examined further in Section 7.

Examination of the literature did not reveal any published K_d values for ^{177}Lu in freshwater. However, data are available from 2 publications for Lu (as a "free" Lu^{3+} ion, rather than in a chelated radiopharmaceutical form) in suspended sediment and freshwater. Parameter values could be calculated from these studies, and the data are shown in the table below.

Table 9: Lu K_d calculated from published data on natural lanthanide element suspended particulate matter and filtered river water.

Location (reference)	Kd (L kg^{-1}) (range)	Comment
Yangtze River, China (Zhang et al., 1998)	100,000 (67,000 - 130,000)	Average K_d for lanthanide element in filtered water and suspended sediments from 7 locations along a river. Areas affected by municipalities and WWTWs were avoided.
Athabasca River, Canada (Turcotte et al., 2022)	260,000 – 290,000	Based on 2 sampling locations and a suspended particulate load of 11 mg L^{-1}.

Several reports in the literature presented potentially useful information but were missing key details. For example, Atakoglu and Yalcin (2022) described the use of lake sediment samples but only 3 samples had detectable Lu (elemental) values, ranging from 0.0037-0.0114 Bq kg^{-1} (Atakoglu and Yalcin, 2022). The researchers did not detect Lu in water samples so the data cannot be used to help derive a freshwater-sediment K_d value.

Literature-based K_d values determined for lanthanide elements in natural chemical forms broadly align with the IRAT2 default value. This is clearly not the case for the K_d values derived in this project. Different chemical forms of the same radionuclide can behave differently in the environment, which may explain the inconsistency. Of note, the available information on the IAEA SRS-19 has not identified any ^{177}Lu specific values (IAEA, 2001).

7 IRAT2 modelling and field measurement comparisons

The Environment Agency uses IRAT2 for initial assessments of radionuclide discharges to the environment, which includes ^{177}Lu (Environment Agency, 2022a, 2022b). Although these models use the best available data for radionuclide behaviour in a typical WWTW system and the wider environment, it is recognised that there are uncertainties in certain parameters. This is particularly the case for less well studied elements such as Lu. Key element-specific parameters that are uncertain for ^{177}Lu include the sludge partitioning factor and the freshwater sediment sorption K_d value. The environmental sampling of ^{177}Lu described in this project provides new data that can be used to estimate these transfer parameters for the IRAT2 models. Such field data have been used below to review the underpinning calculations in IRAT2. This information can then be used to calculate revised environmental concentrations and doses following discharges of ^{177}Lu to the environment.

7.1 ^{177}Lu source and discharge pathway characteristics

7.1.1 Source term

During this project, 9.2 GBq of ^{177}Lu (NeoRay® form) was administered to a single patient. An ‘excretion factor’ of 0.9 was used to calculate the ^{177}Lu activity discharged to sewer, based on a literature recommendation (IPEM, 2018). This would equate to a discharge of 8.3 GBq from the hospital, per treatment (assumed to be excreted over 1 day). This study was timed so that only a single treatment of ^{177}Lu would be detected in the raw influent and treated effluent of the Cambridge WWTW. However, it has been noted that treatments can be more frequent. For the purposes of estimating an annual dose using IRAT2, an annual discharge needs to be assumed. An annual discharge of 1 TBq y^{-1} corresponds to ~2.5 treatments per week, which is almost double the frequency that has been reported for the hospital. However, this discharge rate may align more closely with the predicted increase in ^{177}Lu therapies expected in the future. A value of 1 TBq y^{-1} has therefore been assumed for the purpose of the dose assessments undertaken in this section.

7.1.2 Wastewater treatment works

In general, ^{177}Lu behaviour in a WWTW is modelled using various parameters, where generic and site-specific values are available in IRAT2. Important assumptions that can be examined using data gathered during the sampling exercise include the flow rate of the sewage through the works, the partitioning of ^{177}Lu between effluent and sludge, and the characteristic duration of treatment of effluent. Together, these factors control the proportion of the ^{177}Lu present in WWTW that is discharged to river and the proportion that is retained in sewage sludge. IRAT2 data and site-specific parameter values, (estimated using the monitoring data collected in this study), are shown in the table below.

Table 10: IRAT2 and site-specific parameters for WWTW effluent discharges to river.

Parameter (units)	IRAT2 Value	Estimated site specific value
Sewage flow rate (m^3 d^{-1})	60 (default) 36,000 (site-specific)	50,000 (37,000 – 77,000)*
Sludge partitioning factor for Lu (unitless)	0.5	0.18#
Effluent residence time (h)	15	24-36

* Sewage flow data was based on daily reported measurements for 2022.

#Estimated using the decay-corrected measured ^{177}Lu activity concentrations in the influent and effluent passing through the Cambridge WWTW, described fully in Section 3.

As previously described, daily sewage flow data for the dates on which sampling was undertaken was not available. Only the minimum reported flow rate of 37,000 m^3 d^{-1} accords with the measured radionuclide concentrations at the Cambridge WWTW (Section 3) and the total ^{177}Lu activity that was excreted following a single treatment (Section 3). A higher flow rate implies more radioactivity present than was known to have been administered. Minimal precipitation occurred in the month prior to this project's sampling, suggesting that it is reasonable to take the minimum value for the raw sewage flow rate.

The sludge partitioning factor was estimated based on measured ^{177}Lu activities in the influent and effluent, assuming the volumetric flows of raw sewage and treated effluent are approximately equal, as described in Section 3. Such an assumption may constitute an oversimplification of the WWTW process but is deemed appropriate for the calculations required in this study.

The effluent residence time was not measured directly but was approximated from the difference in time that ^{177}Lu was first detected in the raw sewage and the effluent. It should be noted that bulk 12-hour sampling was used to generate this data, meaning any finer resolution was not possible. The sludge residence time before its use in agriculture (a likely fate of the generated sludge material for the WWTW in question) is assumed to be 17 days in IRAT2. No alternative site-specific data were available for this parameter.

7.1.3 River

The river flow rate and the freshwater-sediment K_d are key parameters in determining the fate of ^{177}Lu in surface waters to which the treated effluent has been discharged to. IRAT2 default parameters and estimated site-specific values used in this study are shown in the table below (for comparison).

Table 11: River flow rate and ^{177}Lu freshwater-sediment K_d values. Default IRAT2 and site specific (River Cam) data are provided.

Parameter (units)	IRAT2 Value	Estimated site-specific value
River flow rate (L s^{-1})	1,000	3,600 (900 – 10,000)*
Lu freshwater-sediment K_d (L kg^{-1})	220,000	3,000 (1,000 – 5,000)#

*Data from records corresponded to ~5,000 m downstream of the effluent discharge, taken from 1936-1987. More recent data are not available for the stretch of River Cam of interest. The mean flow rate, as well as 5th and 95th percentiles (in brackets) are given.

#Estimated from measurement data at the point of discharge, 500 m, and 1,000 m downstream of the river. It was assumed that ^{177}Lu concentrations in sediment were equal to the LoD and that suspended sediment load in the river water was 9 mg L^{-1}. This is based on measurements described in Section 6.

The site-specific river flow rates given in Table 11 are taken from historical data for a measurement point ~5,000 m downstream of the discharge (UK Centre for Ecology & Hydrology, 2023). The freshwater-sediment K_d value was estimated from measurements made at various points downstream of the Cambridge WWTW. Given that these measurements were made in the summer after a dry period, river flows lower than the mean shown in Table 11 are likely.

The range of freshwater-sediment K_d values estimated for ^{177}Lu contains uncertainties in the underpinning measurement data. Although ^{177}Lu was measurable in the river water, its concentration in the filtered particulate was below the LoD. A ^{177}Lu activity concentration equal to the LoD was assumed for the filtered particulate. Since the actual ^{177}Lu concentration in filtered particulate will be lower than the LoD, the actual freshwater-sediment K_d is likely to be lower than the range presented in Table 11. Of note, the range of values corresponds to measurements at 3 locations (the point of discharge, 500 m downstream, and 1,000 m downstream). The lowest freshwater-sediment K_d value is for the discharge point where measured ^{177}Lu activities in the river water are highest. The highest K_d value was obtained for 1,000 m downstream where the ^{177}Lu activities in the water were ~25% of those at the discharge location. Because the ^{177}Lu sediment concentration is taken as the same LoD at all 3 sampling locations, the different water concentrations mean that the estimated K_d value at the downstream location is necessarily higher than that at the discharge location.

7.2 ^{177}Lu concentrations in the Cambridge WWTW

Lutetium concentration measurements were made for the raw sewage, treated effluent, and sludge at the Cambridge WWTW. These can be compared with values calculated

using the IRAT2 model based on site specific parameter information. The ^{177}Lu activity concentration in raw sewage C_{raw} (Bq kg^{-1}) is calculated in IRAT2 as follows (Environment Agency, 2022b):

$$C_{raw} = \frac{Q}{V\ \rho_{raw}}$$

where *Q* is the radionuclide discharge rate (Bq d^{-1}), *V* is the flow rate of sewage into the WWTW (m^3 d^{-1}) and ρ_{raw} is the density of raw sewage (kg m^{-3}). Using a discharge rate of 8.3 GBq d^{-1} and a site-specific flow rate of raw sewage of 37,000 m^3 d^{-1} (Table 10) yields an average ^{177}Lu activity concentration of 220 Bq L^{-1} in raw sewage. For this calculation, a raw sewage density of 1 kg m^{-3} was assumed. The calculated activity concentration compares well with the measured values of 188 Bq L^{-1} and 220 Bq L^{-1} in Table 2.

The ^{177}Lu activity concentration in the effluent, C_{eff} (Bq L^{-1}), is calculated in IRAT2 with the following equation:

$$C_{eff} = C_{raw}\ F_{eff}\ e^{-\lambda\ t}$$

where F_{eff} is the partitioning of ^{177}Lu to effluent rather than sludge (unitless), λ is the decay constant for ^{177}Lu (~0.0004 hours^{-1}) and *t* is the effluent treatment time (hours). This calculation assumes an effluent density of 1 kg L^{-1} (Environment Agency, 2022b). As the decay-corrected ratio of the effluent concentration to raw sewage has been used to derive the partitioning factor described previously, this equation will give the same result as the measured value when using a partitioning factor of (1 – sludge partitioning factor) 0.82. A comparison is therefore not needed.

The sludge partitioning factor is also used to calculate the ^{177}Lu activity concentration in sludge C_{slu} (Bq kg^{-1}) with the following equation:

$$C_{slu} = C_{raw}\ F_{slu}\ \frac{SS_{slu}}{SS_{raw}}\ e^{-\lambda\ t}$$

where F_{slu} is the partitioning of the element to sludge rather than effluent (unitless), SS_{slu} and SS_{raw} (both unitless fractions) are the suspended solid content of raw sewage and treated sludge, respectively. IRAT2 considers a solid fraction of raw sewage of 0.0005 and a solid fraction of sludge of 0.05. The former was not measured at the Cambridge WWTW, but an average of the latter was determined as 0.27. Using this value, a sludge partitioning factor of 0.18 (from Table 10), and neglecting radioactive decay (the sludge was sampled daily), the ^{177}Lu activity concentration in sludge is calculated to be 20,000 Bq kg^{-1}. This value is significantly higher than the measured range of 130-330 Bq kg^{-1} (dry) in this study. It is worthwhile to note that a ^{177}Lu activity concentration of 190 Bq kg^{-1} was measured prior to the administration of the treatment. The background level is similar to the measured sludge concentrations and suggests that ^{177}Lu had not reached the sludge that was sampled. This phenomenon would account for the significant discrepancy between the calculated and measured ^{177}Lu activity concentrations in the sludge (~2 orders of magnitude difference).

7.3 ^{177}Lu river concentrations

The measured ^{177}Lu activity concentrations in the River Cam can be compared with the values that are estimated using a simple dilution model for a river, like the one used in IRAT2. Such a comparison can help inform the selection of the freshwater-sediment K_d value for ^{177}Lu. The river model only requires 4 parameters:

- The radionuclide discharge rate.
- The river flow rate.
- The suspended sediment load.
- The freshwater-sediment K_d.

