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Generalised Derived Constraints for Radioisotopes of Polonium, Lead, Radium and Uranium

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GENERALISED DERIVED CONSTRAINTS FOR RADIOISOTOPES OF POLONIUM, LEAD, RADIUM AND URANIUM

ABSTRACT

The 1990 recommendations of the International Commission on Radiological Protection (ICRP) introduced the concept of the dose constraint and in the NRPB response to the recommendations the concept of a generalised derived constraint (GDC) was introduced. Generalised derived constraints apply to discharges of radionuclides to the environment and are based on the upper value of constraint on effective dose for members of the public of 0.3 mSv y^{-1}. Generalised derived constraints have been calculated for discharges to atmosphere, rivers and sewers for the radiologically significant isotopes of polonium, lead, radium and uranium. The most recent age-dependent dosimetric models have been used and the methods are as used in calculating GDCs for radioisotopes of other elements, such as strontium, published previously. The GDC s presented here are intended as convenient reference levels against which proposed discharges can be compared.

Generalised derived constraints are calculated using deliberately cautious assumptions and are in terms of annual discharges, assuming that the releases to the environment are continuous. If a proposed discharge is greater than about 30% of the GDC then the doses should be examined more closely, taking account of site-specific factors.

PREPARED BY M P HARVEY AND J R SIMMONDS

INTRODUCTION

1 The 1990 recommendations of the International Commission on Radiological Protection (ICRP, 1991) introduced the concepts of effective dose and dose constraint. NRPB has published guidance on the ICRP recommendations and has considered their implications for public exposure (NRPB, 1993a,b). In considering the implications of the 1990 ICRP recommendations for public exposure NRPB noted that generalised derived limits (GDLs) for environmental materials should still be based on the overall dose limit for members of the public. However, derived quantities for discharges of radionuclides to the environment are clearly related to the current operation of a single controlled source and should therefore be based on the appropriate dose constraint (NRPB, 1993b). Generalised derived constraints (GDCs) have previously been published for isotopes of strontium, ruthenium, iodine, caesium, plutonium, americium and curium (NRPB, 2000a). In this document GDCs are given for isotopes of polonium, lead, radium and uranium based on the upper value of the constraint on effective dose for members of the public of 0.3 mSv y^{-1} recommended by NRPB (1993b). Generalised derived limits for the same radioisotopes have also recently been published for a range of environmental materials (NRPB, 2000b). Advice on the application of GDLs has also been published (NRPB, 1998).

2 Generalised derived constraints are intended to be convenient reference quantities against which proposed controlled discharges to the environment can be compared. They are expected to be particularly useful for small (non-nuclear industry) users of radioactive materials discharging low levels of radionuclides to the environment. The GDCs may not be relevant to authorised discharges from nuclear sites where discharges can be greater and the dispersion conditions may be very different from those assumed here; for example, liquid discharges are mainly to the sea not to sewers or small rivers. Generalised derived constraints are related to the dose constraint by a defined model and are calculated such that compliance with the GDC should ensure virtual certainty of compliance with the constraint. They are intended for general application and are based on a generic definition of the discharge location and the receiving environment. The GDC does not replace the requirement on the dischargers of radioactive material to optimise their use of sources or management of practices so that exposures of members of the public are kept as low as reasonably achievable.

3 This report considers three types of discharge of radionuclides to the environment and GDCs are presented for each. Small users of radioactivity, such as hospitals and universities, discharge small quantities of radionuclides to the sewerage system or directly to rivers in addition to discharging to atmosphere. GDCs for discharges to sewers and to rivers have therefore also been determined. The GDCs have been calculated using effective dose as defined in ICRP Publication 60 (ICRP, 1991). The latest age-dependent dose coefficients for members of the public were used in the calculations (ICRP, 1996).

4 This report presents GDCs for discharges to atmosphere, rivers and sewers for the radioisotopes of four elements for which GDLs in environmental materials have already been published (NRPB, 2000b). The methods and data used in their calculation are outlined and the important exposure pathways for each GDC are discussed. Advice is also given on when site-specific assessments are required.

BASIS FOR GDCs

5 A dose constraint is the upper bound on the annual effective dose that members of the public may receive from the planned operation of a single controlled source; the dose constraint places an upper bound on the outcome of optimisation studies. The quantity to be compared with the dose constraint is the annual dose to the overall critical group summed over all exposure pathways, arising from the current and future operations of a controlled source (NRPB, 1993b). The exposure pathways to be considered include those which are expected to arise in the future from current operations, since these can be influenced by current or future control procedures. It does not include exposures from past discharges, since these cannot be influenced by current or future control procedures. However, account should be taken of any build-up of radioactivity in the environment owing to present and future operation (NRPB, 1993b). For proposed controlled sources, NRPB has recommended a maximum dose constraint for public exposure of 0.3 mSv y^{-1}, with the proviso that dose constraints lower than this could be set where such doses are readily achievable (NRPB, 1993a). The GDCs presented here are based on this upper value of the dose constraint. They represent the annual discharge of a particular radionuclide by a single mode of discharge which is calculated to give a dose of 0.3 mSv y^{-1} to the critical group. The GDCs are intended for screening purposes to enable the doses from low levels of discharge of radionuclides to the environment to be assessed. In particular, they enable the impact of proposed discharges from small users of radioactivity, such as hospitals, to be estimated, without necessarily carrying out a full site-specific dose assessment.

6 Generalised derived constraints have been calculated for three modes of discharge: to atmosphere, to rivers, and to sewers. In each case doses are calculated for all relevant exposure pathways and are summed. For discharge to atmosphere the radionuclide is assumed to be discharged as particles, while for discharges to rivers and to sewers the radionuclide is assumed to be discharged in solution. The disposal of solid forms of radioactive waste is outside the scope of this document. For each of the three modes of discharge, cautious assumptions are made about the nature of the discharge and the location of the critical group relative to the discharge point. For example, it has been necessary to adopt generic values for the height of the discharge point for atmospheric releases, the characteristics of the river receiving liquid discharges and the type of sewerage system. The use of cautious assumptions is intended to ensure that compliance with the GDC should also lead to compliance with the dose constraint. Nevertheless, as discussed later, site-specific assessments will be required if a proposed discharge is a significant fraction of the relevant GDC.

7 The GDCs are for continuous discharges of radionuclides to the environment and are for annual discharges, which are assumed to continue for 50 years. The ingrowth of radioactive progeny has been considered for this 50 year period. The GDCs have been calculated assuming that annual average conditions apply. They, therefore, do not apply to uncontrolled or controlled short-term releases nor to releases which vary significantly over the year.

8 The age groups considered in calculating GDCs are infants (1 year old), children (10 years old) and adults (assumed to be 20 years old), taking into account variations in the dose coefficients and dietary and other habits with age. In addition, for radionuclides where the ingestion of milk is likely to be the dominant exposure pathway, calculations are also performed for infants on an all-milk diet in the first year of life based on dose coefficients for a 3 month old. These age groups are the same as those considered in the calculations of GDLs (NRPB, 2000b) and again the GDCs are based on the dose to the most restrictive age group. The use of the ingestion dose coefficient for a 3 month old, together with a milk intake more applicable to an older infant to represent the first year of life, will lead to a cautious estimate of the GDC. This is particularly the case for radioisotopes where there is a marked reduction in the dose coefficient between 3 and 12 months. It is not considered appropriate to use the 3 month old dose coefficient for intakes of other foods as they are generally only consumed by older infants for whom a lower dose coefficient usually applies. Although data on dose coefficients are available for additional age groups (ICRP, 1996), the ages considered here are thought to cover the range and to be adequate for the purposes of calculating GDCs. For calculating the doses from intakes of radionuclides the lifetime of an individual is taken to be 70 years. Although it is slightly shorter than the average lifetime of individuals in the UK, its use is sufficiently cautious because intakes of radionuclides and the resulting risks decrease in old age.

9 The values of the effective dose coefficients for intake by inhalation and ingestion are as described elsewhere (ICRP, 1996). They have been calculated for each age group considered using the most recent age-dependent dosimetric models. Tables 1 and 2

TABLE 1 Dose coefficients for intake by ingestion

		Committed effective dose per unit intake (Sv Bq^{-1})			
Nuclide	f_1*	Infant (3 months)	Infant (1 y)	Child (10 y)	Adult (20 y)
^{210}Po	$5.0\ 10^{-1}$	$2.60\ 10^{-5}$	$8.80\ 10^{-6}$	$2.60\ 10^{-6}$	$1.20\ 10^{-6}$
^{210}Pb	$2.0\ 10^{-1}$	$8.40\ 10^{-6}$	$3.60\ 10^{-6}$	$1.90\ 10^{-6}$	$6.90\ 10^{-7}$
^{226}Ra	$2.0\ 10^{-1}$	$4.70\ 10^{-6}$	$9.60\ 10^{-7}$	$8.00\ 10^{-7}$	$2.80\ 10^{-7}$
^{234}U	$2.0\ 10^{-2}$	$3.70\ 10^{-7}$	$1.30\ 10^{-7}$	$7.40\ 10^{-8}$	$4.90\ 10^{-8}$
^{235}U	$2.0\ 10^{-2}$	$3.50\ 10^{-7}$	$1.30\ 10^{-7}$	$7.10\ 10^{-8}$	$4.70\ 10^{-8}$
^{238}U	$2.0\ 10^{-2}$	$3.40\ 10^{-7}$	$1.20\ 10^{-7}$	$6.80\ 10^{-8}$	$4.50\ 10^{-8}$

* The gut transfer factors (f_1) for each nuclide given are the same for all age groups with the following exceptions:

Po	3 month old: 1.0	
Pb	3 month old: $6.0\ 10^{-1}$	1 y old and 10 y old: $4.0\ 10^{-1}$
Ra	3 month old: $6.0\ 10^{-1}$	1 y old and 10 y old: $3.0\ 10^{-1}$
Isotopes of U	3 month old: $4.0\ 10^{-2}$	

TABLE 2 Dose coefficients for intake by inhalation

			Committed effective dose per unit intake (Sv Bq^{-1})		
Nuclide	f_1	Type*	Infant (1 y)	Child (10 y)	Adult (20 y)
^{210}Po	$1.0\ 10^{-1}$	M	$1.10\ 10^{-5}$	$4.60\ 10^{-6}$	$3.30\ 10^{-6}$
^{210}Pb	$1.0\ 10^{-1}$	M	$3.70\ 10^{-6}$	$1.50\ 10^{-6}$	$1.10\ 10^{-6}$
^{226}Ra	$1.0\ 10^{-1}$	M	$1.10\ 10^{-5}$	$4.90\ 10^{-6}$	$3.50\ 10^{-6}$
^{234}U	$2.0\ 10^{-2}$	M	$1.10\ 10^{-5}$	$4.80\ 10^{-6}$	$3.50\ 10^{-6}$
^{235}U	$2.0\ 10^{-2}$	M	$1.00\ 10^{-5}$	$4.30\ 10^{-6}$	$3.10\ 10^{-6}$
^{238}U	$2.0\ 10^{-2}$	M	$9.40\ 10^{-6}$	$4.00\ 10^{-6}$	$2.90\ 10^{-6}$

* Absorption type M (moderate) describing absorption from the respiratory tract.

give the values for the effective dose coefficients used in this report for intake by ingestion and inhalation, respectively. The recommended default absorption types for particulate aerosols are used to select the appropriate inhalation dose coefficients for the GDC calculations (ICRP, 1996).

