using science to
create a better place

Radionuclide discharges to sewer – A field investigation

Science Report – SC020150/SR2

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency's Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive,
Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84432-819-2

Further copies of this report are available from:
The Environment Agency's National Customer Contact Centre by emailing:
enquiries@environment-agency.gov.uk
or by telephoning 08708 506506.

Author(s):
[1]Punt A, [2]Wood M & [1]Rose D

Dissemination Status:
Publicly available / released to all regions

Keywords:
Radioiodine, iodine, I-131, sewer, discharge, hospital, dose

Research Contractors:
Enviros Consulting Ltd,
Building D5
Culham Science Centre
Abingdon
OXON OX14 3DB

University of Liverpool,
Radioecology Unit

WRc plc
Frankland Road
Blagrove
Swindon SN5 8YF

Environment Agency's Project Manager:
David Copplestone, Richard Fairclough House,
Knutsford Road, Warrington WA4 1HG

Science Project Number:
SC020150/SR2

Product Code:
SCHO0907BNGB-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

The work of the Environment Agency's Science Group is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The science programme focuses on five main areas of activity:

- **Setting the agenda**, by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science**, by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science**, by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards;
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Steve Killeen

Head of Science

Executive summary

This project, *Radionuclide discharges to sewer - A field investigation* (SC020150 Part B), was undertaken by Enviros Consulting Ltd with support from the Institute for Sustainable Water Integrated Management and Ecosystem Research at the University of Liverpool.

The study was commissioned by the Environment Agency in response to an application for increased iodine-131 discharges from the Royal Marsden Hospital in South West London. An initial radiological assessment of the application indicated that doses could exceed 0.3 mSv per year. The assessment showed that people might be exposed to iodine-131 in the rivers and brooks receiving treated effluent from the Hogsmill sewage treatment works. Environment Agency guidelines state that if initial predictions suggest that doses could be greater than 0.02 mSv per year, a more detailed assessment should be carried out, including site-specific information and monitoring where applicable.

This study investigated iodine-131 activity concentrations in crude sewage, during sewage treatment, in sewage effluent and sludge cake and in river water and sediment around the Hogsmill sewage plant from discharges from the Royal Marsden Hospital.

Based on a total administration of 15.1 GBq of iodine-131 between three patients over three consecutive days in February 2006, the sampling found activity concentrations of iodine-131 in:

- crude sewage of on average 26 Bq l^{-1}, reaching a maximum of 50 Bq l^{-1};
- treated effluent of on average 11 Bq l^{-1} and in all samples, less than 20 Bq l^{-1};
- primary settled sludge up to 76 Bq l^{-1}, in activated sludge up to 130 Bq l^{-1} and in dewatered sludge cake up to 1,800 Bq kg^{-1} (dw).
- river water up to 20 Bq l^{-1} and river sediment up to 67 Bq kg^{-1} (dw);
- intertidal sediment, where the Beverley Brook meets the Thames Estuary, up to 570 Bq kg^{-1} (dw).

Based on a survey of gamma dose in air, external exposure at most points around the Hogsmill sewage works and along Beverley Brook was indistinguishable from background (19 nSv h^{-1}). At the works, slightly elevated dose rates in air were measured (up to 31 nSv h^{-1}) near to freshly dewatered sludge cake representing, in round numbers, about 10 nSv h^{-1} above background. Based on pessimistic exposure times (1,000 h y^{-1}) external exposure is still minimal (0.01 mSv y^{-1} above background), around one per cent of the annual 'controllable' dose limit to a member of the public. Over intertidal sediments, external exposure could also be elevated, but again would be likely to be no more than a few percent of the annual dose limit.

Of the total activity administered to patients at the hospital, most is excreted and enters the sewer system. This study showed that, of this, more than half is lost through decay or association with solids in the sewer, about two per cent is likely to be transferred to dewatered sludge cake at the Hogsmill works and about one third is likely to be discharged after treatment to the Hogsmill River and Beverley Brook.

Acknowledgements

The authors of this study gratefully acknowledge the guidance and support of Environment Agency staff, particularly Dr David Copplestone and Dr John Titley in ensuring the successful completion of this project.

We would also like to acknowledge Thames Water staff who allowed us onto the Hogsmill sewage works site and who kindly provided us with data on sewage flow rates. We would particularly like to thank Royal Marsden NHS Foundation Trust staff who worked closely with us, allowing careful timing of the study in relation to their iodine-131 administration regime.

Finally, we would like to thank Enviros staff Duncan Jackson and Chris Carter who provided guidance and support throughout this project and made invaluable comments on this report, and Dr Karen Smith who worked hard on collating information and preparing the final document.

Dr Adrian Punt
Project Coordinator (Enviros)

Contents

1 Introduction

This project, *Radionuclide discharges to sewer - A field investigation* (SC020150 Part B), was undertaken by Enviros Consulting Ltd with support from the Institute for Sustainable Water Integrated Management and Ecosystem Research at the University of Liverpool. It is the second[1] of two pieces of work commissioned by the Environment Agency to determine the radiological implications of authorised discharges of radioactive waste to sewer.

1.1 Background

The Environment Agency has a statutory responsibility to assess and authorise discharges of radioactivity under the Radioactive Substances Act (1993). Within England and Wales, the Environment Agency has issued around 130 permits for the discharge of radioactive substances to sewer. These discharges predominantly arise from hospitals, universities and research laboratories ('small users'), although there is also a contribution from nuclear licensed sites.

The NHS Trust Royal Marsden Hospital in Sutton, South West London is authorised to discharge to sewer a range of radionuclides used in medical diagnosis and cancer treatment. These include fluorine-18, carbon-14, phosphorus-32, chromium-51, strontium-89, yttrium-90, technetium-99m, indium-111, iodine-123, iodine-125, iodine-131 and samarium-153. Sewage from the Sutton area has, since 1999, been treated at the Thames Water Hogsmill works in the Kingston area of London, approximately 8.5 km to the west of the Royal Marsden Hospital. Treated sewage effluent from the Hogsmill works is discharged to the Hogsmill River. Some of the effluent is also piped back to the now closed Worcester Park Sewage works and then into the Beverley Brook where it helps to maintain the flow through the brook, particularly in summer. The brook then flows northward through Wimbledon Common and Richmond Park, before its confluence with the Thames Estuary near Putney Bridge.

In 2006, the NHS Trust applied for an increase in their discharge authorisation limit for iodine-131. Following this application, a preliminary radiological assessment was carried out by the Environment Agency using its initial radiological assessment system (Allott *et al.,* 2006; Lambers and Thorne, 2006). The results from the radiological assessment predicted doses above 0.3 mSv per year to people making use of Beverley Brook and its margins in Wimbledon Common and Richmond Park. Most of the dose was predicted to arise from iodine-131 in water, sediment and fish. This study therefore investigated the behaviour and fate of iodine-131 during sewage treatment and in the Beverley Brook. A week-long campaign of monitoring iodine-131 and dose rates was used to follow the dispersion of known discharges of the isotope. Further monitoring of intertidal sediment where the brook meets the Thames Estuary was also undertaken.

There are limited pathways of exposure for discharges of treated effluent to the Hogsmill River, which runs west to the Thames in the Kingston area, so this was not considered further.

---

[1] The initial study, P3-109A, *Radionuclide partitioning during sewage treatment – A laboratory investigation* (Punt *et al*., 2006) is also available from the Environment Agency.

1.2 Project aims

The aim of this project was to carry out monitoring and sampling to determine the fate and activity concentrations of iodine-131 discharged from the Royal Marsden NHS Hospital to the Hogsmill sewage treatment works and thence to the Beverley Brook. The project had the specific objectives of:

- determining the planned administration regime of iodine-131 at the hospital and scheduling the monitoring work to coincide with periods of elevated release to sewer;

- monitoring iodine-131 activity concentrations in crude sewage, through the treatment process, and in final effluent and sludge cake solids at the Hogsmill sewage works;

- monitoring iodine-131 activity concentrations in the Beverley Brook which receives treated sewage effluent from the Hogsmill works;

- calculating water-bed sediment partition coefficients for iodine-131 specific to this site, for possible inclusion within a site-specific assessment;

- monitoring air kerma around the sewage works and over water and bank in the Beverley Brook;

- undertaking a preliminary assessment of external radiological exposure at the sewage works and over water and sediment in the brook, based on a hypothetical exposure time of 1,000 hours per year.

Further monitoring was carried out to collect data on activity concentrations of iodine-131 and other gamma-emitting radionuclides and to assess external exposure over intertidal sediment where the Beverley Brook enters the Thames Estuary. Assessing iodine-131 uptake by fish was outside the remit of this project.

2 Methods

The behaviour of iodine-131 after discharge to sewer has been studied previously and monitoring has been carried out on discharges from the Royal Marsden Hospital and other sites. Information on the environmental fate and behaviour of iodine-131 is summarised in Appendix 1. Appendix 2 describes previous studies conducted around sewage works receiving iodine-131 from authorised discharges. This information was taken into account when planning this study.

Monitoring and sampling work was carried out over a one-week period in February/March 2006, with further follow-up monitoring in July 2006. A summary of the survey methodology is given below and further details are provided in Appendix 3.

The timing of the main survey was designed to coincide with a schedule of three thyroid ablation treatments which involved both ionic (NaI) and complexed metaiodobenzyguanidine (mIBG) forms of radioiodine, with a total administered activity of 15.1 GBq iodine-131. There had been no administrations the week before, but within the month prior to the survey 53 GBq of iodine-131 had been administered. During the few days prior to the July survey, 17 GBq had been administered; over the whole preceding month, 40 GBq had been administered. The site had in 2006 an annual authorised discharge limit of 400 GBq, with a typical weekly application of up to10 GBq. Administrations are made most, but not all weeks and are typically administered on Tuesdays.

The activity administered during the spring survey was around 1.5 times higher than the normal maximum administrations in any week. The survey was planned according to the scheduled administration of three treatments on one day (Tuesday 28th February). However, due to last-minute changes at the hospital only one administration was made on the Tuesday (5.6 GBq NaI), with the other administrations given on the Wednesday (6.6 GBq mIBG) and on the Thursday (3 GBq NaI). The administration of radioiodine over three consecutive days is not typical, but due to the last-minute alteration to the administration programme, it was not possible to reschedule the sampling.

During the survey, activity concentrations of iodine-131 were monitored in crude sewage, primary treated sewage, activated sludge and in final effluent throughout the week. Additional samples of primary sludge and final dewatered solids were collected (see Figure 2.1). River water and river bed samples were collected from three sites downstream of the effluent outfall on a daily basis (West Barnes Lane – sampling point 2; Wimbledon Common – sampling point 3; and Richmond Park – sampling point 4). Occasional water samples were collected from a point upstream of the outfall (sampling point 1) and water and sediment samples collected from where the brook meets the Thames Estuary (sampling point 5), as shown in Figure 2.2. Additional bank sediment was also collected from Richmond Park.

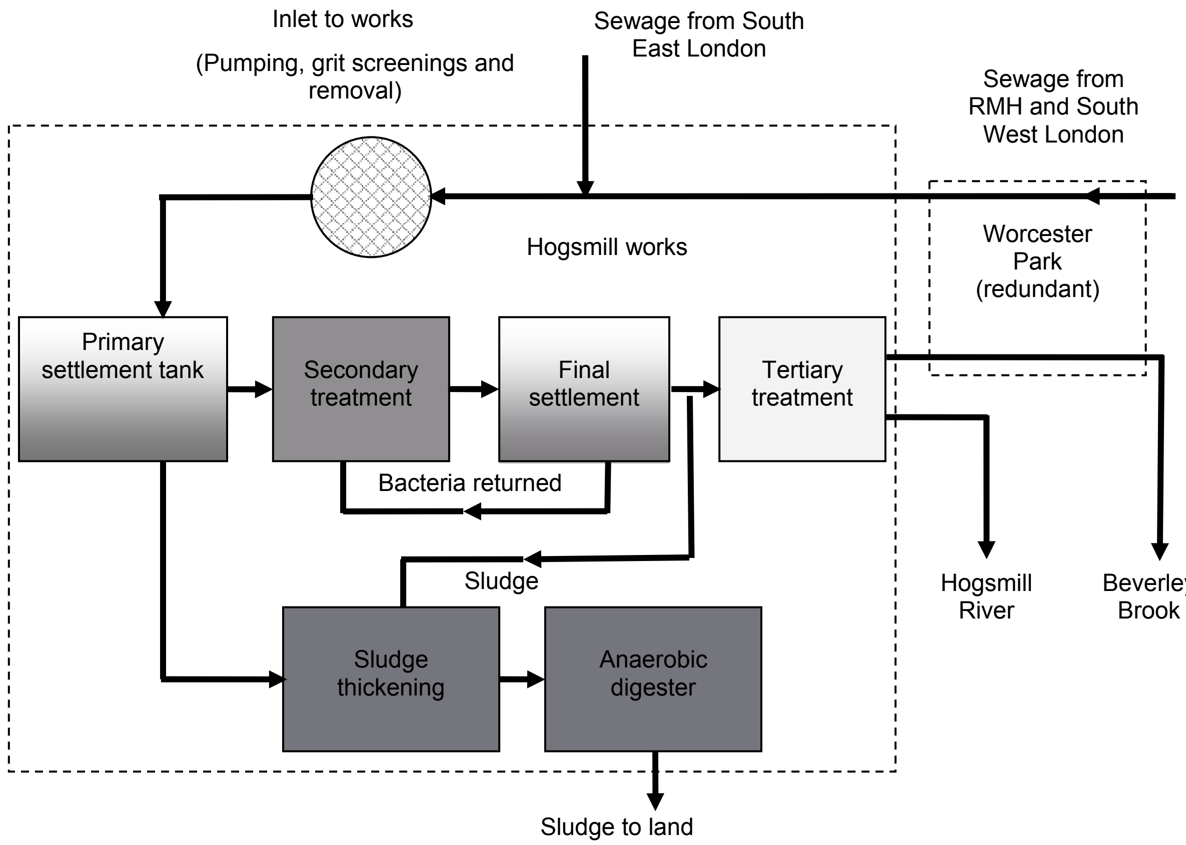

Figure 2.1: Schematic showing the process layout of the Hogsmill works and discharge routes to the Hogsmill River and Beverley Brook

Gamma dose in air was assessed at various points around the sewage works and over water and bank along the length of Beverley Brook.