The radionuclide discharge rate is well constrained, and the river flow rate is likely variable across 3 orders of magnitude. The suspended sediment load was measured as 9 mg L^{-1} during this project, which is notably lower than the IRAT2 default value of 40 mg L^{-1}. As noted above, the freshwater-sediment K_d values were estimated to be in the range 1,000-5,000 L kg^{-1}, although the ^{177}Lu measurements in sediment were below the LoD. Using the LoD in the calculations implies that the actual K_d is lower than the determined values.

Equations are available for calculating radionuclides concentrations in rivers (Environment Agency, 2022b). Units have been adapted to correspond to the measurement conditions in this study. The radionuclide activity concentration in unfiltered river water (C_{unf} in Bq L^{-1}) is:

$$C_{unf} = \frac{QF_{eff}}{V}$$

where Q is the discharge rate (Bq d^{-1}) from the hospital, F_{eff} is the fraction of activity which remains in the liquid effluent leaving the treatment works and V is the river flow rate (L d^{-1}).

For a discharge rate of 8.3 GBq d^{-1}, a partition factor to effluent of 0.82 (Table 5), and the river flow rate of 310,000,000 L d^{-1} (Table 11 and converted from L s^{-1}), an average ^{177}Lu activity concentration of 22 Bq L^{-1} can be calculated for unfiltered water.

The ^{177}Lu activity concentration in filtered river water C_{filt} (Bq L^{-1}) can be calculated by:

$$C_{filt} = \frac{C_{unf}}{1+K_d\,S}$$

where S is the suspended sediment load (kg L ^{1}). Using the values presented above, the filtered water concentration is determined to be 20 Bq L^{-1}.

The calculated ^{177}Lu activity concentration in unfiltered water (22 Bq L^{-1}) and filtered water (20 Bq L^{-1}) compare well with the measured concentrations at the discharge point. These were 25 Bq L^{-1} on the first day after the ^{177}Lu administration and 30 Bq L^{-1} after 2 days. However, these values are markedly higher than the highest concentrations measured 500

m downstream (9.1 Bq L^{-1} at sample point 3b, 1 day after ^{177}Lu administration, Table 4) and 1,000 m downstream (6.3 Bq L^{-1} at sample point 3c, 2 days after ^{177}Lu administration, Table 4). The discrepancy could be explained if ^{177}Lu is dispersed longitudinally (down the river) with increasing distance from the discharge point. Further investigation into these inconsistent findings may be beneficial.

The ^{177}Lu activity concentration in sediment C_{sed} (Bq kg^{-1}) can be calculated by:

$$C_{sed} = C_{filt}\, K_d$$

Lutetium concentrations in sediment can be calculated using the range of K_d values derived from measurements. Taking 20 Bq L^{-1} as the filtered water ^{177}Lu concentration, a comparison of the measurement and IRAT2 modelling results is shown in Table 12.

Table 12: Comparison of predicted IRAT2 model ^{177}Lu sediment concentrations with River Cam measurement data.

	Minimum (Bq kg^{-1})	Maximum (Bq kg^{-1})
Calculated ^{177}Lu values using IRAT2 modelling data*	20,000	100,000
Measured ^{177}Lu values (suspended sediment)#	13,000	16,000
Measured ^{177}Lu values (bed sediment)**	<2.8	620

*Calculated using a ^{177}Lu concentration of 20 Bq L^{-1} in filtered water and a freshwater-sediment K_d range of 1,000-5,000 L kg^{-1}.

#Derived from the minimum and maximum measured values of ^{177}Lu particulates in water (Table 4) and a suspended sediment concentration of 0.000009 kg L^{-1} (i.e., 9×10^{-6} kg L^{-1}). The measured ^{177}Lu concentrations were below LoD, implying the actual ^{177}Lu level in suspended sediment is lower than the values derived.

**Minimum and maximum values of ^{177}Lu in sediment, as described in Table 4.

The lower end of the K_d range (1,000 L kg^{-1}) used in the above calculations is better aligned with the measured ^{177}Lu values in suspended sediment than the calculated ^{177}Lu values. However, it should be noted that the measured values correspond to LoD measurements, therefore the actual value would be somewhat lower, implying that the K_d may be lower than 1,000 L kg^{-1}. The ^{177}Lu concentration in bed sediment is lower. This would be expected if a minor fraction of the contaminated suspended sediments is rapidly deposited to the riverbed and become mixed with uncontaminated sediments. In this case, the remainder of ^{177}Lu would remain suspended and be dispersed downstream. Sedimentation to a riverbed is a variable process which varies temporally and spatially with river flow. Sediment can be deposited or scoured away in different parts of the river under different conditions. Moreover, ^{177}Lu discharges are infrequent and any radioactivity

from previous treatments that may have accumulated in bed sediments would have largely decayed by the time of this project's sampling. Overall, these results suggest that ^{177}Lu accumulation in sediment is therefore not considered to be a significant pathway.

7.4 Dose assessment

The IRAT2 models are designed to estimate radiation doses to people and wildlife using simple and cautious assessments (i.e., a screening assessment) but can also be configured with some site-specific values (i.e., a refined assessment). Together, these types of assessment fulfil the first 2 stages in the Environment Agency's dose assessment process, as shown in Figure 10. If dose criteria are exceeded for a Stage 2 (refined) assessment, then a detailed site-specific assessment should be considered.

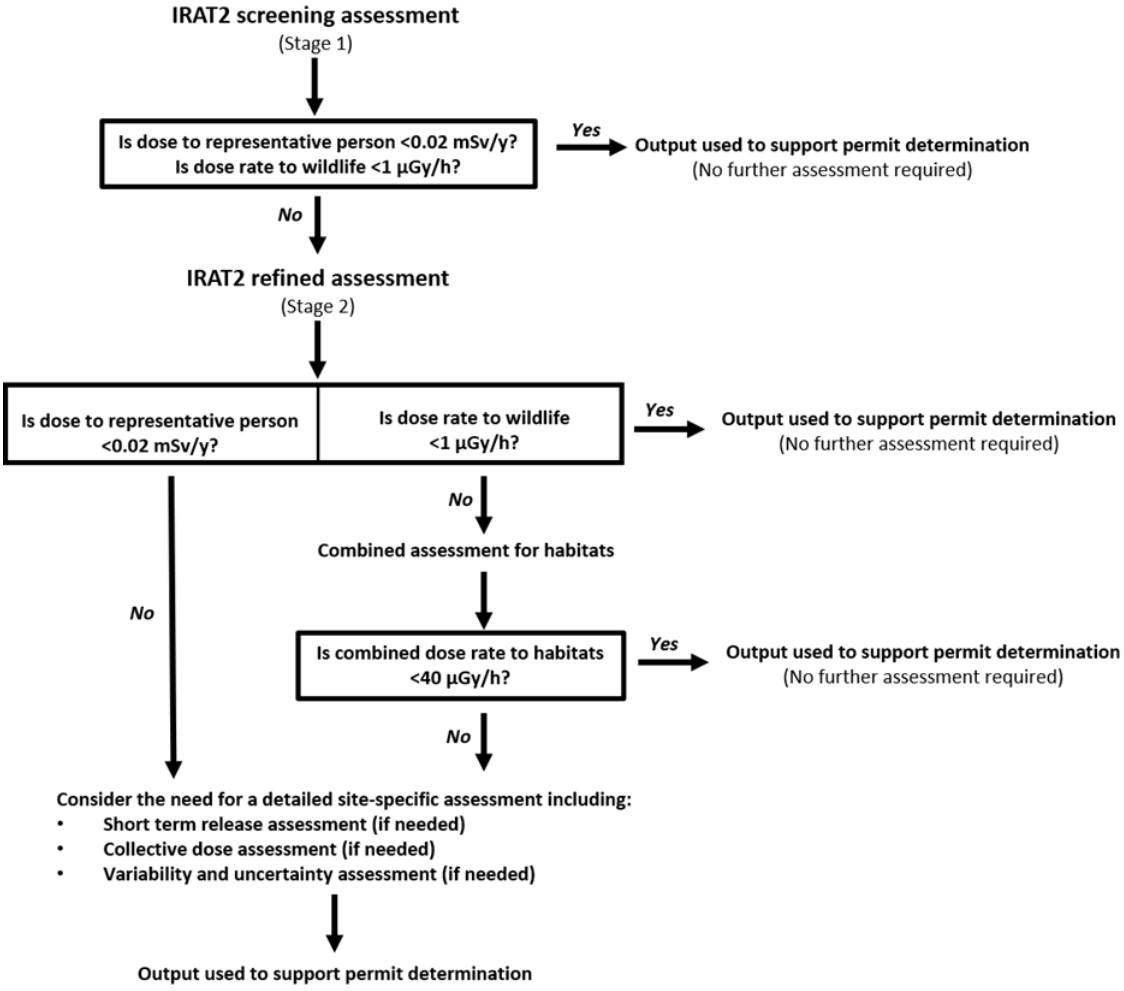


Figure 10: Stages of the Environment Agency's dose assessment process when permitting radioactive waste discharges (reproduced from Environment Agency, 2022a).

It is appropriate to consider both stages of assessment for the purposes of examining the potential radiological impacts of the clinical use of ^{177}Lu.

- A Stage 1 screening assessment is of interest because it informs (in generic terms) on the potential scale of exposures resulting from the use of ^{177}Lu. A calculation for a generic site using the sludge partitioning factor and freshwater-sediment K_d values derived from this site-specific study illustrates how calculated exposures may change with the use of potentially more appropriate ^{177}Lu parameter data.

- A Stage 2 refined assessment provides the opportunity to examine the potential exposures associated with the hospital studied.

In both cases, an annual ^{177}Lu discharge rate of 1 TBq y^{-1} has been assessed. A more detailed assessment is beyond the scope of this project.

The calculations have been made using the current reference version of the IRAT2 models. These are available as 4 spreadsheets covering discharges to air, sewers, rivers, and estuaries. Only the 'sewer' and 'river' pathways are relevant to the discharge under consideration. The assessment spreadsheet enables some site-specific parameters to be defined (e.g., annual discharge rate). For releases to sewer, this includes the sewage flow rate at the WWTW and the flow rate of the receiving brook (if relevant, but not in this case), or river. It also holds conservative default values which can be used for a generic assessment. Previously collated data on average flow rates for some WWTWs in England is also available and this information can be used to refine an assessment.

The assessment spreadsheets are based on Dose Per Unit Release (DPUR) values (μSv y^{-1} per Bq y^{-1}) for 109 radionuclides, including ^{177}Lu. It is necessary to modify the DPUR calculations to change parameters such as the freshwater-sediment K_d value. For these calculations, version 9 of the assessment spreadsheets (issued on 4 January 2023) was used, supported by the Environment Agency's internal DPUR spreadsheets version 5.0 for sewer (7 December 2020) and version 3.0 for river (16 December 2020).

7.5 Screening assessment

The screening assessment involves calculating doses to all exposure groups for all pathways, assuming an annual ^{177}Lu discharge of 1 TBq. For the calculation involving the measured sludge partitioning fraction and freshwater-sediment K_d, the values used were:

- ^{177}Lu partitioning fraction (to sludge): 0.18

- ^{177}Lu freshwater-sediment K_d: 3,000 L kg^{-1}

Calculations have also been performed using the maximum and minimum values within the estimated range for the freshwater-sediment K_d (1,000 – 5,000 L kg^{-1}). The calculated doses using the various input parameters are shown in the table below.

Table 13: Input parameters and calculated does rates to humans for the screening assessment of a 1 TBq y^{-1} ^{177}Lu discharge to sewer. Default flow data and measured sludge partitioning factor and freshwater-sediment K_d values have been used.