10 As presented here, GDCs relate the discharge of a single radionuclide from a single mode of discharge to the upper value on the constraint on effective dose for members of the public. In practice, sites are likely to discharge a number of radionuclides by more than one mode and this needs to be taken into account, as outlined later.

GDCs FOR DISCHARGES TO ATMOSPHERE, RIVERS AND SEWERS

11 The general approach and formulae used to calculate the GDCs for discharges to atmosphere, to rivers and to sewers are given in Appendices A, B and C, respectively, together with the data on occupancy and intakes of air, terrestrial and aquatic foods used in the calculations. The methodology used is the same as used for the calculation of previous GDCs and the data are generally the same as those used to calculate GDLs (NRPB, 2000a,b).

12 The release to atmosphere is assumed to be from a height of 1 m above the ground and the members of the critical group are assumed to live 100 m from the release point, obtaining all of their food from an area 500 m from the release point. Further details of the assumptions adopted are given in Appendix A. Five exposure pathways are considered:

(a) internal irradiation from inhalation of radionuclides in air,
(b) external irradiation from radionuclides in the plume,
(c) external irradiation from radionuclides deposited on the ground,
(d) internal irradiation from inhalation of deposited radionuclides resuspended into the air,
(e) internal irradiation from the ingestion of radionuclides in terrestrial foods and the inadvertent ingestion of soil.

The doses from each of these exposure pathways are summed to obtain the GDC. For the radionuclides considered in this document equivalent doses to the skin and lens of the eye are not explicitly considered as these doses are less restrictive than the effective dose in determining the GDC. This would not necessarily be the case for some other radionuclides, notably the noble gases for which these doses may need to be considered. In estimating the doses the release is taken to continue for 50 years allowing for any build-up of radionuclides in the environment.

13 Table 3 gives the calculated GDCs for discharges to atmosphere for the six radionuclides considered in this document. Appendix D presents the contributions of the different exposure pathways to the overall dose used in calculating the GDCs. The GDCs are based on the limiting age group, which is indicated in Table 3.

14 Generalised derived constraints for discharges to rivers are also given in Table 3. They are again for the most restrictive age group which is indicated in the table. The discharges are assumed to be to a generic river with a flow of 1 $m^3 s^{-1}$. This flow is relatively low and so will generally result in a cautious estimate of the concentrations of radionuclides in river water and hence radiation doses. Full details of the river characteristics and other data used in the calculations are given in Appendix B. The exposure pathways included in calculating the GDCs are:

(a) internal irradiation from the ingestion of radionuclides in drinking water,
(b) internal irradiation from the ingestion of radionuclides in freshwater fish,
(c) external irradiation from radionuclides deposited on river sediments,
(d) internal irradiation from the inhalation of radionuclides resuspended into the air from sediments,
(e) internal irradiation from ingestion of radionuclides in terrestrial foods grown on irrigated land.

The GDC is based on the sum of doses from all exposure pathways. The relative contributions of the different exposure pathways to the overall dose are given in Appendix D.

TABLE 3 Generalised derived constraints for releases to atmosphere, rivers and sewers

	Releases to atmosphere		Releases to river		Releases to sewers*	
Nuclide	GDC ($Bq\ y^{-1}$)	Limiting age group	GDC ($Bq\ y^{-1}$)	Limiting age group	GDC ($Bq\ y^{-1}$)	Limiting age group
^{210}Po	$3\ 10^9$	1 y old	$4\ 10^9$	1 y old	$7\ 10^7$	1 y old
^{210}Pb	$8\ 10^9$	1 y old	$3\ 10^9$	Adult	$8\ 10^6$	1 y old
^{226}Ra	$3\ 10^9$	Adult	$3\ 10^9$	Adult	$1\ 10^7$	First year†
^{234}U	$4\ 10^9$	10 y old	$2\ 10^{11}$	Adult	$5\ 10^8$	First year
^{235}U	$4\ 10^9$	10 y old	$2\ 10^{11}$	Adult	$3\ 10^8$	Adult
^{238}U	$5\ 10^9$	10 y old	$2\ 10^{11}$	Adult	$5\ 10^8$	First year

* The GDCs are all limited by application of sewage sludge to land.
† First year – refers to infants in the first year of life on an all-milk diet.

15 Radionuclides discharged to a sewerage system can give rise to exposures in a number of different ways. If the radionuclide becomes associated with the sewage sludge then exposure could result to the workers at the sewage treatment works; the sludge might also be used for land treatment leading to the transfer of radionuclides to terrestrial foods. In some cases sewage sludge is incinerated or sent to landfill sites. However, if the radionuclide is not transferred to the sludge but remains in the water phase then it would be discharged to a river, giving rise to the same exposure pathways as in the case of a direct discharge to a river. There is little information available on the extent to which radionuclides discharged to sewers would partition between the sludge and the water. A recent study has been carried out to investigate the fate of radionuclides to public sewers and this considers the partitioning of radionuclides and the exposure from different routes of sewage sludge disposal (Titley *et al*, 1999).

16 For simplicity, a cautious approach is taken in calculating GDCs for discharge to sewers. Two distinct possibilities are considered: that all of the radioactivity is transferred to sludge and that all of the activity remains in water. In the former case, two separate situations are considered: firstly, the doses to sewage plant workers are calculated and, secondly, the doses due to the ingestion of radionuclides in foods grown on land treated with sludge are calculated. In the latter case doses are calculated as for discharge to a river. The three exposure scenarios are considered to be mutually exclusive and GDCs have been calculated for all three and the most restrictive taken to be the GDC for this discharge route. Full details of the methods, assumptions and data used in these calculations are given in Appendix C. It is assumed that the discharge goes to a small sewage treatment works serving 500 people. The exposure pathways considered for the sewage plant workers are:

(a) external irradiation from radionuclides in sewage sludge stored in tanks,
(b) internal irradiation from the inhalation of radionuclides resuspended from the sludge,
(c) internal irradiation from the inadvertent ingestion of radionuclides in the sludge.

The sludge produced by a small works could be used to treat a limited area of land used for raising sheep, beef or dairy cattle. The exposure pathways considered are:

(a) external irradiation from radionuclides in the soil,
(b) internal irradiation from the inadvertent ingestion of radionuclides in the soil,
(c) internal irradiation from the inhalation of radionuclides resuspended from the soil,
(d) internal irradiation from the ingestion of radionuclides in animal products.

The limited area of land treated meant that it is not considered feasible for the land to be used for more than one animal product. Doses are therefore calculated for products from each type of animal and the most restrictive taken. The exposure pathways for radionuclides discharged to the river are as described in paragraph 14.

17 Table 3 gives the GDCs for discharges to sewers; the values are the most restrictive from those calculated for the three scenarios considered and the limiting case is indicated in Table 3. The limiting age group is also indicated. In all cases the limiting scenario is exposure from treatment of land with sewage sludge. Details of the relative contributions of the different exposure pathways to the overall dose used to calculate the GDCs are given in Appendix D.

SITE-SPECIFIC ASSESSMENTS

18 Generalised derived constraints are intended for screening purposes and have been calculated using a set of generic assumptions such that the resultant doses are expected to be overestimated in most circumstances. However, it is possible for underestimation to occur in particular circumstances - for example, where the discharge occurs under different circumstances or if additional exposure pathways are present. It has, therefore, been recommended that an implied dose of 0.1 mSv y^{-1} is a reasonable level at which to trigger further investigation (NRPB, 1993b). This corresponds to about 30% of the GDC for discharges and if this is exceeded then the situation should be examined more closely, taking account of site-specific factors, the source of the activity and the length of time the situation is likely to persist. As the GDC is based on the upper value of constraint on effective dose for members of the public, a lower investigation level might also be necessary if a lower dose constraint is considered appropriate for the particular practice of interest; in this case the GDC can simply be scaled by the ratios of the particular dose constraint to the upper value (0.3 mSv y^{-1}).

19 In practice, discharges of more than one radionuclide and from more than one route will occur. Account must be taken of exposures from all radionuclides discharged and this can be done by summing proportions of the relevant GDCs (see equation 1).

$$\Sigma_i A_i/\mathrm{GDC}_i \leq 1 \qquad (1)$$

where A_i = discharge rate of radionuclide i in Bq y^{-1},
GDC_i = GDC for radionuclide i in Bq y^{-1}.

20 For some sites, direct radiation from a source on site may contribute to the exposure of members of the public. This exposure also needs to be included with that from discharges in comparison with the dose constraint. It is also likely that radionuclides will be discharged from more than one route – for example, discharges to atmosphere and to the sewerage system may occur from the same location. In this case the critical group for the different discharge routes is unlikely to be the same and so summing fractions of the GDC is very cautious and is not recommended. If a site-specific dose assessment is required then a more realistic approach could be adopted where account is taken of exposure from all routes using a combination of critical group and average habits (Robinson *et al*, 1994).

21 A discharge greater than 30% of the GDC does not of course, necessarily imply that an effective dose of 0.1 mSv y^{-1} will be exceeded. Significantly different radiation doses will result from discharges occurring under different circumstances than those assumed in the generic cases considered here, which have been chosen to give cautious estimates of the resulting doses. For releases to atmosphere, significantly lower concentrations of radionuclides in air or on the ground than those assumed here would arise for discharges from a greater height. In the case of discharges to a river, the characteristics of the river, particularly the volumetric flow rate, have a significant effect on the extent to which the radionuclide is diluted, and hence on doses. In many cases the receiving river is likely to have a higher flow and dilution is likely to be greater than assumed here, but it may also be possible for the dilution to be less. Similarly, for discharges to sewers, cautious assumptions have been made about the size of the treatment plant and hence the degree of dilution that would occur for the radionuclide discharged. Discharges of radionuclides to a smaller sewage treatment works than that assumed are unlikely. However, the size of water body receiving treated effluent may be smaller than that assumed, and in some cases doses from the receiving water body could become limiting. The assumed location of the critical group relative to the discharge point also has a significant effect on the estimated doses. For discharges to atmosphere doses will generally be lower for groups living further from the discharge point and higher for those living closer. Similarly, for discharges to a river, the location of the drinking water abstraction point relative to the discharge location will have a significant effect on the resulting estimated activity concentrations in water, and hence on doses.

22 If a proposed discharge is a significant fraction of the GDC and worthy of further investigation, then the first factor to consider is the nature of the discharge and the location of the critical group. The information in Appendix D could then be examined to determine which exposure pathways are important and refining the dose calculations for the important pathways could be considered. Care has to be taken, however, as the relative importance of different exposure pathways may change for different discharge assumptions. For example, for discharges to atmosphere, the locations of the critical group and the representative point where they are assumed to obtain their food can affect the relative importance of the doses from ingestion of terrestrial foods and inhalation. In addition, particular pathways may not always be relevant for the situation of interest. For example, river water may not be used for human drinking water supplies. However, the fact that a pathway does not exist at present does not necessarily mean that it will not exist in the future and that it should not be considered. In many circumstances, including site-specific information on the discharge and critical group location may be sufficient to reduce estimated doses to acceptable levels. However, if the estimated doses are still considered significant, then a more rigorous site-specific assessment could be required looking in detail at the exposure pathways and the data used to calculate doses. Factors to be considered in site-specific calculations of GDLs, as discussed elsewhere (NRPB, 1998), may also be relevant here.