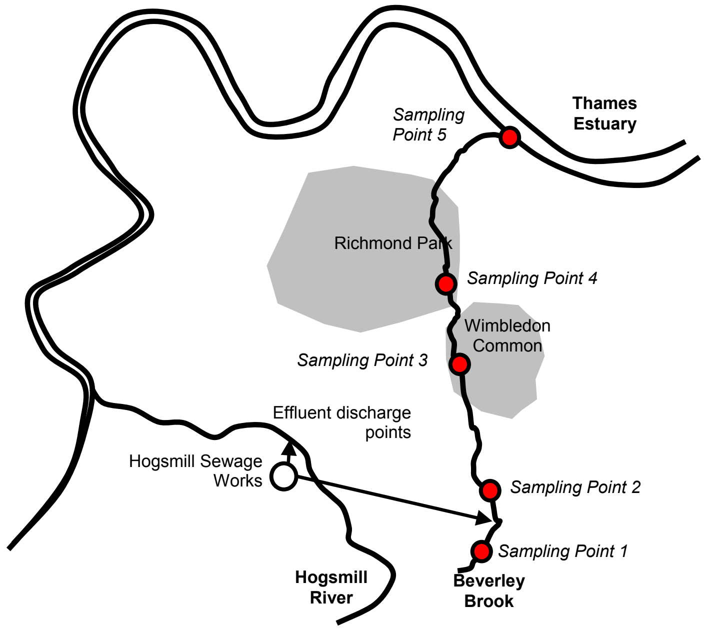

Figure 2.2: Schematic showing the location of the Hogsmill works, effluent discharge points for the compensation flow and course of the Beverley Brook

3 Fate of iodine-131 discharged to the Hogsmill sewage works

The main results from the study are presented in Appendix 4 and are summarised here. Overall, 116 environmental samples were collected and 85 air kerma rates recorded.

3.1 Hogsmill sewage works and receiving rivers

Sewage from the south west area of London, including that from the Royal Marsden Hospital, is collected in the vicinity of the old Worcester Parks works, from where it falls under gravity through a dedicated pipeline to the Hogsmill works. At Hogsmill, it is combined with sewage from the south eastern areas of London prior to treatment. Overall, the Hogsmill site provides treatment for an estimated population equivalent of 410,000 to 420,000, with approximately a third of the flow derived from the old Worcester Park catchment.

The Hogsmill works has four 35-metre diameter primary settlement tanks and a secondary treatment activated (aerated) sludge plant. Final effluent undergoes tertiary treatment using sand bed filters before discharge to the river. Of the average daily flow through the works of about 95,000 m^3, about 80 per cent is discharged to the Hogsmill River. The remaining 20 per cent is pumped back to the site of the old Worcester Park works where it is discharged to the Beverley Brook to maintain water flow, particularly under dry weather conditions. The brook flows northward and passes through popular and publicly accessible points on Wimbledon Common and Richmond Park before meeting the Thames near Putney Bridge. The course of the Beverley Brook and location of the sampling points visited is shown in Figure 2.2.

The maximum consented rate of compensation flow to the Beverley Brook is 20,000 m^3 per day, however the pumps typically operate at about 15,000 m^3 per day. Under dry weather conditions, the compensation flow can account for 80 to 90 per cent of the flow in the brook at the point of discharge and over the entire length of the brook, can still account for a significant fraction (up to a third).

Sludge generated from primary and secondary treatment at the Hogsmill works undergoes, on average, 17 days of initial anaerobic digestion and a further six to nine days of subsequent anaerobic digestion prior to dewatering. Approximately 16 tonnes of dewatered solids are produced on a daily basis. These are temporarily stored on site and subsequently spread to farmland. Storage times vary from days to months, depending upon demand from farmers.

Key flow data is summarised in Table 3.1 below.

Table 3.1: Key flow data

Media	Average flow five-year period	Flow during sampling programme
Crude sewage inputs to Hogsmill	95,000 m^3/d	77,070 m^3/d
Treated effluent outputs from Hogsmill	95,000 m^3/d	77,070 m^3/d
Treated effluent flow to Beverley Brook	18,000 m^3/d	13,900 m^3/d
Treated effluent flow to Hogsmill River	78,000 m^3/d	63,170 m^3/d
Beverley Brook flow at Wimbledon	48,400 m^3/d	26,800 m^3/d
Hogsmill River flow at Kingston	116,000 m^3/d	81,100 m^3/d
Percentage flow in Hogsmill from the works	37%	52%
Percentage flow in the Beverley from the works	67%	78%

Note: crude sewage and effluent flow rate provided by Thames Water (Wallis, personal communication). Beverley Brook flow data taken from Environment Agency River Flow Archive

The table above illustrates the importance of the discharged effluent to flows in both the Beverley Brook and Hogsmill River, where it accounts for a significant proportion of flow even under average river flow conditions. The survey was conducted following a period of relatively little rain and flows (0.32 $m^3 s^{-1}$) were lower than average (0.55 $m^3 s^{-1}$). However, they were higher than the minimum Q95 flow of 0.22 $m^3 s^{-1}$ and do not represent the worst case situation of minimum dilution.

Average flow rates in both the Beverley Brook and Hogsmill River are influenced by episodic high flows associated with storm events, and actual flow through these water courses is typically lower than the values quoted above.

3.2 Iodine-131 discharges from Royal Marsden Hospital

Iodine-131 is primarily used by the Royal Marsden Hospital (RMH) in neuroblastoma and thyroid cancer treatment. Following administration (typically intravenously), most of the iodine-131 is then excreted from each treated patient, with about 50 per cent loss within 24 hours and 75 per cent loss within 48 hours. The Royal Marsden monitors total iodine-131 activity in the body of patients every few hours, typically for four days following administration, using a full body gamma spectrometer. An exponential regression formula was used in this study to interpolate between measurements, and both measured and interpolated data were then combined to provide an estimate of total activity within the patients and to describe variation with time. The results were decay-corrected to calculate the activity of iodine-131 that was excreted by the patients. This is presented both as a function of time and a cumulative total in Figure 3.1[2].

[2] Although some iodine will be transferred to bedding via patient sweat we have assumed that any reduction in activity not accounted for by decay represents activity that has entered the sewer.

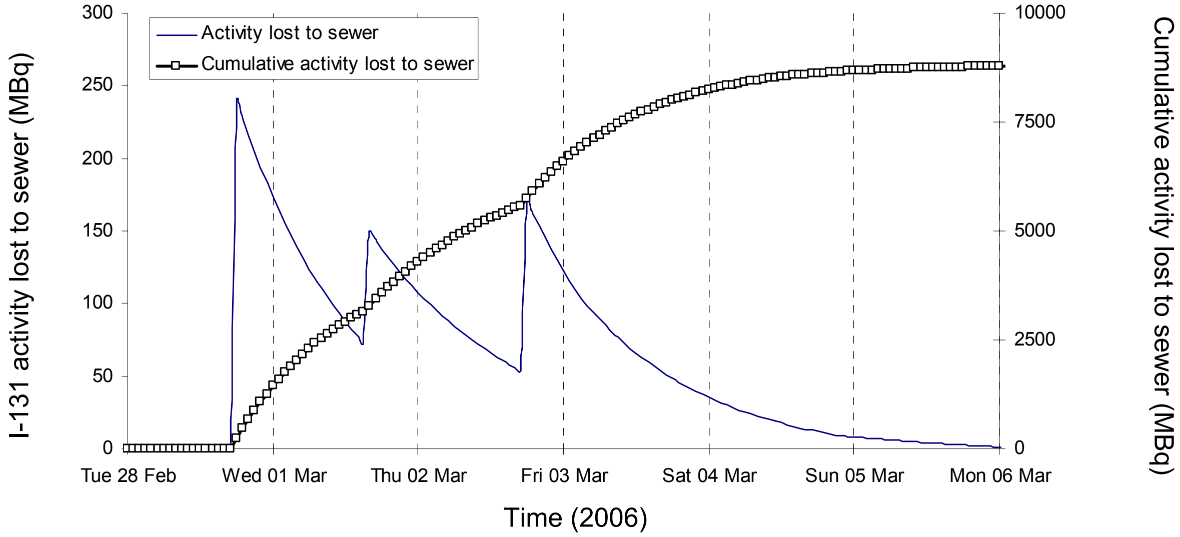

Figure 3.1: Iodine-131 discharged to sewer

During the survey period, approximately 10 GBq of iodine-131 activity was discharged to sewer while the patients were at the hospital.

3.3 Summary of results found

The results over the week are summarised in Table 3.2. Concentrations of iodine-131 at the sewage works were highest associated with sludge; the mean value for primary sludge was 49 Bq kg^{-1} dw, for activated sludge 102 Bq kg^{-1} dw and for dewatered solids, 900 Bq kg^{-1} dw. In treated effluent, activity was on average 11 Bq l^{-1}. Mean concentrations measured in the three downstream sites in Beverley Brook waters were comparable to, or up to a factor of two lower than, the mean value in effluent. Riverine sediments were in the range 12 to 49 Bq kg^{-1} (dw). Activities associated with intertidal sediment where the Beverley Brook meets the Thames Estuary were higher, between 82 and 570 Bq kg^{-1} dw.

The decrease in activity concentrations in the brook water with distance was consistent with available hydrological data, indicating additional dilution with increased flow along the length of the brook. Although some iodine became associated with sediment in the riverine section of the brook, this was generally low and partition coefficients were on average 7 l kg^{-1} (with a range of 1-26 l kg^{-1}).

Mean measured dose rates in air were at, or near to, expected background values of 17-20 nSv h^{-1} at most locations. Marginally elevated dose rates (20-22 nSv h^{-1}) were measured over bed at Beverley Brook and somewhat higher values (27-31 nSv h^{-1}) were measured adjacent to dewatered solids at Hogsmill works.

Table 3.2: Summary of monitoring data

Sample location	Dates	Media	I-131 activity concentration (Bq l^{-1} or Bq kg^{-1} dw)		Mean measured dose rate (and range) nSv h^{-1}	[3]Dose rate calculated from mean I-131 conc. (nSv h^{-1})
			Mean	Range		
Hogsmill STW	28 Feb – 5 Mar	Crude sewage	26	1.5-50	13 (6-15)	0.9
	28 Feb – 5 Mar	Primary treated effluent	23	9.1-34	17 (14-18)	0.8
	1 and 2 Mar	Primary sludge	49	20-76	No data	1.8
	28 Feb – 5 Mar	Activated sludge	102	44-130	14 (12-19)	3.6
	3 Mar	[4]Dewatered solids	900	410-1,800	28 (27-31)	32
	28 Feb – 5 Mar	Treated effluent	11	1-17	No data	0.4
Beverley Brook 1	2 and 4 Mar	Water	2	<1-3	No data	0.1
Beverley Brook 2	28 Feb – 5 Mar	Water	12	1.4-18	22 (21-22)	0.4
	28 Feb – 5 Mar	Bed sediment	49	31-67		1.8
	28 Feb – 5 Mar	Bank sediment	No data	No data	21 (20-22)	No data
Beverley Brook 3	28 Feb – 5 Mar	Water	6.3	1-10	15 (12-19)	0.2
	28 Feb – 5 Mar	Bed sediment	12	9-14		0.4
	28 Feb – 5 Mar	Bank sediment	No data	No data	20 (20-22)	No data
Beverley Brook 4	28 Feb – 5 Mar	Water	7	1-11	17 (14-20)	0.3
	28 Feb – 5 Mar	Bed sediment	17	13-23		0.6
	2 and 4 Mar	Bank sediment	15	7-25	19 (18-20)	0.5
Beverley Brook 5	4 Mar	Water	7	No data	No data	0.3
	4 Mar	Bed sediment	470	370-570	No data	27
	26 July	Bed sediment	95	58-120	16 (13-21)	5
Back-ground	4 Mar	Richmond Park soil	No data	No data	19 (17-20)	No data

3.4 Assessment of doses from iodine-131 by external exposure

An assessment of external exposure was carried out based on gamma dose rates recorded (Table 3.2) and an assumed exposure of 1,000 hours per year. Results are given in Table 3.3.

Many of the monitoring sites showed no elevation over background (17-20 nSv h^{-1}). The exceptions were a single reading adjacent to freshly dewatered sludge cake (31 nSv h^{-1}) and over water at the Beverley Brook site nearest to the outfall (below 22 nSv h^{-1}). Determining the natural background dose rate above dewatered solids is not straightforward, but assuming a mean natural dose rate in air for the region of 20 nSv h^{-1}, measurements at these locations represent 11 and 2 nSv h^{-1} above background. Based on 1,000 hours per year exposure, this equates to an elevated exposure of 11 and 2 µSv y^{-1}, respectively, to a hypothetical person. This is a conservative assessment, as the relatively low water flow rate and high doses administered during the study period are likely to give higher than typical concentrations in sediment and associated dose rates in air; furthermore, it is unlikely that any individual will spend

[3] US EPA (1993). *External exposure to radionuclides in air, water, and soil*. Federal Guidance Report No. 12, EPA-402-R-93-081 (Oak Ridge National Laboratory, Oak Ridge, TN; US Environmental Protection Agency, Washington, DC).
[4] Air kerma readings were taken adjacent to a large conical pile of dewatered solids. It was not possible to take a reading above the surface of the material.

1,000 hours per year at either location. Even so, the assessed external exposure is minimal and represents no more than one per cent of the annual 'controllable' dose limit to a member of the public.

Table 3.3: Summary of external exposure data

Sample location	Dates	Media	Measured external exposure (and range) μSv y^{-1}	Elevation over background (mean) μSv y^{-1}
Hogsmill STW	28 Feb – 5 Mar	Crude sewage	13 (6-15)	No Elevation
	28 Feb – 5 Mar	Primary treated effluent	17 (14-18)	No Elevation
	1 & 2 Mar	Primary sludge	No data	No data
	28 Feb – 5 Mar	Activated sludge	14 (12-19)	No Elevation
	3 Mar	Dewatered solids	28 (27-31)	7-11
	28 Feb – 5 Mar	Treated effluent	No data	No data
Beverley Brook 1	2 & 4 Mar	Water	No data	No data
Beverley Brook 2	28 Feb – 5 Mar	Water	22 (21-22)	1-2
	28 Feb – 5 Mar	Bed sediment		
	28 Feb – 5 Mar	Bank sediment	21 (20-22)	1-2
Beverley Brook 3	28 Feb – 5 Mar	Water	15 (12-19)	No Elevation
	28 Feb – 5 Mar	Bed sediment		
	28 Feb – 5 Mar	Bank sediment	20 (20-22)	Up to 2
Beverley Brook 4	28 Feb – 5 Mar	Water	17 (14-20)	No Elevation
	28 Feb – 5 Mar	Bed sediment		
	2 & 4 Mar	Bank sediment	19 (18-20)	No Elevation
Beverley Brook 5	4 Mar	Water	No data	No Data
	4 Mar	Bed sediment	No data	No Elevation
	26 July	Bed Sediment	16 (13-21)	No Elevation
Background	4 Mar	Richmond Park soil	19 (17-20)	

Where the Beverley Brook meets the Thames Estuary, concentrations of iodine-131 in intertidal sediment indicated that some elevation in external dose rates might be expected (Table 3.2). Direct measurements of gamma dose, however, showed no elevation over background.