Input parameter	IRAT2 default	Study best estimate	Study low K_d (L kg^{-1})	Study high K_d (L kg^{-1})
^{177}Lu sludge partitioning factor (unitless)	0.5	0.18	-	-
^{177}Lu freshwater-sediment K_d (L kg^{-1})	220,000	3,000	1,000	5,000
Exposure group	**Radiation dose using IRAT2 default data (µSv y^{-1})**	**Radiation dose using study best estimate (µSv y^{-1})**	**Radiation dose using study low K_d (µSv y^{-1})**	**Radiation dose using study high K_d (µSv y^{-1})**
Sewage treatment worker	2,700	1,200	1,200	1,200
Child playing in brook	400	80	30	120
Angler (river)	78	29	27	36
Irrigated food consumer (river)	1.9	23	24	21
Fishing family (estuary/coastal)	0.40	0.66	0.66	0.66
Farming family (sewage sludge to land)	30	11	11	11

Most combinations of parameter values clearly exceed the 20 µSv y^{-1} screening criterion using the IRAT2 default parameters. Doses to workers at the WWTW are particularly high. Here, even a single dose of the ^{177}Lu medical treatment would exceed the dose criterion for the IRAT2 default parameters and would only marginally be below it for the values derived in this study. The ‘child in brook,’ ‘angler,’ and ‘irrigated food consumer’ pathways

also exceed the screening criterion of 20 μSv y^{-1} for all the combinations of new parameter values considered. Although, the combination of site-specific values for the ^{177}Lu sludge partitioning factor and the lower end of the freshwater-sediment K_d range provide doses that are close to the screening criterion. Compared with default IRAT2 value, the reduced ^{177}Lu freshwater-sediment K_d values led to lower doses for the exposure groups spending time along the riverbank (i.e., child playing in the brook and angler). However, consumers of food irrigated by river water appear to be more exposed when the calculations use site specific data. This is because more radioactivity remains in the river water.

Wildlife exposures increase by an order of magnitude when default IRAT2 assumptions are replaced by this project's estimates for ^{177}Lu sludge partitioning factor. This result is shown in the table below.

Table 14: Input parameters and calculated dose rates to wildlife for the screening assessment of a 1 TBq y^{-1} ^{177}Lu discharge to sewer. Default flow data and measured sludge partitioning factor and freshwater-sediment K_d values have been used.

Input parameter	IRAT2 default	Study best estimate	Study low K_d (L kg^{-1})	Study high K_d (L kg^{-1})
^{177}Lu sludge partitioning factor (unitless)	0.5	0.18	-	-
^{177}Lu freshwater-sediment K_d (L kg^{-1})	220,000	3,000	1,000	5,000
Wildlife exposure group	**Dose rate using IRAT2 default data (μGy h^{-1})**	**Dose rate using study best estimate (μGy h^{-1})**	**Dose rate using study low K_d (μGy h^{-1})**	**Dose rate using study high K_d (μGy h^{-1})**
River wildlife	11	160	170	150
Coastal wildlife	0.22	0.35	0.35	0.35
Terrestrial wildlife (sludge to land)	0.0027	0.0096	0.0096	0.0096

Biota associated with river water are more exposed when a lower ^{177}Lu freshwater-sediment K_d is used, as more radioactivity remains in the water column. In this case, the screening threshold of 1 μGy h^{-1} is exceeded by 1-2 orders of magnitude (i.e., 15-170 times) for river wildlife. The most exposed reference organism for ^{177}Lu is insect larvae.

Non-human biota dose calculations in IRAT2 are based on DPUR values that are calculated using the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) Tool (version 1.2) (Brown et al., 2008). Here, ERICA (version 1.2) also uses Ce as an analogue for Lu when calculating DPUR values for non-human biota (Brown et al., 2016). Recalculating the DPURs for non-human biota was beyond the scope of this project as it requires the use of the ERICA modelling tool.

Upon reviewing the published literature, Lu specific concentration ratios (which determine the uptake of ^{177}Lu into non-human biota) for 3 freshwater reference organisms in ERICA were identified. The Lu specific concentration ratios in the wildlife transfer database for fish, mollusc and vascular plant are 470, 250, and 250 respectively (Copplestone et al., 2013). These values are different to the concentration ratios used in the IRAT2 derivation of the DPURs (170, 1,100 and 880 for fish, mollusc, and vascular plant, respectively). Hence, the Lu specific values significantly diverge from the IRAT2 derivation values. Calculations were performed in ERICA (version 1.2) to assess the likely impact of modifying the ^{177}Lu freshwater-sediment K_d value and the 3 specific concentration ratios. Recalculating the DPURs for non-human biota fully is beyond the scope of this project.

The total dose rate for various freshwater reference organisms was calculated using the original ERICA (version 1.2) parameter values. Comparisons were made using the best estimate freshwater-sediment K_d and the 3 Lu specific concentration ratios for each reference organism. For both sets of calculations, a 1 Bq L^{-1} input of ^{177}Lu into the water column was assumed. The results are shown in the table below.

Table 15: Total dose rates to freshwater reference organisms calculated using original and modified ERICA (version 1.2) ^{177}Lu freshwater-sediment K_d and concentration ratio values. A 1 Bq L^{-1} input of ^{177}Lu was used in all calculations.

Freshwater reference organism	Total dose rate (original ERICA parameters) (µGy h^{-1})	Total dose rate (modified ERICA parameters using best estimate from this study) (µGy h^{-1})	Total dose rate ratio (modified: original ERCIA parameters)
Amphibian	0.01	0.01	1.00
Benthic fish	3.37	0.07	0.02
Bird	0.40	0.40	1.00
Crustacean	6.55	0.13	0.02

Freshwater reference organism	Total dose rate (original ERICA parameters) (µGy h^{-1})	Total dose rate (modified ERICA parameters using best estimate from this study) (µGy h^{-1})	Total dose rate ratio (modified: original ERCIA parameters)
Insect larvae	12.70	0.17	0.01
Mammal	0.02	0.02	1.00
Mollusc - bivalve	3.90	0.05	0.01
Mollusc - gastropod	4.26	0.05	0.01
Pelagic fish	0.02	0.04	2.75
Phytoplankton	0.54	0.54	1.00
Reptile	3.43	0.08	0.02
Vascular plant	7.28	0.07	0.01
Zooplankton	0.07	0.07	1.00

The last column in Table 15 also provides the ratio between the 2 sets of total dose rates. For the freshwater organisms (benthic fish, crustacean, insect larvae, mollusc-bivalve, mollusc-gastropod, reptile, and vascular plant) the results show that use of the modified ERICA values leads to a reduction in the total dose by 2 orders of magnitude. An opposite result was apparent for pelagic fish (increased by a factor of ~3). This is reasonable as the best estimate Lu freshwater-sediment K_d value indicates that a greater proportion of ^{177}Lu is retained in solution. Accordingly, a greater amount of ^{177}Lu can be taken up by the pelagic fish that lives in the water column. Finally, for the amphibian, bird, mammal, phytoplankton, and zooplankton there was no difference in the dose rates calculated.

Insect larvae are the most exposed reference organism group in the screening dose assessment results (as shown in Table 14). On that basis, it would be expected that the calculated dose rates should be reduced by 2 orders of magnitude if the wildlife DPURs were to be recalculated. Any recalculated DPUR values might also consider using the latest version of the ERICA Tool (version 2) (Brown et al., 2016).

7.6 Site specific assessment

The main refinements from the screening assessment presented above reflect the key characteristics of the site and its discharges. These are:

- The discharge is directly to a river (not to brook or estuary/coastal environment).
- Sludge is only used for agriculture (not incinerated).
- The IRAT2 flow rate for the actual WWTW is 36,000 m^3 d^{-1} (rather than the default of 60,000 m^3 d^{-1}).
- The river flow rate is 3.6 m^3 s^{-1} (rather than the default of 1 m^3 s^{-1}) based on the historical mean value.

The highest dose to the sewage treatment worker is substantially reduced owing to the increased dilution of ^{177}Lu. This is due to using the IRAT2 flow rate for the actual WWTW (rather than the higher default value). Doses associated with the river are reduced in proportion to the higher river flow rate: default value ratio. For the assumed 1 TBq y^{-1} ^{177}Lu discharge (~130 treatments per year), only the angler marginally exceeds the screening criterion for the IRAT2 default assumptions. For the site-specific parameter values the doses are well below the criterion. This information is summarised in the table below.

Table 16: Input parameters and calculated dose rates to humans for the refinement assessment of a 1 TBq y^{-1} ^{177}Lu discharge to sewer. Default flow data and measured sludge partitioning factor and freshwater-sediment K_d values have been used.

Input parameters	IRAT2 default	Study best estimate	Study low K_d (L kg^{-1})	Study high K_d (L kg^{-1})
^{177}Lu Sludge partitioning factor (unitless)	0.5	0.18	-	-
^{177}Lu freshwater-sediment K_d (L kg^{-1})	220,000	3,000	1,000	5,000
Exposure group	**Radiation dose using IRAT2 defaults (µSv y^{-1})**	**Radiation dose using study best estimate (µSv y^{-1})**	**Radiation dose using study low K_d (µSv y^{-1})**	**Radiation dose using study high K_d (µSv y^{-1})**
Sewage treatment worker	4.5	1.9	1.9	1.9

Input parameters	IRAT2 default	Study best estimate	Study low K_d (L kg^{-1})	Study high K_d (L kg^{-1})
Angler dose (river)	22	8.0	7.4	10
Irrigated food consumer (river)	0.53	6.3	6.8	5.9
Farming family (sewage sludge to land)	0.050	0.018	0.018	0.018

As with the human assessment, dose rates to wildlife are substantially reduced when using the site-specific information. Again, this is due to the increased dilution of ^{177}Lu resulting from using the lower IRAT2 flow rate and the higher river flow rate. However, dose rates to river wildlife remain substantially greater than the 1 µGy h^{-1} screening criterion. As discussed in Section 7.4, wildlife DPUR values were not recalculated using ERICA as part of this study. Hence, there are further refinements to this assessment that could potentially be undertaken that are out of scope of this project. As with the screening assessment, biota associated with river water are more exposed when a lower ^{177}Lu freshwater-sediment K_d is used, as a greater portion of radioactivity remains in solution. This information is summarised in the table below.

Table 17: Input parameters and calculated dose rates to wildlife for the refinement assessment of a 1 TBq y^{-1} ^{177}Lu discharge to sewer. Default flow data and measured sludge partitioning factor and freshwater-sediment K_d values have been used.

Input parameter	IRAT2 default	Study best estimate	Study low K_d (L kg^{-1})	Study high K_d (L kg^{-1})
^{177}Lu sludge partitioning factor (unitless)	0.5	0.18	-	-
^{177}Lu freshwater-sediment K_d (L kg^{-1})	220,000	3,000	1,000	5,000
Wildlife exposure group	**Dose rate using IRAT2 defaults (µGy h^{-1})**	**Dose rate using study best estimate (µGy h^{-1})**	**Dose rate using study low K_d (µGy h^{-1})**	**Dose rate using study high K_d (µGy h^{-1})**

Input parameter	IRAT2 default	Study best estimate	Study low K_d (L kg^{-1})	Study high K_d (L kg^{-1})
River wildlife	3.0	44	47	41
Terrestrial wildlife (sludge to land)	4.4×10^{-6}	1.6×10^{-6}	1.6×10^{-6}	1.6×10^{-6}

7.7 External dose rates

The IRAT2 model calculates doses to exposure groups considering both internal and exposure pathways. The above dose calculations consider the consequences of changing the freshwater-sediment K_d, which determines the ^{177}Lu activity concentration that transfers from the water to sediment in the dose assessment. The assessment then uses different methods to calculate the dose from both internal and external exposures which might occur. Published literature data are used to calculate external exposures from river sediment external dose coefficients. External exposure dose coefficients in the literature have changed since IRAT2 was first produced. Updated values are available in the US EPA Federal Guidance Report 15 (FGR 15) which revises the dose coefficients for external exposure from sediments (US EPA, 2025). The external dose rate above sediment is calculated by multiplying the ^{177}Lu activity concentration in the sediment by the reference person described by the International Commission on Radiological Protection (ICRP) (ICRP, 2002; 2007). The effective external dose coefficients are tabulated in in the latest Federal Guidance Report 15 (US EPA, 2025).