23 In calculating the GDCs for release to a sewer, the discharge is assumed to be to a small rural sewage treatment works. In many cases, for example for large hospitals, discharge would be to a larger sewage treatment works perhaps serving 100 000 people. In this case the radionuclides would become dispersed in a greater volume of sewage and hence doses would be expected to be lower. However, there is not always a simple relationship between the size of the sewage treatment works and the resulting doses as additional exposure pathways could arise from land treatment and from incineration of the sludge which may also occur. A recent study has shown that doses from discharges of radionuclides to a large urban works are lower than those from a rural works and indicates that a site-specific study for discharges to a large sewage treatment works would give significantly lower doses than those estimated here (Titley *et al*, 1999).

CONCLUSIONS

24 Generalised derived constraints have been presented in this report for discharges of the most significant radioisotopes of polonium, lead, radium and uranium. Discharges to atmosphere, to rivers and to sewers have been considered. The GDCs are based on an annual effective dose constraint of 0.3 mSv for members of the public and take account of the 1990 recommendations of ICRP, including the definition of effective dose (ICRP, 1991). In each case the GDC is the most restrictive of those calculated for the three age groups considered.

25 If proposed discharges from a particular source exceed about 30% of the GDC then doses to the most exposed group should be examined more closely taking into account site-specific factors.

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26 The calculation of the GDCs was carried out under the formal quality assurance procedures of the NRPB Environmental Assessments Department. Mrs A L Jones also made a valuable contribution to the project.

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Appendix A

PRINCIPLES AND METHODS FOR CALCULATING GDCs FOR DISCHARGES TO ATMOSPHERE

Introduction

Generalised derived constraints (GDCs) are estimates of the amount of activity discharged to the environment, which, if not exceeded, mean that it is very unlikely that members of the public would receive an effective dose above the maximum values of the dose constraint of 0.3 mSv y^{-1} (NRPB, 1993). The discharges have been related to the dose constraint using cautious environmental modelling and a cautious dose assessment. Atmospheric releases were assumed to continue for 50 years under the same conditions, and the resulting build-up in the environment was modelled. The exposed individuals were assumed to live and produce food close to the discharge point and to have critical group habits and intakes.

Some of the radionuclides considered are likely to have radioactive decay products (progeny) and the ingrowth and decay of these were taken into account when determining the GDCs. The ingrowth of progeny was considered if significant ingrowth is likely to occur in the 50 year discharge period. The radionuclides considered for ingrowth of progeny were ^{235}U, ^{238}U, ^{226}Ra and ^{210}Pb. For ^{235}U and ^{238}U all the short-lived progeny (^{235}U includes ^{231}Th; ^{238}U includes ^{234}Th, ^{234}Pa and ^{234m}Pa) were assumed to exist in secular equilibrium with the parent. For ^{226}Ra the short-lived progeny (^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) were assumed to exist in secular equilibrium for all GDCs. The ingrowth of the longer-lived progeny of ^{226}Ra (^{210}Pb and ^{210}Po) was considered for all pathways except for inhalation and external gamma dose from immersion in the plume. For ^{210}Pb the short-lived progeny ^{210}Bi was assumed to be in secular equilibrium for all pathways. The ingrowth of the longer-lived progeny of ^{210}Pb (^{210}Po) was again considered for all pathways except for inhalation and external gamma dose from immersion in the plume.

This appendix is in three parts, the first section describes the environmental modelling performed, the second details the dose assessment, and the final part describes the calculation of the GDCs for discharge to atmosphere. The GDCs themselves are given in Table 3 of the main text.

Environmental models

Atmospheric dispersion and deposition modelling

Activity concentrations of each radionuclide in the plume were calculated using a Gaussian plume atmospheric dispersion model (Clarke, 1979; Jones, 1980), assuming a 1 m high stack and uniform wind rose. The atmospheric conditions assumed are given in Table A1. A semi-urban environment was modelled assuming 100% occupancy at 100 m from the release point and that all food consumed was produced on land 500 m from the release point. The dry deposition velocities and washout coefficients are given in Table A2 (Simmonds *et al*, 1995). The predicted activity concentrations in air from a continuous release rate of 1 Bq s^{-1} and the resulting deposition rates are given in Table A3.

TABLE A1 Atmospheric conditions assumed

Pasquill stability category	Frequency of occurrence (%)
A	1
B	9
C	21
D	50
E	8
F	10
G	2

TABLE A2 Deposition to ground from the plume

Factor	Parameter value
Dry deposition velocity (m s^{-1})	10^{-3}
Washout coefficient (1 m particles) (s^{-1})	10^{-4}

TABLE A3 Predicted activity concentration in air and deposition rates per Bq s^{-1} of discharge from a 1 m high stack

	Distance from stack	
Factor	100 m	500 m
Ground-level air concentration (Bq m^{-3})	$8.8\ 10^{-5}$	$4.3\ 10^{-6}$
Deposition rate (Bq $m^{-2}\ s^{-1}$)	$9.0\ 10^{-8}$	$4.7\ 10^{-9}$

Foodchain modelling

Activity concentrations in foods resulting from 50 years of continuous atmospheric discharges were predicted using the dynamic foodchain model FARMLAND (Brown and Simmonds, 1995). It was assumed that activity in the plume deposited on to soil, some activity was directly intercepted by the plants, and that a fraction of the intercepted activity was transferred into the plant. Build-up in soil over 50 years, uptake of activity from soil into plants, and the transfer of activity into animal products was modelled. The activity concentrations in food products in the 50th year of discharge were derived using equation A1:

$$A_f = A_{f(u)} R_f \qquad \text{(A1)}$$

where A_f = food product activity concentration in the 50th year grown 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}),
$A_{f(u)}$ = food product activity concentration in the 50th year per unit deposition rate (Bq kg^{-1} per Bq $m^{-2}\ s^{-1}$) (Table A4),
R_f = deposition rate to ground of activity from the plume 500 m from the release point (Bq $m^{-2}\ s^{-1}$ per Bq s^{-1}) (Table A3).

Soil, external dose, resuspension modelling and soil ingestion

The predicted activity concentrations in soil in the 50th year of continuous deposition from a plume were modelled using the soil model part of the FARMLAND model (Brown and Simmonds, 1995), allowing for migration down the soil profile. Effective dose rates from external exposure above soil 100 m from the release point were calculated using equation A2.

TABLE A4 Predicted activity concentrations of radionuclides in foods in the 50th year per unit deposition rate

Nuclide	50th year activity concentrations in foods per unit deposition rate (Bq kg^{-1} or Bq l^{-1} per Bq m^{-2} s^{-1})								
	Domestic fruit	Green and domestic vegetables	Potatoes and root vegetables	Cow meat	Cow offal	Sheep meat	Sheep offal	Milk	Milk products
^{210}Po	$6.8\ 10^4$	$1.2\ 10^5$	$9.7\ 10^4$	$6.2\ 10^4$	$1.7\ 10^6$	$2.0\ 10^5$	$2.3\ 10^6$	$2.7\ 10^3$	$3.0\ 10^4$
^{210}Pb	$1.8\ 10^5$	$1.3\ 10^5$	$1.6\ 10^4$	$3.4\ 10^4$	$6.8\ 10^4$	$4.4\ 10^4$	$8.8\ 10^4$	$1.2\ 10^4$	$1.4\ 10^5$
^{210}Po as progeny of ^{210}Pb	$4.2\ 10^3$	$9.6\ 10^3$	$7.2\ 10^3$	$1.8\ 10^4$	$3.0\ 10^5$	$9.3\ 10^4$	$1.0\ 10^6$	$4.7\ 10^2$	$5.1\ 10^3$
^{226}Ra	$3.7\ 10^5$	$1.3\ 10^5$	$3.1\ 10^3$	$2.0\ 10^4$	$2.0\ 10^4$	$4.2\ 10^4$	$4.2\ 10^4$	$1.6\ 10^4$	$1.8\ 10^5$
^{210}Pb as progeny of ^{226}Ra	$2.0\ 10^5$	$2.5\ 10^2$	$1.4\ 10^4$	$4.3\ 10^3$	$8.0\ 10^3$	$4.3\ 10^3$	$8.0\ 10^3$	$1.4\ 10^3$	$1.5\ 10^4$
^{210}Po as progeny of ^{226}Ra	$3.9\ 10^3$	$2.5\ 10^2$	$4.9\ 10^2$	$2.3\ 10^3$	$3.9\ 10^4$	$1.1\ 10^4$	$1.2\ 10^5$	$6.0\ 10^1$	$6.6\ 10^2$
^{234}U	$4.5\ 10^4$	$1.1\ 10^5$	$2.9\ 10^3$	$7.6\ 10^3$	$7.6\ 10^3$	$1.7\ 10^4$	$1.7\ 10^4$	$2.3\ 10^4$	$2.5\ 10^5$
^{235}U	$4.5\ 10^4$	$1.1\ 10^5$	$2.9\ 10^3$	$7.6\ 10^3$	$7.6\ 10^3$	$1.7\ 10^4$	$1.7\ 10^4$	$2.3\ 10^4$	$2.5\ 10^5$
^{238}U	$4.5\ 10^4$	$1.1\ 10^5$	$2.9\ 10^3$	$7.6\ 10^3$	$7.6\ 10^3$	$1.7\ 10^4$	$1.7\ 10^4$	$2.3\ 10^4$	$2.5\ 10^5$

$$D_{ext} = D_{ext(u)}\, R_n \qquad \text{(A2)}$$

where D_{ext} = external dose rate in the 50th year from deposition of activity 100 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),

$D_{ext(u)}$ = external dose rate in the 50th year per unit deposition rate (Sv y^{-1} per Bq m^{-2} s^{-1}) (Table A5) (Carey *et al, to be published*),

R_n = deposition rate to ground of activity from the plume 100 m from the release point (Bq m^{-2} s^{-1} per Bq s^{-1}) (Table A3).