Dilution of effluent discharged to the Beverley Brook was minimal and during low river flows, dilution along the entire length of the brook might only be a factor of two. It was also determined that the majority of activity discharged in treated effluent was to the Hogsmill River and not the Beverley Brook. Although a higher degree of dilution was expected within this river, overall activity concentrations could be a factor of two or greater than those in Beverley Brook. Additionally, peak activities associated with multiple administrations on the same day could result in transient peaks of activity concentration three times those measured in this study. Nonetheless, annual external exposure was predicted to be a small percentage of the public dose limit.

3.5 Recommendations

Based on the preliminary dose assessment, external radiological exposure associated with iodine-131 discharges from the Royal Marsden Hospital would all be low and a small percentage of the annual dose limit for a member of the public.

Activity concentrations of iodine-131 in the Hogsmill River could be a factor of two or greater than those in the Beverley Brook. Therefore, environmental activity concentrations and exposure pathways associated with the Hogsmill River should be assessed.

Despite the relatively low percentage of activity transferred to sludge cake solids, activity concentrations were still elevated and measurements up to 1,800 Bq kg^{-1} were recorded. The potential variability in activity concentration in sludge cake and potential exposure pathways may need to be assessed further.

The study also highlighted some general points of interest that should be considered when undertaking assessments associated with discharge authorisations. The use of an annual mean river flow in dilution calculations may be overly optimistic and may not adequately represent actual dilution over the majority of time that would influence the exposure a member of the public could receive. Also, 'environmental sinks' may exist, particularly in estuarine areas, potentially at points quite distant from an effluent outfall. These sinks could represent areas of enhanced exposure not included in routine assessment methods and therefore, the possibility of their existence needs to be considered.

The results of this study could be used to review the current modelling approach for iodine-131 used by the Environment Agency in its initial radiological assessment procedure. In particular, the data could be used to assess the degree of conservatism in the system.

References

ALLOTT, RW, LAMBERS, B AND TITLEY, JG. 2006. *Initial radiological assessment methodology – Part 1: User report*. Environment Agency Science Report: SC030162/SR1.

LAMBERS, B AND THORNE, MC. 2006. *Initial radiological assessment methodology – Part 2: Methods and input data*. Environment Agency Science Report: SC030162/SR2.

PUNT, A, MILLWARD, G AND GARDNER, M. 2007. *Radionuclide partitioning during sewage treatment – A laboratory investigation*. Environment Agency Science Report: SC020150B/SR.

Glossary

- Activated sludge – a high solid content sludge produced via a biological treatment phase using pumped air to aerate the sewage.
- Anaerobic digestion – the biological treatment of sludge under anoxic conditions used to destroy pathogens in the solids prior to application to land.
- Crude sewage – sewage that has been through primary screening to remove grit and other large solids, but has not undergone any further treatment.
- Dewatered solids – final sewage solids where the water has been removed via compression, and the solids can then be spread to land.
- Effluent – treated water that is discharged to river.
- Primary settled sludge – solids settled out during primary settlement.
- Primary settlement – process that removes approximately 50 per cent of solids by gravitational settling.

List of abbreviations

- Bq – Becquerel
- NaI – Sodium iodine
- mIBG – metaiodobenzyguanidine
- nSv – nano-seiverts (10^{-9} seiverts)
- μSv – micro-seiverts (10^{-6} seiverts)
- mSv – milli-seiverts (10^{-3} seiverts)
- RMH – Royal Marsden Hospital

Appendix 1 – Use and behaviour of iodine-131

Iodine-131 is a relatively short-lived radionuclide with a physical half-life of eight days. It emits gamma photons (364 keV) and beta particles with an average energy of 192 keV and a maximum energy of 607 keV. Given the tendency of the human thyroid to accumulate iodine, radioiodine, particularly iodine-131, is used in thyroid cancer treatment.

Driver and Packer (2001) estimated that 55 per cent of iodine is excreted by patients within the first 24 hours following administration, and that 85 per cent is discharged to sewer over a typical in-patient stay of five days. Fenner and Martin (1997) provide similar estimates, with an anticipated loss via excretion of 50 per cent in 22 hours and 90 per cent in 75 hours. These are further substantiated by McDonnell and Wilkins (1991) and Titley *et al*. (1999), who provide estimates of 50 per cent loss within 24 hours and 90 per cent loss within 48 hours respectively.

A1.1 Application of iodine-131 at the Royal Marsden Hospital

Iodine-131, in the chemical forms of sodium iodide (NaI) and metaiodobenzyguanidine (mIBG), is one of the main radionuclides used within the Royal Marsden Hospital. Of the 400 GBq or so administered per year, the greatest use is for therapeutic administration, particularly for thyroid cancer, thyrotoxicosis and neuroblastoma treatment. Iodine is metabolised relatively rapidly within a patient's body and, within about 24 hours, approximately half the iodine will have been excreted from the patient through the urine. In hospitals such as Royal Marsden, where there are no delay and decay tanks for temporary storage of waste water, this iodine will enter the sewer direct through the hospital foul drain system.

A1.2 Environmental behaviour of iodine-131

In aquatic environments, iodine tends to remain predominantly in dissolved form, primarily as iodide (I^-), or the slightly more reactive iodate (IO_3^-) under oxygenated conditions. Both species are generally repulsed from the negative charges on most sediments. However, sorption to organic material and clay sediments (particularly illite) can occur, particularly when the pH decreases (which results in more positive charges on sediment particles) (Kaplin *et al*., 2000). Iodine can also form organic complexes with humic substances (Oktay *et al*., 2001) and this can prompt removal with biosolids during sewage treatment (Rädlinger and Klaus, 2000).

In fresh water systems, the partition coefficient for iodine is typically less than one l kg^{-1} for clayey silt and sandy sediments, but can be of the order of 100 to 200 l kg^{-1} when solids are organic rich (Bird and Schwartz, 1996). Sheppard *et al*. (1995) found that iodine sorption to solids is limited by chloride competition and should therefore decrease with increases in salinity.

It is generally accepted that iodine association with solids, within either river systems or sewage works, should be low and that during sewage treatment most of the iodine (80-90 per cent) will be discharged to rivers with the treated sewage effluent (Ham *et al*., 2003).

A1.3 References

BIRD GA AND SCHWARTZ W. 1996. Distribution coefficients, Kds, for iodine in Canadian Shield Lake sediments under oxic and anoxic conditions. *Journal of Environmental Radioactivity*, 35, 3, 261-279.

DRIVER I AND PACKER S. 2001. Radioactive waste discharge quantities for patients undergoing radioactive iodine therapy for thyroid carcinoma. *Nuclear Medicine Communications*, 22, 1129-1132.

FENNER FD AND MARTIN JE. 1997. Behaviour of NaI-131 and Meta (I-131) Iodobenzylguanidine (MIBG) in municipal sewerage. *Health Physics*, 73, 2, 333-339.

HAM GJ, SHAW S, CROCKETT GM AND WILKINS BT. 2003. *Partitioning of radionuclides with sewage sludge and transfer along terrestrial food chain pathways from sludge-amended land – A review of data*. National Radiological Protection Board, NRPB-W32.

KAPLIN DI, SERNE RJ, PARKER KE AND KUTNYAKOV IV. 2000. Iodine sorption to subsurface sediments and illitic minerals. *Environmental Science and Technology*, 34, 399-405.

MCDONNELL CE AND WILKINS S. 1991. *Radiation exposure of sewer workers associated with radioactive discharges from hospitals*. DOE Report No: DoE/HMIP/RR/91/031. Department of the Environment: HMIP-commissioned research.

OKTAY SD, SANTSCHI PH, MORAN JE AND PANKAJ S. 2001. I-129 and I-127 transport in the Mississippi River. *Environmental Science and Technology*, 35, 4470-4476.

RÄDLINGER G AND HEUMANN KG. 2000. Transformation of iodine in natural and waste water systems by fixation on humic substances. *Environmental Science and Technology*, 34, 3932-3936.

SHEPPARD MI, THIBAULT DH, MCMURRAY J AND SMITH PA. 1995. Factors affecting the soil sorption of iodine. *Water, Air and Soil Pollution*, 83, 51-67.

TITLEY JG, CAREY AD, CROCKETT GM, HAM GJ, HARVEY MP, MOBBS SF, TOURNETTE C, PENFOLD JSS AND WILKINS BT. 2000. *Investigation of the source and fate of radioactive discharges in public sewers*. Environment Agency R&D Technical Report P288. Environment Agency.

Appendix 2 – Assessment of results in relation to previous studies

Prior to this study, there was no contemporary data on the impact of iodine-131 discharges from Royal Marsden Hospital, although previous studies had been undertaken. A number of other studies which have assessed the activity concentration of iodine-131 in sewage works at other sites in the UK and in other countries are also available. A summary of the results from this study and previous investigations is given below.

A2.1 Summary of results from this study

Based on a total administration of 15.1 GBq of iodine-131 between three patients over three consecutive days in February 2006, the sampling found activity concentrations of iodine-131 in:

- crude sewage of on average 26 Bq l^{-1}, reaching a maximum of 50 Bq l^{-1};
- treated effluent of on average 11 Bq l^{-1} and in all samples, less than 20 Bq l^{-1};
- primary settled sludge up to 76 Bq l^{-1}, in activated sludge up to 130 Bq l^{-1} and in dewatered sludge cake up to 1,800 Bq kg^{-1} (dw);
- river water up to 20 Bq l^{-1} and river sediment up to 67 Bq kg^{-1} (dw);
- intertidal sediment, where the Beverley Brook meets the Thames Estuary, up to 570 Bq kg^{-1} (dw).

A2.2 Previous studies relating to discharges from Royal Marsden Hospital

McDonnell and Wilkins (1991) carried out monitoring when sewage from the Sutton area (including that from the hospital) was treated at the Worcester Park works (in early 1999, Worcester Park was closed and sewage was then diverted to the Hogsmill works).The authors found that activity concentrations of sludge varied markedly, from five Bq kg^{-1} to approximately 1,000 Bq kg^{-1}. The study does not, however, indicate whether sludge values were derived based on dry or wet weight and is therefore difficult to interpret. The same group also reported little difference in activity concentrations of iodine-131 in crude sewage and in treated effluent and therefore concluded that the overall fraction of iodine-131 removed by treatment was small.

Titley *et al*. (2000) carried out further work in the late 1990s at Worcester Parks. Their study was timed to coincide with a thyroid ablation treatment of 20 GBq of iodine-131. Samples included effluent and sludge from the primary settlement and activated sludge plant. These indicated iodine-131 activities in primary solids of 61 to 1,300 Bq kg^{-1}, primary settled sewage of 112 to 234 Bq kg^{-1}, activated sludge of 42 to 114 Bq kg^{-1} and in final effluent of 20 to 51 Bq kg^{-1}. The authors concluded that their monitoring results were comparable to those found by McDonnell and Wilkins (1991).

Heaton (2000) carried out a preliminary study of iodine-131 in discharges from the Royal Marsden Hospital which were treated at the Hogsmill works. Over a 28-day period in 1999, iodine-131 activity concentrations in final effluent were all below 3 Bq l^{-1}. The reason for the lower activities in effluent recorded in this study compared to others is unknown.

A2.3 A historic perspective of other studies

A number of other studies have been carried out and are briefly summarised below.

Erlandsson *et al*. (1989) determined that in a treatment plant in Lune in southern Sweden, the concentration of iodine-131 in digested sludge was approximately 2,000 times that in treated liquid sewage, but that less than 14 per cent of the activity arriving at the plant left in the sludge. He also noted that the mean residence time for water in the works was one to two days, whilst that of sludge was three to four weeks.

At the Oak Ridge sewer, Tennessee, Stetar *et al*. (1993) estimated that within crude sewage, about three per cent of iodine-131 activity was associated with solids; and that the overall removal efficiency was three to five per cent, with 55 per cent of iodine-131 received at the sewage works being discharged with the treated effluent. Although it is not discussed explicitly within the paper, the results indicate that around 40 per cent of the iodine-131 may have been retained in the sewer and/or lost through decay.

Barci-Funel *et al*. (1993) noted that sludge contained up to 55 Bq kg^{-1} (dw) iodine-131 associated with administrations of 0.02 to 7.4 GBq, and estimated that approximately one per cent of that administered was transferred to the final dewatered solids in a sewage treatment plant in Nice, France.

Dickson (1994) reports a study associated with discharges from the Amersham (now GE Healthcare) White Lion Road Laboratories and associated Maple Lodge sewage treatment works. Samples were collected from the sewage system and treatment works on one day and the analysis included iodine-125 and iodine-131. Unfortunately, due to high limits of detection (up to 120,000 Bq l^{-1}) no results for iodine-131 were generated. However, a concentration factor was estimated between raw and digested (and presumably dewatered) sludge of at least six for iodine-125 (which has a half-life of approximately 60 days).

Dalmasso *et al*. (1997) monitored iodine-131 in sewage solids from two sewage treatment plants in Nice and St Laurent, which produced 45 and 11 tonnes of dewatered sewage solids respectively on a daily basis. The Nice works received sewage from a hospital where administrations ranged from 0.1 to 10 GBq, with two to three administrations per day. Over a 2.5 month period, activity concentrations in sewage solids varied from three to 320 Bg kg^{-1} (dw). Urine from patients who received a dose greater than 0.4 GBq was stored for seven weeks prior to discharge to sewer, and hence it is difficult to compare these results to other studies. Nonetheless, the authors estimated that about two per cent of the iodine administered to patients was transferred to the final solids. At the St Laurent site, activities in sludge varied from five to 110 Bq kg^{-1} (dw) and peaked one month following a single administration of 0.2 GBq.

Fenner and Martin (1997) also describe the varying behaviour of ionic and organically complexed forms of iodine-131 discharged to sewer and received at the Ann Arbor treatment works at Michigan. They found that 17 per cent of mIBG, but only 1.1 per cent of NaI, was present in the primary sludge. These results are confirmed by Martin (1997). Fenner and Martin (1997) concluded that the behaviour of different chemical forms of radioiodine was significantly different and attributed this to the greater positive charge of the mIBG form and hence affinity for binding to biosolids. They noted that organic material can accumulate within the sewer system, particularly under low flow conditions, and that mIBG forms of radioiodine may therefore be retained within the sewer system.

Puhakainen (1998) monitored iodine-131 at a wastewater plant in Finland, which received discharges from a hospital in Helsinki with daily administrations of 3.7 to 7.4 GBq iodine-131. Activity concentrations in the crude sewage typically reached 48 Bq l^{-1} (representing a flux of around five GBq per day) and peaked on the day or the day after administration. Activity concentrations in the final effluent ranged from four to 32 Bq l^{-1} (representing a flux of 0.4 to three GBq per day). Most of the iodine was assessed to have reached the works within three to four days of administration. Overall, 80 per cent of the activity received at the works was estimated to be discharged with the treated effluent. Following an administration of 18.5 GBq to three patients over two days, iodine-131 activity concentration in primary sludge (before digestion) reached 8,700 Bq kg^{-1} (dw).