The value used in the IRAT2 DPUR calculation is the ^{177}Lu value for external dose rate from soil contaminated to a depth of 1 cm, taken from FGR 12 (US EPA, 1993) adjusted using ICRP 60 dosimetry (US EPA, 2002). It is worth noting that this is for the 'adult' reference person geometry. A comparison of the effective dose coefficient value used in IRAT2 with that for the adult geometry in FGR 15 (US EPA, 2025) gives almost identical results. The original dose coefficient (in Sv per Bq s m^{-3}) was 1.99×10^{-19} compared with the new value of 1.93×10^{-19}. These results are provided in the table below.

Table 18: ^{177}Lu effective dose rate coefficients for soil contaminated to 1 cm. from FGR 12 (effective) (US EPA, 1993) adjusted using ICRP 60 dosimetry (US EPA, 2002) and adult, newborn, 1-, 5-, 10-, and 15-year-old from FGR 15 (US EPA, 2025).

1aw32q	Adult (IRAT2: adult)	Newborn (IRAT2: offspring)	1-yr-old (IRAT2 infant)	5-yr old	10-yr-old (IRAT2 child)	15-yr-old
FGR12	FGR15	FGR15	FGR15	FGR15	FGR15	FGR15

1aw32q	Adult (IRAT2: adult)	Newborn (IRAT2: offspring)	1-yr-old (IRAT2 infant)	5-yr old	10-yr-old (IRAT2 child)	15-yr-old
1.99×10^{-19}	1.93×10^{-19}	2.62×10^{-19}	2.43×10^{-19}	2.27×10^{-19}	2.17×10^{-19}	1.96×10^{-19}

Table 18 also presents the external dose coefficients for the other geometries (newborn, 1-, 5-, 10- and 15-year-old) that are available in FGR 15 (US EPA, 2000) but were absent in FGR12. Adopting these new ^{177}Lu values in IRAT2 will have the effect of increasing the external dose contribution to offspring, infant and child exposure groups spending time on or near sediments (e.g., child playing in a brook, angler, or fishing family) but reducing the external dose contribution for the equivalent adult exposure groups.

7.8 Dose assessment conclusions

This project has indicated that the ^{177}Lu sludge partitioning factor of 0.5. as currently defined in IRAT2, may be too high. Measurement data suggests that a value of 0.18 may be more appropriate. This value was derived by comparing measured ^{177}Lu concentrations in influent and treated effluent. However, using a lower partitioning factor to estimate ^{177}Lu concentrations in sludge leads to calculated values that far exceed the measured values. This may be due to the timing of sampling undertaken during this study whereby ^{177}Lu had not yet entered the processed sludge that was analysed. Measured ^{177}Lu concentrations in the sludge remained at similar levels throughout the sampling period of the project.

Measured ^{177}Lu concentrations in river water accorded well with those estimated using a simple dilution model at the discharge location. In contrast, ^{177}Lu concentrations at 1,000 m downstream were only ~25% of the calculated value. There may be several reasons for this discrepancy. For example, ^{177}Lu as a radiopharmaceutical may partition to the water column to a greater extent (and be dispersed further downstream) than more common Lu chemical forms. Alternatively, the 1,000 m sampling point was located just before a weir in the river which may have affected the water flow and/or sedimentation processes and by extension ^{177}Lu partitioning behaviour. Finally, it is possible that less ^{177}Lu dispersion and dilution occurred at 1,000 m than predicted by the simple dilution model (used to calculate the sediment and water concentrations). Further research is required to identify the factors responsible for the inconsistent measured and calculated ^{177}Lu concentrations in river.

Measured ^{177}Lu concentrations in suspended sediment and water concentrations were used to derive a freshwater-sediment K_d for Lu, which was much lower than the IRAT2 default value (by 3 orders of magnitude).

The doses calculated using IRAT2 screening assumptions exceeded the 20 μSv y^{-1} criterion for the sewage treatment worker, child playing in brook, angler, and irrigated food consumers when a nominal 1 TBq y^{-1} discharge was assumed. However, doses were significantly lower for all exposure groups, except the irrigated food consumer, when the

new ^{177}Lu sludge partitioning fraction and freshwater-sediment K_d. values were used (from this project). The refined assessment for people using site specific flow rates resulted in reduced doses for all cases for the same 1 TBq y^{-1} discharge. Doses were all well below the screening criterion when site specific values were adopted for the dose calculations.

These dose assessment results collectively show that ^{177}Lu doses arising from exposure to contaminated river water increase when site specific data are used e.g., for the irrigated food consumer. As might be expected, doses which arise from exposure to contaminated sediment decrease e.g., for child playing in brook and an angler. This is because this study indicates that ^{177}Lu in a radiopharmaceutical form may behave conservatively and largely remain in the water phase. For the purposes of dose assessment, this key finding indicates that more ^{177}Lu can be transferred to land through the irrigation pathway and less activity becomes bound to river sediments, thus reducing the external dose contribution.

Consideration of new literature studies demonstrated that updates are available for the external dose coefficients used in IRAT2. For ^{177}Lu, there is a small reduction in the external dose coefficient of ~3% for the adult exposure groups. If implemented into IRAT2, these new external dose coefficients would reduce the external doses from sediment to adult exposure groups by ~3%. The new literature also provides age specific external dose coefficients for offspring, infant, and child exposure groups which if implemented into IRAT2 would increase the external doses from sediment by up to 30%.

Dose rates to wildlife exceed the 1 µGy h^{-1} criterion when using both the IRAT2 default assumptions and the revised ^{177}Lu parameter data calculated in the study. This is the case for both default and site-specific water flow rates. Dose rates to wildlife are higher when the revised parameter data are used because they indicate higher ^{177}Lu levels in river water. In general, biota doses for the most exposed organism groups are calculated from exposure to radioactivity in the river water. However, the non-human biota ^{177}Lu dose rate calculations were performed with the DPUR values (calculated in the ERICA Tool (version 1.2)) that are based on a Ce analogue for Lu. The DPUR values were not recalculated fully for this study. Changing the relevant default parameters within the ERICA Tool to reflect the K_d value determined in this study and adjusting the default ^{177}Lu concentration ratios for 3 reference organisms (fish, mollusc, and vascular plant), was explored. Of note, it led to a reduction in the dose rate contribution from ^{177}Lu by ~2 orders of magnitude. This would consequently reduce the dose rates reported in Tables 14 and 17 accordingly.

8 Conclusions and recommendations

The environmental behaviour of ^{177}Lu has been investigated to better understand the human and environmental health consequences from the potential widespread adoption of novel ^{177}Lu based cancer treatments in the future. Following administration of 9.2 GBq ^{177}Lu NeoRay® in the Addenbrookes hospital, this project sampled the nearby Cambridge WWTW and the River Cam (which receives treated effluent from the Cambridge WWTW). Lutetium concentrations were measured in the following wastewater systems:

- Sewage influent.
- Final effluent.
- Primary and secondary sewage sludge.
- Sewage sludge cake.
- At the WWTW discharge point to the River Cam (river water and sediment).
- 500 m from the discharge point (river water and sediment).
- 1,000 m from the discharge point (river water and sediment).

These monitoring data were used to calculate key transfer parameters for ^{177}Lu such as the sludge partitioning factor and freshwater-sediment K_d value. Comparisons were made to the current parameter values used in IRAT2.

A freshwater-sediment K_d value of 3,000 L kg^{-1} was empirically determined. This value is 2 orders of magnitude lower than the corresponding K_d value of the Ce analogue of choice currently used in the IRAT2 methodology (220,000 L kg^{-1}). Similarly, the measured sludge partitioning factor of 0.18 is significantly smaller than the Ce analogue value used in IRAT2 (0.5). The monitoring datasets collectively indicate that Lu behaves differently in the environment compared to other lanthanide elements such as Ce. On that basis, Ce may not be a fully appropriate analogue for ^{177}Lu environmental dose assessments. However, this monitoring study only tracked the behaviour of ^{177}Lu in one wastewater system (i.e., one WWTW and receiving river) after a single medical administration. Other credible ^{177}Lu discharge scenarios may possess notably different characteristics, and these differences could affect radionuclide partitioning behaviour in the environment. For example, the published scientific literature indicates that the ^{177}Lu chemical form may also strongly influence the radionuclide's fate and transport in the environment. Lutetium bound to a radiopharmaceutical (as examined in this project) remains conservatively in the water and is not readily scavenged by particulate matter and deposited into sediments. Markedly different behaviour is expected for Lu in more common forms e.g., dissolved Lu^{3+} ions. Chemical speciation effects may account for the low ^{177}Lu concentrations measured in the sediments in this investigation. Other factors such as spatial and temporal variations in the freshwater environment and the presence of environmental sinks could also be important.

Irrespective of the exact mechanism, less deposition of ^{177}Lu into sediments (as measured in this project) would likely translate to a lower external dose rate to people and non-human biota. Current dose estimates could therefore be potentially reduced to reflect this. Dose calculations were performed using the best estimate sludge partitioning factor and freshwater-sediment K_d from this study to support this conclusion. Regardless, further research may be beneficial to clarify the exact role of Lu chemical behaviour on its partition behaviour in wastewater environments. This would aid the assessment of medical administrations of different ^{177}Lu chemical compounds to the one examined in this project (i.e., ^{177}Lu NeoRay®) and help reduce uncertainties in environmental dose assessments.

Doses to relevant exposure groups were calculated using the IRAT2 default transfer parameter values (i.e., Ce data) and the ^{177}Lu specific values generated from this project. A nominal 1 TBq y^{-1} discharge of ^{177}Lu was assumed for all cases. For the default values, the doses calculated using IRAT2 screening assumptions exceeded the 20 µSv y^{-1} criterion for several exposure groups. These included the sewage treatment worker, child in brook, angler, and irrigated food consumers. However, ^{177}Lu doses were significantly reduced when the measured values for sludge partitioning factor and freshwater-sediment K_d were used. One exception to this was the irrigated food consumer. This may be attributed to higher ^{177}Lu concentrations measured in the river water than indicated by the IRAT2 predictions, reducing external doses due to contaminated sediment. On the other hand, more radioactivity is available in irrigation water to contaminate the food pathway.

Dose assessments for ^{177}Lu exposures in a freshwater environment revealed that doses to wildlife exceeded the 1 µGy h^{-1} criterion for all assumptions. Doses further exceeded the criterion when this project's measured sludge partitioning factor and K_d were used. This can be attributed to more ^{177}Lu activity remaining in solution, from which biota doses are calculated. However, these non-human biota dose rate calculations were performed with the DPUR values calculated in the ERICA (version 1.2) which use Ce as an analogue of Lu. The default parameters within the ERICA Tool were subsequently changed to reflect the freshwater-sediment K_d determined in this study, and the doses to fish, mollusc and vascular plant were recalculated. Default ^{177}Lu concentration ratios for these 3 reference organisms were also adjusted using updated literature values. These combined changes led to 2 orders of magnitude reduction in the dose rate contribution from ^{177}Lu. Such a change would similarly reduce the wildlife dose rates calculated.

A refined assessment typically resulted in reduced doses for the same 1 TBq y^{-1} discharge scenario. The dose to the angler exceeds the criterion marginally when the default IRAT2 parameter values were adopted, because of the high default K_d (220,000 L kg^{-1}). Human doses were all well below the screening criterion when site specific parameters were used. However, doses to wildlife remained well above the screening criterion for both IRAT2 default and measured K_d parameter values. It may therefore be beneficial to recalculate the DPURs for wildlife for ^{177}Lu in order to accommodate more robust assessments.