TABLE A5
Predicted external dose rates from deposited activity, resuspended activity concentrations in air in the 50th year per unit deposition rate and effective dose from the plume per unit discharge

Nuclide	Effective dose rate above undisturbed soil per unit deposition rate (Sv y^{-1} per Bq m^{-2} s^{-1})	Resuspended activity concentration in air per unit deposition rate (Bq m^{-3} per Bq m^{-2} s^{-1})	Effective dose from the plume per unit discharge (Sv y^{-1} per Bq s^{-1})
^{210}Po	2.8 10^{-6}	4.9 10^{-1}	7.6 10^{-17}
^{210}Pb	4.0 10^{-3}	9.0 10^{-1}	2.5 10^{-14}
^{226}Ra	1.7 10^{1}	1.0 10^{0}	7.1 10^{-14}
^{234}U	7.5 10^{-4}	1.0 10^{0}	4.4 10^{-15}
^{235}U	1.3 10^{0}	1.0 10^{0}	6.1 10^{-12}
^{238}U	2.1 10^{-1}	1.0 10^{0}	5.5 10^{-14}

Resuspension of deposited activity was modelled using a time-dependent resuspension model (Simmonds *et al,* 1995), the ground-level air concentrations from resuspension at 100 m from the point of release were calculated using equation A3:

$$A_{res} = A_{res(u)}\, R_n \qquad \text{(A3)}$$

where A_{res} = activity concentration from resuspension of activity deposited 100 m from the point of discharge in the 50th year (Bq m^{-3} per Bq s^{-1}),

$A_{res(u)}$ = activity concentration from resuspension of activity per unit deposition rate in the 50th year of discharge (Bq m^{-3} per Bq m^{-2} s^{-1}) (Table A5).

(It should be noted that progeny ingrowth for ^{210}Pb and ^{226}Ra was negligible for this exposure pathway.)

The activity concentrations in soil used to calculate doses from soil ingestion, in the 50th year of discharge, were derived using equation A4:

$$A_s = A_{s(u)}\, R_s \qquad \text{(A4)}$$

where A_s = soil activity concentration in the 50th year in the top 1 cm of pasture 100 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}),

$A_{s(u)}$ = soil activity concentration in the 50th year per unit deposition rate (Bq kg^{-1} per Bq m^{-2} s^{-1}) (Table A6),

R_s = deposition rate to ground of activity from the plume 100 m from the release point (Bq m^{-2} s^{-1} per Bq s^{-1}) (Table A3).

Effective dose rates from the plume 100 m from the point of release were modelled using a semi-infinite cloud model. The dose rates are given in Table A5.

Nuclide	Soil activity concentration in 50th year in the top 1 cm of pasture ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ s^{-1}$)
^{210}Po	$3.9\ 10^{-2}$
^{210}Pb	$2.8\ 10^{-1}$
^{210}Po as progeny of ^{210}Pb	$2.5\ 10^{-1}$
^{226}Ra	$3.2\ 10^{-1}$
^{210}Pb as progeny of ^{226}Ra	$3.5\ 10^{-2}$
^{210}Po as progeny of ^{226}Ra	$3.1\ 10^{-2}$
^{234}U	$3.3\ 10^{-1}$
^{235}U	$3.3\ 10^{-1}$
^{238}U	$3.2\ 10^{-1}$

TABLE A6 Predicted soil concentrations from deposited activity, in the 50th year per unit deposition rate

Dose calculations

Six exposure pathways were considered for the atmosphere GDC: external exposure to the plume and from activity deposited on to the soil, internal exposure from inhalation of the plume and resuspended activity, ingestion of foods produced on land contaminated by activity from the plume, and inadvertent ingestion of soil contaminated by activity from the plume. The age groups considered in the dose calculations were infants in the first year of life on an all-milk diet, 1 year old infants, 10 year old children and adults.

Inhalation doses

Effective doses to each age group from inhalation of the plume and resuspended activity were calculated using equations A5 and A6, respectively.

$$D_{ip} = A_a B D_{inh} \qquad (A5)$$

$$D_{ires} = A_{res} B D_{inh} \qquad (A6)$$

	Age groups		
	1 y	10 y	Adult
Inhalation rates ($m^3\ y^{-1}$)	1900	5500	7300
Ingestion rates for soil ($kg\ y^{-1}$)	0.044	0.018	0.0083
Food intake rates (kg or $l\ y^{-1}$)			
Domestic fruit	35	50	75
Green and domestic vegetables	15	35	80
Potatoes and root vegetables	45	95	130
Cow meat	10	30	45
Cow offal	2.75	5	10
Sheep meat	3	10	25
Sheep offal	2.75	5	10
Milk*	320	240	240
Milk products	45	45	60

* Milk intake of 350 $l\ y^{-1}$ assumed for unweaned infants in the first year of life.

TABLE A7 Critical group inhalation rates and food ingestion rates (Carey et al, to be published)

where D_{ip} = effective dose from inhalation of the plume 100 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),
D_{ires} = effective dose from inhalation of resuspended activity deposited 100 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),
A_a = activity concentration in the plume 100 m from the point of discharge (Bq m^{-3} per Bq s^{-1}) (Table A3),
A_{res} = activity concentration from resuspension of activity deposited 100 m from the point of discharge in the 50th year (Bq m^{-3} per Bq s^{-1}) (equation A3),
B = inhalation rate (m^3 y^{-1}) (Table A7),
D_{inh} = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text).

An occupancy of 100% was assumed 100 m from the point of release. (It should be noted that the contribution from progeny for ^{210}Pb and ^{226}Ra was considered to be negligible for this pathway.)

External exposure

Effective doses to each age group due to external exposure from activity deposited over 50 years on to soil from the plume were calculated using equation A7:

$$D_{dep} = D_{ext} \left(F_{ind}\, T_{ind} + F_{out}\, T_{out} \right) \tag{A7}$$

where D_{dep} = effective dose from external irradiation from soil contaminated by deposition from the plume, in the 50th year 100 m from the point of release (Sv y^{-1} per Bq s^{-1}),
D_{ext} = external dose rate in the 50th year from deposition of activity 100 m from point of discharge (Sv y^{-1} per Bq s^{-1}) (equation A2),
F_{ind} = fraction of year spent indoors (Table A8),
T_{ind} = indoor location factor,
F_{out} = fraction of year spent outdoors (Table A8),
T_{out} = outdoor location factor.

The location factor is defined as the ratio of dose received in the protected location (indoors or outdoors) to that received outdoors over undisturbed soil for the period during which the exposed person is in the location. The location factor therefore describes the shielding offered at a particular location compared with the situation where no shielding is available. The indoor and outdoor location factors are 0.1 and 1.0, respectively (Simmonds *et al*, 1995). The age-dependent occupancies are given in Table A8.

TABLE A8 Occupancies associated with external exposure from deposited activity

	Occupancy (fraction of year)		
	Age group		
Habit	1 y	10 y	Adult
Indoors	0.9	0.8	0.5
Outdoors	0.1	0.2	0.5

Effective doses from external exposure to the plume 100 m from the point of discharge were estimated using the dose rates given in Table A5. Exposure to the plume was assumed to be independent of location factor and age.

Ingestion of foods

Ingestion doses to each age group from foods produced 500 m from the point of discharge were calculated using equation A8:

$$D_{\mathrm{food}} = \Sigma_{\mathrm{f}} A_{\mathrm{f}} I_{\mathrm{f}} D_{\mathrm{ing}} \qquad \text{(A8)}$$

where D_{food} = effective dose (summed over all foods) from foods produced 500 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),
A_{f} = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A1),
I_{f} = ingestion rate of each food (kg y^{-1}) (Table A7),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The dose from ingrowth of progeny would be (eg ingrowth of ^{210}Po for ^{210}Pb and ingrowth of ^{210}Po and ^{210}Pb for ^{226}Ra):

$$D_{\mathrm{food}} = \Sigma_{\mathrm{f}} \left[(A_{\mathrm{f}} D_{\mathrm{ing}}) + (A_{\mathrm{f+n}} D_{\mathrm{ing+n}}) \right] I_{\mathrm{f}} \qquad \text{(A9)}$$

where D_{food} = effective dose (summed over all foods) from foods produced 500 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),
A_{f} = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A1) for parent,
$A_{\mathrm{f+n}}$ = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A1) for progeny, n, assuming progeny supported by parent (^{210}Po for ^{210}Pb and ingrowth of ^{210}Po and ^{210}Pb for ^{226}Ra),
D_{ing} = ingestion dose coefficient for parent (Sv Bq^{-1}) (Table 1 of the main text),
$D_{\mathrm{ing+n}}$ = ingestion dose coefficient for progeny, n (Sv Bq^{-1}) (Table 1 of the main text),
I_{f} = ingestion rate of each food (kg y^{-1}) (Table A7).

Inadvertent ingestion of soil

Doses from inadvertent ingestion of soil to each age group from contaminated soil 100 m from the point of discharge were calculated using equation A10:

$$D_{\mathrm{soil}} = A_{\mathrm{s}} I_{\mathrm{s}} D_{\mathrm{ing}} \qquad \text{(A10)}$$

where D_{soil} = effective dose from foods produced 500 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),
A_{s} = activity concentrations in soil produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A4),
I_{s} = ingestion rate of soil (kg y^{-1}) (Table A7),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The contribution from progeny from ^{210}Pb and ^{226}Ra was included in the same manner as for the food pathway assuming that the progeny was supported by the parent.

Total dose

The total effective dose per unit discharge rate for each age group from each radionuclide was calculated by summing the dose estimates from the five exposure pathways described above using equation A11:

$$D_{\rm tot} = D_{\rm food} + D_{\rm dep} + D_{\rm extp} + D_{\rm ip} + D_{\rm ires} + D_{\rm soil} \qquad \text{(A11)}$$

where $D_{\rm tot}$ = total effective dose per unit discharge rate (Sv y^{-1} per Bq s^{-1}),

$D_{\rm extp}$ = effective external dose per unit discharge rate from the plume (Sv y^{-1} per Bq s^{-1}) (Table A5).

The total dose to infants in the first year of life (3 month old) was calculated by adding the doses to 3 month olds from ingestion of milk only, to the inhalation, ingestion of soil and external doses for 1 year old infants.

Calculation of GDCs for discharges to atmosphere

The GDCs for each age group and radionuclide were calculated using equation A12:

$$\text{GDC} = T\,\text{Dose Constraint}/D_{\rm tot} \qquad \text{(A12)}$$

where GDC = GDC for atmospheric discharges (Bq y^{-1}),

T = conversion factor from seconds to years (s y^{-1}).

The dose constraint used was 0.3 mSv y^{-1}, which was the maximum dose constraint recommended by NRPB (1993). The most restrictive GDC for each radionuclide is presented in Table 3 of the main text.

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Appendix B

PRINCIPLES AND METHODS FOR CALCULATING GDCs FOR DISCHARGES TO RIVERS

Introduction

Generalised derived constraints (GDCs) for rivers are estimates of the amount of activity discharged to rivers, which, if not exceeded, mean that it is very unlikely that members of the public would receive an effective dose above the maximum dose constraint of 0.3 mSv y^{-1} (NRPB, 1993). The discharges have been related to the dose constraint using cautious environmental modelling and dose assessment. Discharges were assumed to continue for 50 years to a river of low volumetric flow, and the resulting build-up in the environment was modelled. Doses were calculated for individuals who spend time on the river bank, drink water and eat fish from the river, and produce and consume green vegetables and potatoes on land irrigated by the river water. Critical group habits and critical intakes of foods produced within the river catchment were used (Robinson, 1996).