In addition to the Worcester Park results, Titley *et al*. (2000) provide monitoring data from two other large urban sewage treatment works (the Beckton works in greater London and the Knostrop works in Leeds). At the Beckton site, iodine-131 activities in crude sewage at the time of sampling were about one Bq l^{-1}, with approximately two-thirds of the activity associated with solids in the sewage. Activity concentrations in the final effluent were less than one Bq l^{-1}. Analysis of primary and secondary sludge indicated that the majority of activity in the sample was associated with solid material. At the Knostrop site, iodine-131 activities ranged from five to 25 Bq l^{-1} in the primary settlement tanks, eight to 28 Bq l^{-1} in the secondary treatment tanks and three to 31 Bq l^{-1} in the final effluent.

Akinmboni *et al*. (2005) describe a study to assess the impact of iodine-131 discharges to sewer in the Ringsend works, which provides waste water treatment for the City of Dublin. Sampling was timed to coincide with iodine-131 administrations in two Dublin hospitals and activity concentrations of influent, effluent and sewage sludge cake were assessed. The authors found that activity concentrations of iodine-131 in influent ranged from less than one Bq l^{-1} to 21 Bq l^{-1}, while activity concentrations in effluent ranged from less than one Bq l^{-1} to 5.8 Bq l^{-1}. Concentrations in influent samples peaked between 10 and 24 hours following administration and in effluent samples, between 32 and 47 hours following administration. Iodine-131 activity concentrations in dewatered sewage solids ranged from 119 Bq kg^{-1} to 605 Bq kg^{-1}.

Nakamura *et al*. (2005) present the results of a study to assess iodine-123 activity concentration in sewage at the Kurume works in Japan, where they found that less than five per cent of the iodine-123 administered was detected in the final effluent. The lower value compared to that of iodine-131 may relate to the shorter half-life of iodine-123 (13.2 hours, approximately 15 times more rapid than that of iodine-131) and correspondingly greater loss due to decay during transit through the sewage system.

A2.4 Summary

The studies described above provide a broad range of data from a number of sites and tend to confirm the fact that, although iodine is clearly particle reactive and becomes associated with solids in the sewer and during sewage treatment, only a limited percentage of iodine-131 is retained with dewatered solids. This discrepancy arises because of the relatively long process and retention time of solids during sewage treatment (potentially a number of weeks) relative to the half-life of iodine-131.

However, the results of these studies are not necessarily comparable. For instance, different sampling and preparation methods were used, and the distinction between sludge and dewatered solids was not always clearly made. Finally, these studies were not always well-timed or of sufficient duration to ensure that peak activities were recorded during the study, and rarely did mass balance calculations account for loss of activity through decay.

A2.4 References

AKINMBONI R, MCMAHON CA, LONG SC AND COLGAN PA. 2005. Environmental impact assessment of iodine-131 discharged from hospitals in Ireland. *The Second International Conference on Radioactivity in the Environment*, 2–6 October 2005, Nice, France.

BARCI-FUNEL G, DALMASSO J, MAGNE J AND ARDISSON G. 1993. Simultaneous detection of short-lived TI-201, Tc-99m, and I-131 isotopes in sewage sludge using low energy photon spectrometry. *The Science of the Total Environment*, 130-131, 37-42.

DALMASSO J, BARCI-FUNEL G, MAGNE J, BARCI V AND ARDISSON G. 1997. Study of the transfer of medically used radionuclides in sewage systems. *Radiochimica Acta,* 78, 167-171.

DICKSON DMJ. 1994. A study of the radiological implications of releases of radionuclides to sewer systems. Department of Environment Report No. DoE/HMIP/RR/94/002.

ERLANDSSON B, BJURMAN B AND MATTSSON S. 1989. Calculation of radionuclide ground deposition by means of measurement on sewage sludge. *Water, Air and Soil Pollution*, 45, 329-344.

FENNER FD AND MARTIN JE. 1997. Behaviour of NaI-131 and Meta (I-131) Iodobenzylguanidine (MIBG) in municipal sewerage. *Health Physics*, 73, 2, 333-339.

HEATON P. 2000. *Non-nuclear radionuclide fate in London*. MSc Dissertation. University of Manchester.

MCDONNELL CE AND WILKINS S. 1991. *Radiation exposure of sewer workers associated with radioactive discharges from hospitals*. DOE Report No: DoE/HMIP/RR/91/031. Department of the Environment: HMIP-commissioned research.

NAKAMURA A, HAYABUCHI N, OSAKI T AND OSAKI S. 2005. Output of radiopharmaceutical nuclides of known injected doses from a municipal sewage treatment system. *Health Physics*, 88, 163-168.

PUHAKAINEN M. 1998. Detection of radionuclides in sewage water and sludge. *Radiochemistry*, 40, 510-514.

STETAR EA, BOSTON HL, LARSEN IL AND MOBLEY MH. 1993. The removal of radioactive cobalt, caesium and iodine in a conventional municipal waste water treatment plant. *Water Environment Research*, 65, 5, 630-638.

TITLEY JG, CAREY AD, CROCKETT GM, HAM GJ, HARVEY MP, MOBBS SF, TOURNETTE C, PENFOLD JSS AND WILKINS BT. 2000. *Investigation of the source and fate of radioactive discharges in public sewers*. Environment Agency R&D Technical Report P288. Environment Agency.

Appendix 3 – Study methodology

During the initial survey, the following samples and readings were collected.

A3.1 Monitoring of iodine-131 administration

As part of their routine practices, the Royal Marsden Hospital collected the following data and information for this study:

- The timing, activity and chemical form of iodine-131 administered was recorded by Royal Marsden Hospital staff. During the week of sampling, a total of 15.1 GBq was administered; this was higher than typical weekly maximums which tend to be below 10 GBq.

- For four days post-administration, the activity in each patient's body was monitored at the hospital using a whole body counter which integrates results from four gamma spectrometers positioned under the patient's body. Based on the size and mass of the patient, the total activity in the body was calculated. This practice was routinely undertaken by the hospital.

A3.2 Sampling at the Hogsmill sewage works

At the Hogsmill sewage works, the following samples were collected by project staff:

- Crude sewage influent was collected using a custom-deployed autosampler positioned over the crude sewage influent stack. Samples of 25 ml were collected every 15 minutes and bulked over a four-hour period to provide a 400 ml sample for analysis.

- Primary settled sewage was sampled using an in situ autosampler that collected five-litre samples over a 24-hour period using a 15-minute sampling interval. A 400 ml subsample was collected from this every 24 hours for analysis.

- Primary sludge was collected from the primary settlement tank pumps. However, due to the low suspended solid load in the sewage at the time of sampling, this was not done routinely during the survey period and it was only possible to collect two samples.

- Spot samples of activated sludge were collected on a daily basis from the outflow of the aeration plant using a bucket.

- Final effluent discharged to the Beverley Brook following tertiary treatment was collected with a second custom-deployed autosampler, following the same regime used for that of crude sewage. Additionally, three spot samples of final effluent discharged to the Hogsmill River (where only around a third of the flow passed through the tertiary treatment plant) and three spot samples of final effluent were collected.

- Dewatered sewage solids (sludge cake) of 500 g were collected from freshly produced and stockpiled solids.

A3.3 Sampling along the Beverley Brook

In the Beverley Brook, the following samples were collected:

- Daily samples (one litre) of river water were collected at three sites immediately downstream of the sewage effluent outfall, and one water sample was collected (at low water) from where the Beverley Brook meets the Thames Estuary. Water samples were collected from the centre of the channel.

- Daily samples (500 g) of river bed sediment were collected at three sites immediately downstream of the sewage effluent outfall. Samples were collected from multiple points across the river bed by scraping up the submerged sediment to a depth of two to three cm. The solids in the container were allowed to settle before excess water was decanted off.

- Two surface sediment samples were collected from where the Beverley Brook meets the Thames Estuary near Putney Bridge during the initial survey. A further six surface and subsurface sediment samples were collected in the subsequent visit in July. Surface sediment scrapes were collected to a depth of one to two cm and subsurface sediment scrapes below this to a depth of five to six cm. Due to the highly unconsolidated nature of these sediments, it was not possible to take samples to an exact depth.

- Two sets of soil profile samples were collected from the bottom of the bank of the brook where it passes through Richmond Park. Samples were collected from the face of the bank at four to six cm, two to four cm and zero to two cm above the water surface at the time of sampling.

- Two upstream (control) water samples were collected with the method outlined in point one.

A3.4 Analysis of samples

All samples were delivered to the ISO17025 accredited LGC laboratories on the day of collection. Solid samples were dried to a constant weight and whole liquid samples (unfiltered) were analysed using matrix-matched geometries. All samples from the initial survey were analysed using a high resolution germanium spectrometer with a count time of 10,000 seconds and iodine-131 activity concentrations (Bq l^{-1} or Bq kg^{-1} dw) reported. Sediment samples collected during the July visit were analysed in a similar fashion, but a count time of 24 hours was used and all gamma-emitting radionuclides detected were reported.

A3.5 Determination of gamma dose in air

In addition to the sample collection, a number of air kerma readings were collected and these were converted into dose rates. In all instances, a count time of 600 seconds was used. The measurements included:

- Daily measurements of air dose recorded on gantries over the crude sewage influent stack, the primary settled effluent outflow stack and the activated sludge beds, with a mini-instrument 6-80 meter and an energy compensated Geiger Muller tube. In these instances, the centre point of the probe was positioned one metre above the surface of the gantry and was therefore 1.5 to 1.75 metres above the surface of the sewage.

- Additional gamma dose in air measurements were made adjacent (within two metres) of the anaerobic digester tanks, adjacent to the dewatered and stockpiled sewage solids (within one metre) and on a gantry over digested, but not dewatered sludge (a height of three to four metres over the sludge surface).

- Daily measurements of air dose one metre over water (assessed in the middle of the channel) and one metre over soil at the base bank adjacent to the waters edge (typically 1.5 metres above the water surface), at the top of the bank (typically three to four metres above the water surface) and where possible at a mid-point were made at the three main downstream sites in the Beverley Brook.

- During the July survey, air dose one metre above intertidal sediments was measured from eight locations around and across the intertidal areas of the Thames Estuary where the Beverley Brook flows at low water.

- Background dose rate was assessed in triplicate in an open area of Richmond Park which was 50 metres from the brook edge and any overhanging trees.

The intrinsic count rates and cosmic background were subtracted from the measured counts prior to calculating the dose rate, and a conversion factor of 0.87 was used to derive doses (nSv) from measured gamma exposure (nGy).

Appendix 4 – Monitoring and survey results

A4.1 Sewage and effluent sampling

As described in Chapter 2, a range of samples were collected during the survey period. The results of these are described below and illustrated in Figures A4.1 to A4.8. The error bars on the graphs indicate the counting errors. All results from liquid or sludge samples represent the total activity concentration in the bulk sample (within both dissolved and particulate phases).

A4.1.1 Crude sewage

The iodine-131 activity concentration in crude sewage samples is illustrated in Figure A4.1. A bar chart has been used to illustrate the sample integration period and the uncertainty associated with each measurement plotted.

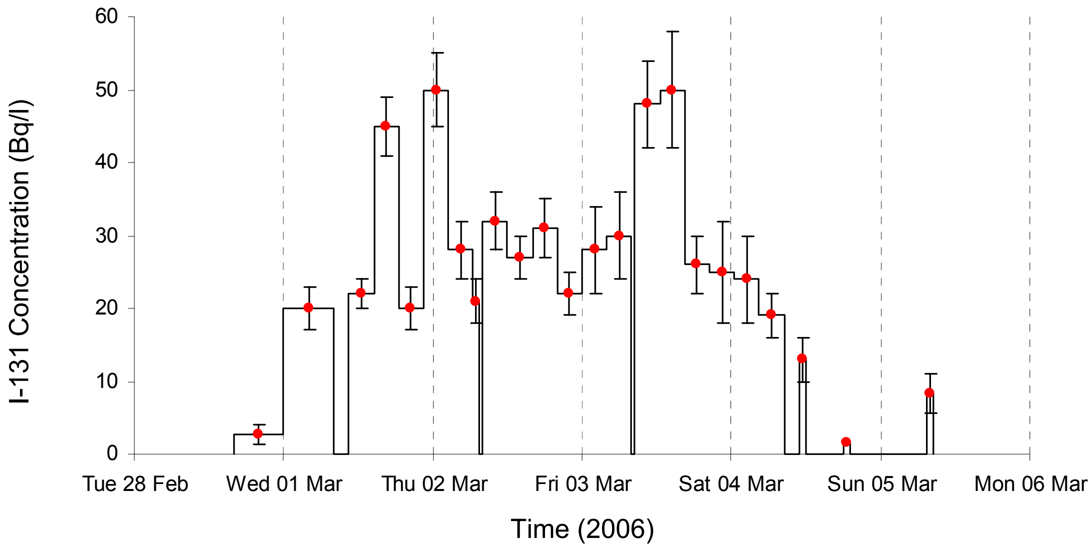

Figure A4.1: Iodine-131 activity concentration in crude sewage

The results show that iodine-131 activity concentrations in crude sewage increased in the first 24 to 36 hours following the initial administration and peaked at about 50 Bq l^{-1}. Following this peak, activity concentrations remained relatively constant at around 30 Bq l^{-1} and then peaked again, at around 50 Bq l^{-1}, midday on Friday 3rd March. Thereafter, activity concentrations decreased, but were still elevated (around 10 Bq l^{-1}) when the last sample was collected on the Sunday afternoon. Overall, the average activity concentration in crude sewage during the survey was 26 Bq l^{-1}.

A4.1.2 Primary and secondary sewage treatment

The activity concentration in the 24-hour integrated primary settled sewage showed a similar trend to that observed in the crude sewage (Figure A4.2).