Overall, this study indicates that medically administered ^{177}Lu is more water soluble than the Ce analogue currently used in the IRAT2 methodology. This result implies that Lu more easily passes through a WWTW and reaches the freshwater environment than Ce, but a smaller fraction of ^{177}Lu then binds to river sediment. Calculated external doses to

people and non-human biota may decrease by a factor of 100 if Lu specific information is used instead of Ce data. However, it is possible that ^{177}Lu bound to a radiopharmaceutical possesses different chemical properties to lanthanides in their elemental form. Of note, most of the lanthanide data used in dose assessment calculations to date have been based on the elemental form. This project's key findings are consistent with those of the published literature, although the number of studies on this topic is limited. There is no information on the chemical stability of ^{177}Lu radiopharmaceutical complexes in the environment or on their propensity to undergo chemical changes. As a result, the inconsistent behaviour of Lu and Ce in wastewater environments is not fully understood.

Reflecting the above conclusions, 2 recommendations for further work are proposed to help address identified uncertainties and to improve environmental dose assessments.

- Recalculation of the DPURs for wildlife for ^{177}Lu may be considered for the purposes of aiding refined dose assessments.

- Laboratory scale research may be useful to determine the significance of the radionuclide chemical form on ^{177}Lu partitioning behaviour in wastewater systems. This includes assessing the stability of different Lu chemical compounds over time.

References

ATAKOGLU, O.O. AND YALCIN, F., 2022. Evaluation of the surface water and sediment quality in the Duger basin (Burdur, Turkey) using multivariate statistical analyses and identification of heavy metals. Environmental Monitoring and Assessment, 194, 484. Available from: https://doi.org/10.1007/s10661-022-10147-z [Accessed 5 June 2026]

BARQUERO, R., VELASCO, J., ANDRES, C., TORRES, R. AND RUANO, R., 2022. Estimate of activity discharged into the sewer network in neuroendocrine treatments with ^{177}Lu-DOTA-TATE. Applied Radiation and Isotopes, 190, 110459. Available from: https://doi.org/10.1016/j.apradiso.2022.110459 [Accessed 5 June 2026]

BROWN, J.E., ALFONSO, B., AVILA, R., BERESFORD, N.A., COPPLESTONE, D., PRÖHL, G. AND ULANOVSKY, A., 2008. The ERICA Tool. Journal of Environmental Radioactivity, 99, 1371-1383. Available from: https://doi.org/10.1016/j.jenvrad.2008.01.008 [Accessed 5 June 2026]

BROWN, J., ALFONSO, B., AVILA, R., BERESFORD, N.A., COPPLESTONE, D. AND HOSSEINI, A., 2016. A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals. Journal of Environmental Radioactivity, 153, 141-148. Available from: https://doi.org/10.1016/j.jenvrad.2015.12.011 [Accessed 5 June 2026]

CHIPIGA, L.A., ZVONOVA, I.A., VODOVATOV, A.V., PETRYAKOVA, A.V., STANZHEVSKY, A.A., VAZHENINA, D.A., SMOLIARCHUK, M.Y. AND RYZHOV, S.A., 2023. Improvement of the approach to definition of patient release criteria after radionuclide therapy. Radiation Hygiene, 16 (2), 19–31. Available from: https://doi.org/10.21514/1998-426x-2023-16-2-19-31 [Accessed 5 June 2026]

CHUDAEV, O.V., BRAGIN, I.V., KHARITONOVA, N.A. AND CHELNOKOV, G.A., 2016. Distribution and Geochemistry of Rare-Earth Elements in Rivers of Southern and Eastern Primorye (Far East of Russia). IOP Conference Series: Earth and Environmental Science, 33, 012002. Available from: https://iopscience.iop.org/article/10.1088/1755-1315/33/1/012002 [Accessed 5 June 2026]

COPPLESTONE, D., BERESFORD, N.A., BROWN, J. AND YANKOVICH, T.L., 2013. An international database of radionuclide concentration ratios for wildlife: Development and uses. Journal of Environmental Radioactivity, 126, 288-298. Available from: https://doi.org/10.1016/j.jenvrad.2013.05.007 [Accessed 5 June 2026]

DASH, A., PILLAI, M.R.A. AND KNAPP JR, F.F., 2015. Production of ^{177}Lu for Targeted Radionuclide Therapy: Available Options. Nuclear Medicine and Molecular Imaging, 49 (2), 85-107. Available from: https://doi.org/10.1007/s13139-014-0315-z [Accessed 5 June 2026]

DEBERTIN, K. AND JIANPING, R., 1989. Measurement of the activity of radioactive samples in Marinelli beakers. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 278 (2),

541-549. Available from: https://doi.org/10.1016/0168-9002(89)90877-2 [Accessed 5 June 2026]

DELKER, A., FENDLER, W.P., KRATOCHWIL, C., BRUNEGRAF, A., GOSEWISCH, A., GILDEHAUS, F.J., TRITSCHLER, S., STIEF, C.G., KOPKA, K., HABERKORN, U., BARTENSTEIN, P. AND BÖNING, G., 2015. Dosimetry for ^{177}Lu-DKFZ-PSMA-617: a new radiopharmaceutical for the treatment of metastatic prostate cancer. European Journal of Nuclear Medicine and Molecular Imaging, 43 (1), 42-51. Available from: https://doi.org/10.1007/s00259-015-3174-7 [Accessed 5 June 2026]

ENVIRONMENT AGENCY, 2022a. Initial Radiological Assessment Tool 2: Part 1 User Guide [online]. Environment Agency, Bristol. Available from: https://assets.publishing.service.gov.uk/media/63528534d3bf7f1943006c5f/Initial_radiological_assessment_tool_2_-_part_1_user_guide.pdf [Accessed 5 June 2026]

ENVIRONMENT AGENCY, 2022b. Initial Radiological Assessment Tool 2: Part 2 Methods and Input Data [online]. Environment Agency, Bristol. Available from: https://assets.publishing.service.gov.uk/media/63528573d3bf7f1943006c60/Initial_radiological_assessment_tool_2_-_part_2_methods_and_input_data.pdf [Accessed 5 June 2026]

ENVIRONMENT AGENCY, 2026. Pollution Inventory Datasets 2013-2024 [online]. Available from: https://www.data.gov.uk/dataset/cfd94301-a2f2-48a2-9915-e477ca6d8b7e/pollution-inventory [Accessed 29 May 2026].

FITZGERALD, J., 2002. FitzPeaks Gamma Analysis and Calibration Software. User Guide version 3.40.

GILBERT, K., 2024, Anglian Water. Personal communication.

GILLETT, D., 2024. Cambridge University Hospitals NHS Foundation Trust. Personal communication.

HELMER, R.G., BROWNE, E. AND BÉ, M.M., 2002. International Decay Data Evaluation Project. Journal of Nuclear Science and Technology, 39 (sup2), 455–458. Available from: https://doi.org/10.1080/00223131.2002.10875138 [Accessed 5 June 2026]

HENNRICH, U. AND KOPKA, K., 2019. Lutathera®: The First FDA- and EMA-Approved Radiopharmaceutical for Peptide Receptor Radionuclide Therapy. Pharmaceuticals, 12 (3), 114. Available from: https://doi.org/10.3390/ph12030114 [Accessed 5 June 2026]

INTERNATIONAL ATOMIC ENERGY AGENCY, 1994. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments [online]. IAEA Technical Reports Series No. 364. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/trs472_web.pdf [Accessed 5 June 2026]

INTERNATIONAL ATOMIC ENERGY AGENCY, 2001. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment [online]. IAEA Safety Reports Series No. 19. Available from:

https://www.iaea.org/publications/6024/generic-models-for-use-in-assessing-the-impact-of-discharges-of-radioactive-substances-to-the-environment [Accessed 5 June 2026]

INTERNATIONAL ATOMIC ENERGY AGENCY, 2010. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments [online]. IAEA Technical Reports Series No. 472. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/trs472_web.pdf [Accessed 5 June 2026]

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 2002. Basic Anatomical and Physiological Data for Use in Radiological Protection Reference Values. ICRP Publication 89 [online]. Annals of the ICRP 32 (3-4). Available from: https://www.icrp.org/publication.asp?id=icrp%20publication%2089 [Accessed 5 June 2026]

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 2007. Recommendations of the International Commission on Radiological Protection. ICRP Publication 103 (Users Edition) [online]. Annals of the ICRP 37 (2-4). Available from: https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103%20(Users%20Edition) [Accessed 5 June 2026]

INSTITUTE OF PHYSICS AND ENGINEERING IN MEDICINE, 2018. Excretion Factors: the percentage of administered radioactivity released to sewer for routinely used radiopharmaceuticals [online]. IPEM Advice Notice. Available from: https://www.ipem.ac.uk/media/bpajgexw/excretion-factors-sept-2018.pdf [Accessed 5 June 2026]

IVANOVICH, M. AND HARMON, R.S., 1982. Uranium Series Disequilibrium: Applications to Environmental Problems. Oxford: Oxford University Press.

KURTH, J., KRAUSE, B.J., SCHWARZENBÖCK, S.M., STEGGER, L., SCHÄFERS, M. AND RAHBAR, K., 2018. External radiation exposure, excretion, and effective half-life in ^{177}Lu-PSMA-targeted therapies. EJNMMI Research, 8 (1), 32. Available from: https://doi.org/10.1186/s13550-018-0386-4 [Accessed 5 June 2026]

LANG, A., WEBB, K., STASIOW REED, A., CONNOLLY, M., MCMAHON, M. AND TEAGUE, N., 2026. Behaviour of radionuclides in wastewater systems: a laboratory study. Environment Agency, Bristol.

LEVART, D., KALOGIANNI, E., CORCORAN, B., MULHOLLAND, N. AND VIVIAN, G., 2019. Radiation precautions for inpatient and outpatient ^{177}Lu-DOTATATE peptide receptor radionuclide therapy of neuroendocrine tumours. EJNMMI Physics 6:7. Available from: https://doi.org/10.1186/s40658-019-0243-1 [Accessed 5 June 2026]

MOBBS, S., ABRAITIS, P., MITCHELL, N., JOHNSTON, H., BUTLER, R., TURNER, T., SMITH, J., DEAN, R. AND LANG, A., 2026. Radionuclide transfer parameter review. Environment Agency, Bristol.

PIPER, D.Z. AND BAU, M., 2013. Normalized rare earth elements in water, sediments and wine: identifying sources and environmental redox conditions. American Journal of

Analytical Chemistry 4, 69-83. Available from: https://doi.org/10.4236/ajac.2013.410A1009 [Accessed 5 June 2026]

SCHÖTZIG, U., SCHRADER, H., SCHÖNFELD, E., GÜNTHER, E., AND KLEIN, R., 2001. Standardisation and decay data of ^{177}Lu and ^{188}Re. Applied Radiation and Isotopes, 55 (1), 89-96. Available from: https://doi.org/10.1016/S0969-8043(00)00362-6 [Accessed 20 May 2026].

SHIRLEY, V.S., BROWNE, E. AND LEDERER, C.M., 1978. Table of isotopes. 7th ed. New York: John Wiley and Sons.

SHOLKOVITS, E.R., 1995. The aquatic chemistry of rare earth elements in rivers and estuaries. Aquatic Geochemistry 1, 1-34. Available from: https://link.springer.com/article/10.1007/BF01025229 [Accessed 5 June 2026]

SMITH, J.G. AND SIMMONDS, J.R., 2015. The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment Used in PC-CREAM 08 [online]. Health Protection Agency Report HPA-RPD-058. Available from: https://assets.publishing.service.gov.uk/media/5a8017c040f0b6230269177c/HPA-RPD-058_June_2015.pdf [Accessed 5 June 2026]

SOCOTEC, 2024. Investigating the fate and behaviour of ^{177}Lu Bound to a Chelator Based Radiopharmaceutical Agent Discharged into Wastewater Systems in the UK. Unpublished Report.