Some of the radionuclides considered are likely to have radioactive decay products (progeny) and the ingrowth and decay of these were taken into account when determining the GDCs. The ingrowth of progeny was considered if significant ingrowth is likely to occur in the 50 year discharge period. The radionuclides considered for ingrowth of progeny were ^{235}U, ^{238}U, ^{226}Ra and ^{210}Pb. For ^{235}U and ^{238}U all the short-lived progeny (^{235}U includes ^{231}Th; ^{238}U includes ^{234}Th, ^{234}Pa and ^{234m}Pa) were assumed to exist in secular equilibrium with the parent. For ^{226}Ra the short-lived progeny (^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) were assumed to exist in secular equilibrium for all GDCs. Radon was included in the decay chain as it is assumed to be contained within the environmental media rather than be released to atmosphere. The ingrowth of the longer-lived progeny of ^{226}Ra (^{210}Pb and ^{210}Po) was considered for all exposure pathways except for ingestion of drinking water and ingestion of freshwater fish. For ^{210}Pb the short-lived progeny ^{210}Bi was assumed to be in secular equilibrium with the parent for all exposure pathways. The ingrowth of the longer-lived progeny of ^{210}Pb (^{210}Po) was again considered for all pathways, except ingestion of drinking water and ingestion of freshwater fish.

This appendix is in three parts, the first section describes the environmental modelling performed, the second details the dose assessment, and the final part describes the calculation of the GDCs for discharges to rivers. The GDCs themselves are given in Table 3 of the main text.

Environmental models

River dispersion modelling

Activity concentrations of each radionuclide released into the river were calculated using a compartmental model (Simmonds *et al*, 1995). A single compartment is defined, into which the activity was discharged. Four main processes are modelled, downstream transport of radionuclides in solution and in association with suspended sediment, sedimentation of radionuclides to the river bed, and downstream transport of radionuclides in bed sediment. The river compartment was defined using the parameters given in

Table B1. The river was considered to have properties similar to small rivers in eastern England, ie slow flowing, relatively low average flows (0.25 to 5 $m^3 s^{-1}$) sustained by groundwater during dry spells and used for irrigation and public supply (IoH/BGS, 1994).

The partitioning of radionuclides between the solution and solid phases and the concentration in freshwater fish are defined by the parameters given in Table B2, and the resulting activity concentrations for unit discharges are shown in Table B3. It was assumed that the activity concentrations in bed sediments attained equilibrium with the discharges by year 50.

At an irrigation rate of 0.1 $m^3 y^{-1}$ per m^2 (MAFF, 1990), applied over a dry period of four weeks in summer, a few per cent of the river flow is sufficient to irrigate enough land to provide green vegetables and potatoes for up to 2000 individuals and to provide for the water needs of several thousand individuals.

TABLE B1 Assumed river characteristics

River characteristic	Parameter value
River section	
Length (m)	500
Width (m)	5
Water depth (m)	1
Water volume (m^3)	2500
Bed sediment depth (m)	0.3
Dry sediment density (kg m^{-3})	1500
River suspended sediment load (kg m^{-3})	0.04
River water flows	
Velocity (m s^{-1})	0.2
Volumetric flow ($m^3 s^{-1}$)	1
Bed sediment flow	
Velocity (m s^{-1})	0.000 0317
Volumetric flow ($m^3 s^{-1}$)	0.000 0476

TABLE B2 Element-dependent sediment water distribution coefficients, sedimentation factors and fish concentration factors for freshwater (Simmonds et al, 1995)

Element	Distribution coefficient, K_d (Bq kg^{-1} per Bq l^{-1})	Sedimentation factor, k'(m^{-1})	Fish concentration factor (Bq t^{-1} per Bq m^{-3})
Po	$1\ 10^{4}$	$2\ 10^{-6}$	$5\ 10^{1}$
Pb	$1\ 10^{4}$	$2\ 10^{-6}$	$3\ 10^{2}$
Ra	$5\ 10^{2}$	$2\ 10^{-6}$	$5\ 10^{1}$
U	$5\ 10^{1}$	$2\ 10^{-6}$	$1\ 10^{1}$

TABLE B3 Predicted activity concentrations of radionuclides in river water and sediments in the 50th year of discharge

	50th year activity concentrations per Bq s^{-1} discharged		
Nuclide	Filtered water (Bq m^{-3})	Suspended sediment (Bq kg^{-1})	Bed sediment (Bq kg^{-1})
^{210}Po	$7.0\ 10^{-1}$	$7.1\ 10^{0}$	$9.1\ 10^{-3}$
^{210}Pb	$7.0\ 10^{-1}$	$7.1\ 10^{0}$	$2.0\ 10^{-2}$
^{226}Ra	$9.6\ 10^{-1}$	$4.9\ 10^{-1}$	$2.0\ 10^{-2}$
^{234}U	$9.8\ 10^{-1}$	$5.0\ 10^{-2}$	$1.4\ 10^{-2}$
^{235}U	$9.8\ 10^{-1}$	$5.0\ 10^{-2}$	$1.4\ 10^{-2}$
^{238}U	$9.8\ 10^{-1}$	$5.0\ 10^{-2}$	$1.4\ 10^{-2}$

Foodchain modelling

Concentrations in freshwater fish resulting from the discharges of radionuclides were predicted using the element-dependent equilibrium transfers given in Table B2. Concentrations in terrestrial foods from irrigation with the river water were predicted using the dynamic foodchain model FARMLAND and are given in Table B4 (Brown and Simmonds, 1995). It was assumed that some activity in the irrigated water was deposited directly on to soil, except for a fraction that was intercepted by plants and some of the intercepted activity was transferred into the plant. Build-up in soil over 50 years and the uptake into plants from soil were modelled. The activity concentrations in food products in the 50th year of discharge for an irrigation rate of 0.1 $m^3 y^{-1}$ per m^2 (MAFF, 1990) were derived using equation B1:

$$A_f = A_{f(u)}\, I_{app}\, [R_{fil} + (R_{sus}\, S)] \tag{B1}$$

where A_f = activity concentrations in food products in the 50th year grown on land irrigated by the river 500 m downstream of the point of discharge ($Bq\ kg^{-1}$ per $Bq\ s^{-1}$),

$A_{f(u)}$ = activity concentrations in food products in the 50th year per unit deposition rate ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ y^{-1}$) (Table B4),

I_{app} = irrigation water application rate ($m^3\ y^{-1}$ per m^2),

R_{fil} = activity concentration in filtered river water per unit discharge ($Bq\ m^{-3}$ per $Bq\ s^{-1}$) (Table B3),

R_{sus} = activity concentration in river suspended sediment per unit discharge ($Bq\ kg^{-1}$ per $Bq\ s^{-1}$) (Table B3),

S = suspended sediment load ($kg\ m^{-3}$) (Table B1).

TABLE B4 Predicted activity concentrations of radionuclides in foods in the 50th year per unit deposition rate (from irrigation)

	50th year activity concentrations in foods from a surface deposit of irrigation water ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ y^{-1}$)	
Nuclide	Green and domestic vegetables	Potatoes and root vegetables
^{210}Po	$1.13\ 10^{-2}$	$9.33\ 10^{-3}$
^{210}Pb	$1.12\ 10^{-2}$	$6.96\ 10^{-5}$
^{210}Po as progeny of ^{210}Pb	$9.14\ 10^{-4}$	$5.18\ 10^{-6}$
^{226}Ra	$1.16\ 10^{-2}$	$2.51\ 10^{-5}$
^{210}Pb as progeny of ^{226}Ra	$2.19\ 10^{-5}$	$1.12\ 10^{-4}$
^{210}Po as progeny of ^{226}Ra	$2.20\ 10^{-5}$	$3.96\ 10^{-6}$
^{234}U	$1.02\ 10^{-2}$	$8.23\ 10^{-6}$
^{235}U	$1.02\ 10^{-2}$	$8.23\ 10^{-6}$
^{238}U	$1.02\ 10^{-2}$	$8.23\ 10^{-6}$

Dose calculations

Five exposure pathways were considered for the river GDC: external exposure to riverbed sediments and internal exposure from inhalation of resuspended riverbed sediments, and ingestion of freshwater fish, drinking water, and foods produced on land irrigated with river water. The age groups considered in the dose calculations were 1 year old infants, 10 year old children and adults.

External dose from bed sediments

Effective doses to each age group from external exposure to well-mixed riverbed sediment 500 m downstream of the discharge point were calculated using equation B2:

$$D_{\mathrm{RB,ext}} = D_{\mathrm{ext(u)}}\, R_{\mathrm{B}}\, O \tag{B2}$$

where $D_{\mathrm{RB,ext}}$ = external dose above well-mixed sediment in the 50th year of discharge 500 m downstream from the discharge point (Sv $\mathrm{y^{-1}}$ per Bq $\mathrm{s^{-1}}$),

$D_{\mathrm{ext(u)}}$ = external dose rate above well-mixed sediment per unit activity concentration (Sv $\mathrm{h^{-1}}$ per Bq $\mathrm{kg^{-1}}$) (Table B5),

R_{B} = activity concentration in riverbed sediment from a unit discharge rate to a river flowing at 1 $\mathrm{m^3\,s^{-1}}$, 500 m downstream from the release point (Bq $\mathrm{kg^{-1}}$ per Bq $\mathrm{s^{-1}}$) (Table B3),

O = occupancy of riverbank sediment (h $\mathrm{y^{-1}}$) (Table B6).

Doses from inhalation of resuspended bed sediment

Effective doses to each age group from inhalation of resuspended riverbed sediments were calculated using equation B3:

$$D_{\mathrm{RB,inh}} = R_{\mathrm{B}}\, B\, L\, D_{\mathrm{inh}}\, O_{\mathrm{frac}} \tag{B3}$$

where $D_{\mathrm{RB,inh}}$ = effective dose from inhalation of resuspended riverbed sediment (Sv $\mathrm{y^{-1}}$ per Bq $\mathrm{s^{-1}}$),

B = breathing rate ($\mathrm{m^3\,y^{-1}}$) (Table B6),

L = concentration of suspended sediment in air (kg $\mathrm{m^{-3}}$),

D_{inh} = inhalation dose coefficient (Sv $\mathrm{Bq^{-1}}$) (Table 2 of the main text),

O_{frac} = fraction of the year spent occupying sediment (dimensionless) (values in Table B6 divided by hours in a year).

TABLE B5 Predicted external dose rates above well-mixed sediment per unit activity concentration (Carey et al, to be published)

Nuclide	Effective dose rate (Sv $\mathrm{h^{-1}}$ per Bq $\mathrm{kg^{-1}}$)
$^{210}\mathrm{Po}$	$2.4\ 10^{-16}$
$^{210}\mathrm{Pb}$	$5.5\ 10^{-14}$
$^{226}\mathrm{Ra}$	$3.1\ 10^{-10}$
$^{234}\mathrm{U}$	$9.2\ 10^{-15}$
$^{235}\mathrm{U}$	$2.0\ 10^{-11}$
$^{238}\mathrm{U}$	$4.6\ 10^{-12}$

TABLE B6 Critical group habits (Robinson, 1996)

	Age groups		
	1 y	10 y	Adult
Occupancy of sediment (h $\mathrm{y^{-1}}$)	30	500	500
Intake rates			
Inhalation ($\mathrm{m^3\,y^{-1}}$)	1900	5500	7300
Drinking water ($\mathrm{m^3\,y^{-1}}$)	0.26	0.35	0.60
Freshwater fish (t $\mathrm{y^{-1}}$)	0.001	0.005	0.02
Green vegetables (kg $\mathrm{y^{-1}}$)	15	35	80
Potatoes and root vegetables (kg $\mathrm{y^{-1}}$)	45	95	130

The concentration of suspended sediment in air used was 10^{-7} kg m^{-3} (Simmonds *et al.* 1995). (It should be noted that the contribution from progeny for ^{210}Pb and ^{226}Ra was negligible for this pathway.)