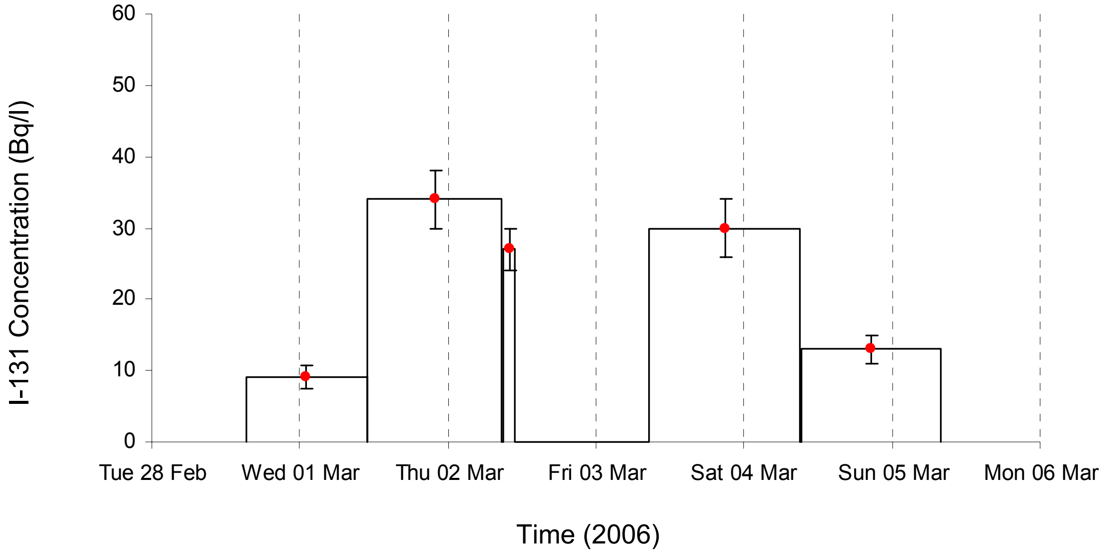

Figure A4.2: Iodine-131 activity concentration in primary settled sewage

Peak activities through the middle of the survey period were of the order of 30 to 40 Bq l^{-1}. The average activity concentration during the survey period was 23 Bq l^{-1}.

Only two primary sludge samples were collected. These had activity concentrations of 20 Bq l^{-1} (Wednesday 1st March) and 76 Bq l^{-1} (Thursday 2nd March).

Daily spot samples of activated sludge were collected at the outflow point from the aeration treatment plant and the results are given in Figure A4.3. These show that activity concentrations in the bulk sample rose from about 44 Bq l^{-1} to about 130 Bq l^{-1} at the end of the study (an average of 102 Bq l^{-1}). It appears that by Sunday 5th March, these activities were stabilising.

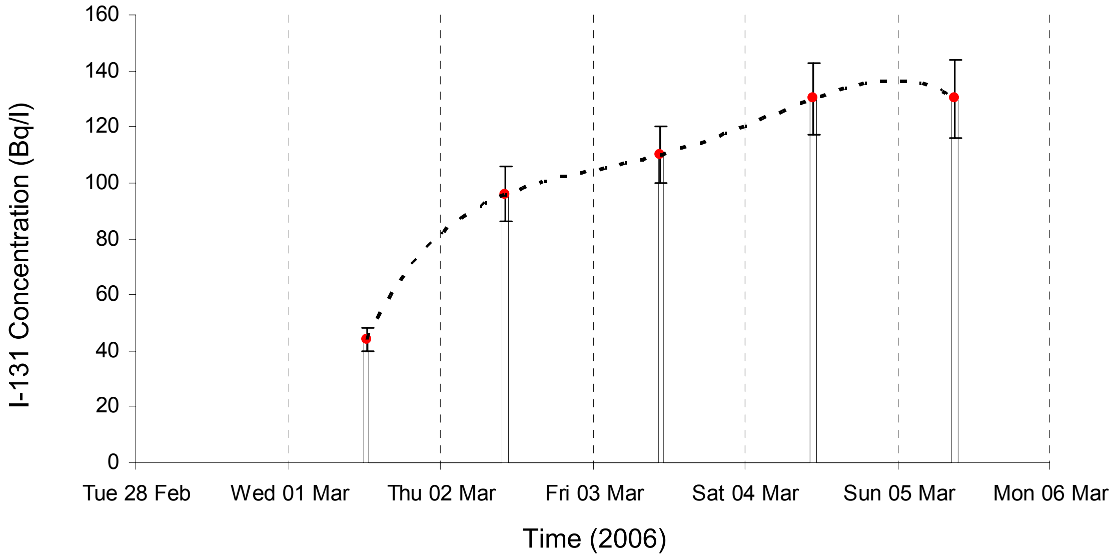

Figure A4.3: Iodine-131 activity concentration in activated sludge

Activated sludge beds operate using a 10-day sludge age; that is, the residence time of solids in this part of the system is 10 days. It is therefore likely that activities at this point will increase more slowly than in crude sewage, as the system slowly reaches equilibrium. Equally, activities will then decline more slowly than in crude sewage, and hence may have remained elevated for a number of days after the survey finished.

A4.1.3 Final effluent

Activity concentrations of iodine-131 in the final effluent (following tertiary treatment via sand bed filtration) discharged to Beverley Brook are illustrated in Figure A4.4.

The results show that activity concentrations increased over three days following the initial administration, then decreased slightly. With the exception of the initial period, activities were between 10 and 20 Bq l^{-1}. At the end of the study, the activity concentration in the final effluent was still elevated, at about 10 Bq l^{-1}. Over the study period, the average activity concentration in the final effluent discharged to the Beverley Brook was 11 Bq l^{-1}.

In addition to these results, a number of effluent spot samples were also collected. These consisted of three spot samples of final effluent discharged to the Hogsmill River and three concurrent samples of final effluent discharged to the Beverley Brook. At the time of the study, only about two-thirds of the effluent discharged to the Hogsmill River was undergoing tertiary treatment. Activity concentrations in effluent discharged to the Hogsmill River were consistently higher by a factor of about 1.5 (r^2 = 0.96, n = 3). This factor was applied to the dataset collected for discharges to the Beverley Brook, to provide an estimate of the activity discharged to the Hogsmill River during the survey period. Based on this calculation, activities in the effluent discharged to the Hogsmill River would typically have been between 15 and 30 Bq l^{-1}, with an average activity concentration of 17 Bq l^{-1}.

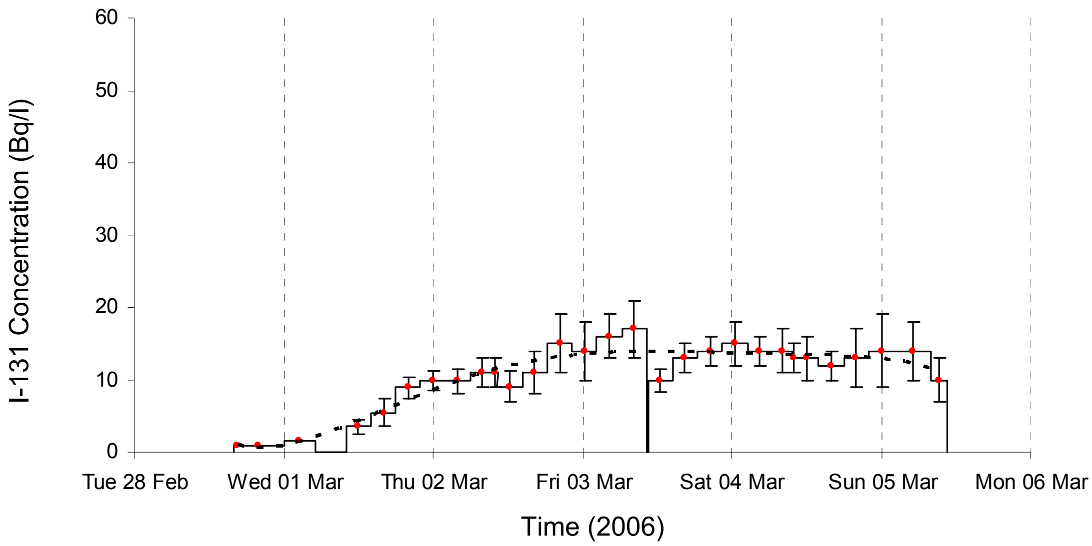

Figure A4.4: Iodine-131 activity concentration in final effluent discharged to the Beverley Brook

During the survey period, mean activities in the final effluent discharged to the Beverley Brook were about a factor of two lower than those in the crude sewage and those to the Hogsmill River were a factor of 1.5 lower.

A4.1.4 Sludge cake solids

A limited number of sludge cake solid samples following dewatering were also collected for iodine-131 analysis. The activity concentration in solids produced by the dewatering plant within 12 hours of collection was 1,800 Bq kg^{-1}. Two samples were also collected from material that had been stockpiled ready for transfer to land as a soil conditioner. These had activities of 400 to 500 Bq kg^{-1}.

A4.2 River water and sediment sampling

During the survey period, daily spot samples of river water and river bed sediment were collected from the Beverley Brook. Additional samples of bank sediment and intertidal sediment where the brook meets the Thames Estuary were also collected. No samples from the Hogsmill River were collected.

A4.2.1 River water

River water at three points downstream of the effluent outfall was collected over five consecutive days. The main sampling points were located at West Barnes Lane (0.8 km), Wimbledon Common (4.0 km) and Richmond Park (6.1 km).

Activity concentrations in river water from the main river sampling points are illustrated in Figures A4.5 to A4.7. These all show a general profile similar to that in the effluent. At the site closest to the sewage effluent outfall, activity concentrations in river water were between 1.5 and 20 Bq l^{-1} (with an average peak activity concentration of 14.5 Bq l^{-1}). At Wimbledon Common activities were lower, at around 10 Bq l^{-1}. Values recorded at Richmond Park were similar to those at Wimbledon Common, with an average peak activity concentration of 8.5 Bq l^{-1}. At the end of the study, the activity concentration in river water was still elevated above 5.0 Bq l^{-1}. The last value measured at the middle site, Wimbledon Common, was below the limit of detection. As iodine-131 activity concentrations measured in samples collected both upstream and downstream of this site were positive, this value is considered to be spurious.

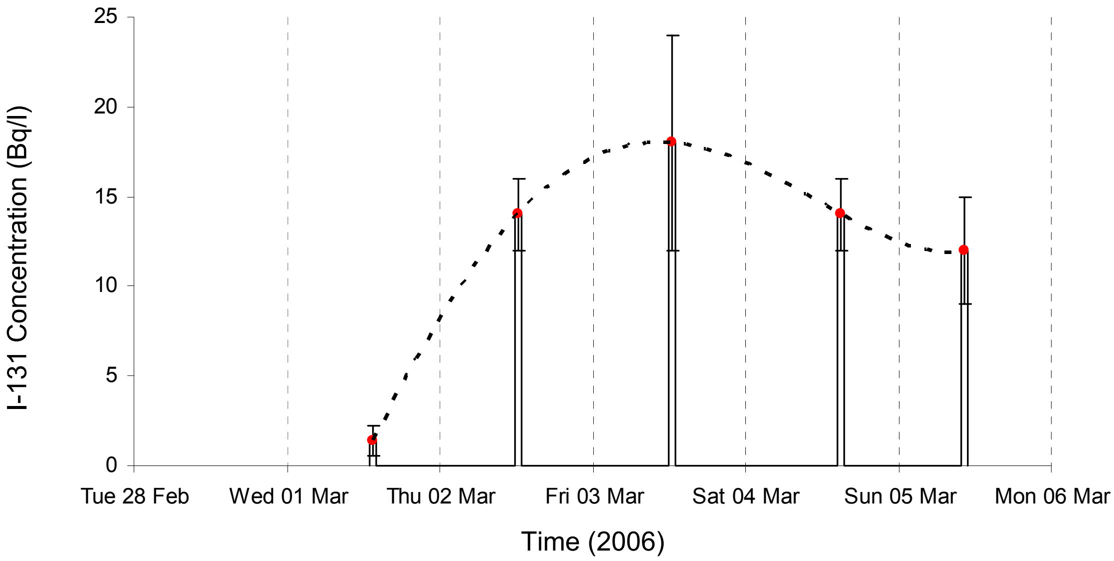

Figure A4.5: Iodine-131 activity concentrations in river water at West Barnes Lane

In addition to the three sampling sites, a single river water sample was collected (Saturday 4th March) upstream of Ashlone Warf, near to the confluence of the brook with the Thames Estuary, about 11 km from the point of sewage effluent discharge.

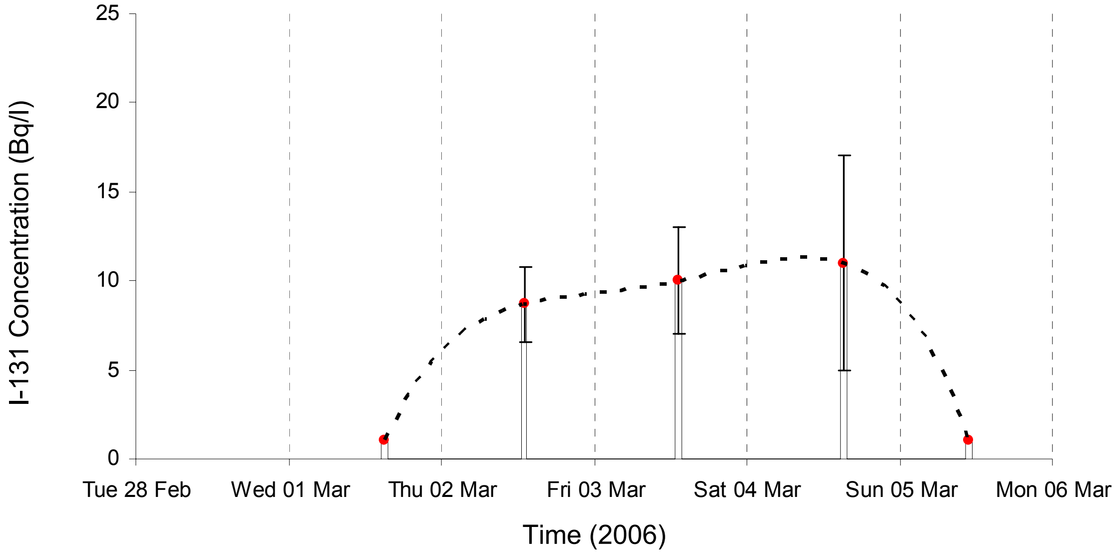

Figure A4.6: Iodine-131 activity concentrations in river water at Wimbledon Common

The activity concentration of river water by the Ashlone Warf was 7.0 Bq l^{-1}. This suggests that during relatively low river flow conditions, there is a factor of two dilution of effluent along the entire length of the brook.