TURCOTTE, P., SMYTH, S.A., GAGNÉ, F. AND GAGNON, C., 2022. Lanthanides release and partitioning in municipal wastewater effluents. Toxics, 10 (5), 254. Available from: https://doi.org/10.3390/toxics10050254 [Accessed 5 June 2026]

UK CENTRE FOR ECOLOGY & HYDROLOGY, 2023. National River Flow Archive [online]. Available from https://nrfa.ceh.ac.uk/data/station/meanflow/33003 [Accessed 11 June 2026]

UNIVERSITY OF CAMBRIDGE, 2024. Cambridge weather in June 2024 [online]. Available from: https://www.cl.cam.ac.uk/weather/period-graph?2024_06. [Accessed 5 June 2026]

U.S. ENVIRONMENTAL PROTECTION AGENCY, 1993. External Exposure to Radionuclides in Air, Water, and Soil [online]. Guidance Report No. 12 EPA 402-R-93-081, Washington. Available from: https://www.epa.gov/sites/default/files/2015-05/documents/402-r-93-081.pdf [Accessed 5 June 2026]

U.S. ENVIRONMENTAL PROTECTION AGENCY, 2002. DCFPAK: Dose Coefficient File Package for Sandia National Laboratory [online]. Oak Ridge National Laboratory Dosimetry Research Group Output.

U.S. ENVIRONMENTAL PROTECTION AGENCY, 2025. External Exposure to Radionuclides in Air, Water, and Soil [online]. Federal Guidance Report No. 15 EPA 402-R-00-001. Available from: https://www.epa.gov/radiation/federal-guidance-report-no-15-external-exposure-radionuclides-air-water-and-soil [Accessed 5 June 2026]

WELTJE, L., HEIDENREICH, H., ZHU, W., WOLTERBEEK, H.T., KORHAMMER, S., DE GOEIJ, J.J.M. AND MARKERT, B., 2002. Lanthanide concentrations in freshwater plants and molluscs, related to those in surface water, pore water and sediment. A case study in The Netherlands. The Science of the Total Environment. 286 (1-3), 191-214. Available from: https://doi.org/10.1016/S0048-9697(01)00978-0 [Accessed 5 June 2026]

List of abbreviations and acronyms

DPUR	Dose Per Unit Release
ERICA	Environmental Risk from Ionising Contaminants: Assessment and Management
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IPEM	Institute of Physics and Engineering in Medicine
IRAT/IRAT2	Initial Radiological Assessment Tool (version 2)
LoD	Limit of Detection
PSMA	Prostate specific membrane antigen
WWTW	Wastewater Treatment Works

Glossary

Glossary	
Chelator	A chemical compound that securely binds to metal ions.
Effluent removal factor or removal efficiency	Measure how effectively a wastewater treatment process removes substances such as pollutants. It is calculated by dividing the difference between influent and effluent concentrations by the raw influent concentration.
Exposure groups	A defined set of individuals that are expected to receive similar levels of radiation exposure from a specific source. The exposure groups defined for IRAT2 are in the IRAT2 guidance.
Freshwater sediment K_d	The distribution coefficient (Kd) for freshwater-sediment measures how strongly a substance binds to sediment compared to how much remains in the freshwater environment.
Limit of Detection (LoD)	Lowest quantity or concentration of a component that can be reliably detected with a given analytical method.
Sludge partitioning factor	Describes how a chemical substance, nutrient or metal distributes itself between the solid sewage sludge and liquid phases in wastewater treatment.
Sediments (suspended and deposited)	Suspended sediments are those carried within the water column. Deposited sediments are those that settle on the riverbed. Reference to ‘sediment’ in this report refers to deposited sediment unless specifically stated.
Uncertainty budget	Identifies, quantifies, and combines all sources of uncertainty in a measurement.

Glossary	
Units Bq/L and Bq/kg	Bq/L – Becquerel per litre and is a unit used to measure the radioactivity per unit volume of a substance. 1 Bq equals on radioactive disintegration per second, therefore 1 Bq/L means that every litre contains enough radioactive material of undergo one radioactive disintegration per second. Bq/kg – Becquerel per kilogram and is a unit used to measure the radioactivity per unit mass of a substance. 1 Bq equals on radioactive disintegration per second, therefore 1 Bq/kg means that every kg contains enough radioactive material of undergo one radioactive disintegration per second.

Appendix A: Sample properties

Table A1: Key properties of crude sewage sludge samples taken from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0608	ND3339	01/07/2024 9:30 AM	Sewage (sludge)	1.1	5	18.6
24-0608	ND3340	01/07/2024 1:30 PM	Sewage (sludge)	1.1	5	18.6
24-0609	ND3356	02/07/2024 9:30 AM	Sewage (sludge)	1.0	4	15.9
24-0609	ND3357	02/07/2024 1:30 PM	Sewage (sludge)	1.0	5	15.9
24-0610	ND3371	03/07/2024 9:30 AM	Sewage (sludge)	1.0	4	18.6
24-0610	ND3372	03/07/2024 1:30 PM	Sewage (sludge)	1.0	3	18.6
24-0611	ND3386	04/07/2024 9:30 AM	Sewage (sludge)	1.0	6	18.3
24-0611	ND3387	04/07/2024 1:30 PM	Sewage (sludge)	1.0	6	18.3
24-0612	ND3402	05/07/2024 9:30 AM	Sewage (sludge)	1.0	4	12.6
24-0612	ND3403	05/07/2024 1:30 PM	Sewage (sludge)	1.0	4	12.6

Table A2: Key properties of final effluent samples taken from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0608	ND3341	01/07/2024 9:30 AM	Effluent	1.1	5	18.6
24-0608	ND3342	01/07/2024 1:30 PM	Effluent	1.1	4	18.6
24-0609	ND3358	02/07/2024 9:30 AM	Effluent	1.0	3	15.9
24-0609	ND3359	02/07/2024 1:30 PM	Effluent	1.0	3	15.9
24-0610	ND3373	03/07/2024 9:30 AM	Effluent	1.0	4	18.6
24-0610	ND3374	03/07/2024 1:30 PM	Effluent	1.0	5	18.6
24-0611	ND3388	04/07/2024 9:30 AM	Effluent	1.0	5	18.3
24-0611	ND3389	04/07/2024 1:30 PM	Effluent	1.0	4	18.3
24-0612	ND3404	05/07/2024 9:30 AM	Effluent	1.0	4	12.6
24-0612	ND3405	05/07/2024 1:30 PM	Effluent	1.0	4	12.6

Table A3: Key properties of sewage sludge cake samples taken from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)	Moisture content (%)
24-0591	ND3298-2	28/06/2024 12:30 PM	Sludge (solid)	1.0	4	13.5	73%
24-0608	ND3355	01/07/2024 9:00 AM	Sludge (solid)	1.3	5	18.6	74%
24-0608	ND3343	02/07/2024 9:00 AM	Sludge (solid)	1.2	5	18.6	66%
24-0609	ND3445	03/07/2024 9:00 AM	Sludge (solid)	1.0	5	15.9	79%
24-0610	ND3446	04/07/2024 9:30 AM	Sludge (solid)	0.9	3	18.6	72%
24-0611	ND3390	05/07/2024 9:38 AM	Sludge (solid)	1.1	4	18.3	74%

Table A4: Key properties of primary sewage sludge samples taken from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0591	ND3299-2	28/06/2024 1:30 PM	Sludge (liquid)	2.0	4	13.5
24-0608	ND3346	02/07/2024 9:30 AM	Sludge (liquid)	2.5	5	18.6
24-0609	ND3362	03/07/2024 9:30 AM	Sludge (liquid)	2.5	4	15.9
24-0610	ND3377	04/07/2024 9:30 AM	Sludge (liquid)	2.5	4	18.6
24-0611	ND3393	05/07/2024 9:15 AM	Sludge (liquid)	2.5	5	18.3

Table A5: Key properties of secondary sewage sludge samples taken from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0608	ND3347	01/07/2024 9:30 AM	Sludge (liquid)	1.1	5	18.6
24-0608	ND3348	01/07/2024 1:30 PM	Sludge (liquid)	1.1	4	18.6
24-0609	ND3363	02/07/2024 9:30 AM	Sludge (liquid)	1.0	3	15.9
24-0609	ND3364	02/07/2024 1:30 PM	Sludge (liquid)	1.0	3	15.9
24-0610	ND3378	03/07/2024 9:30 AM	Sludge (liquid)	1.0	3	18.6
24-0610	ND3379	03/07/2024 1:30 PM	Sludge (liquid)	1.0	3	18.6
24-0611	ND3394	04/07/2024 9:30 AM	Sludge (liquid)	1.0	5	18.3
24-0611	ND3395	04/07/2024 1:30 PM	Sludge (liquid)	1.0	4	18.3
24-0612	ND3408	05/07/2024 9:30 AM	Sludge (liquid)	1.0	4	12.6
24-0612	ND3409	05/07/2024 1:30 PM	Sludge (liquid)	1.0	4	12.6

Table A6: Key properties of settled sewage supernatant samples taken from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0608	ND3344	01/07/2024 9:30 AM	Effluent	1.0	5	18.6
24-0608	ND3345	01/07/2024 1:30 PM	Effluent	1.0	5	18.6
24-0609	ND3360	02/07/2024 9:30 AM	Effluent	1.0	3	15.9
24-0609	ND3361	02/07/2024 1:30 PM	Effluent	1.0	4	15.9
24-0610	ND3375	03/07/2024 9:30 AM	Effluent	1.0	4	18.6
24-0610	ND3376	03/07/2024 1:30 PM	Effluent	1.0	4	18.6
24-0611	ND3391	04/07/2024 9:30 AM	Effluent	1.0	4	18.3
24-0611	ND3392	04/07/2024 1:30 PM	Effluent	1.0	4	18.3
24-0612	ND3406	05/07/2024 9:30 AM	Effluent	1.0	4	12.6
24-0612	ND3407	05/07/2024 1:30 PM	Effluent	1.0	4	12.6

Table A7: Key properties of River Cam water samples taken at the point of discharge from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0196	ND1304	05/03/2024 11:06 AM	Natural Water (NW)	5.0	3	8.6
24-0591	ND3301-2	28/06/2024 10:21 AM	Natural Water (NW)	5.0	4	13.5
24-0591	ND3301ADD1-3	28/06/2024 10:21 AM	Particulates on 0.45 µm filter			
24-0591	ND3301ADD2-4	28/06/2024 10:21 AM	0.45 µm filtered water			
24-0608	ND3349	02/07/2024 10:52 AM	Natural Water (NW)	5.2	5	18.6
24-0609	ND3365	03/07/2024 10:20 AM	Natural Water (NW)	5.0	4	15.9
24-0609	ND3365ADD1	03/07/2024 10:20 AM	Particulates on 0.45 µm filter			
24-0609	ND3365ADD2	03/07/2024 10:20 AM	0.45 µm filtered water			
24-0610	ND3380	04/07/2024 10:30 AM	Natural Water (NW)	5.0	3	18.6
24-0610	ND3380ADD1	04/07/2024 10:30 AM	Particulates on 0.45 um filter			
24-0610	ND3380ADD2	04/07/2024 10:30 AM	0.45 um filtered water			

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0611	ND3396	05/07/2024 10:40 AM	Natural Water (NW)	5.0	4	18.3
24-0611	ND3396A DD1	05/07/2024 10:40 AM	Particulates on 0.45 um filter			
24-0611	ND3396A DD2	05/07/2024 10:40 AM	0.45 um filtered water			
24-0659	ND3676	12/07/2024 10:30 AM	Natural Water (NW)	5.0	4	12.7
24-0659	ND3676A DD1	12/07/2024 10:30 AM	Particulates on 0.45 um filter			
24-0659	ND3676A DD2	12/07/2024 10:30 AM	0.45 um filtered water			
24-0687	ND3795	19/07/2024 10:45 AM	Natural Water (NW)	5.0	4	18.6