Dose from ingestion of water

Doses to each age group from ingestion of filtered river water abstracted 500 m downstream of the point of discharge were calculated using equation B4:

$$D_{water} = R_{fil} I_{water} D_{ing} \qquad \text{(B4)}$$

where D_{water} = effective dose from drinking filtered river water 500 m downstream of the point of discharge (Sv y^{-1} per Bq s^{-1}),
R_{fil} = activity concentrations in filtered river water 500 m downstream of the point of discharge (Bq m^{-3} per Bq s^{-1}) (Table B3),
I_{water} = ingestion rate of water (m^{-3} y^{-1}) (Table B6),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

(It should be noted that the contribution from progeny for ^{210}Pb and ^{226}Ra was negligible for this pathway.)

Dose from ingestion of freshwater fish

Ingestion doses to each age group from freshwater fish caught 500 m downstream from the point of discharge were calculated using equation B5:

$$D_{fish} = R_{fil} I_{fish} C_{fish} D_{ing} \qquad \text{(B5)}$$

where D_{fish} = effective dose from ingestion of freshwater fish caught 500 m downstream of the point of discharge (Sv y^{-1} per Bq s^{-1}),
R_{fil} = activity concentrations in the filtered fraction of river water 500 m downstream from the point of discharge (Bq m^{-3} per Bq s^{-1}) (Table B3),
I_{fish} = ingestion rate of freshwater fish (t y^{-1}) (Table B6),
C_{fish} = concentration factor for freshwater fish (Bq t^{-1} per Bq m^{-3}) (Table B2),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

(It should be noted that the contribution from progeny for ^{210}Pb and ^{226}Ra was negligible for this pathway.)

Dose from ingestion of foods

Ingestion doses to each age group from foods produced on land irrigated with river water abstracted 500 m downstream from the point of discharge were calculated using equation B6:

$$D_{food} = \Sigma_f A_f I_f D_{ing} \qquad \text{(B6)}$$

where D_{food} = effective dose summed over all foods produced on land irrigated with river water abstracted 500 m downstream from the point of discharge (Sv y^{-1} per Bq s^{-1}),
A_f = activity concentrations in each food after irrigation with river water (Bq kg^{-1} per Bq s^{-1}) (equation B1),
I_f = ingestion rate of each food (kg y^{-1}) (Table B6),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The dose from ingrowth of progeny would be (eg ingrowth of ^{210}Po for ^{210}Pb and ingrowth of ^{210}Po and ^{210}Pb for ^{226}Ra):

$$D_{\mathrm{food}} = \Sigma_{\mathrm{f}} \left[(A_{\mathrm{f}} D_{\mathrm{ing}}) + (A_{\mathrm{f+n}} D_{\mathrm{ing+n}}) \right] I_{\mathrm{f}} \qquad \text{(B7)}$$

where D_{food} = effective dose (summed over all foods) from foods produced 500 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),

A_{f} = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A1) for parent,

$A_{\mathrm{f+n}}$ = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A1) for progeny, n, assuming progeny supported by parent (^{210}Po for ^{210}Pb and ingrowth of ^{210}Po and ^{210}Pb for ^{226}Ra),

D_{ing} = ingestion dose coefficient for parent (Sv Bq^{-1}) (Table 1 of the main text),

$D_{\mathrm{ing+n}}$ = ingestion dose coefficient for progeny, n (Sv Bq^{-1}) (Table 1 of the main text),

I_{f} = ingestion rate of each food (kg y^{-1}) (Table B6).

Total dose

The total effective dose per unit discharge rate for each age group from each radionuclide was calculated by summing the dose estimates from the five exposure pathways described above using equation B8:

$$D_{\mathrm{tot}} = D_{\mathrm{food}} + D_{\mathrm{fish}} + D_{\mathrm{water}} + D_{\mathrm{RB,inh}} + D_{\mathrm{RB,ext}} \qquad \text{(B8)}$$

where D_{tot} = total effective dose per unit discharge rate (Sv y^{-1} per Bq s^{-1}).

Calculation of GDCs

The GDCs for each age group and radionuclide were calculated using equation B9:

$$\mathrm{GDC} = T\,\text{Dose Constraint}/D_{\mathrm{tot}} \qquad \text{(B9)}$$

where GDC = GDC for river discharges (Bq y^{-1}),

T = conversion factor from seconds to years (s y^{-1}).

The dose constraint used was 0.3 mSv y^{-1} which was the maximum dose constraint recommended by NRPB (1993). The most restrictive GDC for each radionuclide is presented in Table 3 of the main report.

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Appendix C

PRINCIPLES AND METHODS FOR CALCULATING GDCs FOR DISCHARGES TO SEWERS

Introduction

Generalised derived constraints (GDCs) for sewers are estimates of the amount of activity discharged to sewers, which, if not exceeded, mean that it is very unlikely that sewage plant workers or members of the public would receive an effective dose above the maximum dose constraint of 0.3 mSv y^{-1} (NRPB, 1993). The discharges have been related to the dose constraint using cautious models for radionuclide transport and dose assessment. The sewer collection and treatment system used was assumed to serve a small rural community, and was characterised by low volumetric effluent flow. The effluent is treated at the works to remove suspended solids and biochemical oxygen demand through primary and secondary treatment of liquid and solid phases. Treated effluents are then assumed to be discharged to a river of low volumetric flow, and treated sludges applied to nearby farmland. Discharges of radionuclides to sewers were assumed to continue for 50 years under the same conditions, and the resulting build-up in the river and farmland environments were modelled.

The calculations accounted for three separate exposure groups as follows:

(a) sewage plant workers who were considered to spend a working year at the sewage treatment works, and were exposed to sludges and effluents,
(b) members of the public who were exposed to river water that has received treated effluent, as described in Appendix B,
(c) the third group was assumed to live on land treated repeatedly with sewage sludge and to consume animal products produced from the treated land - foods consumed were assumed to have been produced within either the river catchment or on treated farmland, intakes were assumed to be at critical group levels.

Some of the radionuclides considered are likely to have radioactive decay products (progeny) and the ingrowth and decay of these were taken into account when determining the GDCs. The ingrowth of progeny was considered if significant ingrowth is likely to occur in the 50 year discharge period. The radionuclides considered for ingrowth of progeny were ^{235}U, ^{238}U, ^{226}Ra and ^{210}Pb. For ^{235}U and ^{238}U all the short-lived progeny (^{235}U includes ^{231}Th; ^{238}U includes ^{234}Th, ^{234}Pa and ^{234m}Pa) were assumed to exist in secular equilibrium with the parent. For ^{226}Ra the short-lived progeny (^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) were assumed to exist in secular equilibrium for all GDCs. Radon was included in the decay chain as it is assumed to be contained within the environmental media rather than be released to atmosphere. The ingrowth of the longer-lived progeny of ^{226}Ra (^{210}Pb and ^{210}Po) was only included for the exposure pathways resulting from sewage applied to land and those for river GDCs (see Appendix B). For ^{210}Pb the short-lived progeny ^{210}Bi was assumed to be in secular equilibrium with its parent for all exposure pathways. The ingrowth of the longer-lived progeny of ^{210}Pb (^{210}Po) was again only included for exposure pathways resulting from sewage applied to land and those for river GDCs.

This appendix is in three parts, the first section describes the environmental modelling performed, the second details the dose assessment, and the final part describes the calculation of the GDCs for discharge to sewers. The GDCs themselves are given in Table 3 of the main text.

Environmental models

Sewer transport and treatment modelling

Activity concentrations of each radionuclide released into effluent in the sewer were calculated using the simple dilution approach used in river modelling (Simmonds *et al*, 1995), using estimates of effluent flow. The volume of effluent flow was derived from *per caput* water usage combined with information on the sizes of community served by small rural sewage treatment works (Sinnott, 1978). Disposed activity is assumed to be discharged continuously into the raw sewage effluent and to flow in pipes to the sewage treatment works. The main processes considered were dilution of activity in the effluent, collection of effluent in settling tanks at the sewage treatment works, separation of suspended solids from the liquid effluent, and treatment of liquid effluent and sludges. Instant transport from the disposal point to the sewage treatment works was assumed, radioactive decay during transport and treatment was not considered. Radionuclide partitioning between the solution and solid phases was

TABLE C1 Sewage effluent, flows and treatment times assumed

Characteristic		Parameter value
Raw effluent	Suspended sediment load (%)	0.05
	Volumetric flow ($m^3 s^{-1}$)	0.000 695
Treatment works	Population served	500
	Dry sludge production ($kg\ y^{-1}$)	10,000
Liquid effluent treatment times (h)	Primary settlement	4
	Biological filtration	7
	Final settlement	4
	Total time	15
Solid sludge treatment times (h)	Primary settlement	4
	Pasteurisation	2
	Digestion	300
	Storage	350
	Total time	656
Treated sludge	Solid content (%)	5

*TABLE C2 Predicted activity concentrations of radionuclides in sewage effluent and sludges in the 50th year of discharge**

Sewage material	50th year activity concentrations per Bq s^{-1} unit discharge (Bq l^{-1})
Raw effluent arriving at works	1.44
Sludges during treatment	144
Treated effluent at disposal	1.44
Treated sludge at disposal	144

* It is assumed that 1 kg is equal to 1 litre of sewage.

not modelled because of the lack of reliable information on the behaviour of the elements of interest in sewage effluent and because, on disposal, the treated effluent still contains suspended solids and the treated sludges still contain a high level of water. The GDCs were therefore calculated using the conservative assumption that all the disposed activity remained 100% with the effluent or 100% with the sludge. The most restrictive GDC calculated using the two assumptions was then adopted.

The largest influence on activity concentrations in sewage effluents and sludges will be the total flow of effluent, which depends on the size of the works, which in turn is dependent on the population served. Small effluent flows will result in higher activity concentrations and potentially higher individual doses. Statistics for the Thames Water region show that approximately 30% of the total number of sewage treatment works serve populations of less than about one thousand (Sinnott, 1978). Given the relatively large number of small sewage treatment works it is reasonable to assume that some disposers of radioactive materials may be served by small rural sewage treatment works.

The sizes of sewage treatment works, effluent characteristics, treatment processes and timescales are shown in Table C1, and the modelled activity concentrations in the effluent and sludges are shown in Table C2.

Modelling disposal of sewage effluent

Treated sewage effluents are normally discharged into water bodies such as rivers or estuaries. The GDC for sewers was calculated assuming the effluents were discharged into a small rural river with the same characteristics and exposure pathways as those used for the river GDC, which is described in Appendix B. The effect of radioactive decay on the radionuclides being disposed to river was taken into account, using the treatment times for the liquid phase of the effluent given in Table C1.