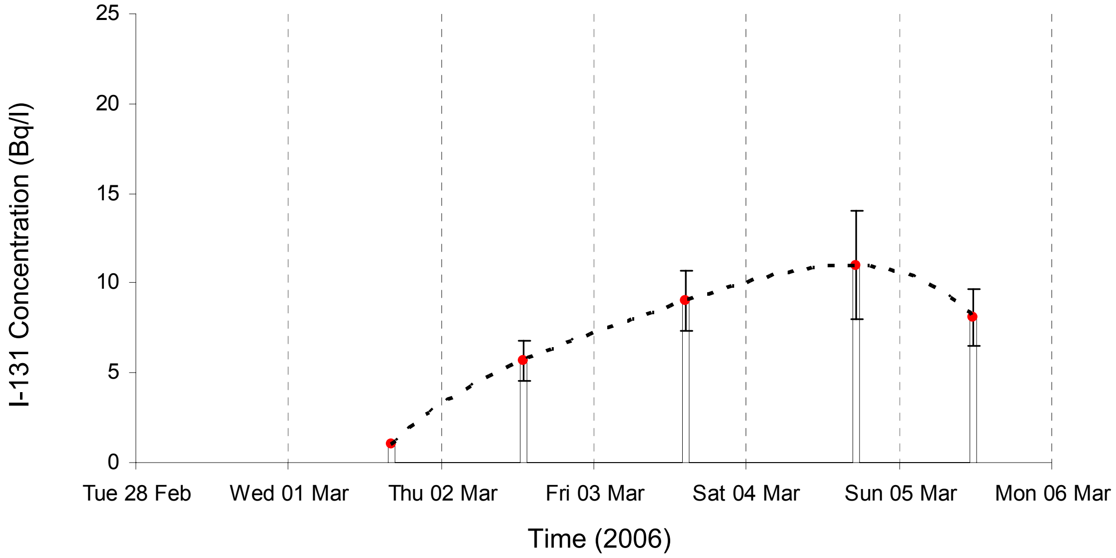

Figure A4.7: Iodine-131 activity concentrations in river water at Richmond Park

Two water samples were also collected less than 0.5 km upstream of the effluent discharge point, to determine background activity concentrations of iodine-131 in the river water. One sample was below the limit of detection (around one Bq l^{-1}) the other gave a positive result of 3 Bq l^{-1}. At this point sewage fungus was observed in the brook, potentially indicating a small and unregulated release of sewage to the surface drain system in the area.

A4.2.2 Bed and bank sediment

Scrape samples of subsurface river bed sediment were collected at each of the three main sampling points and the results ranged from 9 to 67 Bq kg^{-1}. Activity concentrations were consistently higher at the site nearest to the discharge point (mean 49 Bq kg^{-1}) compared to the two sites further downstream (means of 12 and 19 Bq kg^{-1}).

In addition to these riverine sediments, a limited number of sediment samples were collected from the intertidal banks where the Beverley Brook meets the Thames Estuary. Two surface samples were collected during the initial survey period and three surface and subsurface samples were collected in the follow-on survey in July 2006.

The results show that iodine-131 activity concentrations associated with intertidal sediment were significantly higher (370 and 570 Bq kg^{-1}) than those of the three main river sampling sites during the February survey. The mean iodine-131 surface sediment sample activity concentration at each site, as a function of distance from the sewage effluent outfall, is illustrated in Figure A4.8.

Figure A4.8: Mean iodine-131 activity concentration in surface sediment

During the July visit, a further three surface and three subsurface sediment samples were collected from around the mouth of Ashlone Warf. Iodine-131 activity concentrations associated with surface sediment ranged from 100 to 120 Bq kg^{-1} (dw), while that of subsurface sediment ranged from 58 to 92 Bq kg^{-1} (dw).

During the July survey, activity concentrations of other gamma emitters in sediment were also determined. These provided positive values for beryllium-7 (77 to 100 Bq kg^{-1} dw); potassium-40 (480 to 540 Bq kg^{-1} dw); caesium-137 (7.8 to 9.4 Bq kg^{-1} dw); actinium-228, radium-224, lead-212, bismuth-212 and radium-226 (23 to 44 Bq kg^{-1} dw); thallium-208, thorium-234, lead-214, and bismuth-214 (10 to 20 Bq kg^{-1} dw); and, uranium-235 (1.5 to 2.3 Bq kg^{-1} dw). Overall activities of the other radionuclides were consistent between the three sampling sites and surface and subsurface sediment.

In addition to bed sediment samples, a series of bank soil samples from near to the water's edge where the soil was well saturated, were also collected in Richmond Park.

Activity concentrations in the initial bank sediments collected on the 2nd March were comparable to the river bed samples. Those collected on the 4th March were lower despite the higher activity in the water. However, near to the water's edge the bank sediments were highly variable and it was not possible to collect samples of a similar nature.

A4.3 Gamma dose in air survey

Air kerma measurements were made at one metre over soil, sediment and water using a GM tube and a Mini-Instrument 6-80 meter. At the Hogsmill works, air kerma was measured at one metre above gantries or walkways suspended over the crude sewage influent point and activated sludge beds. Gamma dose rates were calculated from the instrument calibration certificate.

A4.3.1 Determination of background

Background gamma dose rates in air were calculated in an open area in Richmond Park, away from the brook. The background dose rate based on three consecutive readings was 19 nSv h^{-1}. Further background rates taken at the Hogsmill works in open grass areas, away from any treatment process, were similar at 24 nSv h^{-1}.

A4.3.2 Monitoring at Hogsmill works

Daily measurements of gamma dose in air were taken over the crude sewage influent stack, the primary settled sewage outlet and the activated sludge beds. In all instances, the dose rate was lower than background. In addition, a series of *ad hoc* measurements were taken adjacent to the anaerobic sludge digesters and above the digested sludge storage beds. The measured dose rate was comparable to, or less than, background.

Daily gamma dose measurements were compared to activity concentrations in corresponding sewage samples. Although there was some indication that these increased as the activity concentration in the underlying sewage increased, the results were not statistically significant.

One reading above background (31 nSv h^{-1}) was recorded adjacent to the recently dewatered sludge solids with an iodine-131 activity concentration of 1,800 Bq kg^{-1} (dw).

A4.3.3 Monitoring over water and bank

Daily measurements of gamma dose in air were also taken over river water and bank sediment at the three main river monitoring points.

At all river sites, dose rates measured over water or bank were comparable to, or less than, background. There was no statistically significant correlation between the gamma dose rate and the activity concentration in the water, and the higher values recorded at West Barnes Lane may relate to the narrower and more confined geometry of the channel.

Dose rates over the riverbank were comparable to background. Higher rates were measured at the top of the bank at West Barnes Lane. However, at this point measurements were taken over five metres away from the brook and less than three metres from a road. These readings are therefore considered to be dominated by sources other than river water.

During further monitoring undertaken in July 2006, gamma dose rates were assessed over intertidal sediment where the Beverley Brook enters the Thames Estuary. These showed that at this time, external exposure (21 nSv h^{-1}) was similar to background.

Appendix 5 – Iodine fluxes and behaviour

As outlined in Appendix 2, a number of studies have tried to assess the flux and fate of radioiodine discharged to sewer; these have shown that this can vary depending upon the chemical form of iodine administered. To provide further information, a 'flux balance' approach was adopted here. This combined crude sewage and effluent flow rates with measured activity concentrations, to assess the cumulative inventory of activity concentration that was received and then subsequently discharged to river via treated effluent. Despite the fact that administrations were made on three consecutive days, it was not possible to 'track' these as separate pulses through the sewage works and therefore no comment can be made on potentially different behaviours of the NaI and mIBG chemical forms of iodine-131.

In addition to the treated effluent discharges to Beverley Brook, effluent (with a flow rate approximately five times that of the Beverley) was also discharged to the Hogsmill River. Although only limited measurements of activity concentrations in effluent discharged to the river were taken, these showed consistently higher activities (about a factor of 1.5 higher). These may have arisen due to the smaller proportion of effluent discharged to the Hogsmill River undergoing tertiary treatment (about 30 per cent) at the time of the survey. Based on these measurements, over seven times more activity concentration was therefore likely to have been discharged to the Hogsmill River than to the Beverley Brook. This value could be higher if a lower proportion of effluent were to pass through the tertiary treatment beds[5].

As noted in the previous section, activities in crude sewage and effluent were still elevated at the end of the study. Based on the profile of decreasing activity concentrations in crude sewage towards the end of the study, results were extrapolated for a further 24 hours. Although a degree of uncertainty is associated with this procedure, the results are likely to more representative than if the assessment was based on the truncated dataset collected.

Although activity in the dissolved phase will move through the works relatively rapidly (in about a day), that associated with solids will be retained longer. Sludge generated from primary and secondary settlement (following activated sludge treatment) is combined and then undergoes a process of anaerobic digestion, further storage and dewatering before the final sludge cake is produced. Anaerobic digestion is a legislative requirement if solids are to be spread to land and has the primary purpose of reducing the levels of faecal coliforms in the material. The minimum compliance time for treatment is 12 days, however, on average at the Hogsmill works anaerobic digestion lasts for 17 days and the digested sludge is then stored for a further six to nine days prior to dewatering. This represents a period equivalent to about three half-lives for iodine-131 and would therefore lead to a loss of nearly 90 per cent of the activity concentration associated with the primary and secondary sludge.

[5] The tertiary treatment sand beds provide physical filtration of the effluent to remove fine particulate material. It is therefore possible that a proportion of iodine-131 activity in the final effluent is associated with fine particulates. This possible removal mechanism or associated exposure pathways of workers at the Hogsmill site responsible for cleaning the sand beds has not been assessed.

A5.1 Iodine fluxes and retention in the sewer system

To provide further understanding of iodine-131 behaviour in the sewer, sewage treatment works and the natural environment, activity fluxes and retention were calculated along with estimates of dilution in the brook and uptake to sediment.

The activity flux for release to sewer from the patients post-administration, that received in the crude sewage and that discharged in treated effluent is illustrated in Figure A5.1.

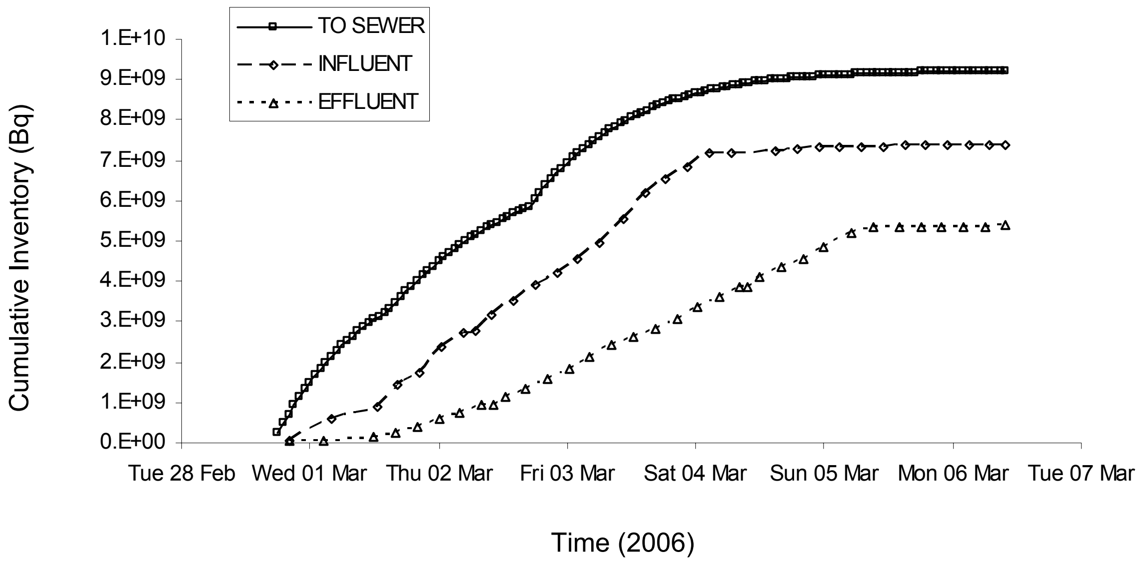

Figure A5.1: Cumulative flux of iodine-131 discharged to sewer, in crude sewage and in final effluent

To provide a more detailed understanding of the flux and fate of iodine-131 activity, three key stages between administration and effluent discharge to river were considered. These were:

- of the activity administered to the patients, the proportion released to sewer, that lost through decay and that retained in the patient when they left the hospital (Figure A5.2a);
- of the activity released to sewer, the proportion subsequently received at the sewage works, that lost through decay and that which cannot be accounted for and is therefore assumed to have been retained within the sewer system (Figure A5.2b);
- of the activity received at the sewage works, the proportion discharged to the Beverley Brook, that discharged to the Hogsmill River, that lost through decay and that which cannot be accounted for and is therefore assumed to have been retained within the sewage works, for instance associated with sewage sludge (Figure A5.2c).

Figure A5.2a shows that of the 15.1 GBq of iodine administered, 65 per cent was released to the sewer, 29 per cent was lost through decay and six per cent was retained in the patient during the duration of the study.

Figure A5.2b shows that of the activity released to sewer, 76 per cent was received at the sewage works and four per cent lost through decay (based on an anticipated transit time of 12 hours); 20 per cent was unaccounted for and was assumed to have been retained within the sewer system.

Discussion with Thames Water staff on site suggested that under dry weather conditions, a proportion of solids in sewage will settle out within the sewer system (particularly in the interconnecting pipe between the old Worcester Park site and the Hogsmill works). They also noted that during the survey period, suspended solid concentrations in the crude sewage were low. It is therefore possible that the proportion of activity unaccounted for was associated with solid material retained within the sewer. Assessing the activity concentration of this material was beyond the scope of the project, but it was anticipated to be similar to that associated with either primary sludge or activated sludge (of the order of 100 Bq l^{-1}).

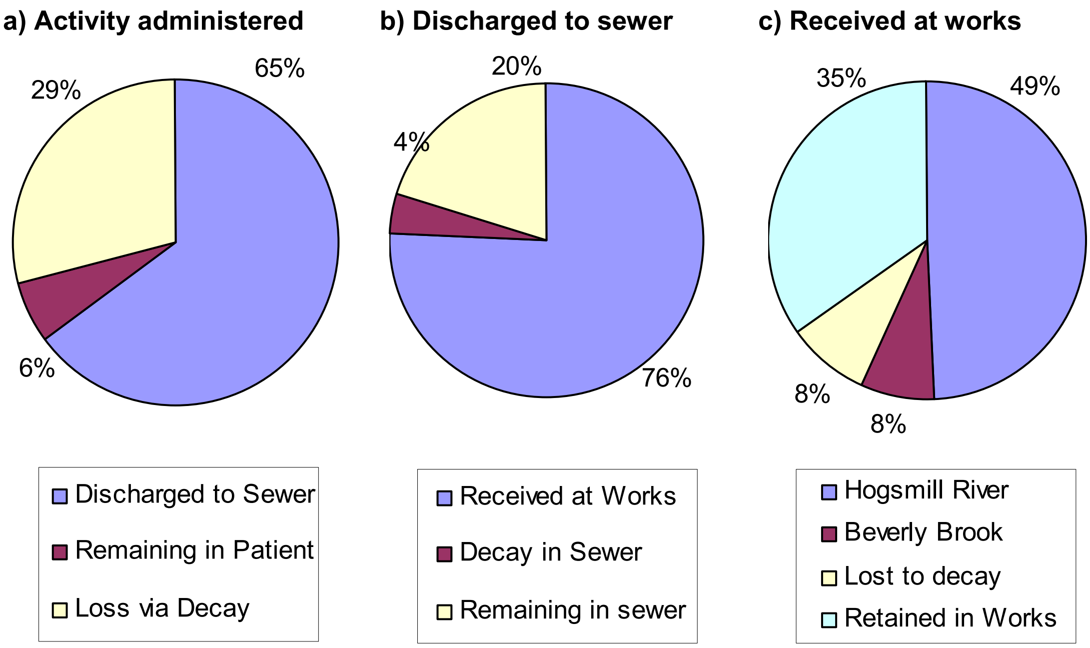

Figure A5.2: Fate of iodine-131 activity administered

Further discussions with site staff highlighted the fact that heavy rainfall after a dry weather period leads to a sudden increase in solids received at the site. Such an event could lead to a pulse of iodine-131 associated with solids previously retained in the sewer being received at the works. The additional flux of activity into the works under such an event would depend upon the discharge regime from the hospital and the retention time in the sewer (and hence loss through decay). Assessing this was beyond the scope of this study.