Table A8: Key properties of River Cam water samples taken 500 m downstream of the Cambridge WWTW point of discharge.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0196	ND1305	05/03/2024 10:47 AM	Natural Water (NW)	5.0	3	8.6
24-0591	ND3303 -2	28/06/2024 10:00 AM	Natural Water (NW)	5.0	4	13.5
24-0591	ND3303 ADD1-3	28/06/2024 10:00 AM	Particulates on 0.45 µm filter			
24-0591	ND3303 ADD2-3	28/06/2024 10:00 AM	0.45 µm filtered water			
24-0608	ND3351	02/07/2024 10:30 AM	Natural Water (NW)	5.5	4	18.6
24-0609	ND3367	03/07/2024 10:00 AM	Natural Water (NW)	5.0	3	15.9
24-0609	ND3367 ADD1	03/07/2024 10:00 AM	Particulates on 0.45 µm filter			
24-0609	ND3367 ADD2	03/07/2024 10:00 AM	0.45 µm filtered water			
24-0610	ND3382	04/07/2024 10:40 AM	Natural Water (NW)	5.0	4	18.6
24-0610	ND3382 ADD1	04/07/2024 10:40 AM	Particulates on 0.45 µm filter			
24-0610	ND3382 ADD2	04/07/2024 10:40 AM	0.45 µm filtered water			

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0611	ND3398	05/07/2024 10:15 AM	Natural Water (NW)	5.0	4	18.3
24-0611	ND3398 ADD1	05/07/2024 10:15 AM	Particulates on 0.45 µm filter			
24-0611	ND3398 ADD2	05/07/2024 10:15 AM	0.45 µm filtered water			
24-0659	ND3678	12/07/2024 10:00 AM	Natural Water (NW)	5.0	4	12.7
24-0659	ND3678 ADD1	12/07/2024 10:00 AM	Particulates on 0.45 µm filter			
24-0659	ND3678 ADD2	12/07/2024 10:00 AM	0.45 µm filtered water			
24-0687	ND3797	19/07/2024 10:30 AM	Natural Water (NW)	5.0	4	18.6

Table A9: Key properties of River Cam water samples taken 1,000 m downstream of the Cambridge WWTW point of discharge.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0196	ND1306	05/03/2024 10:20 AM	Natural Water (NW)	5.0	3	8.6
24-0591	ND3305 -2	28/06/2024 9:30 AM	Natural Water (NW)	5.0	4	13.5
24-0591	ND3305 ADD1-3	28/06/2024 9:30 AM	Particulates on 0.45 µm filter			
24-0591	ND3305 ADD2-3	28/06/2024 9:30 AM	0.45 µm filtered water			
24-0608	ND3353	02/07/2024 10:18 AM	Natural Water (NW)	5.5	4	18.6
24-0609	ND3369 -2	03/07/2024 9:45 AM	Natural Water (NW)	5.0	4	15.9
24-0609	ND3369 ADD1	03/07/2024 9:45 AM	Particulates on 0.45 µm filter			
24-0609	ND3369 ADD2	03/07/2024 9:45 AM	0.45 µm filtered water			
24-0610	ND3384	04/07/2024 10:20 AM	Natural Water (NW)	5.0	4	18.6
24-0610	ND3384 ADD1	04/07/2024 10:20 AM	Particulates on 0.45 µm filter			
24-0610	ND3384 ADD2	04/07/2024 10:20 AM	0.45 µm filtered water			

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)
24-0611	ND3400	05/07/2024 10:00 AM	Natural Water (NW)	5.0	4	18.3
24-0611	ND3400 ADD1	05/07/2024 10:00 AM	Particulates on 0.45 µm filter			
24-0611	ND3400 ADD2	05/07/2024 10:00 AM	0.45 µm filtered water			
24-0659	ND3680	12/07/2024 9:30 AM	Natural Water (NW)	5.0	4	12.7
24-0659	ND3680 ADD1	12/07/2024 9:30 AM	Particulates on 0.45 µm filter			
24-0659	ND3680 ADD2	12/07/2024 9:30 AM	0.45 µm filtered water			
24-0687	ND3799	19/07/2024 10:10 AM	Natural Water (NW)	5.0	4	18.6

Table A10: Key properties of River Cam sediment samples taken at the point of discharge from the Cambridge WWTW.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)	Moisture content (%)
24-0195	ND1301	05/03/2024 11:06 AM	Sediment (SED)	1.4	4	11.4	63%
24-0591	ND3302-2	28/06/2024 10:21 AM	Sediment (SED)	1.0	4	13.5	51%
24-0608	ND3350	02/07/2024 10:52 AM	Sediment (SED)	2.5	4	18.6	55%
24-0609	ND3366	03/07/2024 10:20 AM	Sediment (SED)	2.0	4	15.9	70%
24-0610	ND3381	04/07/2024 10:30 AM	Sediment (SED)	1.8	3	18.6	69%
24-0611	ND3397	05/07/2024 10:40 AM	Sediment (SED)	2.3	5	18.3	61%
24-0659	ND3677	12/07/2024 10:30 AM	Sediment (SED)	1.0	4	12.7	67%
24-0687	ND3796	19/07/2024 10:45 AM	Sediment (SED)	2.0	4	18.6	69%

Table A11: Key properties of River Cam sediment samples taken 500 m downstream of the Cambridge WWTW point of discharge.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)	Moisture content (%)
24-0195	ND1302	05/03/2024 10:47 AM	Sediment (SED)	1.6	4	8.3	56%
24-0591	ND3304-2	28/06/2024 10:00 AM	Sediment (SED)	1.0	4	13.5	23%
24-0608	ND3352	02/07/2024 10:30 AM	Sediment (SED)	1.5	5	18.6	28%
24-0609	ND3368	03/07/2024 10:00 AM	Sediment (SED)	1.0	3	15.9	54%
24-0610	ND3383	04/07/2024 10:40 AM	Sediment (SED)	2.2	4	18.6	72%
24-0611	ND3399	05/07/2024 10:15 AM	Sediment (SED)	1.9	4	18.3	82%
24-0659	ND3679	12/07/2024 10:00 AM	Sediment (SED)	1.5	4	12.7	37%
24-0687	ND3798	19/07/2024 10:30 AM	Sediment (SED)	1.0	4	18.6	68%

Table A12: Key properties of River Cam sediment samples taken 1,000 m downstream of the Cambridge WWTW point of discharge.

Job ID	Sample ID	Sample date and time	Matrix	Volume (L or kg)	Count rate (CPS)	Temperature (°C)	Moisture content (%)
24-0195	ND1303	05/03/2024 10:20 AM	Sediment (SED)	1.4	4	10.9	61%
24-0591	ND3306-2	28/06/2024 9:30 AM	Sediment (SED)	1.0	4	13.5	68%
24-0608	ND3354	02/07/2024 10:18 AM	Sediment (SED)	2.2	4	18.6	71%
24-0609	ND3370	03/07/2024 9:45 AM	Sediment (SED)	1.0	4	15.9	79%
24-0610	ND3385	04/07/2024 10:20 AM	Sediment (SED)	2.1	4	18.6	67%
24-0611	ND3401	05/07/2024 10:00 AM	Sediment (SED)	2.1	5	18.3	73%
24-0659	ND3681	12/07/2024 9:30 AM	Sediment (SED)	1.5	4	12.7	79%
24-0687	ND3800	19/07/2024 10:10 AM	Sediment (SED)	2.4	4	18.6	79%

Appendix B: Other radionuclides identified

This study focussed on the behaviour of ^{177}Lu in wastewater systems. However, collected samples were also analysed for other gamma emitting radionuclides and the results for these radionuclides are reported here for completeness. Unfortunately, a source term of the other radionuclides was not available to be examine these results in more detail.

Table B1: Other radionuclide concentrations in crude sewage samples taken from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	^{235}U*	Unit
24-0608	ND3339	10.2 ± 0.84	<2.9	<9.7	<0.41	Bq/L
24-0608	ND3340	59.6 ± 4.1	<2.7	<5.4	<0.70	Bq/L
24-0609	ND3356	50.5 ± 2.8	<1.2	<3.2	<0.38	Bq/L
24-0609	ND3357	6.90 ± 0.55	<1.4	<3.7	<0.23	Bq/L
24-0610	ND3371	9.91 ± 0.72	<1.7	<4.6	<0.41	Bq/L
24-0610	ND3372	0.82 ± 0.31	<2.5	<8.5	<0.34	Bq/L
24-0611	ND3386	1.3 ± 0.28	<2.0	<5.5	<0.31	Bq/L
24-0611	ND3387	<0.52	<3.6	<12	<0.46	Bq/L
24-0612	ND3402	1.50 ± 0.33	<2.2	<7.7	<0.29	Bq/L
24-0612	ND3403	5.06 ± 0.39	<1.1	<4.0	<0.22	Bq/L

*^{235}U is not accredited.

Table B2: Other radionuclide concentrations in final effluent samples taken from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0608	ND3341	<0.32	<2.2	<7.0	<0.32	Bq/L
24-0608	ND3342	0.75 ± 0.26	<2.3	<7.0	<0.31	Bq/L
24-0609	ND3358	1.10 ± 0.15	<1.1	<3.7	<0.20	Bq/L
24-0609	ND3359	1.81 ± 0.19	<1.0	<3.7	<0.21	Bq/L
24-0610	ND3373	2.98 ± 0.53	<3.6	<13	<0.51	Bq/L
24-0610	ND3374	2.69 ± 0.52	<3.0	<6.2	<0.63	Bq/L
24-0611	ND3388	1.66 ± 0.39	<2.9	<9.7	<0.40	Bq/L
24-0611	ND3389	1.89 ± 0.55	<4.0	<14	<0.56	Bq/L
24-0612	ND3404	0.42 ± 0.16	<1.3	<4.0	<0.21	Bq/L
24-0612	ND3405	1.01 ± 0.30	<2.3	<8.2	<0.3	Bq/L

*^{235}U is not accredited.

Table B3: Other radionuclide concentrations in sewage sludge cake samples taken from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:$^{238}U/^{226}Ra$. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0591	ND3298-2	325 ± 26	43 ± 7.4	55 ± 12	1.28 ± 0.47	Bq/kg dry
24-0608	ND3355	604 ± 36	37 ± 7.6	56 ± 13	<2.14	Bq/kg dry
24-0608	ND3343	842 ± 51	45 ± 11	51 ± 18	<3.14	Bq/kg dry
24-0609	ND3445	716 ± 39	33 ± 13	<46	<3.83	Bq/kg dry
24-0610	ND3446	404 ± 25	26.9 ± 6	41.3 ± 9.6	<1.64	Bq/kg dry
24-0611	ND3390	955 ± 57	41.6 ± 8.7	52 ± 13	<2.77	Bq/kg dry

*^{235}U is not accredited.

Table B4: Other radionuclide concentrations in primary sludge samples taken from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:$^{238}U/^{226}Ra$. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0591	ND3299-2	10.7 ± 0.86	<1.1	6.1 ± 1.8	<0.24	Bq/L
24-0608	ND3346	5.37 ± 0.38	<0.96	<2.6	<0.21	Bq/L
24-0609	ND3362	8.05 ± 0.57	<1.4	<3.9	<0.22	Bq/L
24-0610	ND3377	14.1 ± 0.87	<1.1	<3.0	<0.27	Bq/L
24-0611	ND3393	15.6 ± 1.0	<2.0	<5.8	<0.33	Bq/L

*^{235}U is not accredited.