Modelling disposal of sewage sludge

In the UK, treated sludges may be disposed of by several routes, depending on the size and location of the sewage treatment works. The main disposal routes for treated sludges are disposal to sea, to farmland, to landfill and to incinerators. Approximately 50% of treated sludges are currently disposed of to land and this proportion may increase because disposals of sludge to sea ceased in 1998, and landfilling is becoming more expensive. For the same reasons, the use of incinerators for sludges from large urban sewage treatment works is also due to increase. In radiological protection terms, the discharge of radionuclides to small sewage treatment works is likely to be the most significant because the effluent volumes are small, giving less dilution. The most significant disposal route for sludge from small and medium rural sewage treatment works is treatment of land (Sinnott, 1978). In addition, one area of land may be treated repeatedly with sludge from the same works, potentially allowing build-up in soil. In small rural sewage treatment works, sludges may be stored in batches before being applied to land. Radioactive decay for the radionuclides of interest here was considered to be negligible for the time periods given in Table C1 and so these times were neglected.

Foodchain modelling

For disposals of sewage sludge, only animal products were considered because of the restrictions on the application of sewage sludge on land used to produce foods that may be eaten raw (DOE, 1996). The sewage treatment works considered produced enough sludge to treat a few tens of hectares of pasture land, sufficient for ten cows or sheep. Conditioning of the soil was assumed to occur annually in early spring, approximately one month before grazing animals were allowed on to the pasture. It was assumed that application was directly on to permanent pasture that the grass grew after the application and before animals were allowed on to it. Therefore, there would be no direct contamination of the grass by radionuclides in the sludge. The dynamic foodchain model FARMLAND (Brown and Simmonds, 1995) was used to predict the activity concentrations in cattle meat and offal, milk, and sheep meat and offal from annual applications over 50 years per unit deposit (equation C1). The activity concentrations were scaled by the application rate of sewage sludge which was assumed to be 8 kg m^{-2} y^{-1} (WRC, 1992):

$$A_f = A_{f(u)}\, SL_{app}\, SL_{conc} \qquad \text{(C1)}$$

where A_f = food product activity concentration in the 50th year grown on land treated with sewage sludge (Bq kg^{-1} per Bq s^{-1}),
$A_{f(u)}$ = food product activity concentration in the 50th year per unit deposition rate (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table C3),
SL_{app} = sewage sludge application rate (kg m^{-2} y^{-1}),
SL_{conc} = sewage sludge activity concentration per unit discharge (Bq kg^{-1} per Bq s^{-1}) (Table C2).

The foodchain modelling used for treated sewage effluent disposal to a river is as described in Appendix B.

TABLE C3
Predicted activity concentrations in foods from 50 years of surface deposition (sewage sludge application to land)

Nuclide	Activity concentration in foods from 50 years of application of sewage sludge at unit rate (Bq kg^{-1} or Bq l^{-1} per Bq m^{-2} y^{-1})				
	Cow meat	Cow liver	Cow milk	Sheep meat	Sheep liver
^{210}Po	4.0 10^{-5}	1.1 10^{-3}	1.7 10^{-6}	3.4 10^{-4}	4.1 10^{-3}
^{210}Pb	3.5 10^{-4}	7.1 10^{-4}	1.3 10^{-4}	5.2 10^{-4}	1.0 10^{-3}
^{226}Ra	2.8 10^{-4}	2.8 10^{-4}	2.3 10^{-4}	5.9 10^{-4}	5.9 10^{-4}
^{234}U	3.7 10^{-5}	3.7 10^{-5}	1.1 10^{-4}	2.0 10^{-4}	2.0 10^{-4}
^{235}U	3.7 10^{-5}	3.7 10^{-5}	1.1 10^{-4}	2.0 10^{-4}	2.0 10^{-4}
^{238}U	3.7 10^{-5}	3.7 10^{-5}	1.1 10^{-4}	2.0 10^{-4}	2.0 10^{-4}

Modelling sludge application to soil and external dose

The predicted soil concentrations from application of sewage sludge at 8 kg m^{-2} y^{-1} were modelled using the soil module of FARMLAND (Brown and Simmonds, 1995), which allows for migration down the soil profile. Soil activity concentrations in the top 1 cm of the soil were calculated using equation C2. Effective dose rates from per unit discharge for external exposure above soil were derived using an external dose model (Carey *et al, to be published*) and were calculated using equation C3.

$$A_s = A_{s(u)}\, SL_{app}\, SL_{conc} \qquad \text{(C2)}$$

$$D_{ext} = D_{ext(u)}\, SL_{app}\, SL_{conc} / T \qquad \text{(C3)}$$

where A_s = activity concentration in the top 1 cm of soil after 50 years of treatment with sewage sludge (Bq kg^{-1} per Bq s^{-1}),

$A_{s(u)}$ = activity concentration in the top 1 cm of soil per unit deposit after 50 years (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table C4),

D_{ext} = external dose rate in year 50 from application of sewage sludge to land per unit discharge (Sv y^{-1} per Bq s^{-1}),

$D_{ext(u)}$ = external dose rate in year 50 per unit deposition rate (Sv y^{-1} per Bq m^{-2} s^{-1}) (Table C4) (Carey *et al, to be published*),

T = number of seconds in a year.

TABLE C4 Predicted activity concentrations and external dose rates in the 50th year above undisturbed soil per unit deposit and external dose rates above well-mixed sewage sludge in tanks per unit activity concentration

Nuclide	50th year activity concentrations in soil per unit deposit (Bq kg^{-1} per Bq m^{-2} y^{-1})	50th year effective external dose rate 1 m above soil per unit deposit (Sv y^{-1} per Bq m^{-2} s^{-1})	Effective external dose rate 1 m above sludge in tanks (Sv h^{-1} per Bq kg^{-1})
^{210}Po	3.85 10^{-2}	2.80 10^{-6}	1.80 10^{-15}
^{210}Pb	2.85 10^{-1}	4.03 10^{-3}	3.10 10^{-13}
^{226}Ra	3.19 10^{-1}	1.70 10^{1}	3.84 10^{-10}
^{234}U	3.30 10^{-1}	7.54 10^{-4}	3.11 10^{-14}
^{235}U	3.30 10^{-1}	1.29 10^{0}	3.79 10^{-11}
^{238}U	3.20 10^{-1}	2.06 10^{-1}	6.78 10^{-12}

Dose calculations

Doses to three separate exposed groups were performed for the sewer GDC: to workers at the sewage treatment works, to groups exposed to discharges of treated sewage effluent to river, and to groups exposed to farmland treated with sewage sludge. Critical group food intakes and habits were used (Robinson, 1996).

Exposure of sewage plant workers

Sewage plant workers were assumed to spend an entire working year at the sewage treatment works. The exposure pathways considered (adults only) were: inadvertent ingestion of sewage effluent, inhalation of resuspended sewage effluent and external exposure to tanks containing effluents and sludges.

Doses from inhalation of resuspended sewage sludge

Effective doses from the inhalation of resuspended sewage sludge at an air concentration of 10^{-7} kg m^{-3} (of sludge, Northrop *et al,* 1980) were calculated using equation C4:

$$D_{tw,inh} = SL_{conc}\, B\, L\, D_{inh}\, O \qquad (C4)$$

where $D_{tw,inh}$ = effective dose from inhalation of resuspended of sewage sludge at the sewage treatment works (Sv y^{-1} per Bq s^{-1}),

B = breathing rate (m^3 h^{-1}) (Table C5),

L = concentration of suspended sludge in air (kg m^{-3}),

D_{inh} = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text),

O = occupancy of sewage treatment works (h y^{-1}) (Table C5).

Doses from inadvertent ingestion of sewage sludge

Effective doses from the inadvertent ingestion of sewage sludge were calculated using equation C5:

$$D_{\mathrm{tw,inad}} = SL_{\mathrm{conc}}\, I_{\mathrm{inad}}\, D_{\mathrm{ing}}\, O_{\mathrm{tank}} \qquad \text{(C5)}$$

where $D_{\mathrm{tw,inad}}$ = effective dose from inadvertent ingestion of sewage sludge (Sv y^{-1} per Bq s^{-1}),
I_{inad} = inadvertent ingestion rate of sewage sludge (kg h^{-1}) (Table C5),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text),
O_{tank} = occupancy above sewage sludge tanks (h y^{-1}) (Table C5).

TABLE C5 Critical group habits for exposure to sewer discharges (Robinson, 1996)

Habit	Age groups 1 y	 10 y	 Adult
Occupancy of sewage treatment works (h y^{-1})	-	-	2000
Occupancy above sludge tanks (h y^{-1})	-	-	1000
Intake rates			
Inhalation at works (m^3 h^{-1})	-	-	0.83
Inhalation (m^3 y^{-1})	1900	5500	7300
Sewage sludge inadvertent ingestion (kg h^{-1})	-	-	0.000 005
Soil inadvertent ingestion (kg y^{-1})	0.044	0.018	0.0083
Food intake rates (kg y^{-1})			
Milk	320	240	240
Cattle meat	10	30	45
Cattle offal	2.8	5	10
Sheep meat	3.0	10	25
Sheep offal	2.8	5	10

Doses from exposure to sludge tanks

Effective doses from external exposure to tanks containing sewage sludge were calculated using equation C6:

$$D_{\mathrm{tw,ext}} = D_{\mathrm{tw,ext(u)}}\, SL_{\mathrm{conc}}\, O_{\mathrm{tank}} \qquad \text{(C6)}$$

where $D_{\mathrm{tw,ext}}$ = external dose at the sewage treatment works from tanks of well-mixed sludge in the 50th year of discharge (Sv y^{-1} per Bq s^{-1}),
$D_{\mathrm{tw,ext(u)}}$ = external dose rate above tanks containing well-mixed sludge per unit activity concentration (Sv h^{-1} per Bq kg^{-1}) (Table C4).

Total dose at sewage treatment works

The total effective dose to the sewage plant workers was calculated by summing the dose estimates from the three exposure pathways using equation C7:

$$D_{\mathrm{tw,tot}} = D_{\mathrm{tw,inad}} + D_{\mathrm{tw,inh}} + D_{\mathrm{tw,ext}} \qquad \text{(C7)}$$

where $D_{\mathrm{tw,tot}}$ = total effective dose per unit discharge rate to sewage plant workers (Sv y^{-1} per Bq s^{-1}).

Exposure to farmland treated with sewage sludge

Four exposure pathways were considered for the disposal of treated sewage sludge applied to land: external exposure to soil treated with sludge, internal exposure from inhalation of resuspended soil, inadvertent ingestion of soil, and ingestion of foods produced on land treated with sewage sludge. The age groups considered in the dose calculations were infants in the first year of life on an all-milk diet, 1 year olds, 10 year olds and adults. Ingrowth of progeny was assumed to occur over a 50 year period for ^{226}Ra and ^{210}Pb.