Figure A5.2c shows that of the activity received at the sewage works, 49 per cent was discharged with effluent to the Hogsmill River and eight per cent to the Beverley Brook. During an anticipated transit time of 24 hours through the works, eight per cent will have been lost through decay and 35 per cent, potentially associated with solids, retained at the works.

The data outlined above was combined to provide percentages of total activity administered retained, lost or transferred at each stage in the process. This is illustrated in Figure A5.3. The results show that during the survey, over 65 per cent of the activity administered was discharged to sewer, but only about 50 per cent was received at the sewage works. Of this, about a third was discharged with treated sewage effluent and the remainder potentially associated with solids, retained on site.

Assuming that about eight per cent of the total activity administered is retained on solids (Figure A5.3), after three half-lives about two per cent would remain in the dewatered sludge cake. This value is consistent with that described for other studies (see Appendix 2).

The potential fraction of activity transferred to land would then depend upon the length of time solids were stockpiled on site. Although it is possible that fresh material could be collected and land spread immediately, it is probable that, on average, this material would be retained on site for a number of weeks and that there would be further significant loss of activity through decay.

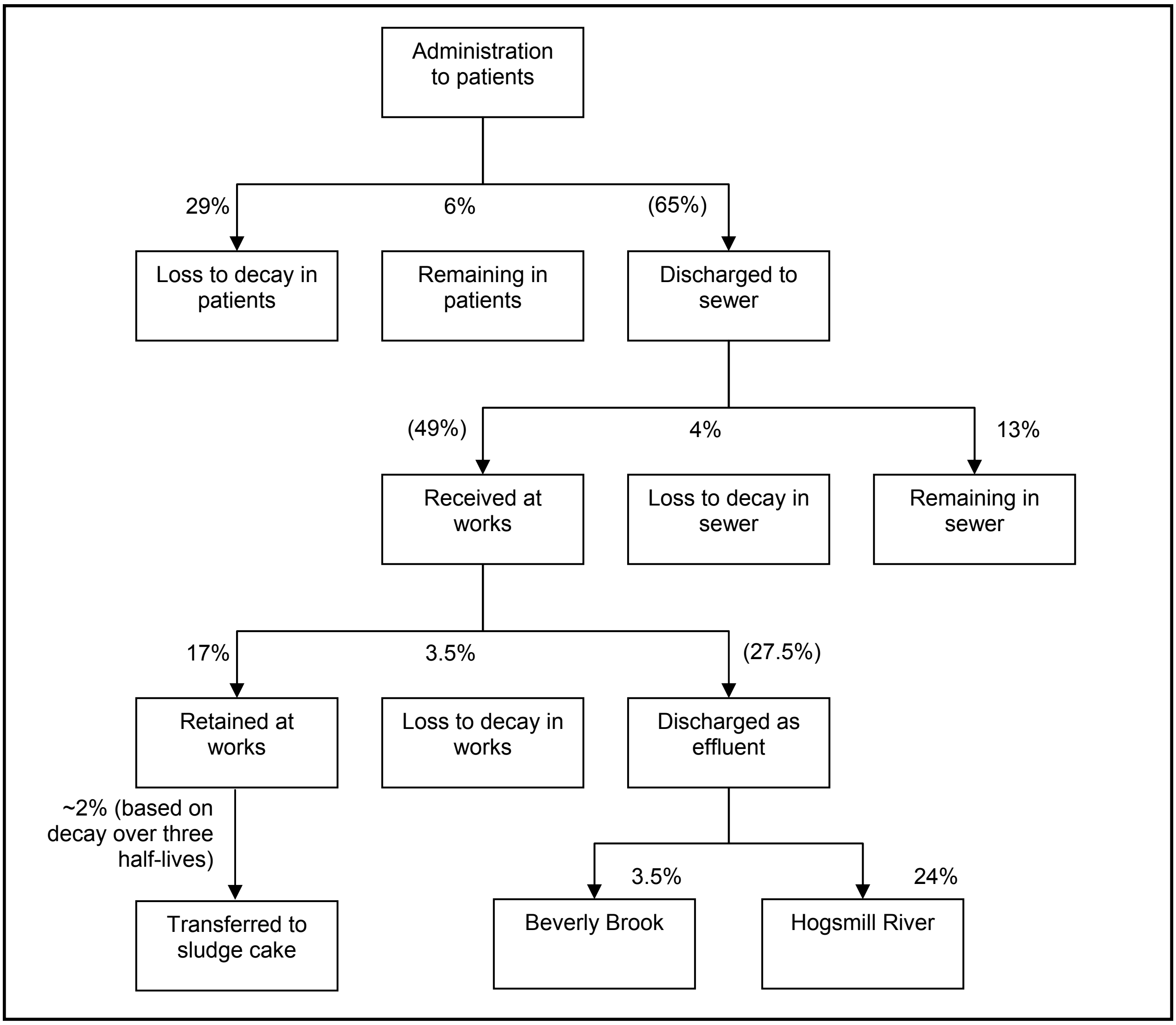

Figure A5.3: Percentage of iodine-131 administered retained, lost or transferred

A5.2 Dilution in the receiving rivers

Activity concentrations for river water in the Beverley Brook indicated that during the survey (with relatively low flow conditions[6] of 0.31 $m^3 s^{-1}$), there was little dilution of the effluent at the West Barnes Lane site (less than 10 per cent dilution) by the natural flow of the brook and that, over the entire length of the brook, there was about a factor of two dilution. Discussions with Thames Water staff suggest that during summer drought conditions, there is no flow in the brook upstream of the discharge point and hence no dilution of effluent at the point of outfall. This indicates the importance of the effluent flow from the works in maintaining water levels in the brook, but also shows that there can be little or no dilution in the receiving water course.

Flow rates in the Beverley Brook are monitored by the Environment Agency at a single automated station at Wimbledon Common. A preliminary comparison of river flow rates recorded at this site and treated effluent flow rates from the Hogsmill works between 2000 and 2005 was undertaken. This suggested that, on average, 46 per cent of the flow at Wimbledon Common would arise from effluent discharged (on average, there would only be a factor of two dilution at this point). Under low river flow conditions, 70 per cent of the flow would be derived from the effluent discharged, and hence the dilution would be lower.

The assessment of river flow rates also shows that flows are ‘flashy’ and that high flow events are restricted to short periods of high rainfall. These short-term events bias the average river flow; for instance, over a six-year period approximately 70 per cent of the mean daily flows recorded were below the average river flow determined over the same period. This raises the question of whether mean flows are appropriate parameters to use when assessing dilution for dose assessment modelling studies. Also, a significant proportion of the flow monitored arises from effluent discharge itself and would therefore lead to overestimated dilution. Addressing these issues further was beyond the scope of this project.

As mentioned in the previous section, over seven times more activity is discharged from the sewage works to the Hogsmill River compared to the Beverley Brook. Although the Hogsmill River has a higher flow rate (mean of 1.3 $m^3 s^{-1}$), this is less than a factor of three greater than that in the Beverley Brook. It is therefore reasonable to assume that activity concentrations of iodine-131 in the Hogsmill River could be, on average, over double those measured during this study in the Beverley Brook. Also, the same issues with flow assessments discussed above could apply. Addressing these issues further was beyond the scope of this project.

During this study, the iodine-131 administrations were given over three consecutive days. This is not typical of normal practice, where generally all administrations are made on the same day (normally a Tuesday). Although this is unlikely to affect the average activity concentration in the brook determined over a week-long period, it could indicate that peak activities, although more transient, could be a factor of three higher. Nonetheless, when assessing possible exposure of the public, average annual values rather than peak ones are typically used and this short-term variability is less important.

---

[6] Compared to the mean river flow of 0.53 $m^3 s^{-1}$ determined over a five-year period (data supplied by the Environment Agency).

A5.3 Uptake to sediment

Although all gamma dose rate measurements in the Beverley Brook were comparable to, or less than, background, potential adsorption of iodine to sediments and resulting external exposure is a process included within the Environment Agency assessment methods. This adsorption is based on the concentration ratio between water and sediment, the partition coefficient.

The results given in Appendix 4 show no statistically significant correlation between riverine sediment activity concentration and that in water (r^2 = 0.3, n = 15); therefore, a large degree of uncertainty is associated with any determination of the partition coefficient (defined here as activity concentration in the bed sediment, Bq kg^{-1} (dw), divided by activity concentration in the overlying water, Bq l^{-1})[7]. Based on the data given in Section 3.3, a mean partition coefficient of six l kg^{-1} was calculated for the three main river sampling sites (with a range of one to 26 l kg^{-1}). These values were comparable to, if not higher than, those discussed in Appendix 1 for sand-silt type sediments.

Following the method discussed above, the data collected during March 2006 for the intertidal sediments where the Beverley Brook enters the Thames was also assessed. The results implied a partition coefficient of 53 to 81 l kg^{-1}, approximately an order of magnitude higher than mean values observed in the upper areas of the brook. However, water samples were collected at low water and were not likely to be indicative of the typical water concentration averaged over a tidal cycle. Water samples were not collected during the return visit in July, so no further partition coefficient values could be determined from these additional sediment samples.

Preferential accumulation of other gamma-emitting radionuclides in these intertidal sediments was also identified and it is possible that the final tidal reaches of the Beverley Brook, including the Ashlone Warf, were acting as an 'environmental sink', accumulating contaminants from the river water. This feature is typical of estuarine environments and arises due to fine-grained sediment retention and recycling through the action of the tides and the influence of increasing salinity on the chemical properties of contaminants and fine particulate material in the river water. It is also possible that there was an additional input of iodine-131 from other discharges to the Thames Estuary. The confluence of the Thames and the Hogsmill River is non-tidal and accumulation of fine-grained bed sediment has not occurred. This phenomenon is therefore likely to be restricted to the mid and outer reaches of the Thames, which are tidal.

Partition coefficients for saturated bank sediment were comparable to or lower than those determined for the river bed sediment.

[7] Note that the partition coefficient is more accurately applied to the ratio of activity associated with suspended sediment and that dissolved in the water, but in the field of radiation protection it is also used to represent the ratio of activity in water to that in bed sediment. This latter includes chemical adsorption of a contaminant to a sedimentary particle, as well as the physical processes responsible for the exchange of particles between the water column and the bed sediment. This value therefore tends to be highly site-specific and is dominated by the grain size of the bed sediment, rather than the chemical properties of the contaminant under consideration.

Appendix 6 – Data

Table A6.1: Iodine-131 activity concentration in crude sewage

Time	I-131 activity concentration (Bq l^{-1}) Data	+/- Error	Notes
28/02/2006 20:00	2.7	1.3	
01/03/2006 04:00	20.0	3.0	
01/03/2006 12:30	22.0	2.0	
01/03/2006 16:30	45.0	4.0	
01/03/2006 20:30	20.0	3.0	
02/03/2006 00:30	50.0	5.0	
02/03/2006 04:30	28.0	4.0	
02/03/2006 07:00	21.0	3.0	Incomplete: approx one hour integration
02/03/2006 10:00	32.0	4.0	
02/03/2006 14:00	27.0	3.0	
02/03/2006 18:00	31.0	4.0	
02/03/2006 22:00	22.0	3.0	
03/03/2006 02:00	28.0	6.0	
03/03/2006 06:00	30.0	6.0	
03/03/2006 10:30	48.0	6.0	
03/03/2006 14:30	50.0	8.0	
03/03/2006 18:30	26.0	4.0	
03/03/2006 22:30	25.0	7.0	
04/03/2006 02:30	24.0	6.0	
04/03/2006 02:30	24.0	6.0	
04/03/2006 06:30	19.0	3.0	Failed to complete (1.3 hours out of four)
04/03/2006 06:30	19.0	3.0	Failed to complete (1.3 hours out of four)
04/03/2006 11:30	13.0	3.0	Spot sample
04/03/2006 11:30	13.0	3.0	Spot sample
04/03/2006 18:30	<1.5		Spot sample
05/03/2006 08:00	8.3	2.6	Spot sample
05/03/2006 08:00	8.3	2.6	Spot sample

Table A6.2: Iodine-131 activity concentration in primary settled sewage

Time	I-131 activity concentration (Bq l^{-1}) Data	+/- Error	Notes
01/03/2006 01:05	9.1	1.7	24-hour integrated samples collected from the primary settled sewage outflow
01/03/2006 21:52	34	4	
02/03/2006 09:55	27	3	
03/03/2006 20:50	30	4	
04/03/2006 20:30	13	2	

Table A6.3: Iodine-131 activity concentration in primary settled sludge

Time	I-131 activity concentration ($Bq\ l^{-1}$) Data	+/- Error	Notes
01/03/06 11:10	20	2	Samples collected from the primary sludge pumping house
02/03/06 08:35	76	8	

Table A6.4: Iodine-131 activity concentration in activated sludge

Time	I-131 activity concentration ($Bq\ l^{-1}$) Data	+/- Error	Notes
01/03/2006 12:20	44	4	Spot samples collected by bucket from the outflow point of the activated sludge plant
02/03/2006 10:20	96	10	
03/03/2006 10:45	110	10	
04/03/2006 10:45	130	13	
05/03/2006 09:05	130	14	

Table A6.5: Iodine-131 activity concentration in dewatered solids

Time	I-131 activity concentration ($Bq\ kg^{-1}$ dw) Data	+/- Error	Notes
03/03/2006 09:15	1800	170	Dewatered solids produced over the last 12 hours
03/03/2006 09:15	510	50	Stockpiled material
03/03/2006 09:15	410	46	Stockpiled material

Table A6.6: Iodine-131 activity concentration in final effluent discharged to the Beverley Brook