Table B5: Other radionuclide concentrations in secondary sludge samples taken from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0608	ND3347	61.1 ± 4.2	<2.7	<5.5	<0.70	Bq/L
24-0608	ND3348	71.6 ± 4.9	<2.7	<5.2	<0.70	Bq/L
24-0609	ND3363	105 ± 5.7	<1.8	<5.2	<0.43	Bq/L
24-0609	ND3364	94.8 ± 6.2	<2.8	<5.4	<0.76	Bq/L
24-0610	ND3378	212 ± 13	<3.3	<6.3	<1.01	Bq/L
24-0610	ND3379	123 ± 6.8	<3.2	<9.7	<0.70	Bq/L
24-0611	ND3394	197 ± 12	<3.2	<6.0	<0.95	Bq/L
24-0611	ND3395	177 ± 11	<2.9	<5.5	<0.88	Bq/L
24-0612	ND3408	76.2 ± 4.2	<1.7	<4.0	<0.40	Bq/L
24-0612	ND3409	70.9 ± 4.0	<1.7	<4.3	<0.38	Bq/L

*^{235}U is not accredited.

Table B6: Other radionuclide concentrations in settled sewage supernatant samples taken from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U: $^{238}U/^{226}Ra$. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0608	ND3344	2.23 ± 0.41	<2.5	<4.9	<0.51	Bq/L
24-0608	ND3345	54.5 ± 3.8	<2.5	<5.4	<0.70	Bq/L
24-0609	ND3360	35.2 ± 2.1	<1.7	<3.8	<0.33	Bq/L
24-0609	ND3361	14.00 ± 0.88	<1.3	<3.6	<0.30	Bq/L
24-0610	ND3375	11.5 ± 1.1	<2.5	<5.2	<0.58	Bq/L
24-0610	ND3376	3.83 ± 0.61	<3.7	<13	<0.53	Bq/L
24-0611	ND3391	2.22 ± 0.47	<3.0	<6.2	<0.61	Bq/L
24-0611	ND3392	2.48 ± 0.58	<3.6	<7.8	<0.76	Bq/L
24-0612	ND3406	1.35 ± 0.26	<1.5	<4.0	<0.24	Bq/L
24-0612	ND3407	3.29 ± 0.37	<1.8	<5.7	<0.24	Bq/L

*^{235}U is not accredited.

Table B7: Other radionuclide concentrations in water samples taken at the point of discharge from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0196	ND1304	3.21 ± 0.31	<1.1	<4.1	<0.18	Bq/L
24-0591	ND3301-2	0.72 ± 0.14	<0.88	<2.5	<0.18	Bq/L
24-0591	ND3301ADD1-3	0.159 ± 0.049	<0.3	<0.96	<0.050	Bq/L
24-0591	ND3301ADD2-4	<0.21	<0.91	<2.4	<0.18	Bq/L
24-0608	ND3349	0.77 ± 0.17	<1.2	<3.9	<0.18	Bq/L
24-0609	ND3365	1.3 ± 0.21	<1.3	<3.8	<0.19	Bq/L
24-0609	ND3365ADD1	0.277 ± 0.029	<0.12	<0.37	<0.020	Bq/L
24-0609	ND3365ADD2	0.86 ± 0.17	<0.9	<2.4	<0.18	Bq/L
24-0610	ND3380	0.72 ± 0.13	<0.88	<2.4	<0.19	Bq/L
24-0610	ND3380ADD1	0.119 ± 0.021	<0.12	<0.38	<0.020	Bq/L
24-0610	ND3380ADD2	0.51 ± 0.17	<1.3	<3.8	<0.19	Bq/L
24-0611	ND3396	0.40 ± 0.11	<0.83	<2.4	<0.18	Bq/L

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0611	ND3396ADD1	0.109 ± 0.022	<0.15	<0.54	<0.020	Bq/L
24-0611	ND3396ADD2	<0.20	<1.2	<3.8	<0.19	Bq/L
24-0659	ND3676	0.392 ± 0.096	<0.83	<2.4	<0.18	Bq/L
24-0659	ND3676ADD1	0.105 ± 0.018	<0.11	<0.38	<0.020	Bq/L
24-0659	ND3676ADD2	<0.23	<1.6	<5.1	<0.22	Bq/L
24-0687	ND3795	0.58 ± 0.14	<1.2	<3.7	<0.18	Bq/L

*^{235}U is not accredited.

Table B8: Other radionuclide concentrations in water samples taken 500 m from the Cambridge WWTW point of discharge. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0196	ND1305	0.50 ± 0.13	<1.1	<4.1	<0.17	Bq/L
24-0591	ND3303-2	<0.21	<1.3	<3.9	<0.19	Bq/L
24-0591	ND3303ADD1-3	<0.056	<0.3	<0.94	<0.050	Bq/L
24-0591	ND3303ADD2-3	<0.23	<1.3	<3.9	<0.19	Bq/L
24-0608	ND3351	<0.17	<1.2	<3.7	<0.18	Bq/L
24-0609	ND3367	0.38 ± 0.11	<0.86	<2.4	<0.17	Bq/L
24-0609	ND3367ADD1	0.044 ± 0.015	<0.12	<0.36	<0.020	Bq/L
24-0609	ND3367ADD2	<0.23	<1.2	<3.7	<0.18	Bq/L
24-0610	ND3382	<0.15	<0.91	<2.5	<0.18	Bq/L
24-0610	ND3382ADD1	<0.020	<0.12	<0.38	<0.020	Bq/L
24-0610	ND3382ADD2	<0.22	<1.3	<3.7	<0.18	Bq/L
24-0611	ND3398	<0.15	<0.88	<2.4	<0.17	Bq/L
24-0611	ND3398ADD1	<0.021	<0.13	<0.38	<0.020	Bq/L
24-0611	ND3398ADD2	<0.16	<0.84	<2.4	<0.17	Bq/L
24-0659	ND3678	<0.15	<1.2	<3.8	<0.18	Bq/L

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0659	ND3678ADD1	<0.019	<0.12	<0.38	<0.020	Bq/L
24-0659	ND3678ADD2	<0.20	<1.2	<3.7	<0.19	Bq/L
24-0687	ND3797	0.32 ± 0.12	<1.2	<3.7	<0.18	Bq/L

*^{235}U is not accredited.

Table B9: Other radionuclide concentrations in water samples taken 1,000 m from the Cambridge WWTW point of discharge. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0196	ND1306	<0.18	<1.6	<4.7	<0.21	Bq/L
24-0591	ND3305-2	<0.24	<1.6	<5.1	<0.21	Bq/L
24-0591	ND3305ADD1-3	<0.057	<0.29	<0.98	<0.050	Bq/L
24-0591	ND3305ADD2-3	<0.23	<1.3	<3.9	<0.18	Bq/L
24-0608	ND3353	<0.18	<1.2	<3.7	<0.18	Bq/L
24-0609	ND3369-2	0.34 ± 0.12	<1.2	<3.8	<0.18	Bq/L
24-0609	ND3369ADD1	<0.025	<0.16	<0.54	<0.020	Bq/L
24-0609	ND3369ADD2	<0.22	<1.2	<3.8	<0.18	Bq/L
24-0610	ND3384	<0.15	<0.87	<2.5	<0.18	Bq/L
24-0610	ND3384ADD1	<0.020	<0.13	<0.38	<0.020	Bq/L
24-0610	ND3384ADD2	<0.20	<1.2	<3.9	<0.18	Bq/L
24-0611	ND3400	<0.14	<0.86	<2.4	<0.17	Bq/L
24-0611	ND3400ADD1	<0.020	<0.11	<0.39	<0.020	Bq/L
24-0611	ND3400ADD2	<0.16	<0.86	<2.4	<0.17	Bq/L
24-0659	ND3680	<0.14	<1.2	<3.7	<0.18	Bq/L
24-0659	ND3680ADD1	<0.020	<0.12	<0.38	<0.020	Bq/L

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0659	ND3680ADD2	<0.19	<1.2	<3.7	<0.18	Bq/L
24-0687	ND3799	<0.12	<0.83	<2.5	<0.17	Bq/L

*^{235}U is not accredited.

Table B10: Other radionuclide concentrations in sediment samples taken at the point of discharge from the Cambridge WWTW. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2 σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0195	ND1301	38.5 ± 2.8	<1.2	213 ± 17	0.84 ± 0.12	Bq/kg dry
24-0591	ND3302-2	<0.46	7.9±2.5	171 ± 16	1.52 ± 0.19	Bq/kg dry
24-0608	ND3350	<0.31	8.4 ± 1.9	188 ± 13	1.12 ± 0.16	Bq/kg dry
24-0609	ND3366	<1.9	<16	299 ± 36	<2.64	Bq/kg dry
24-0610	ND3381	<1.3	<9.7	164 ± 28	<1.39	Bq/kg dry
24-0611	ND3397	<0.52	16.7 ± 3.3	182 ± 15	0.76 ± 0.20	Bq/kg dry
24-0659	ND3677	<1.8	<12	213 ± 28	<2.2	Bq/kg dry
24-0687	ND3796	<1.7	<13	207 ± 30	<2.3	Bq/kg dry

*^{235}U is not accredited.

Table B11: Other radionuclide concentrations in sediment samples taken 500 m from the Cambridge WWTW point of discharge. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0195	ND1302	25.2 ± 1.9	10.3 ± 2	115 ± 13	0.84 ± 0.17	Bq/kg dry
24-0591	ND3304-2	8.58 ± 0.74	<1.8	58.7 ± 6	1.27 ± 0.16	Bq/kg dry
24-0608	ND3352	13.2 ± 0.87	<2.4	66.4 ± 6.9	1.75 ± 0.19	Bq/kg dry
24-0609	ND3368	30.4 ± 2.9	<9.1	60 ± 16	<1.95	Bq/kg dry
24-0610	ND3383	75.7 ± 5.4	24.6 ± 9.8	162 ± 34	<1.83	Bq/kg dry
24-0611	ND3399	150 ± 11	55 ± 14	291 ± 40	<3.27	Bq/kg dry
24-0659	ND3679	32.0 ± 3.0	<9.2	51 ± 15	<1.89	Bq/kg dry
24-0687	ND3798	76.4 ± 4.8	20 ± 5.8	117 ± 19	<1.45	Bq/kg dry

*^{235}U is not accredited.

Table B12: Other radionuclide concentrations in sediment samples taken 1,000 m from the Cambridge WWTW point of discharge. ^{235}U has been calculated assuming a natural activity ratio of 0.045 for ^{235}U:^{238}U/^{226}Ra. Results are decay corrected to the sampling date. Uncertainties are quoted at 2σ based on a total uncertainty budget.

Job ID	Sample ID	^{131}I	^{7}Be	^{40}K	$^{235}U^{*}$	Unit
24-0195	ND1303	24.1 ± 1.8	9.2 ± 2.1	183 ± 18	0.91 ± 0.23	Bq/kg dry
24-0591	ND3306-2	3.8 ± 1.5	<11	177 ± 29	<1.57	Bq/kg dry
24-0608	ND3354	5.9 ± 1.8	<16	206 ± 34	<2.70	Bq/kg dry
24-0609	ND3370	4.3 ± 1.6	<14	197 ± 31	<2.64	Bq/kg dry
24-0610	ND3385	7.0 ± 1.8	<14	203 ± 32	<2.64	Bq/kg dry
24-0611	ND3401	13.4 ± 2.5	<17	233 ± 36	<3.02	Bq/kg dry
24-0659	ND3681	8.5 ± 1.7	<11	219 ± 31	<1.89	Bq/kg dry
24-0687	ND3800	15.7 ± 2.1	<12	202 ± 31	<1.64	Bq/kg dry

*^{235}U is not accredited.

Would you like to find out more about us or your environment?

Then call us on:

03708 506 506 (Monday to Friday, 8am to 6pm)

Email: enquiries@environment-agency.gov.uk

Or visit our website
www.gov.uk/environment-agency

Incident hotline

0800 807060 **(24 hours)**

Floodline

0345 988 1188 **(24 hours)**

Find out about call charges (https://www.gov.uk/call-charges)

Environment first

Are you viewing this onscreen? Please consider the environment and only print if absolutely necessary. If you are reading a paper copy, please don't forget to reuse and recycle.

Environment Agency
Horizon House,
Deanery Road,
Bristol
BS1 5AH