External exposure to treated soil

Effective doses to each age group from external exposure to land treated with sewage sludge were calculated using equation C8:

$$D_{\text{occ,ext}} = D_{\text{ext}}\,(F_{\text{ind}}\,T_{\text{ind}} + F_{\text{out}}\,T_{\text{out}}) \qquad \text{(C8)}$$

where $D_{\text{occ,ext}}$ = effective dose in the 50th year of discharge arising from external irradiation from soil allowing for occupancy over land treated with sewage sludge (Sv y^{-1} per Bq s^{-1}),
D_{ext} = external dose rate in the 50th year per unit discharge (Sv y^{-1} per Bq s^{-1}) (equation C3),
F_{ind} = fraction of a year spent indoors,
T_{ind} = indoor location factor,
F_{out} = fraction of a year spent outdoors,
T_{out} = outdoor location factor.

The term 'location factor' is defined as the ratio of dose received in the protected location (indoors or outdoors) to that received outdoors over undisturbed soil for the period during which the exposed person is in the location. It therefore describes the shielding offered at a particular location compared with the situation where no shielding is available. The indoor and outdoor location factors used are 0.1 and 1.0, respectively (Simmonds *et al*, 1995). The age-dependent indoor and outdoor occupancies are given in Table A8 of Appendix A.

Internal exposure to treated soil

Effective doses to each age group from inhalation and inadvertent ingestion of soil from the top 1 cm of the soil profile were calculated using equations C9 and C10, respectively:

$$D_{\text{inh}} = A_s\,B\,L\,D_{\text{inh}} \qquad \text{(C9)}$$

$$D_{\text{inad}} = A_s\,I_{\text{s,inad}}\,D_{\text{ing}} \qquad \text{(C10)}$$

where D_{inh} = effective doses from inhalation of resuspended soil from the top 1 cm after treatment with sewage sludge for 50 years (Sv y^{-1} per Bq s^{-1}),
D_{inad} = effective doses from inadvertent ingestion of soil from the top 1 cm after treatment with sewage sludge for 50 years (Sv y^{-1} per Bq s^{-1}),
B = breathing rate (m^3 y^{-1}) (Table C5),
L = concentration of suspended soil in air (kg m^{-3}),
$I_{\text{s,inad}}$ = inadvertent ingestion rate of soil (kg y^{-1}) (Table C5),
D_{inh} = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The concentration of suspended soil in air was assumed to be 10^{-7} kg m^{-3} (Simmonds *et al*, 1995).

Doses from ingestion of foods

Ingestion doses to each age group from foods produced on land treated with sewage sludge were calculated using equation C11:

$$D_{\text{food}} = A_f I_f D_{\text{ing}} \qquad \text{(C11)}$$

where D_{food} = effective dose from each food produced on land treated with sewage sludge for 50 years (Sv y^{-1} per Bq s^{-1}),
A_f = activity concentrations in each food after treatment with sewage sludge (Bq kg^{-1} per Bq s^{-1}) (equation C1),
I_f = ingestion rate of each food (kg y^{-1}) (Table C5),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

Three different food types were considered: milk, beef products (beef and offal), and sheep products (mutton and offal). The area of land that could be treated with sewage sludge was small, therefore only one food type was considered to be produced and consumed. Of the three food types, the one that gave rise to the maximum dose was used.

Total dose

The total effective dose per unit discharge rate from land application pathways for each age group from each radionuclide was calculated by summing the dose estimates from the four exposure pathways described above using equation C12:

$$D_{\text{sl,tot}} = D_{\text{food}} + D_{\text{inh}} + D_{\text{occ,ext}} + D_{\text{inad}} \qquad \text{(C12)}$$

where $D_{\text{sl,tot}}$ = total effective dose from treated land per unit discharge rate (Sv y^{-1} per Bq s^{-1}).

Exposure to treated effluent discharged to a river

Exposure to treated effluent discharged to a river considered five exposure pathways. The dose calculation is as described in Appendix B.

Calculation of the GDC for discharges to sewers

The GDC for discharges to sewers was calculated by considering which of the three exposed groups (workers at the sewage treatment works, groups exposed to discharges of treated sewage effluent to river, and groups exposed to farmland treated with sewage sludge) would receive the highest dose.

The GDC for workers at the sewage treatment works was calculated using equation C13 and the GDC for sludge disposal was calculated using equation C14. The GDC for rivers was calculated as described in Appendix B.

$$\text{GDC}_{\text{tw}} = T\,\text{Dose Constraint}/D_{\text{tw,tot}} \qquad \text{(C13)}$$

$$\text{GDC}_{\text{sl}} = T\,\text{Dose Constraint}/D_{\text{sl,tot}} \qquad \text{(C14)}$$

where GDC_{tw} = GDC for sewage plant workers at the treatment works (Bq y^{-1}),
GDC_{sl} = GDC for sludge applied to land (Bq y^{-1}),
T = conversion factor from seconds to years (s y^{-1}).

The dose constraint is 0.3 mSv y^{-1}, the maximum recommended by NRPB (1993).

The overall GDC (Bq y^{-1}) for discharges to sewers was then taken to be the minimum of GDC_{tw}, GDC_{sl} and the GDC for discharges to rivers (Appendix B). The most restrictive GDC for discharges to sewers for each radionuclide is presented in Table 3 of the main text and the limiting case is indicated.

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Appendix D

IMPORTANT EXPOSURE PATHWAYS FOR GDCs

Introduction

Details of the limiting exposure pathways and age groups for the generalised derived constraints (GDCs) presented in the main report are discussed in this appendix in the light of the models and data used.

GDCs for discharges to atmosphere

The GDCs for atmosphere considered exposure of infants (1 year old), children (10 years old), and adults. Infants in the first year of life (3 months old) whose diet was assumed to consist entirely of milk were also considered. Table 3 of the main text indicates the limiting age group for each radionuclide and these are discussed here. The most important pathways for the GDCs for atmosphere vary depending on radionuclide and are shown in Table D1. For all the radionuclides plume inhalation is the most important exposure pathway contributing between 53% and 100% of the dose. For the isotopes of uranium the dose to a child is limiting and is almost entirely from inhalation, with a small contribution from external irradiation from deposited activity for ^{235}U. For ^{210}Po and ^{210}Pb both inhalation and ingestion of foods are important, with infants as the limiting age group. For ^{226}Ra the adult age group is limiting, with inhalation as the most important pathway; external irradiation from deposited activity contributes about a third of the dose with ingestion of food less important, contributing only about 5%.

It should be noted that the situation modelled in determining the GDCs is cautious but could occur. If the conditions were different to those modelled, eg a different stack height, or the critical group was located in a different place, the limiting age groups and pathways may change. A different stack height to that considered for the GDC would result in different air concentrations at various points away from the stack. The location of the critical group relative to the emission point and where the group's food is grown are important. Differences in these distances can affect the relative importance of the exposure pathways. These factors should be borne in mind when applying the GDCs.

GDCs for discharges to rivers

The GDCs for rivers were calculated for six radionuclides for the three age groups, infants (1 year old), children (10 years old) and adults. Table 3 of the main text indicates the limiting age group for each radionuclide and these are discussed here. The most important pathways for the GDCs for rivers vary, depending on the radionuclide as shown in Table D2. The drinking water pathways contribute significantly to the GDC for all radionuclides except for ^{210}Pb and ^{226}Ra. Freshwater fish intakes dominate the GDC for ^{210}Pb and ^{226}Ra. Irrigation of terrestrial foods is only important for ^{210}Po, where it contributes 21% of the dose. Doses from consumption of animal products were not considered, because land used to raise animals is not normally irrigated. External exposure from swimming in river water was not considered as this pathway does not contribute significantly to the overall dose.

TABLE D1
Contributions of exposure pathways to the GDC for atmosphere

Nuclide	Limiting age group	Plume inhalation	External from deposited activity	Consumption of foods
^{210}Po	1 y old	66%	-	34% - all foods
^{210}Pb	1 y old	53%	< 0.5%	47% - all foods
^{226}Ra	Adult	69%	26%	5% - all foods
^{234}U	10 y old	100%	-	< 0.5%
^{235}U	10 y old	98%	2%	< 0.5%
^{238}U	10 y old	99%	< 0.5%	< 0.5%

TABLE D2
Contributions of exposure pathways to the GDC for rivers

Nuclide	Limiting age group	Drinking water	Fish ingestion	Inhalation of bank sediments	External from bank sediments	Consumption of terrestrial foods*
^{210}Po	1 y old	66%	13%	-	-	21%
^{210}Pb	Adult	9%	89%	-	-	2%
^{226}Ra	Adult	6%	91%	-	< 0.5%	3%
^{234}U	Adult	68%	23%	-	-	9%
^{235}U	Adult	68%	23%	-	< 0.5%	9%
^{238}U	Adult	68%	23%	-	-	9%

* The terrestrial foods considered were green vegetables and root vegetables and were assumed to be irrigated with river water.

TABLE D3
Contributions of exposure pathways to the GDC for sewers from treatment of land with sewage sludge

Nuclide	Limiting age group	External dose from soil	Inadvertent ingestion of soil	Inhalation of soil	Consumption of foods
^{210}Po	1 y old	-	12%	-	88% - sheep meat and offal
^{210}Pb	1 y old	-	14%	-	86% - sheep meat and offal
^{226}Ra	3 month old	18%	6%	-	76% - milk
^{234}U	3 month old	-	11%	4%	85% - milk
^{235}U	Adult	91%	1%	3%	5% - milk
^{238}U	3 month old	7%	10%	4%	79% - milk

GDCs for discharges to sewers

The GDCs for sewers were calculated for six radionuclides for the four age groups, infants (3 months old and 1 year old), children (10 years old) and adults. Table 3 of the main text indicates the limiting age group for each radionuclide and these are discussed here. The GDC for sewers differs from the GDC for atmosphere and rivers because of the nature of sewage treatment and disposal. Raw incoming effluent is composed of water and suspended solids. During treatment the water and suspended solids are physically separated and are disposed of in different ways. Three distinct exposed groups are considered, those exposed during sewage treatment, effluent disposal to inland watercourses, and sludge disposal to farmland.

The GDC for disposal to sewers is limited either by exposure at the works or by disposal of sludge to land. Exposures from effluent disposal to inland river courses do not contribute to the GDC for any radionuclides. The most important pathways for the

GDCs for discharge to sewers vary depending on the radionuclide. For all the radionuclides considered, exposure from disposal of sludge to land was limiting. The contributions of the exposure pathways to the GDC are shown in Table D3. The limiting age group for most of the radionuclides is 3 month olds with 1 year olds limiting for ^{210}Po and ^{210}Pb and adults limiting for ^{235}U. Ingestion of foods is important for the majority of the radionuclides, except for ^{235}U, where external dose from soil is important.

Effects of different sizes of sewage treatment works on the GDCs for discharges to sewers

The GDCs for discharges to sewers were calculated making the cautious assumption that discharges occurred to a small rural sewage treatment works serving a population of 500. Many disposers may discharge to a larger works. The size of a sewage treatment works is controlled by the population served which affects the amount of sewage effluent produced. If the population is larger then the quantity of effluent is larger, dilution of disposed radionuclides is higher and, as a result, the predicted doses are lower. The effect of different sizes of sewage treatment works on the GDCs is discussed in more detail elsewhere*.

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* NRPB (2000). Generalised derived constraints for radioisotopes of strontium, ruthenium, iodine, caesium, plutonium, americium and curium. *Doc NRPB.* **11** (2), 1–41.