Time	I-131 activity concentration (Bq l^{-1})		Notes
	Data	+/- Error	
28/02/2006 16:30	<1.0		Bucket spot sample
28/02/2006 20:00	<1.0		Bucket spot sample
01/03/2006 02:30	1.5	1.0	Five-hour sample, three bottles empty
01/03/2006 12:00	3.5	1.0	
01/03/2006 16:00	5.5	1.9	
01/03/2006 20:00	8.9	1.5	
02/03/2006 00:00	9.9	1.3	
02/03/2006 04:00	9.8	1.6	
02/03/2006 08:00	11.0	2.0	
02/03/2006 10:05	11.0	2.0	Bucket spot sample
02/03/2006 12:20	9.1	2.1	
02/03/2006 16:20	11.0	3.0	
02/03/2006 20:20	15.0	4.0	
03/03/2006 00:20	14.0	4.0	
03/03/2006 04:20	16.0	3.0	
03/03/2006 08:20	17.0	4.0	
03/03/2006 12:30	9.9	1.5	
03/03/2006 16:30	13.0	2.0	
03/03/2006 20:30	14.0	2.0	
04/03/2006 00:30	15.0	3.0	
04/03/2006 04:30	14.0	2.0	
04/03/2006 08:05	14.0	3.0	
04/03/2006 10:05	13.0	2.0	Bucket spot sample
04/03/2006 12:00	13.0	3.0	
04/03/2006 16:00	12.0	2.0	
04/03/2006 20:00	13.0	4.0	
05/03/2006 00:00	14.0	5.0	
05/03/2006 05:00	14.0	4.0	
05/03/2006 09:15	10.0	3.0	

Table A6.7: Iodine-131 activity concentration in final effluent discharged to the Hogsmill River

Time	I-131 activity concentration (Bq l^{-1})		Notes
	Data	+/- Error	
01/03/2006 15:40	3.7	2.1	Bucket spot sample
02/03/2006 09:45	16	2	Bucket spot sample
04/03/2006 10:00	20.0	4.0	Bucket spot sample

Table A6.8: Iodine-131 activity concentration in Beverley Brook river water

Location	Time	I-131 activity concentration ($Bq\ l^{-1}$)		Notes
		Data	+/- Error	
Green Lane (Site 1)	02/03/2006 11:15	< 3.0		Shallow and narrow watercourse, very little flow. Evidence of sewage fungus present.
	04/03/2006 14:35	2.8	1.8	
West Barnes Lane (Site 2)	01/03/2006 13:30	1.4	0.8	First side immediately down stream of the discharge point. Slight decrease in flow during the week noticeable.
	02/03/2006 12:15	14	2	
	03/03/2006 12:25	18	6	
	04/03/2006 15:00	14	2	
	05/03/2006 10:25	12	3	
Wimbledon Common (Site 3)	01/03/2006 15:05	<1		Site under foot bridge on edge of Wimbledon Common.
	02/03/2006 13:00	8.7	2.1	
	03/03/2006 13:20	10	3	
	04/03/2006 15:10	11	6	
	05/03/2006 10:55	<1		
Richmond Park Site 4)	01/03/2006 16:10	<1		Site at south east corner of Richmond Park.
	02/03/2006 13:00	5.7	1.1	
	03/03/2006 14:30	9	1.7	
	04/03/2006 17:10	11	3	
	05/03/2006 11:45	8.1	1.6	
Ashlone Warf (Site 5)	04/03/2006 13:30	6.6	2.9	Upstream of the Warf.

Table A6.9: Iodine-131 activity concentration in river bank soil

Time	I-131 activity concentration ($Bq\ kg^{-1}$ dw)		Notes
	Data	+/- Error	
02/03/06 14:00	20	6	0-2 cm above waters edge
02/03/06 14:00	17	6	2-4 cm above waters edge
02/03/06 14:00	11	4	4-6 cm above waters edge
04/03/06 16:30	8.7	2.6	0-2 cm above waters edge
04/03/06 16:30	6.7	1.4	2-4 cm above waters edge
04/03/06 16:30	< 1.0		4-6 cm above waters edge

Table A6.10: Iodine-131 activity concentration in Beverley Brook river bed sediment

Location	Time	I-131 activity concentration (Bq kg^{-1} dw)		Notes
		Data	+/- Error	
West Barnes Lane (Site 2)	01/03/2006 13:00	37	4	Sediment coarse with numerous shell fragments.
	02/03/2006 11:45	31	5	
	03/03/2006 12:00	48	6	
	04/03/2006 14:30	67	7	
	05/03/2006 09:55	62	7	
Wimbledon Common (Site 3)	01/03/2006 14:35	11	2	Sediment coarse and 'gritty'.
	02/03/2006 12:30	10	3	
	03/03/2006 12:50	14	3	
	04/03/2006 00:00	9	2.8	
	05/03/2006 10:25	14	5	
Richmond Park (Site 4)	01/03/2006 15:40	13	2	Sediment coarse and sandy.
	02/03/2006 14:00	20	6	
	03/03/2006 14:00	23	3	
	04/03/2006 16:40	25	4	
	05/03/2006 11:15	16	2	
Ashlone Warf (Site 5)	04/03/2006 13:10	370	39	Upstream of Ashlone Warf on the side of the bank, sediment fine-grained and anoxic.
	04/03/2006 13:20	570	54	In the mouth of the Warf, sediment very fine-grained and oxic at surface to 1 to 2 cm.

Table A6.11: Additional measurements of activity concentrations of gamma-emitting radionuclides in sediment at the mouth of Ashlone Warf

	Sediment activity concentrations (Bq kg^{-1} dw)					
	Replicate 1		Replicate 2		Replicate 3	
	Surface	Subsurface	Surface	Subsurface	Surface	Subsurface
Sample date	26/07/2006	26/07/2006	26/07/2006	26/07/2006	26/07/2006	26/07/2006
Sample time	11:30	11:35	11:05	11:50	10:45	10:50
Be-7	84 ± 13	90 ± 14	94 ± 19	77 ± 12	100 ± 20	84 ± 12
K-40	480 ± 50	490 ± 50	560 ± 60	530 ± 50	40 ±50	510 ±50
Mn-54	< 1	< 2	< 1	< 1	< 2	< 1
Fe-59	< 1	< 1	< 1	< 1	< 1	< 1
Co-57	< 1	< 1	< 1	< 1	< 1	< 1
Co-58	< 2	< 1	< 1	< 1	< 1	< 1
Co-60	< 1	< 1	< 3	< 1	< 1	< 1
Zn-65	< 1	< 1	< 3	< 1	< 1	< 1
Ni-95	< 1	< 1	< 1	< 1	< 1	< 1
Zi-95	< 1	< 1	< 1	< 1	< 1	< 1
Ru-103	< 1	< 1	< 1	< 1	< 1	< 1
Ag-110m	< 1	< 1	< 1	< 1	< 1	< 1
Sb-124	< 1	< 1	< 1	< 1	< 1	< 1
Sb-125	< 1	< 1	< 1	< 1	< 1	< 1
I-131	100 ± 10	92 ± 9	120 ± 10	58 ± 6	120 ± 10	82 ± 9
Cs-134	< 1	< 1	< 1	< 1	< 1	< 1
Cs-137	7.9 ± 1.0	7.8 ± 1.0	9.0 ± 1.3	7.6 ± 1.0	9.4 ± 1.2	8.8 ± 1.1
Ce-144	< 2	< 2	< 3	< 2	< 2	< 2
Eu-154	< 1	< 1	< 1	< 1	< 1	< 1
Eu-155	< 1	< 1	< 2	< 1	< 1	< 1
Ac-228	26 ± 5	23 ± 4	30 ± 5	29 ± 5	30 ± 5	27 ± 4
Ra-224	27 ± 3	28 ± 3	31 ± 3	30 ± 3	31 ± 3	24 ± 2
Pb-212	29 ± 3	30 ± 3	34 ± 4	32 ± 3	29 ± 3	33 ± 3
Bi-212	30 ± 8	35 ± 8	44 ± 12	38 ± 9	27 ± 8	32 ± 9
Tl-208	9.7 ± 1.6	10 ± 2	12 ± 2	11 ± 2	10 ± 2	11 ± 2
Th-234	46 ± 12	53 ± 21	55 ± 28	65 ± 23	59 ± 14	66 ± 25
Ra-226	25 ± 25	26 ± 26	35 ± 35	24 ± 24	21 ± 21	22 ± 22
Pb-214	14 ± 2	18 ± 2	20 ± 3	18 ± 2 1	6 ± 2	18 ± 2
Bi-214	15 ± 2	18 ± 2	17 ± 3	17 ± 2	16 ± 2	17 ± 2
U-235	2.1 ± 0.7	1.6 ± 0.7	1.5 ± 1.0 2.	1 ± 0.7	2.3 ± 0.8	2.3 ± 0.7
Th-227	< 3	< 3	< 4	< 3	< 3	< 3
Ra-223	< 3	< 4	< 4	< 4	< 3	< 4
Am-241	< 1	< 2	< 1	< 1	< 2	< 3

Table A6.12: Gamma dose in air measurements

Site	Time	Counts (integrated over 600 s)	µGy h^{-1}	nSv h^{-1}	Note
On gantry over crude sewage inlet (probe ~ 1.75 m above water surface)	02/03/2006 07:50	671	0.007	5.9	1.75 m above water level
	02/03/2006 08:05	780	0.017	15.1	"
	03/03/2006 08:35	780	0.017	15.1	Replicate 1
	03/03/2006 08:45	787	0.018	15.6	Replicate 2
	03/03/2006 08:55	766	0.016	13.9	Replicate 3
	04/03/2006 08:35	778	0.017	14.9	Replicate 1
	04/03/2006 08:45	741	0.014	11.8	Replicate 2
	04/03/2006 09:15	793	0.019	16.1	Replicate 3
	05/03/2006 07:55	727	0.012	10.6	Low flow
On gantry over primary settled sewage outlet (probe ~ 1.75 m above water surface)	03/03/2006 07:55	848	0.024	20.8	Replicate 1
	03/03/2006 08:10	804	0.020	17.1	Replicate 2
	03/03/2006 08:20	803	0.020	17.0	Replicate 3
	04/03/2006 07:55	771	0.016	14.3	Replicate 1
	04/03/2006 08:05	813	0.020	17.8	Replicate 2
	04/03/2006 08:15	817	0.021	18.2	Replicate 3
	05/03/2006 07:30	773	0.017	14.5	
On gantry over outlet from activated sludge tanks (probe ~ 1.75 m above water surface)	04/03/2006 09:55	767	0.016	14.0	Replicate 1
	04/03/2006 10:10	764	0.016	13.7	Replicate 2
	04/03/2006 10:25	784	0.018	15.4	Replicate 3
	05/03/2006 08:10	829	0.022	19.2	
	03/03/2006 10:00	739	0.013	11.6	Replicate 1
	03/03/2006 10:10	751	0.015	12.6	Replicate 2
	03/03/2006 10:40	745	0.014	12.1	Replicate 3
Sludge settlement pond	04/03/2006 17:25	729	0.012	10.8	Over bed (approx 2 m), back of raw sewage pump house
Adjacent (within 1 m) from the base of fresh dewatered solids pile	03/03/2006 09:20	920	0.031	26.8	Replicate 1
	03/03/2006 09:30	925	0.031	27.2	Replicate 2
	03/03/2006 09:40	974	0.036	31.3	Replicate 3
Adjacent to stockpiled dewatered solids	04/03/2006 10:55	877	0.027	23.2	1 m from solids pile
On dewatered solids storage yard	04/03/2006 11:05	815	0.021	18.0	12 m from any solids
At side of anaerobic digestion tanks	04/03/2006 10:40	698	0.009	8.2	1 m from tank side
Beverley Brook – West Barnes Lane (Site 2)	01/03/2006 13:15	876	0.027	23.1	Over water
	02/03/2006 11:50	855	0.025	21.3	Over water
	03/03/2006 11:55	859	0.025	21.7	Over water
	04/03/2006 14:35	849	0.024	20.8	Over water
	01/03/2006 13:25	858	0.025	21.6	Bottom of bank
	02/03/2006 12:00	911	0.030	26.0	Bottom of bank
	03/03/2006 12:10	839	0.023	20.0	Bottom of bank
	04/03/2006 14:50	864	0.025	22.1	Bottom of bank
	05/03/2006 09:55	869	0.026	22.5	Over water
	01/03/2006 13:35	958	0.034	30.0	Top of bank
	02/03/2006 12:10	904	0.029	25.4	Top of bank
	03/03/2006 12:25	905	0.029	25.5	Top of bank

Site	Time	Counts (integrated over 600 s)	μGy h^{-1}	nSv h^{-1}	Note
Beverly Brook 2 – Wimbledon Common (Site 3)	01/03/2006 14:40	749	0.014	12.5	Over water
	02/03/2006 12:50	823	0.021	18.7	Over water
	03/03/2006 13:15	760	0.015	13.4	Over water
	04/03/2006 15:40	776	0.017	14.7	Over water
	05/03/2006 10:30	798	0.019	16.6	Over water
	01/03/2006 15:45	797	0.019	16.5	Bottom of bank
	03/03/2006 13:00	852	0.024	21.1	Bottom of bank
	04/03/2006 15:50	839	0.023	20.0	Bottom of bank
	05/03/2006 10:40	835	0.023	19.7	Bottom of bank
	01/03/2006 14:55	824	0.022	18.7	Top of bank
	02/03/2006 13:00	865	0.025	22.2	Top of bank
	03/03/2006 12:50	862	0.025	21.9	Top of bank
Beverly Brook 3 – Richmond Park	02/03/2006 13:50	813	0.020	17.8	Over water
	03/03/2006 14:10	837	0.023	19.8	Over water
	04/03/2006 16:30	775	0.017	14.6	Over water
	05/03/2006 11:20	768	0.016	14.1	Over water
	02/03/2006 14:05	837	0.023	19.8	Bottom of bank
	03/03/2006 14:20	822	0.021	18.6	Bottom of bank
	04/03/2006 16:40	810	0.020	17.6	Bottom of bank
	01/03/2006 16:00	872	0.026	22.8	Bottom of bank
	02/03/2006 14:30	858	0.025	21.6	Top of bank
	02/03/2006 14:15	876	0.027	23.1	Top of bank
	03/03/2006 14:00	857	0.025	21.5	Top of bank
Front of STW operations building	04/03/2006 17:35	884	0.027	23.8	Over grass, TQ1935758299 ± 7 m
Richmond Park	05/03/2006 11:35	839	0.023	20.0	Replicate 1
Richmond Park	05/03/2006 11:45	844	0.023	20.4	Replicate 2
Richmond Park	05/03/2006 11:55	800	0.019	16.7	Replicate 3

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Published by:

Environment Agency
Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk