Generalised Derived Constraints for Radioisotopes of Hydrogen, Carbon, Phosphorus, Sulphur, Chromium, Manganese, Cobalt, Zinc, Selenium, Technetium, Antimony, Thorium and Neptunium

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ABSTRACT

The 1990 recommendations of the International Commission on Radiological Protection (ICRP) introduced the concept of the dose constraint and the National Radiological Protection Board (now part of the Health Protection Agency) response to the recommendations introduced the concept of a generalised derived constraint (GDC). 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 hydrogen, carbon, phosphorus, sulphur, chromium, manganese, cobalt, zinc, selenium, technetium, antimony, thorium and neptunium. The methods are as used in calculating GDCs for radioisotopes of other elements, such as caesium and polonium, published previously. The GDCs 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 estimated doses corresponding to this discharge should be examined more closely, taking account of site-specific factors.

This report also contains some additional generalised derived limits for environmental materials containing isotopes of technetium, thorium and neptunium, which have not been published previously.

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Approval: August 2010
Publication: September 2010
£21.00
ISBN 978-0-85951-672-3

This work was undertaken under the Environmental Assessment Department's Quality Management System, which has been approved by Lloyd's Register Quality Assurance to the Quality Management Standards ISO 9001:2008 and TickIT Guide Issue 5.5, Certificate No: LRQ 0956546.

Report Version 1.0

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1 INTRODUCTION

Generalised derived constraints (GDCs) are intended to be convenient reference quantities against which proposed controlled discharges to the environment can be compared. They are based on the 1990 recommendations of the International Commission on Radiological Protection (ICRP, 1991), which introduced the dose constraint. The National Radiological Protection Board (NRPB, now part of the Health Protection Agency, HPA) published guidance on the ICRP recommendations and their implications for public exposure (NRPB, 1993a,b). In considering the implications of the 1990 ICRP recommendations for public exposure it was 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) and also for isotopes of polonium, lead, radium and uranium (NRPB, 2002). In this document, GDCs are given for isotopes of hydrogen, carbon, phosphorus, sulphur, chromium, manganese, cobalt, zinc, selenium, technetium, antimony, thorium and neptunium, 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 (GDLs) for the same radioisotopes have also been published for a range of environmental materials (NRPB, 2005a). However, GDLs were not published previously for the full range of environmental materials for isotopes of technetium, thorium and neptunium; this report also gives GDLs for these elements.

In 2007, ICRP published new recommendations in publication 103 (ICRP, 2007) which maintain the concept of the dose constraint but which introduced some changes to the calculation of effective dose. The HPA has published advice on the application of the recommendations in the UK (HPA, 2009) and maintained the upper value of the constraint on effective dose for members of the public of 0.3 mSv y^{-1}. ICRP will publish revised dose coefficients for intakes of radionuclides taking account of the changes adopted in the 2007 recommendations but until these are available the GDCs published previously and those given here are considered to be valid. The 2007 recommendations also introduced the concept of the representative person to replace the term critical group. HPA considers that in the context of GDCs the representative person is equivalent to the critical group and the latter term is retained in this report for consistency with previous publications giving GDLs and GDCs.

Generalised derived constraints 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.

This report considers discharges to atmosphere, rivers and the sewerage system, each relevant to the discharge of small quantities of radionuclides by small users of radioactivity, such as hospitals and universities. The GDCs have been calculated using effective dose as calculated in ICRP Publication 60 (ICRP, 1991). The relevant age-dependent dose coefficients for members of the public were used in the calculations (ICRP, 1996). The methods and data used in their calculation are outlined in this report and the important exposure pathways for each GDC are discussed. The methods are generally as used for previous GDC calculations (NRPB, 2002) except that account has been taken of the exposure of the fetus using dose coefficients from ICRP Publications 88 and 95 (ICRP, 2001, 2004), as was the case in the GDL report for the same elements (NRPB, 2005a). Advice is also given on when site-specific assessments are required.

2 BASIS FOR GDCs

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 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, a maximum dose constraint for public exposure of 0.3 mSv y^{-1} is recommended, with the proviso that dose constraints lower than this could be set where such doses are readily achievable, for example for new nuclear power stations (HPA, 2009, 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. 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 carrying out a full site-specific dose assessment.

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.

GDCs apply to continuous, annual discharges of radionuclides to the environment. These discharges are assumed to continue for 50 years to allow for the build up of long lived radionuclides in the environment. The estimated activity concentrations in the 50th year of discharge are used to calculate the GDCs and, where necessary, the in-growth of radioactive progeny has been included 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 or to releases which vary significantly over the year.

The main age groups considered in calculating GDCs are infants (1 year old), children (10 years old) and adults, taking into account variations in the dose coefficients and dietary and other habits with age. Exposure to the fetus is also considered for tritium, carbon-14, sulphur-35, selenium-75, phosphorus-32 and phosphorus-33, as outlined below. In addition, for radionuclides for which 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, 2005a) and 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 be adequate for the purposes of calculating GDCs. For calculating doses from intakes of radionuclides, the lifetime of an individual is taken to be 70 years (with intake by an adult assumed to be at age 20 y). Although the average lifetime of individuals in the UK is somewhat greater than 70 y, this calculation is considered to be sufficiently cautious because of the reduced time for any risks to be expressed for exposure at later ages.

The values of the effective dose coefficients for intake by inhalation and ingestion are as described elsewhere (ICRP, 1996; ICRP, 2001). They have been calculated for each age group considered using age-dependent dosimetric models. For tritium, both organically bound tritium (OBT) and tritiated water (HTO) were considered. It was assumed that HTO and OBT would be present in foodstuffs and HTO would be present in drinking water and soil. Two forms of sulphur were considered: organic and inorganic. Tables 1 and 2 give the values for the effective dose coefficients used in this document for intake by ingestion and inhalation, respectively. The recommended (ICRP, 1996) default absorption types for particulate aerosols were used to select the appropriate inhalation dose coefficients for the GDC calculations. Tables 1 and 2 also include the offspring dose coefficients for fetal exposure (ICRP, 2001) for relevant radionuclides taken from ICRP Publication 88 (ICRP, 2001). ICRP has also published dose coefficients for infants from ingestion of radionuclides in mothers' milk (ICRP, 2005). Guidance was published by HPA on the application of these two sets of dose coefficients (HPA, 2008), which supplemented the advice published by NRPB in 2005, (NRPB, 2005b) on the application of dose coefficients for embryo and fetus from intakes of radionuclides by the mother, which provided ratios of fetal to adult doses for those radionuclides for which the fetus receives a higher dose than the mother, following intake by the mother. Following this advice, fetal exposure is taken into account for tritium, carbon-14, sulphur-35, selenium-75, phosphorus-32 and phosphorus-33. The simple approach recommended in NRPB 2005b is used based on the annual intake by an adult together with the offspring dose coefficient (ICRP, 2001). This approach takes account of the nine months of pregnancy and implicitly allows for intakes by the infant through breast feeding for three months (NRPB, 2005b).

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.

TABLE 1 Dose coefficients for intake by ingestion

Nuclide	Gut transfer factor (f_1) – All age groups	Gut transfer factor (f_1) – 3 months old	Committed effective dose per unit intake (Sv Bq^{-1})				
			Offspring[a]	Infant (3 months)	Infant (1 y)	Child (10 y)	Adult (20 y)
HTO	$1.0\ 10^{0}$	$1.0\ 10^{0}$	$3.1\ 10^{-11}$	$6.4\ 10^{-11}$	$4.8\ 10^{-11}$	$2.3\ 10^{-11}$	$1.8\ 10^{-11}$
OBT	$1.0\ 10^{0}$	$1.0\ 10^{0}$	$6.3\ 10^{-11}$	$1.2\ 10^{-10}$	$1.2\ 10^{-10}$	$5.7\ 10^{-11}$	$4.2\ 10^{-11}$
^{14}C	$1.0\ 10^{0}$	$1.0\ 10^{0}$	$8.0\ 10^{-10}$	$1.4\ 10^{-9}$	$1.6\ 10^{-9}$	$8\ 10^{-10}$	$5.8\ 10^{-10}$
^{32}P	$8.0\ 10^{-1}$	$1.0\ 10^{0}$	$2.5\ 10^{-8}$	$3.1\ 10^{-8}$	$1.9\ 10^{-8}$	$5.3\ 10^{-9}$	$2.4\ 10^{-9}$
^{33}P	$8.0\ 10^{-1}$	$1.0\ 10^{0}$	$4.8\ 10^{-9}$	$2.7\ 10^{-9}$	$1.8\ 10^{-9}$	$5.3\ 10^{-10}$	$2.4\ 10^{-10}$
^{35}S (organic)	$1.0\ 10^{0}$	$1.0\ 10^{0}$	$1.6\ 10^{-9}$	$7.7\ 10^{-9}$	$5.4\ 10^{-9}$	$1.6\ 10^{-9}$	$7.7\ 10^{-10}$
^{35}S (inorganic)	$1.0\ 10^{0}$	$1.0\ 10^{0}$	$2.0\ 10^{-10}$	$1.3\ 10^{-9}$	$8.7\ 10^{-10}$	$2.7\ 10^{-10}$	$1.3\ 10^{-10}$
^{51}Cr	$1.0\ 10^{-1}$	$2.0\ 10^{-1}$		$3.5\ 10^{-10}$	$2.3\ 10^{-10}$	$7.8\ 10^{-11}$	$3.8\ 10^{-11}$
^{54}Mn	$1.0\ 10^{-1}$	$2.0\ 10^{-1}$		$5.4\ 10^{-9}$	$3.1\ 10^{-9}$	$1.3\ 10^{-9}$	$7.1\ 10^{-10}$
^{57}Co	$1.0\ 10^{-1}$	$6.0\ 10^{-1}$		$2.9\ 10^{-9}$	$1.6\ 10^{-9}$	$5.8\ 10^{-10}$	$2.1\ 10^{-10}$
^{58}Co	$1.0\ 10^{-1}$	$6.0\ 10^{-1}$		$7.3\ 10^{-9}$	$4.4\ 10^{-9}$	$1.7\ 10^{-9}$	$7.4\ 10^{-10}$
^{60}Co	$1.0\ 10^{-1}$	$6.0\ 10^{-1}$		$5.4\ 10^{-8}$	$2.7\ 10^{-8}$	$1.1\ 10^{-8}$	$3.4\ 10^{-9}$
^{65}Zn	$5.0\ 10^{-1}$	$1.0\ 10^{0}$		$3.6\ 10^{-8}$	$1.6\ 10^{-8}$	$6.4\ 10^{-9}$	$3.9\ 10^{-9}$
^{75}Se	$8.0\ 10^{-1}$	$1.0\ 10^{0}$	$2.7\ 10^{-9}$	$2.0\ 10^{-8}$	$1.3\ 10^{-8}$	$6.0\ 10^{-9}$	$2.6\ 10^{-9}$
^{99}Tc	$5.0\ 10^{-1}$	$1.0\ 10^{0}$		$1.0\ 10^{-8}$	$4.8\ 10^{-9}$	$1.3\ 10^{-9}$	$6.4\ 10^{-10}$
^{99m}Tc	$5.0\ 10^{-1}$	$1.0\ 10^{0}$		$2\ 10^{-10}$	$1.3\ 10^{-10}$	$4.3\ 10^{-11}$	$2.2\ 10^{-11}$
^{125}Sb	$1.0\ 10^{-1}$	$2.0\ 10^{-1}$		$1.1\ 10^{-8}$	$6.1\ 10^{-9}$	$2.1\ 10^{-9}$	$1.1\ 10^{-9}$
^{229}Th	$5.0\ 10^{-4}$	$5.0\ 10^{-3}$		$1.1\ 10^{-5}$	$1.0\ 10^{-6}$	$6.2\ 10^{-7}$	$4.9\ 10^{-7}$
^{225}Ra	$2.0\ 10^{-1}$	$6.0\ 10^{-1}$		$7.1\ 10^{-6}$	$1.20\ 10^{-6}$	$5.0\ 10^{-7}$	$9.9\ 10^{-8}$
^{225}Ac	$5.0\ 10^{-4}$	$5.0\ 10^{-3}$		$4.6\ 10^{-7}$	$1.8\ 10^{-7}$	$5.4\ 10^{-8}$	$2.4\ 10^{-8}$
^{230}Th	$5.0\ 10^{-4}$	$5.0\ 10^{-3}$		$4.1\ 10^{-6}$	$4.1\ 10^{-7}$	$2.4\ 10^{-7}$	$2.1\ 10^{-7}$
^{234}Th	$5.0\ 10^{-4}$	$5.0\ 10^{-3}$		$4.0\ 10^{-8}$	$2.5\ 10^{-8}$	$7.4\ 10^{-9}$	$3.4\ 10^{-9}$
^{237}Np	$5.0\ 10^{-4}$	$5.0\ 10^{-3}$		$2.0\ 10^{-6}$	$2.1\ 10^{-7}$	$1.1\ 10^{-7}$	$1.1\ 10^{-7}$

(a) The offspring dose coefficient includes contributions to the radiation dose delivered *in utero* to the embryo and fetus to birth and post-natally to the offspring from birth to age 70 years from activity retained in the tissues of the newborn child. It relates to unit intake by the mother.

TABLE 2 Dose coefficients for intake by inhalation

Nuclide	f_1	Type[a]	Committed effective dose per unit intake (Sv Bq^{-1})			
			Offspring[b]	Infant (1 y)	Child (10 y)	Adult (20 y)
HTO	N/A[c]	V	$3.1\ 10^{-11}$	$4.8\ 10^{-11}$	$2.3\ 10^{-11}$	$1.8\ 10^{-11}$
OBT	$1.0\ 10^{0}$	M	$6.3\ 10^{-11}$	$1.1\ 10^{-10}$	$5.5\ 10^{-11}$	$4.1\ 10^{-11}$
^{14}C	$1.0\ 10^{-1}$	M	$2.7\ 10^{-10}$	$6.6\ 10^{-9}$	$2.8\ 10^{-9}$	$2.0\ 10^{-9}$
^{32}P	$8.0\ 10^{-1}$	F	$1.0\ 10^{-8}$	$7.5\ 10^{-9}$	$1.8\ 10^{-9}$	$7.7\ 10^{-10}$
^{33}P	$8.0\ 10^{-1}$	F	$2.0\ 10^{-9}$	$7.8\ 10^{-10}$	$2.0\ 10^{-10}$	$9.2\ 10^{-11}$
^{35}S (inorganic)	$1.0\ 10^{-1}$	M	$6.6\ 10^{-11}$	$4.5\ 10^{-9}$	$2.0\ 10^{-9}$	$1.4\ 10^{-9}$
^{51}Cr	$1.0\ 10^{-1}$	S		$2.1\ 10^{-10}$	$6.6\ 10^{-11}$	$3.7\ 10^{-11}$
^{54}Mn	$1.0\ 10^{-1}$	M		$6.2\ 10^{-9}$	$2.4\ 10^{-9}$	$1.5\ 10^{-9}$
^{57}Co	$1.0\ 10^{-1}$	M		$2.2\ 10^{-9}$	$8.5\ 10^{-10}$	$5.5\ 10^{-10}$
^{58}Co	$1.0\ 10^{-1}$	M		$6.5\ 10^{-9}$	$2.4\ 10^{-9}$	$1.6\ 10^{-9}$
^{60}Co	$1.0\ 10^{-1}$	M		$3.4\ 10^{-8}$	$1.5\ 10^{-8}$	$1.0\ 10^{-8}$
^{65}Zn	$1.0\ 10^{-1}$	M		$6.5\ 10^{-9}$	$2.4\ 10^{-9}$	$1.6\ 10^{-9}$
^{75}Se	$8.0\ 10^{-1}$	F	$1.1\ 10^{-9}$	$6.0\ 10^{-9}$	$2.5\ 10^{-9}$	$1.0\ 10^{-9}$
^{99}Tc	$1.0\ 10^{-1}$	M		$1.3\ 10^{-8}$	$5.7\ 10^{-9}$	$4.0\ 10^{-9}$
^{99m}Tc	$1.0\ 10^{-1}$	M		$9.9\ 10^{-11}$	$3.4\ 10^{-11}$	$1.9\ 10^{-11}$
^{125}Sb	$1.0\ 10^{-2}$	M		$1.6\ 10^{-8}$	$6.8\ 10^{-9}$	$4.8\ 10^{-9}$
^{229}Th	$5.0\ 10^{-4}$	S		$1.9\ 10^{-4}$	$8.7\ 10^{-5}$	$7.1\ 10^{-5}$
^{225}Ra	$1.0\ 10^{-1}$	M		$1.80\ 10^{-5}$	$8.40\ 10^{-6}$	$6.30\ 10^{-6}$
^{225}Ac	$5.0\ 10^{-4}$	S		$2.30\ 10^{-5}$	$1.10\ 10^{-5}$	$8.50\ 10^{-6}$
^{230}Th	$5.0\ 10^{-4}$	S		$3.5\ 10^{-5}$	$1.6\ 10^{-5}$	$1.4\ 10^{-5}$
^{234}Th	5.010^{-4}	S		$3.1\ 10^{-8}$	$1.1\ 10^{-8}$	$7.7\ 10^{-9}$
^{237}Np	5.010^{-4}	M		$4.0\ 10^{-5}$	$2.2\ 10^{-5}$	$2.3\ 10^{-5}$

a) Absorption types M (moderate), F (fast) and S (slow) describe absorption from the respiratory tract.

b) The offspring dose coefficient includes contributions to the radiation dose delivered *in utero* to the embryo and fetus to birth and post-natally to the offspring from birth to age 70 years from activity retained in the tissues of the newborn child. It relates to unit intake by the mother.

c) Assumed to be a vapour for which complete absorption from the respiratory tract is assumed and, therefore, there is no relevant f_1 value.

3 GDCS FOR DISCHARGES TO ATMOSPHERE, RIVERS AND SEWERS

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, 2005a).

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. Six exposure pathways are considered and the doses from each of these pathways are summed to obtain the GDC:

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,
f inadvertent ingestion of soil.

Table 3 gives the calculated GDCs for discharges to atmosphere for the twenty radio-nuclides considered here. The GDCs are based on the limiting age group, which is indicated in Table 3. Appendix D presents the contributions of the different exposure pathways to the overall dose used in calculating the GDCs.

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 for discharge to river 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*
^{3}H	2 10^{14}	Fetus	4 10^{14}	Fetus	6 10^{11}	3 month
^{14}C	3 10^{12}	Infant	1 10^{11}	Fetus	1 10^{9}	Infant
^{32}P	4 10^{11}	Fetus	4 10^{8}	Fetus	2 10^{8}	3 month
^{33}P	1 10^{11}	Fetus	2 10^{9}	Fetus	9 10^{8}	Fetus
^{35}S (organic)	4 10^{11}	Infant	1 10^{12}	Fetus	2 10^{8}	3 month
^{35}S (inorganic)	2 10^{12}	Infant	1 10^{13}	Fetus	1 10^{9}	3 month
^{51}Cr	7 10^{13}	Adult	2 10^{14}	Adult	1 10^{10}	Adult w
^{54}Mn	3 10^{11}	Adult	2 10^{12}	Adult	4 10^{8}	Adult w
^{57}Co	2 10^{12}	Adult	9 10^{12}	Adult	2 10^{9}	Adult w
^{58}Co	1 10^{12}	Adult	2 10^{12}	Adult	3 10^{8}	Adult w
^{60}Co	3 10^{10}	Adult	3 10^{11}	Adult	6 10^{7}	Adult
^{65}Zn	1 10^{11}	Infant	1 10^{11}	Adult	2 10^{7}	3 month
^{75}Se	2 10^{11}	Infant	8 10^{11}	Fetus	1 10^{8}	Infant
^{99}Tc	4 10^{10}	Infant	1 10^{12}	Infant	1 10^{7}	3 month
^{99m}Tc	5 10^{14}	Child	3 10^{14}	Infant	2 10^{9}	Adult w
^{125}Sb	2 10^{11}	Adult	6 10^{12}	Infant	6 10^{8}	Adult
^{229}Th	2 10^{8}	Adult	2 10^{11}	Adult	5 10^{7}	3 month
^{230}Th	9 10^{8}	Adult	5 10^{11}	Adult	7 10^{8}	Adult
^{234}Th	2 10^{12}	Adult	3 10^{13}	Infant	2 10^{10}	Adult w
^{237}Np	6 10^{8}	Adult	3 10^{11}	Infant	6 10^{7}	Adult

* 3 month – refers to infants in the first year of life on an all-milk diet.

Adult w – exposure at the sewage works

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 water body, assumed to be a river, giving rise to the same exposure pathways as in the case of a direct discharge to a river. The extent to which radionuclides discharged to sewers would partition between the sludge and the water is very uncertain. Although limited data are available on the partitioning of radionuclides and the exposure from different routes of sewage sludge disposal (Titley et al, 1999), a cautious, simplistic approach is taken in calculating GDCs for discharge to sewers. Two distinct possibilities are considered either that the entire radioactivity is transferred to sludge or 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 above.

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. Details of the relative contributions of the different exposure pathways to the overall dose used to calculate the GDCs are given in Appendix D.

4 IMPORTANCE OF FETAL EXPOSURE

Exposure of the fetus has been considered in estimating GDCs in this document. Fetal exposure was taken into account for tritium, carbon-14, phosphorus-32, phosphorus-33, sulphur-35 and selenium-75. As discussed earlier, a simple approach was adopted in estimating doses to the fetus as recommended in NRPB, 2005b; this applied the fetal dose coefficient (offspring as defined by ICRP in ICRP, 2001) to the annual intake by the mother. As shown in Table 3 exposure to the fetus was limiting for each of these radionuclides for the GDCs for discharges to river. For GDCs for discharges to atmosphere the fetus was limiting for tritium, phosphorus-32 and phosphorus-33 while for discharges to sewer the fetus was only limiting for phosphorus-33. Differences in the estimated doses for the different age groups are due to a combination of differences in the assumed habit data, the relevant dose coefficients and the relative importance of different exposure pathways. For the relevant radionuclides, the fetus tends to be limiting when the estimated dose to an adult is greater than that to a child or infant. For example, for the GDC for discharges to rivers since the ingestion of freshwater fish gives rise to the highest doses and the intake of fish is significantly greater for adults than for infants and children, the dose to the fetus is the highest for all radionuclides where the fetal dose coefficient is greater than that for the adult. For GDCs for discharge to atmosphere in many cases the most important exposure pathway is the ingestion of milk. The intake of milk for an infant is greater than that for an adult, and in many cases the dose coefficient for an infant is higher than that for the fetus, hence it is the dose to the infant that is limiting. However, the fetus is still limiting if the fetus dose coefficient is higher than that for the infant (eg, phosphorus-33) or where there are a number of foods contributing to the dose (eg, tritium).

In many cases the differences between the doses for different age groups are small and essentially the same GDC would be estimated if the fetus had not been considered. Even where the fetus dose is limiting the differences in doses with those for other age groups is less than about a factor of two for selenium-75, carbon-14, sulphur-35 and tritium. For the isotopes of phosphorus the fetal dose coefficient is considerably greater than the corresponding adult dose coefficient and the GDC based on fetal exposure for phosphorus-32 can be from a factor of 2 to 10 times more restrictive than the equivalent GDC based on exposure to the other age groups. For phosphorus-33 the differences can be up to a factor of 20.

A simplified approach was used in estimating the doses to the fetus based on the offspring dose coefficient and an annual intake by the mother. This is cautious and slightly lower doses would have been obtained if the more realistic approach of explicitly taking account of breast feeding had been adopted (NRPB, 2005a).

5 SITE-SPECIFIC ASSESSMENTS

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 there are additional exposure pathways. 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}).

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}.

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 those from discharges for 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).

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 river is likely to have a higher flow and dilution is likely to be greater than assumed here, but it also 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 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.

Where a proposed discharge is a significant fraction of the GDC, and hence is worthy of further investigation, the first factor to consider is the nature of the discharge and the location of the critical group. The information in Appendix D provides the basis for the identification of important exposure pathways so that specific dose calculations can 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 consumption. 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, taking account of 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.

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 or from incineration of the sludge. A study has shown that doses from discharges of radionuclides to a large urban works are lower than those from a rural works, indicating 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).

6 GENERALISED DERIVED LIMITS FOR ISOTOPES OF TECHNETIUM, THORIUM AND NEPTUNIUM

Generalised derived limits have been calculated for the radiologically significant isotopes of technetium, thorium and neptunium, based on the methodologies given previously (NRPB, 2005a). This report gives all relevant GDLs for these isotopes, including some that were published previously. Appendix E gives any additional data and methods used in calculating the GDLs that are not described elsewhere in this report or previously (NRPB, 2005a). In particular, details are given of how the in-growth of progeny is treated in GDLs which take into account multiple exposure pathways.

Generalised derived limits for terrestrial foods, other terrestrial materials and aquatic materials are given in Tables 4, 5 and 6, respectively. In each case the GDL is based on the most restrictive age group, which is indicated. Not all GDLs are presented for each radionuclide as values are only given when the GDL is relevant to the particular radionuclide. For example, generalised derived limits are only presented for grass for ^{99}Tc, for which foods derived from grazing animals are dominant contributors to dose. Generalised derived limits in air are only presented for radionuclides where the inhalation pathway is the most important contributor to dose (see section in Appendix E on important exposure pathways). In addition, GDLs are not given for short-lived radioisotopes, eg, ^{99m}Tc, in materials where time is required for mixing which results in significant radioactive decay. The basis for including specific GDLs was that radionuclides which have a half life of less than 7 days were not included for the GDLs for sewage for the plant operator and application of sewage to farmland; while radionuclides which have a half life of less than 3 months were not included for GDLs for well mixed soil, marine and freshwater sediment and tidal pasture.

Table 4 Generalised derived limits for terrestrial foods[1] (Bq kg^{-1})

Foodstuff[2]	^{99}Tc	^{99m}Tc	^{229}Th	^{230}Th	^{234}Th	^{237}Np
Domestic fruit	$6\ 10^{3}$ i	$2\ 10^{5}$ i	$3\ 10^{1}$	$6\ 10^{1}$	$1\ 10^{3}$ i	$1\ 10^{2}$
Potatoes and other root vegetables	$5\ 10^{3}$ i	$2\ 10^{5}$ i	$2\ 10^{1}$	$4\ 10^{1}$	$9\ 10^{2}$ i	$7\ 10^{1}$
Green and other domestic vegetables	$1\ 10^{4}$ i	$5\ 10^{5}$ i	$3\ 10^{1}$	$6\ 10^{1}$	$3\ 10^{3}$ i	$1\ 10^{2}$
Pig meat	$3\ 10^{4}$ c	$9\ 10^{5}$ c	$5\ 10^{1}$	$1\ 10^{2}$	$5\ 10^{3}$ c	$2\ 10^{2}$
Cow meat	$2\ 10^{4}$ i	$8\ 10^{5}$ i	$5\ 10^{1}$	$1\ 10^{2}$	$4\ 10^{3}$ i	$2\ 10^{2}$
Sheep meat	$6\ 10^{4}$	$2\ 10^{6}$	$8\ 10^{1}$	$2\ 10^{2}$	$1\ 10^{4}$	$4\ 10^{2}$
Offal[3]	$4\ 10^{4}$ i	$1\ 10^{6}$ i	$1\ 10^{2}$	$2\ 10^{2}$	$7\ 10^{3}$ i	$5\ 10^{2}$
Poultry	$4\ 10^{4}$ i	$1\ 10^{6}$ i	$7\ 10^{1}$	$2\ 10^{2}$	$7\ 10^{3}$ i	$3\ 10^{2}$
Butter	$6\ 10^{4}$ i	$2\ 10^{6}$ i	$1\ 10^{2}$	$3\ 10^{2}$	$1\ 10^{4}$ i	$6\ 10^{2}$
Cheese	$3\ 10^{4}$ i	$1\ 10^{6}$ i	$8\ 10^{1}$	$2\ 10^{2}$	$6\ 10^{3}$ i	$4\ 10^{2}$
Milk (Bq l-1)	$3\ 10^{2}$ b	$1\ 10^{4}$ b	$3\ 10^{-1}$ b	$7\ 10^{-1}$ b	$7\ 10^{1}$ b	$1\ 10^{0}$ b
Milk products	$5\ 10^{3}$ i	$2\ 10^{5}$ i	$2\ 10^{1}$ i	$5\ 10^{1}$ i	$9\ 10^{2}$ i	$1\ 10^{2}$ i
Eggs	$1\ 10^{4}$ i	$5\ 10^{5}$ i	$7\ 10^{1}$ i	$2\ 10^{2}$ i	$3\ 10^{3}$ i	$3\ 10^{2}$ i
Cereals	$7\ 10^{3}$ i	$3\ 10^{5}$ i	$2\ 10^{1}$	$5\ 10^{1}$	$1\ 10^{3}$ i	$9\ 10^{1}$

1 The GDLs apply to uniform conditions over a year and are based on the limiting age group, which is for adults unless indicated by

b three month old babies i infants aged 1 year c children aged 10 years

2 The GDLs for food products are expressed as fresh mass.

3 Offal refers to cow and sheep liver

Table 5 Generalised derived limits for the terrestrial environment[1] (Bq kg^{-1})

Material	^{99}Tc	^{229}Th	^{230}Th	^{234}Th	^{237}Np
Air[2] (Bq m^{-3})	NC	$2\ 10^{-3}$	$9\ 10^{-3}$	NC	$5\ 10^{-3}$
Grass[3]	$3\ 10^{3}$ i	NC	NC	NC	NC
Well mixed soil [4]	$9\ 10^{2}$ i	$2\ 10^{3}$	$6\ 10^{3}$ i	NC	$3\ 10^{3}$
Sewage sludge (plant operator)[5]	$3\ 10^{8}$	$1\ 10^{4}$	$3\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{4}$
Sewage sludge (application to farmland) [6]	$8\ 10^{1}$ i	$1\ 10^{3}$ i	$1\ 10^{4}$	$7\ 10^{6}$	$8\ 10^{2}$
Sea-washed pasture [7]	$1\ 10^{3}$ i	$5\ 10^{3}$ b	$1\ 10^{4}$ i	NC	$1\ 10^{4}$

1 The GDLs apply to uniform conditions over a year and are based on the limiting age group, which is for adults unless indicated by b three month old babies i infants aged 1 year c children aged 10 years

2 The GDLs for air are based on the inhalation pathway only

3 The GDLs are expressed as fresh weight.

4 The GDL for ^{229}Th includes ^{225}Ra and ^{225}Ac ingrown in secular equilibrium; The GDL for ^{230}Th includes the maximum in-growth of ^{226}Ra, ^{210}Pb and ^{210}Po over 50 years; The GDL for ^{237}Np includes ^{233}Pa ingrown in secular equilibrium.

5 Refers to the GDL for the plant operator working at the sewage works

6 Refers to the GDL from application of sewage to farmland. The GDL for ^{229}Th includes in-growth of ^{225}Ra and ^{225}Ac over a 50 year period; The GDL for ^{230}Th includes the in-growth of ^{226}Ra, ^{210}Pb and ^{210}Po over a 50 year period.

7 The GDL for ^{229}Th includes ^{225}Ra and ^{225}Ac ingrown in secular equilibrium; The GDL for ^{230}Th includes the maximum in-growth of ^{226}Ra, ^{210}Pb and ^{210}Po over 50 years. The GDL for ^{237}Np includes ^{233}Pa ingrown in secular equilibrium

8 NC = not calculated

Table 6 Generalised derived limits for the aquatic environment[1] (Bq kg^{-1})

Material	^{99}Tc	^{99m}Tc	^{229}Th	^{230}Th	^{234}Th	^{237}Np
Marine fish[2]	2 10^4	5 10^5	2 10^1	5 10^1	3 10^3	9 10^1
Freshwater fish[2]	8 10^4	2 10^6	1 10^2	2 10^2	1 10^4	5 10^2
Crustaceans[2]	8 10^4	2 10^6	1 10^2	2 10^2	1 10^4	5 10^2
Molluscs[2]	8 10^4	2 10^6	1 10^2	2 10^2	1 10^4	5 10^2
Freshwater sediment[3]	1 10^8 i	NC	4 10^4 c	3 10^5 c	NC	7 10^4
Marine sediment[3]	1 10^8 i	NC	1 10^4	8 10^4	NC	2 10^4
Freshwater[4] (Bq l^{-1})	1 10^2 i	NC	1 10^0 c	1 10^1	4 10^3 i	5 10^0
Drinking water (Bq l^{-1})	8 10^2 i	3 10^4 i	3 10^0	8 10^0	2 10^2 i	2 10^1

1 The GDLs apply to uniform conditions over a year and are based on the limiting age group, which for is for adults unless indicated by b three month old babies i infants aged 1 year c children aged 10 years

2 The GDLs for aquatic foodstuffs are for the edible fraction and are expressed as fresh mass.

3 The GDL for ^{229}Th includes ^{225}Ra and ^{225}Ac ingrown in secular equilibrium; The GDL for ^{230}Th includes the maximum in-growth of ^{226}Ra, ^{210}Pb and ^{210}Po over 50 years; The GDL for ^{237}Np includes ^{233}Pa ingrown in secular equilibrium

4 The GDLs for freshwater include activity in the dissolved and suspended sediment fractions. The GDL for ^{229}Th includes in-growth of ^{225}Ra and ^{225}Ac. Note for drinking water and freshwater fish progeny is assumed to be in secular equilibrium; The GDL for ^{230}Th includes in-growth of ^{226}Ra, ^{210}Pb and ^{210}Po over 50 years.

5 NC = not calculated

Note the GDL for ^{234}Th includes ^{234m}Pa in secular equilibrium for the external exposure pathway used to calculate all GDLs.

7 CONCLUSIONS

Generalised derived constraints have been presented in this report for discharges of the most significant radioisotopes of hydrogen, carbon, phosphorus, sulphur, chromium, manganese, cobalt, zinc, selenium, technetium, antimony, thorium and neptunium. 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 are based on the 1990 recommendations of ICRP (1991). In each case the GDC is the most restrictive of those calculated for the age groups considered.

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

Generalised derived limits have also been presented for radioisotopes of technetium, thorium and neptunium. If environmental contamination exceeds about 10% of the GDL the doses to the most exposed group should be examined more closely, taking into account site-specific factors and the likely duration of the situation.

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APPENDIX A Principles and Methods for Calculating GDCs for Discharges to Atmosphere

A1 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 value 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 have critical group habits and intakes (Smith and Jones, 2003).

Some of the radionuclides considered are likely to have radioactive decay products (progeny) and, where necessary, the in-growth and decay of these were taken into account when determining the GDCs. The in-growth of progeny was considered if significant in-growth is likely to occur during the 50 year discharge period. For ^{229}Th, the extent to which progeny were included depended on the particular exposure pathway concerned, as the times involved effects the amount of in-growth and which progeny need to be included. The relevant exposure pathways are those resulting from deposition to the ground. For external exposure from deposition to the ground, all of the progeny of ^{229}Th were included (^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Po). However, for inhalation of resuspended material, the inadvertent ingestion of soil and the ingestion of terrestrial foods, only ^{225}Ra and ^{225}Ac needed to be included. For ^{237}Np, ^{233}Pa was only included for external exposure from deposition to the ground, as doses were insignificant for any other exposure pathway. The same applied to ^{234}Th, for which ^{234m}Pa was assumed to be in secular equilibrium for external exposure pathways.

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 atmosphere. The GDCs themselves are given in Table 3 of the main text.

A2 ENVIRONMENTAL MODELS

A2.1 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, Mayall et al, 1997). The predicted activity concentrations in air from a continuous release 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 µm 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

Factor	Distance from stack	
	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})[1]	9.0 10^{-8}	4.7 10^{-9}

1 The net deposition rate for both ^{3}H and ^{14}C is considered to be zero.

A2.2 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). There were some modifications to the basic models for tritium, ^{14}C and ^{35}S, (see NRPB, 2005) and also for ^{99}Tc (see below). In all cases, it was assumed that some activity in the plume deposited on to soil, while some was directly intercepted by 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:

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

where A_f = activity concentration in the 50th year in the food product grown 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}),

$A_{f(u)}$ = activity concentration in the food product 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).

A review of literature carried out by Ewers (2010) on the transfer of ^{99}Tc in terrestrial foods indicates that values for the soil plant transfer factors for technetium are higher for fresh deposits than for technetium which has been in the soil for some time. The recommended values for the soil plant transfer factor are 5 for a fresh deposit to crops, and 0.5 for older material in soil. For pasture the recommended value for the soil plant transfer factor for use in the foodchain model is 5 in all cases.

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
^{3}H	$1.0\ 10^{2}$	$1.1\ 10^{2}$	$1.0\ 10^{2}$	$8.8\ 10^{1}$	$8.8\ 10^{1}$	$8.8\ 10^{1}$	$8.8\ 10^{1}$	$1.1\ 10^{2}$	$1.1\ 10^{2}$
^{14}C	$5.3\ 10^{2}$	$2.7\ 10^{2}$	$5.3\ 10^{2}$	$8.0\ 10^{2}$	$8.0\ 10^{2}$	$8.0\ 10^{2}$	$8.0\ 10^{2}$	$2.7\ 10^{2}$	$2.9\ 10^{3}$
^{32}P	$4.1\ 10^{4}$	$6.3\ 10^{4}$	$5.1\ 10^{5}$	$6.9\ 10^{4}$	$6.9\ 10^{4}$	$1.1\ 10^{6}$	$4.2\ 10^{5}$	$5.0\ 10^{4}$	$5.5\ 10^{5}$
^{33}P	$5.1\ 10^{4}$	$8.5\ 10^{4}$	$4.6\ 10^{4}$	$6.9\ 10^{5}$	$6.9\ 10^{5}$	$9.0\ 10^{7}$	$3.6\ 10^{7}$	$6.6\ 10^{5}$	$7.3\ 10^{6}$
^{35}S organic	$6.6\ 10^{4}$	$1.2\ 10^{5}$	$9.8\ 10^{4}$	$6.3\ 10^{6}$	$6.3\ 10^{6}$	$1.5\ 10^{7}$	$6.0\ 10^{6}$	$9.8\ 10^{5}$	$1.1\ 10^{7}$
^{35}S inorganic	$6.6\ 10^{4}$	$1.2\ 10^{5}$	$9.8\ 10^{4}$	$6.3\ 10^{6}$	$6.3\ 10^{6}$	$1.5\ 10^{7}$	$6.0\ 10^{6}$	$9.8\ 10^{5}$	$1.1\ 10^{7}$
^{51}Cr	$6.6\ 10^{3}$	$7.0\ 10^{4}$	$2.1\ 10^{0}$	$5.0\ 10^{4}$	$5.0\ 10^{4}$	$8.5\ 10^{4}$	$8.5\ 10^{4}$	$4.4\ 10^{4}$	$4.8\ 10^{5}$
^{54}Mn	$2.2\ 10^{4}$	$1.1\ 10^{5}$	$7.9\ 10^{3}$	$1.9\ 10^{5}$	$7.6\ 10^{6}$	$3.3\ 10^{5}$	$1.3\ 10^{7}$	$1.3\ 10^{5}$	$1.4\ 10^{6}$
^{57}Co	$1.8\ 10^{4}$	$1.1\ 10^{5}$	$8.1\ 10^{2}$	$1.6\ 10^{4}$	$1.6\ 10^{6}$	$2.5\ 10^{4}$	$2.5\ 10^{6}$	$5.8\ 10^{4}$	$6.4\ 10^{5}$
^{58}Co	$1.6\ 10^{4}$	$9.2\ 10^{4}$	$2.6\ 10^{2}$	$6.9\ 10^{3}$	$6.9\ 10^{5}$	$1.2\ 10^{4}$	$1.2\ 10^{6}$	$5.1\ 10^{4}$	$5.6\ 10^{5}$
^{60}Co	$4.4\ 10^{4}$	$1.2\ 10^{5}$	$5.1\ 10^{3}$	$2.9\ 10^{4}$	$2.9\ 10^{6}$	$4.3\ 10^{4}$	$4.4\ 10^{6}$	$7.1\ 10^{4}$	$7.8\ 10^{5}$
^{65}Zn	$3.6\ 10^{4}$	$1.6\ 10^{5}$	$3.0\ 10^{4}$	$1.1\ 10^{5}$	$1.1\ 10^{5}$	$1.1\ 10^{5}$	$1.1\ 10^{5}$	$1.3\ 10^{6}$	$1.4\ 10^{7}$
^{75}Se	$7.0\ 10^{4}$	$1.5\ 10^{5}$	$1.2\ 10^{5}$	$2.6\ 10^{6}$	$6.6\ 10^{7}$	$4.5\ 10^{6}$	$9.0\ 10^{7}$	$3.2\ 10^{5}$	$3.6\ 10^{6}$
^{99m}Tc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{99}Tc	$3.0\ 10^{7}$	$9.2\ 10^{6}$	$7.5\ 10^{6}$	$1.9\ 10^{8}$	$7.4\ 10^{8}$	$1.4\ 10^{8}$	$4.1\ 10^{8}$	$5.6\ 10^{6}$	$6.1\ 10^{7}$
^{125}Sb	$2.5\ 10^{4}$	$1.1\ 10^{5}$	$2.8\ 10^{3}$	$3.2\ 10^{4}$	$3.2\ 10^{6}$	$6.7\ 10^{4}$	$6.7\ 10^{6}$	$3.3\ 10^{3}$	$3.6\ 10^{4}$
^{229}Th	$2.7\ 10^{4}$	$1.1\ 10^{5}$	$1.5\ 10^{3}$	$2.2\ 10^{3}$	$2.2\ 10^{4}$	$1.6\ 10^{3}$	$1.6\ 10^{4}$	$1.7\ 10^{2}$	$1.8\ 10^{3}$
^{225}Ra*	$2.7\ 10^{4}$	$7.1\ 10^{4}$	$2.9\ 10^{3}$	$6.2\ 10^{3}$	$1.9\ 10^{4}$	$9.2\ 10^{3}$	$1.8\ 10^{4}$	$1.8\ 10^{3}$	$2.0\ 10^{4}$
^{225}Ac*	$2.7\ 10^{4}$	$3.3\ 10^{4}$	$2.9\ 10^{3}$	$6.2\ 10^{3}$	$1.9\ 10^{4}$	$8.8\ 10^{3}$	$1.9\ 10^{4}$	$3.1\ 10^{1}$	$3.4\ 10^{2}$
^{230}Th	$2.7\ 10^{4}$	$1.1\ 10^{5}$	$1.5\ 10^{3}$	$2.2\ 10^{3}$	$2.2\ 10^{4}$	$2.2\ 10^{3}$	$2.2\ 10^{4}$	$1.7\ 10^{2}$	$1.8\ 10^{3}$
^{234}Th	$6.3\ 10^{3}$	$6.6\ 10^{4}$	$3.1\ 10^{0}$	$6.6\ 10^{1}$	$6.6\ 10^{2}$	$1.1\ 10^{2}$	$1.1\ 10^{3}$	$1.1\ 10^{2}$	$1.2\ 10^{3}$
^{237}Np	$8.2\ 10^{4}$	$1.1\ 10^{5}$	$2.9\ 10^{3}$	$6.4\ 10^{3}$	$7.8\ 10^{5}$	$4.3\ 10^{3}$	$3.1\ 10^{5}$	$1.2\ 10^{2}$	$1.3\ 10^{3}$

* As progeny of ^{229}Th

A2.3 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 100m from the release point were calculated using equation A2.

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

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) ,

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).

The external dose rate per unit deposition was estimated using the method given in Simmonds et al (1995) and relevant data from ICRP (1983).

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:

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

where A_{res} = activity concentration in air 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 in air 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).

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

$$A_s = A_{s(u)} R_n \quad \text{(A4)}$$

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

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

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

Radionuclide	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})*
^{3}H	0.0	0.0	0.0
^{14}C	0.0	0.0	0.0
^{32}P	0.0	2.6 10^{-1}	0.0
^{33}P	0.0	3.4 10^{-1}	0.0
^{35}S organic	0.0	4.4 10^{-1}	0.0
^{35}S inorganic	0.0	4.4 10^{-1}	0.0
^{51}Cr	2.2 10^{-3}	3.3 10^{-1}	0.0
^{54}Mn	5.8 10^{-1}	5.7 10^{-1}	0.0
^{75}Se	1.1 10^{-1}	4.8 10^{-1}	0.0
^{65}Zn	3.2 10^{-1}	5.5 10^{-1}	0.0
^{57}Co	6.7 10^{-2}	5.6 10^{-1}	0.0
^{58}Co	1.7 10^{-1}	4.2 10^{-1}	0.0
^{60}Co	7.3 10^{0}	7.6 10^{-1}	0.0
^{99m}Tc	7.5 10^{-5}	1.8 10^{-3}	1.0 10^{-12}
^{99}Tc	0.0	1.0 10^{0}	0.0
^{125}Sb	7.9 10^{-1}	6.9 10^{-1}	0.0
^{229}Th	2.2 10^{0}	1.0 10^{0}	0.0
^{230}Th	1.3 10^{-1}	1.0 10^{0}	0.0
^{234}Th	1.1 10^{-3}	3.1 10^{-1}	0.0
^{237}Np	1.8 10^{0}	1.0 10^{0}	0.0

* The external dose from radionuclides in the plume is only considered for the short lived radionuclide, ^{99m}Tc, for all other radionuclides its contribution to the total dose is negligible.

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

Radionuclide	Activity concentration in soil in the 50th year of deposition for the top 1 cm of pasture (Bq kg^{-1} per Bq m^{-2} s^{-1})
^{3}H	8.5 10^{3}
^{14}C	9.7 10^{5}
^{32}P	1.4 10^{5}
^{33}P	2.4 10^{5}
^{35}S organic	7.6 10^{5}
^{35}S inorganic	7.6 10^{5}
^{51}Cr	2.7 10^{5}
^{54}Mn	2.4 10^{6}
^{75}Se	1.1 10^{6}
^{65}Zn	2.0 10^{6}
^{57}Co	2.1 10^{6}
^{58}Co	6.6 10^{5}
^{60}Co	6.6 10^{6}
^{99m}Tc	0.0
^{99}Tc	1.0 10^{7}

Radionuclide	Activity concentration in soil in the 50th year of deposition for the top 1 cm of pasture (Bq kg^{-1} per Bq m^{-2} s^{-1})
^{125}Sb	5.1 10^{6}
^{229}Th*	1.0 10^{7}
^{230}Th	1.0 10^{7}
^{234}Th	2.4 10^{5}
^{237}Np	1.0 10^{7}

*Assumed that the progeny ^{225}Ra and ^{225}Ac have the same activity concentrations as ^{229}Th.

A3 DOSE CALCULATIONS

Six exposure pathways were considered for the GDC for discharge to atmosphere: 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 the fetus (for ^{3}H, OBT, ^{14}C ^{32}P, ^{33}P, ^{35}S(organic and inorganic) and ^{75}Se), infants in the first year of life on an all-milk diet, 1 year old infants, 10 year old children and adults.

A3.1 Inhalation doses

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

$$D_{ip} = A_a\, B\, H_{e(inh)} \quad \text{(A5)}$$

$$D_{ires} = A_{res}\, B\, H_{e(inh)} \quad \text{(A6)}$$

where D_{ip} = effective dose from inhalation of the plume 100m 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 in air 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),

$H_{e(inh)}$ = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text).

The dose from in-growth of progeny (for example in-growth of ^{225}Ra and ^{225}Ac for ^{229}Th) is given by equation A7:

$$D_{ires} = A_{res}\, B\, (H_{e(inh)} + H_{e(inh)+n}) \qquad \text{(A7)}$$

where A_{res} = activity concentration in air 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) for the parent (This assumes that the resuspension for the progeny is the same as the parent).

$H_{e(inh)+n}$ = inhalation dose coefficient for progeny, n (Sv Bq^{-1}) (Table 2 of the main text).

For tritium, the contribution from absorption of vapour through the skin was considered as well as the intake by inhalation. The ICRP inhalation dose coefficient for HTO (ICRP, 1996) does not take into account the skin absorption component. However, ICRP states that for a male sedentary individual the intake from HTO absorbed through the skin is one-third of the total intake, or one-half of the intake from inhalation. Therefore in all cases the total effective dose from tritiated water in the plume was taken to be 1.5 times the dose from inhalation alone.

TABLE A7 Critical group inhalation rates and food ingestion rates (Smith and Jones, 2003)

	Age group		
	1 y	10 y	Adult
Inhalation rates (m^3 y^{-1})	1900	5600	8100
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
Cattle meat	10	30	45
Cattle offal [1]	2.75	5	10
Sheep meat	3	10	25
Sheep offal [1]	2.75	5	10
Milk [2]	320	240	240
Milk products	45	45	60

1 It was assumed that the total offal intake (Smith and Jones, 2003) was split evenly between cattle and sheep offal.
2 The milk intake of 350 l y^{-1} also assumed for unweaned infants in the first year of life.

A3.2 External exposure

Effective doses to each age group due to external exposure from activity deposited over 50 years on to the ground were calculated using equation A8:

$$D_{dep} = D_{ext}\, (F_{ind}\, T_{ind} + F_{out}\, T_{out}) \qquad \text{(A8)}$$

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		
	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.

A3.3 Ingestion of foods

For each age group ingestion doses from foods produced 500 m from the point of discharge were calculated using equation A9:

$$D_{food} = \Sigma_f A_f I_f H_{e(ing)} \qquad \text{(A9)}$$

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),

I_f = ingestion rate of each food (kg y^{-1}) (Table A7),

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The dose from the in-growth of progeny (eg, in-growth of ^{225}Ra and ^{225}Ac for ^{229}Th) for all foods is given by equation A10:

$$D_{food} = \Sigma_f [(A_f H_{e(ing)}) + (A_{f+n} H_{e(ing)+n})] I_f \qquad \text{(A10)}$$

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

A_{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,

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

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

For fruit as no model parameter values were available for the progeny the activity concentration of the progeny was assumed to be the same as the parent in the above equation.

A3.4 Inadvertent ingestion of soil

Doses to each age group from inadvertent ingestion of soil 100 m from the point of discharge were calculated using equation A11:

$$D_{soil} = A_s \, I_s \, H_{e(ing)} \qquad \text{(A11)}$$

where D_{soil} = effective dose from ingestion of soil 100 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),

A_s = activity concentrations in soil 100 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),

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The dose from the in-growth of progeny (eg, in-growth of ^{225}Ra and ^{225}Ac for ^{229}Th) is given by:

$$D_{soil} = A_s \, I_s \, (H_{e(ing)} + H_{e(ing)+n}) \qquad \text{(A12)}$$

This assumes that the activity concentration in the soil for the progeny is the same as that for the parent.

A3.5 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 six exposure pathways described above using equation A13:

$$D_{tot} = D_{food} + D_{dep} + D_{extp} + D_{ip} + D_{ires} + D_{soil} \quad \text{(A13)}$$

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

D_{extp} = effective external dose per unit discharge rate from the plume (Sv y^{-1} per Bq s^{-1}) (Table A5) only calculated for ^{99m}Tc.

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 from 1 year old infants. The dose to a fetus was calculated only for the relevant radionuclides as given in the main text. The calculations were the same as those for adults except that dose coefficients for the fetus were used as appropriate.

A4 CALCULATION OF GDCs FOR DISCHARGES TO ATMOSPHERE

The GDCs for each age group and radionuclide were calculated using equation A14:

$$GDC = T \text{ Dose Constraint}/D_{tot} \quad \text{(A14)}$$

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 is the maximum dose constraint for members of the public as recommended by HPA (NRPB, 1993). The most restrictive GDC for each radionuclide is presented in Table 3 of the main report.

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APPENDIX B Principles and Methods for Calculating GDCs for Discharges to Rivers

B1 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 be to a river of low volumetric flow and to continue for 50 years; 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 (Smith and Jones, 2003).

Some of the radionuclides considered are likely to have radioactive decay products (progeny) and where necessary the in-growth and decay of these were taken into account when determining the GDCs. In-growth of progeny was considered if significant in-growth is likely to occur in the 50 year discharge period. The radionuclides considered for in-growth of progeny were ^{229}Th and ^{237}Np. For ^{229}Th, only the parent was considered for exposure due to drinking water and ingestion of fish, as the river transit time of less than 1 hour would not allow significant in-growth to occur. For all other pathways, including exposure from the sediment and ingestion of irrigated foods, all radiologically significant progeny were included in the dose assessment. For external exposure from the sediment, all progeny were included (^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Po), but for inhalation of sediment and ingestion of irrigated foods only ^{225}Ra and ^{225}Ac were included. For ^{237}Np, ^{233}Pa, was only included for external exposure from sediment, as doses were insignificant for all other exposure pathways. The same applied to ^{234}Th, where ^{234m}Pa was assumed to be in secular equilibrium for external exposure pathways.

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.

B2 ENVIRONMENTAL MODELS

B2.1 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 was defined, into which the activity was discharged. Four main processes were 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).

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})	3.17 10^{-5}
Volumetric flow (m^3 s^{-1})	4.76 10^{-5}

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. Therefore, this route of exposure was also considered.

TABLE B2 Element-dependent sediment water distribution coefficients, sedimentation factors and fish concentration factors for freshwater

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})
H	3 10^{-2} (Kane, 1984)	0	9 10^{-1} (Thompson et al 1972)
C	2 10^{3} (Booth, 1976)	2 10^{-6}	4.6 10^{3} (Thompson et al 1972)
P	1 10^{3} (Martin, 1991)	2 10^{-6}	5 10^{4} (IAEA 2001)
S	3 10^{3} (Martin, 1991)	2 10^{-6}	2 10^{2} (Martin, 1991)
Cr	2 10^{4} (Booth, 1976)	1 10^{-5}	4 10^{1} (Thompson et al 1972)
Mn	5 10^{4} (Zeevaert et al, 1987)	1 10^{-5}	1 10^{2} (Thompson et al 1972)
Co	2 10^{4} (Zeevaert et al, 1987)	1 10^{-5}	3 10^{2} (IAEA 2001)
Zn	1 10^{3} (Booth, 1976)	2 10^{-6}	1 10^{3} (Thompson et al 1972)
Se	3 10^{3} (Kane 1984)	2 10^{-6}	2 10^{2} (IAEA 2001)
Tc	2 10^{2} (IAEA, 1982)	2 10^{-6}	1.5 10^{1} (Thompson et al 1972)
Sb	5 10^{2} (Zeevaert et al, 1987)	2 10^{-6}	1 10^{0} (Thompson et al 1972)
Th	5 10^{6} (Kane 1984)	1 10^{-5}	3 10^{1} (Thompson et al 1972)
Np	3 10^{4} (Simmonds et al, 1995)	1 10^{-5}	1 10^{1} (Thompson et al 1972)

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

Radionuclide	50th year activity concentrations per Bq s^{-1} discharged		
	Filtered water (Bq m^{-3})	Suspended sediment (Bq kg^{-1})	Bed sediment (Bq kg^{-1})
^{3}H	$1.0\ 10^{0}$	$3.0\ 10^{-5}$	0.0
^{14}C	$9.3\ 10^{-1}$	$1.9\ 10^{0}$	$1.4\ 10^{-2}$
^{32}P	$9.6\ 10^{-1}$	$9.6\ 10^{-1}$	$1.4\ 10^{-3}$
^{33}P	$9.6\ 10^{-1}$	$9.6\ 10^{-1}$	$2.3\ 10^{-3}$
^{35}S	$8.9\ 10^{-1}$	$2.7\ 10^{0}$	$5.7\ 10^{-3}$
^{51}Cr	$5.5\ 10^{-1}$	$1.1\ 10^{1}$	$1.3\ 10^{-2}$
^{54}Mn	$3.3\ 10^{-1}$	$1.7\ 10^{1}$	$5.0\ 10^{-2}$
^{57}Co	$5.5\ 10^{-1}$	$1.1\ 10^{1}$	$4.8\ 10^{-2}$
^{58}Co	$5.5\ 10^{-1}$	$1.1\ 10^{1}$	$2.5\ 10^{-2}$
^{60}Co	$5.5\ 10^{-1}$	$1.1\ 10^{1}$	$6.5\ 10^{-2}$
^{65}Zn	$9.6\ 10^{-1}$	$9.6\ 10^{-1}$	$9.2\ 10^{-3}$
^{75}Se	$8.9\ 10^{-1}$	$2.7\ 10^{0}$	$6.8\ 10^{-3}$
^{99}Tc	$9.9\ 10^{-1}$	$2.0\ 10^{-1}$	$1.4\ 10^{-2}$
^{99m}Tc	$9.2\ 10^{-1}$	$1.8\ 10^{-1}$	$2.6\ 10^{-5}$
^{125}Sb	$9.8\ 10^{-1}$	$4.9\ 10^{-1}$	$1.2\ 10^{-2}$
^{229}Th	$5.0\ 10^{-3}$	$2.5\ 10^{1}$	$7.0\ 10^{-2}$
^{230}Th	$5.0\ 10^{-3}$	$2.5\ 10^{1}$	$7.0\ 10^{-2}$
^{234}Th	$5.0\ 10^{-3}$	$2.5\ 10^{1}$	$1.1\ 10^{-2}$
^{237}Np	$4.5\ 10^{-1}$	$1.4\ 10^{1}$	$7.0\ 10^{-2}$

B2.2 Foodchain modelling

Activity 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 (Brown and Simmonds, 1995) and are given in Table B4. There were some modifications to the basic models for tritium, ^{14}C and ^{35}S, see NRPB, 2005. For ^{99}Tc, the same assumptions were made as for an atmospheric deposit as discussed in Appendix A. In all cases, it was assumed that some activity in the irrigated water was deposited directly on to soil, with a fraction intercepted by plants with some of the intercepted activity being transferred into the plant. Build-up in soil over 50 years and the uptake into plants from soil were also 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:

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

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)

Radionuclide	50th year activity concentrations in foods from a surface deposit of irrigation water (Bq kg^{-1} per Bq m^{-2} y^{-1})	
	Green and domestic vegetables	Potatoes and root vegetables
^{3}H (HTO)	$1.61\ 10^{-3}$	$1.61\ 10^{-3}$
^{3}(OBT)	$3.62\ 10^{-4}$	$3.62\ 10^{-4}$
^{14}C	$7.18\ 10^{-2}$	$5.81\ 10^{-2}$
^{32}P	$6.01\ 10^{-3}$	$2.30\ 10^{-3}$
^{33}P	$8.09\ 10^{-3}$	$4.39\ 10^{-3}$
^{35}S	$4.14\ 10^{-2}$	$1.23\ 10^{-2}$
^{51}Cr	$6.71\ 10^{-3}$	$1.81\ 10^{-7}$
^{54}Mn	$1.05\ 10^{-2}$	$3.32\ 10^{-4}$
^{57}Co	$1.02\ 10^{-2}$	$4.21\ 10^{-5}$
^{58}Co	$8.81\ 10^{-3}$	$1.98\ 10^{-5}$
^{60}Co	$1.08\ 10^{-2}$	$1.79\ 10^{-4}$
^{65}Zn	$1.27\ 10^{-2}$	$1.32\ 10^{-3}$
^{75}Se	$1.70\ 10^{-2}$	$1.06\ 10^{-2}$
^{99}Tc	$2.92\ 10^{-1}$	$2.40\ 10^{-1}$
^{125}Sb	$1.06\ 10^{-2}$	$1.05\ 10^{-4}$
^{229}Th	$1.01\ 10^{-2}$	$4.70\ 10^{-5}$
^{225}Ra as a progeny of ^{229}Th	$5.87\ 10^{-3}$	$9.44\ 10^{-5}$
^{225}Ac as a progeny of ^{229}Th	$3.02\ 10^{-3}$	$9.41\ 10^{-5}$
^{230}Th	$1.01\ 10^{-2}$	$4.70\ 10^{-5}$
^{234}Th	$6.39\ 10^{-3}$	$2.64\ 10^{-7}$
^{237}Np	$1.03\ 10^{-2}$	$9.40\ 10^{-5}$

B3 DOSE CALCULATIONS

Five exposure pathways were considered for the GDC for discharges to rivers: 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 the fetus, 1 year old infants, 10 year old children and adults.

B3.1 External dose from bed sediments

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

$$D_{RB,ext} = D_{ext(u)}\, R_B\, O \qquad \text{(B2)}$$

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

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

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

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

B3.2 Doses from inhalation of resuspended bed sediment

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

$$D_{RB,inh} = R_B\, B\, L\, H_{e(inh)}\, O_{frac} \qquad \text{(B3)}$$

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

B = inhalation rate (m^3 y^{-1}) (Table B6),

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

$H_{e(inh)}$ = inhalation dose coefficient (Sv 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).

The dose from in-growth of progeny (eg, in-growth of ^{225}Ra and ^{225}Ac for ^{229}Th) would be:

$$D_{RB,inh} = R_B\, B\, L\, O_{frac}\, (H_{e(inh)} + H_{e(inh)+n}) \qquad \text{(B4)}$$

$H_{e(inh)+n}$ = inhalation dose coefficient for progeny, n (Sv Bq^{-1}) (Table 2 of the main text).

The concentration of suspended sediment in air used was 10^{-7} kg m^{-3} (Simmonds et al, 1995).

TABLE B5 Predicted external dose rates above well-mixed sediment per unit activity concentration*

Radionuclide	Effective dose rate (Sv h^{-1} per Bq kg^{-1})
^{51}Cr	$4.8\ 10^{-12}$
^{54}Mn	$1.5\ 10^{-10}$
^{57}Co	$1.3\ 10^{-11}$
^{58}Co	$1.7\ 10^{-10}$
^{60}Co	$4.7\ 10^{-10}$
^{65}Zn	$1.1\ 10^{-10}$
^{75}Se	$5.4\ 10^{-11}$
^{125}Sb	$6.9\ 10^{-11}$
^{229}Th	$3.5\ 10^{-11}$
^{237}Np	$3.0\ 10^{-11}$

* Based on the model given in Simmonds et al 1995 using data from ICRP, 1983

TABLE B6 Critical group habits (Smith and Jones, 2003)

	Age groups		
	1 y	10 y	Adult
Occupancy of sediment (h y^{-1})	30	500	500[1]
Intake rates			
Inhalation (m^3 y^{-1})	1900	5600	8100
Drinking water (m^3 y^{-1})	0.26	0.35	0.60
Freshwater fish (t y^{-1})	0.001	0.005	0.02
Green vegetables (kg y^{-1})	15	35	80
Potatoes and root vegetables (kg y^{-1})	45	95	130

1 This value is the same as used in previous published GDC reports (NRPB, 2002) for consistency.

B3.3 Dose from ingestion of water

Doses to each age group from ingestion of radionuclides in filtered river water abstracted 500 m downstream from the point of discharge were calculated using equation B5:

$$D_{water} = R_{fil}\ I_{water}\ H_{e(ing)} \qquad \text{(B5)}$$

where D_{water} = effective dose from drinking filtered river water 500 m downstream from 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),

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

B3.4 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 B6:

$$D_{fish} = R_{fil}\, I_{fish}\, C_{fish}\, H_{e(ing)} \qquad (B6)$$

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),

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

B3.5 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 B7:

$$D_{food} = \Sigma_f\, A_f\, I_f\, H_{e(ing)} \qquad (B7)$$

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 from irrigation (Bq kg^{-1} per Bq s^{-1}) (equation B1),

I_f = ingestion rate of each food (kg y^{-1}) (Table B6),

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The dose from in-growth of progeny (eg, in-growth of ^{225}Ac and ^{225}Ra for ^{229}Th) would be:

$$D_{food} = \Sigma_f\, [(A_f\, H_{e(ing)}) + (A_{f+n}\, H_{e(ing)+n})]\, I_f \qquad (B8)$$

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}),

Af = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation B1) for parent,

A_{f+n} = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation B1) for progeny, n, assuming progeny supported by parent

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

$H_{e(ing)+n}$= 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).

B3.6 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 B9:

$$D_{tot} = D_{food} + D_{fish} + D_{water} + D_{RB,inh} + D_{RB,ext} \quad \text{(B9)}$$

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

The dose to a fetus was calculated only for the relevant radionuclides as discussed in the main text. The calculations were the same as those for adults except that dose coefficients for the fetus were used as appropriate.

B4 CALCULATION OF GDCs

The GDCs for each age group and radionuclide were calculated using equation B10:

$$GDC = T \ \text{Dose Constraint}/D_{tot} \quad \text{(B10)}$$

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 is the maximum dose constraint recommended by HPA (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

C1 INTRODUCTION

Generalised derived constraints (GDCs) for discharges to 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 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 considered 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 radionuclides in sludges and effluents,

b members of the public who were exposed to radionuclides in river water that has received treated effluent, as described in Appendix B,

c members of the public assumed to live adjacent to farmland treated repeatedly with sewage sludge and to consume animal products produced from the treated land – foods consumed were assumed to have been produced 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 in-growth and decay of these were taken into account when determining the GDCs. The in-growth of progeny was considered if significant in-growth is likely to occur over the 50 year discharge period. The radionuclides considered for in-growth of progeny were ^{229}Th, ^{230}Th, and ^{237}Np. For ^{229}Th, the progeny ^{225}Ra and ^{225}Ac were included for all exposure pathways. For external exposure from soil, additional shorter lived progeny were included (^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Po). For ^{230}Th progeny in-growth was only included for ingestion of foods, as doses from progeny for other exposure pathways were insignificant. For ^{237}Np, ^{233}Pa was only included for external doses, as doses from ingestion and inhalation were insignificant. The same applied to ^{234}Th, where ^{234m}Pa was assumed to be in secular equilibrium for external exposure pathways.

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.

C2 ENVIRONMENTAL MODELS

C2.1 Modelling of transport of radionuclides in the sewer system

Activity concentrations of each radionuclide released into effluent in the sewer were calculated using a simple dilution approach as 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 a community served by a 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, so that radioactive decay during transport and treatment was not considered. Radionuclide partitioning between the solution and solid phases was 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 cautious assumption that all of 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 size of the 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.

C2.2 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.

TABLE C1 Sewage effluent flows and treatment times assumed

Characteristic		Parameter value
Raw effluent		
	Suspended sediment load (%)	0.05
	Volumetric flow ($m^3\ s^{-1}$)	6.95 10^{-4}
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 unit discharge (Bq l^{-1} per Bq s^{-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

C2.3 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 disposal to landfill is becoming more expensive. For the same reasons, the use of incinerators for sludges from large urban sewage treatment works is also increasing. In relation to radiation exposures, 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 was negligible for the time periods given in Table C1 for the radionuclides considered in this report.

C2.4 Foodchain modelling

For disposals of sewage sludge to land, only animal products were considered because of the restrictions on the application of sewage sludge to land used to produce foods that may be eaten raw (DOE, 1996). This is also consistent with the further guidance (the Safe Sludge Matrix) agreed between Water UK, Sewage operators and the British Retail Consortium (BRC), produced in 2001, (ADAS, 2001). The sewage treatment works considered in calculating GDCs would produce 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). Some modifications were made to the models for tritium, ^{14}C and ^{35}S, (NRPB, 2005). 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 = activity concentration in the 50^{th} year for a food product grown on land treated with sewage sludge (Bq kg^{-1} per Bq s^{-1}),

$A_{f(u)}$ = activity concentration in the 50^{th} year in the food product 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} = activity concentration in sewage sludge per unit discharge (Bq kg^{-1} per Bq s^{-1}) (Table C2).

A review of literature carried out by Ewers (2010) on the transfer of ^{99}Tc to terrestrial foods indicates that appropriate value for the soil plant transfer factors for technetium in pasture remains 5 as given in Brown and Simmonds (1995).

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 sewage sludge application to land

Radionuclide	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})				
	Cattle meat	Cattle liver	Cow's milk	Sheep meat	Sheep liver
^{3}H (HTO)	4.99 10^{-4}	4.99 10^{-4}	5.79 10^{-4}	7.70 10^{-4}	7.70 10^{-4}
^{3}H (OBT)	3.75 10^{-5}	3.75 10^{-5}	3.05 10^{-5}	5.80 10^{-5}	5.80 10^{-5}
^{14}C	2.62 10^{-2}	2.62 10^{-2}	1.27 10^{-2}	4.17 10^{-2}	4.17 10^{-2}
^{32}P	3.90 10^{-3}	3.88 10^{-3}	4.59 10^{-3}	7.61 10^{-3}	3.04 10^{-3}
^{33}P	8.47 10^{-3}	8.43 10^{-3}	8.09 10^{-3}	1.66 10^{-2}	6.63 10^{-3}
^{35}S	8.53 10^{-2}	8.47 10^{-2}	1.32 10^{-2}	1.48 10^{-1}	5.92 10^{-2}
^{51}Cr	8.53 10^{-6}	8.51 10^{-6}	7.49 10^{-6}	4.52 10^{-5}	4.52 10^{-5}
^{54}Mn	1.88 10^{-3}	8.60 10^{-2}	1.42 10^{-3}	2.61 10^{-3}	1.17 10^{-1}
^{57}Co	3.82 10^{-5}	3.81 10^{-3}	1.36 10^{-4}	8.90 10^{-5}	8.92 10^{-3}
^{58}Co	5.54 10^{-6}	5.53 10^{-4}	4.08 10^{-5}	1.51 10^{-5}	1.51 10^{-3}
^{60}Co	2.07 10^{-4}	2.06 10^{-2}	5.01 10^{-4}	3.92 10^{-4}	3.93 10^{-2}
^{65}Zn	2.84 10^{-3}	2.84 10^{-3}	3.37 10^{-2}	2.48 10^{-3}	2.48 10^{-3}
^{75}Se	5.87 10^{-2}	1.46 10^{0}	7.19 10^{-3}	8.31 10^{-2}	1.66 10^{0}
^{99}Tc	5.85 10^{0}	2.35 10^{1}	1.76 10^{-1}	4.29 10^{0}	1.29 10^{1}
^{125}Sb	1.72 10^{-4}	1.72 10^{-2}	1.77 10^{-5}	4.82 10^{-4}	4.82 10^{-2}
^{229}Th	1.13 10^{-5}	1.13 10^{-4}	8.37 10^{-7}	4.95 10^{-6}	4.94 10^{-5}
^{225}Ra as progeny of ^{229}Th	1.05 10^{-4}	1.68 10^{-4}	3.73 10^{-5}	1.13 10^{-4}	1.40 10^{-4}
^{225}Ac as progeny of ^{229}Th	1.04 10^{-4}	1.78 10^{-4}	6.12 10^{-7}	1.08 10^{-4}	1.47 10^{-4}
^{230}Th	1.13 10^{-5}	1.13 10^{-4}	8.38 10^{-7}	4.95 10^{-6}	4.94 10^{-5}
^{226}Ra as progeny of ^{230}Th	1.04 10^{-6}	1.03 10^{-6}	1.47 10^{-7}	1.10 10^{-6}	1.10 10^{-6}
^{210}Pb as progeny of ^{230}Th	5.68 10^{-7}	1.11 10^{-6}	2.00 10^{-7}	3.84 10^{-7}	3.30 10^{-6}
^{210}Po as progeny of ^{230}Th	1.52 10^{-7}	1.21 10^{-6}	1.58 10^{-9}	1.36 10^{-7}	1.38 10^{-6}
^{234}Th	1.07 10^{-8}	1.07 10^{-7}	1.71 10^{-8}	5.37 10^{-8}	5.36 10^{-7}
^{237}Np	7.86 10^{-5}	9.66 10^{-3}	1.43 10^{-6}	1.18 10^{-3}	8.46 10^{-2}

C2.5 Modelling sludge application to soil and external dose

The predicted activity concentrations in soil from application of sewage sludge at a rate of 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. Activity concentrations in the top 1 cm of soil, for pasture, and 30 cm, for well mixed soil, were calculated using equations C2 and C3 respectively. Effective dose rates per unit discharge for external exposure above pasture soil were based on the model given in Simmonds et al 1995 using data from ICRP, 1983 and were calculated using equation C4.

$$A_{sp} = A_{sp(u)} \, SL_{app} \, SL_{conc} \qquad (C2)$$

$$A_{sw} = A_{sw(u)} \, SL_{app} \, SL_{conc} \qquad (C3)$$

$$D_{ext} = D_{ext(u)}\, SL_{app}\, SL_{conc} / T \qquad (C4)$$

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

A_{sw} = activity concentration in the top 30 cm of well mixed soil after 50 years of treatment with sewage sludge (Bq kg^{-1} per Bq s^{-1}),

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

$A_{sw(u)}$ = activity concentration in the top 30 cm of well mixed soil per unit deposit after 50 years (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table C4),

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

$D_{ext(u)}$ = external dose rate in the 50th year for unit deposition rate (Sv y^{-1} per Bq m^{-2} s^{-1}) (Table C5),

T = number of seconds in a year.

TABLE C4 Predicted activity concentrations in undisturbed and well mixed soil in the 50th year per unit deposit

Radionuclide	50th year activity concentrations in pasture soil per unit deposit (Bq kg^{-1} per Bq m^{-2} y^{-1})	50th year activity concentrations in well mixed soil per unit deposit (Bq kg^{-1} per Bq m^{-2} y^{-1})
^{3}H	2.70 10^{-4}	2.70 10^{-4}
^{14}C	3.08 10^{-2}	8.55 10^{-4}
^{32}P	4.37 10^{-3}	1.47 10^{-4}
^{33}P	7.72 10^{-3}	2.63 10^{-4}
^{35}S	2.40 10^{-2}	1.97 10^{-4}
^{51}Cr	8.57 10^{-3}	2.93 10^{-4}
^{54}Mn	7.52 10^{-2}	3.25 10^{-3}
^{57}Co	6.75 10^{-2}	2.83 10^{-3}
^{58}Co	2.10 10^{-2}	7.47 10^{-4}
^{60}Co	2.10 10^{-1}	1.92 10^{-2}
^{65}Zn	6.22 10^{-2}	2.56 10^{-3}
^{75}Se	3.40 10^{-2}	1.26 10^{-3}
^{99}Tc	3.30 10^{-1}	1.13 10^{-1}
^{99m}Tc	0.0	0.0
^{125}Sb	1.60 10^{-1}	1.04 10^{-2}
^{229}Th	3.30 10^{-1}	1.12 10^{-1}
^{230}Th	3.30 10^{-1}	1.13 10^{-1}
^{234}Th	7.44 10^{-3}	2.54 10^{-4}
^{237}Np	3.30 10^{-1}	1.13 10^{-1}

TABLE C5 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

Radionuclide	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})
^{51}Cr	2.20 10^{-3}	6.90 10^{-12}
^{54}Mn	5.81 10^{-1}	1.77 10^{-10}
^{57}Co	6.69 10^{-2}	2.91 10^{-11}
^{58}Co	1.70 10^{-1}	2.06 10^{-10}
^{60}Co	7.27 10^{0}	5.48 10^{-10}
^{65}Zn	3.18 10^{-1}	1.25 10^{-10}
^{75}Se	9.86 10^{-2}	8.72 10^{-11}
^{99m}Tc	0.0	2.98 10^{-11}
^{125}Sb	7.78 10^{-1}	8.84 10^{-11}
^{229}Th	2.20 10^{0}	6.06 10^{-11}
^{230}Th	1.26 10^{-1}	8.61 10^{-14}
^{234}Th	1.08 10^{-3}	4.32 10^{-12}
^{237}Np	1.84 10^{0}	4.92 10^{-11}

C3 DOSE CALCULATIONS

Doses were calculated for three separate exposed groups to determine the sewer GDC: workers at the sewage treatment works; groups exposed to discharges of treated sewage effluent to a river; groups exposed to farmland treated with sewage sludge. In all cases critical group food intakes and habits were used (Smith and Jones, 2003).

C3.1 Exposure of sewage plant workers

Sewage plant workers were assumed to spend all of their 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.

C3.1.1 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} (Northrop et al, 1980) were calculated using equation C5:

$$D_{tw,inh} = SL_{conc}\, B\, L\, H_{e(inh)}\, O \qquad \text{(C5)}$$

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

B = inhalation rate (m^3 h^{-1}) (Table C6),

L = concentration of suspended sludge in air (kg m^{-3}), (1 10^{-7} kg m^{-3})

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

O = occupancy of sewage treatment works (h y^{-1}) (Table C6).

The dose from the in-growth of progeny (eg, in-growth of ^{225}Ra and ^{225}Ac for ^{229}Th) would be:

$$D_{tw,inh} = SL_{conc}\, B\, L\, O\, (H_{e(inh)} + H_{e(inh)+n}) \qquad (C6)$$

$H_{e(inh)+n}$ = inhalation dose coefficient for progeny, n (Sv Bq^{-1}) (Table 2 of the main text).

TABLE C6 Critical group habits for exposure to sewer discharges (Smith and Jones, 2003)

Habit	Age groups		
	1 y	10 y	Adult
Occupancy of sewage treatment works (h y^{-1})[1]	–	–	2000[1]
Occupancy above sludge tanks (h y^{-1})[1]	–	–	1000[1]
Intake rates			
Inhalation at works (m^3 h^{-1})[2]	–	–	0.92
Inhalation (m^3 y^{-1})[2]	1900	5600	8100
Sewage sludge inadvertent ingestion (kg h^{-1})[3]	–	–	$5\ 10^{-6}$
Soil inadvertent ingestion (kg y^{-1})	0.044	0.018	0.0083
Food intake rates (kg y^{-1})			
Milk[4]	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

1 2000 h assumed to be working year of 50 weeks of 40 hours per week. Occupancy of sewage tank assumed to be half this (consistent with NRPB, 2002)

2 Assumed to be same as for an adult member of the public.

3 NRPB (2002)

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

C3.1.2 Doses from inadvertent ingestion of sewage sludge

Effective doses from the inadvertent ingestion of sewage sludge were calculated using equation C7:

$$D_{tw,inad} = SL_{conc}\, I_{inad}\, H_{e(ing)}\, O_{tank} \qquad (C7)$$

where $D_{tw,inad}$ = 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 C6),

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text),

O_{tank} = occupancy above sewage sludge tanks (h y^{-1}) (Table C6).

The dose from in-growth of progeny is given by:

$$D_{tw,inad} = SL_{conc}\, I_{inad}\, O_{tank}\, (H_{e(ing)} + H_{e(ing)\,+n}) \qquad \text{(C8)}$$

$H_{e(ing)\,+n}$ = inhalation dose coefficient for progeny, n (Sv Bq^{-1}) (Table 2 of the main text).

C3.1.3 Doses from exposure to sludge tanks

Effective doses from external exposure to tanks containing sewage sludge were calculated using equation C9:

$$D_{tw,ext} = D_{tw,ext(u)}\, SL_{conc}\, O_{tank} \qquad \text{(C9)}$$

where $D_{tw,ext}$ = external dose at the sewage treatment works from tanks of well-mixed sludge in the 50^{th} year of discharge (Sv y^{-1} per Bq s^{-1}),

$D_{tw,ext(u)}$ = external dose rate above tanks containing well-mixed sludge per unit activity concentration (Sv h^{-1} per Bq kg^{-1}) (Table C5).

C3.1.4 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 C10:

$$D_{tw,tot} = D_{tw,inad} + D_{tw,inh} + D_{tw,ext} \qquad \text{(C10)}$$

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

C3.2 Exposure to farmland treated with sewage sludge

Four exposure pathways were considered for the treatment of agricultural land with sewage sludge: 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 fetus, infants in the first year of life on an all-milk diet, 1 year olds, 10 year olds and adults.

C3.2.1 External exposure to treated soil

Effective doses were calculated for each age group from external exposure to land treated with sewage sludge using equation C11:

$$D_{occ,ext} = D_{ext}\, (F_{ind}\, T_{ind} + F_{out}\, T_{out}) \qquad \text{(C11)}$$

where $D_{occ,ext}$ = effective dose in the 50^{th} year of treatment due to external irradiation from radionuclides in 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 to the sewer (Sv y^{-1} per Bq s^{-1}) (Equation C4),

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.

C3.2.2 Internal exposure to treated soil

Effective doses from inhalation of resuspended material and inadvertent ingestion of soil from the top 1 cm of the soil profile were calculated using equations C12 and C13, respectively:

$$D_{inh} = A_{sp}\, B\, L_{wind}\, H_{e(inh)} \qquad \text{(C12)}$$

$$D_{inad} = A_{sp}\, I_{s,inad}\, H_{e(ing)} \qquad \text{(C13)}$$

For adults additional exposure was assumed to occur from inhalation of resuspended soil while ploughing arable land; it was assumed that pregnant women and hence the fetus was not exposed to this scenario. The dose from this additional pathway was calculated using equation C14

$$D_{inha} = B\, H_{e(inh)}\, (A_{sp}\, L_{wind} + F_{mech}\, A_{sw}\, L_{mech}) \qquad \text{(C14)}$$

where D_{inh} = effective dose 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_{inha} = effective doses to adults from inhalation of resuspended soil from pasture, and arable soil which has been ploughed, 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 = Inhalation rate (m^3 y^{-1}) (Table C6),

L_{wind} = concentration of soil in air due to ambient resuspension (kg m^{-3}),

L_{mech} = concentration of soil in air due to mechanical disturbance (kg m^{-3}),

$I_{s,inad}$ = inadvertent ingestion rate of soil (kg y^{-1}) (Table C6),

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

$H_{e(ing)}$ = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

F_{mech} = fraction of a year spent ploughing, 0.034 (300 h y^{-1}) (assumed to be the same as leisure activities, Smith and Jones, 2003)

The concentrations of suspended soil in air were assumed to be:

$L_{wind} = 10^{-7}$ kg m^{-3} ; $L_{mech} = 10^{-5}$ kg m^{-3} (Simmonds et al, 1995).

The dose from in-growth of progeny would be:

$$D_{inh} = A_{sp}\, B\, L_{wind}\, (H_{e(inh)} + H_{e(inh)+n}) \quad (C15)$$

$$D_{inad} = A_{sp}\, I_{s,inad}\, (H_{e(ing)} + H_{e(ing)+n}) \quad (C16)$$

$$D_{inha} = B\, (H_{e(inh)} + H_{e(inh)+n})\, (A_{sp}\, L_{wind} + F_{mech}\, A_{sw}\, L_{mech}) \quad (C17)$$

Where $H_{e(inh)+n}$ = inhalation dose coefficient for progeny, n (Sv Bq^{-1}) (Table 2 of the main text).

C3.2.3 Doses from ingestion of foods

Ingestion doses were calculated for each age group from ingestion of foods produced on land treated with sewage sludge using equation C18:

$$D_{food} = A_f\, I_f\, H_{e(ing)} \quad (C18)$$

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 C6),

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

Three different food types were considered: milk, cattle products (meat and offal), and sheep products (meat 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 possible food types, the one that gave rise to the maximum dose was used in the GDC calculation.

The dose from in-growth of progeny was considered for ^{229}Th (^{225}Ac and ^{225}Ra) and for ^{230}Th (^{226}Ra, ^{210}Pb and ^{210}Po) as follows:

$$D_{food} = [(A_f\, H_{e(ing)}) + (A_{f+n}\, H_{e(ing)+n})]\, I_f \quad (C19)$$

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)

A_{f+n} = activity concentrations in each food after treatment with sewage sludge (Bq kg^{-1} per Bq s^{-1}) (equation C1) for progeny, n, assuming progeny supported by parent.

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

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

C3.2.4 Total dose from farmland treated with sewage sludge.

The total effective dose per unit discharge rate due to the treatment of agricultural land with sewage sludge was calculated for each age group from each radionuclide by summing the dose estimates from the four exposure pathways described above using equation C20:

$$D_{sl,tot} = D_{food} + D_{inh} + D_{occ,ext} + D_{inad} \quad \text{(C20)}$$

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

For infants in the first year of life the doses considered were the ingestion of milk only for a 3 month old plus the inhalation, ingestion of soil and external doses for a 1 year old. The dose to a fetus was calculated only for the relevant radionuclides as discussed in the main text. The calculations were the same as those for adults except that dose coefficients for fetus were used as appropriate.

C3.3 Exposure to treated effluent discharged to a river

For the group exposed to discharges of treated sewage effluent to a river five exposure pathways were considered. The dose calculation for this group is as described in Appendix B for discharges to a river.

C4 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 a 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 C21 and the GDC for sludge disposal was calculated using equation C22. The GDC for rivers was calculated as described in Appendix B.

$$GDC_{tw} = T \text{ Dose Constraint}/D_{tw,tot} \tag{C21}$$

$$GDC_{sl} = T \text{ Dose Constraint}/D_{sl,tot} \tag{C22}$$

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 value for members of the public recommended by HPA (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

D1 INTRODUCTION

This appendix presents details of the limiting exposure pathways and age groups for the generalised derived constraints (GDCs) presented earlier. The aim is to give information that might be of use if it is necessary to reassess the doses from a proposed discharge because initial estimates are greater than about 30% of the GDC.

D2 GDCs FOR DISCHARGES TO ATMOSPHERE

The GDCs for discharge to atmosphere considered exposure of the fetus, 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. The most important exposure pathway for the GDCs for atmosphere varies depending on the radionuclide and is shown in Table D1. For almost half of the radionuclides considered, the consumption of food is the most important exposure pathway. This pathway contributes almost all the dose for ^{33}P, ^{35}S (both organic and inorganic forms), ^{75}Se, ^{65}Zn and ^{99}Tc. It is also a dominant exposure pathway for ^{14}C. For about a quarter of the radionuclides, the dose due to inhalation of the plume is the most important exposure pathway. This pathway gives 100% of the estimated dose for ^{229}Th and ^{230}Th and is also important for ^{3}H, ^{99m}Tc, ^{234}Th and ^{237}Np. For the remaining radionuclides (^{51}Cr, ^{54}Mn, ^{57}Co, ^{58}Co, ^{60}Co and ^{125}Sb), external irradiation from deposited activity is the most important exposure pathway.

It should be noted that the situation modelled in determining the GDCs is fairly cautious but could occur in practice. If the conditions were different to those modelled, for example, the discharge was from a different stack height, or the critical group was located in a different place, the limiting age groups and pathways may change. Changes to the stack height from 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 also 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.

D3 GDCs FOR DISCHARGES TO RIVERS

The GDCs for discharge to rivers were calculated for 20 radionuclides for the following age groups: fetus, infants (1 year old), children (10 years old) and adults. Table 3 of the main text indicates the limiting age group for each radionuclide. The most important exposure pathways for the GDCs for rivers vary, depending on the radionuclide as shown in Table D2. Ingestion of fish is an important exposure pathway for those radionuclides where exposure to the fetus is limiting, notably ^{32}P and ^{33}P. This pathway is also important for ^{65}Zn where the adult is the limiting age group. External dose from radionuclides on the riverbank is the most important exposure pathway for gamma emitting radionuclides such as ^{54}Mn, and ^{60}Co. The drinking water pathway contributes significantly to the GDC for ^{3}H, ^{99m}Tc, ^{125}Sb and ^{237}Np. Finally, ingestion of food due to irrigation of agricultural land with river water is important for the thorium isotopes and ^{99}Tc. 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 (Jones et al, 2006).

TABLE D1 Contributions of the different exposure pathways to the GDC for atmosphere

Radionuclide	Limiting age group	Percentage contribution to the GDC from each pathway			
		Consumption of foods	Inhalation of the plume	External irradiation from deposited material	External irradiation from the plume
^{3}H	Fetus	46	54	–	-
^{14}C	1 year old	63	37	–	-
^{32}P	Fetus	72	28	–	-
^{33}P	Fetus	98	2	–	-
^{35}S – organic	1 year old	97	3	–	-
^{35}S – inorganic	1 year old	84	16	–	-
^{51}Cr	Adult	6	18	76	-
^{54}Mn	Adult	4	3	93	-
^{57}Co	Adult	3	10	87	-
^{58}Co	Adult	2	12	86	-
^{60}Co	Adult	1	2	97	-
^{65}Zn	1 year old	93	1	6	-
^{75}Se	1 year old	94	2	4	-
^{99}Tc	1 year old	99	1	–	-
^{99m}Tc	10 year old	–	85	10	5
^{125}Sb	Adult	1	8	91	-
^{229}Th	Adult	–	100	–	-
^{230}Th	Adult	–	100	–	-
^{234}Th	Adult	2	97	1	-
^{237}Np	Adult	–	99	1	-

TABLE D2 Contributions of the different exposure pathways to the GDC for rivers

Radionuclide	Limiting age group	Percentage contribution to the GDC from each pathway				
		Drinking water	Ingestion of fish	Inhalation of resuspended material	External irradiation from sediment	Ingestion of irrigated terrestrial foods
^{3}H	Fetus	88	5	-	-	7
^{14}C	Fetus	1	97	-	-	2
^{32}P	Fetus	-	100	-	-	-
^{33}P	Fetus	-	100	-	-	-
^{35}S – organic	Fetus	12	78	-	-	10
^{35}S – inorganic	Fetus	12	78	-	-	10
^{51}Cr	Adult	21	27	-	49	3
^{54}Mn	Adult	3	11	-	85	1
^{57}Co	Adult	6	64	-	28	2
^{58}Co	Adult	5	50	-	44	1
^{60}Co	Adult	4	40	-	55	1
^{65}Zn	Adult	2	96	-	1	1
^{75}Se	Fetus	12	80	-	2	6
^{99}Tc	1 year old	14	1	-	-	85
^{99m}Tc	1 year old	95	5	-	-	-
^{125}Sb	1 year old	92	-	-	2	6
^{229}Th	Adult	1	-	-	3	96
^{230}Th	Adult	2	-	-	-	98
^{234}Th	1 year old	12	1	-	-	87
^{237}Np	1 year old	85	3	-	-	12

D4 GDCS FOR DISCHARGES TO SEWERS

The GDCs for discharge to sewers were calculated for 20 radionuclides for the following age groups: fetus, 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. The GDCs for sewers differ from the GDCs 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. Therefore, three distinct exposed groups are considered: those exposed during sewage treatment, those exposed during effluent disposal to rivers, and those exposed as a result of treatment of agricultural land with sewage sludge.

The limiting case, which is used for the resulting GDC for disposal to sewers is either the group exposed at the works or the group exposed by land treatment. Exposures from effluent disposal to rivers are not limiting for any of the radionuclides considered here. The most important exposure pathways for the GDCs for discharge to sewers vary depending on the radionuclide. For isotopes with short radioactive half-lives and which are also gamma emitting radionuclides, ie, ^{51}Cr, ^{54}Mn, ^{57}Co, ^{58}Co, ^{99m}Tc and ^{234}Th, exposures at the sewage works are limiting. This is because these radionuclides would undergo significant radioactive decay during collection, treatment and storage before application to land. Exposures to these radionuclides at the works would therefore be more important and external dose from sludge in tanks is found to be the main exposure pathway.

For the remaining radionuclides, the limiting group is that exposed due to the treatment of agricultural land with sewage sludge. The contributions to the GDC of the exposure pathways resulting from land treatment are shown in Table D3. The limiting age group for most of the radionuclides is 3 month olds due to the ingestion of milk. The fetus is only limiting for ^{33}P following ingestion of milk by the mother. Ingestion of sheep meat and offal are important for ^{75}Se and ^{237}Np. External dose from soil is important for ^{60}Co and ^{125}Sb. Inhalation of resuspended soil is important for ^{230}Th.

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

Radionuclide	Limiting age group	Percentage contribution to the GDC from each pathway			
		External irradiation from soil	Inadvertent ingestion of soil	Inhalation of resuspended soil	Ingestion of food
^{3}H	3 month old	-	-	-	100 – milk
^{14}C	1 year old	-	-	-	100 – milk
^{32}P	3 month old	-	-	-	100 – milk
^{33}P	Fetus	-	-	-	100 – milk
^{35}S – organic	3 month old	-	-	-	100 – milk
^{35}S – inorganic	3 month old	-	-	-	100 – milk
^{60}Co	Adult	99	-	-	1 – sheep and cow offal
^{75}Se	1 year old	1	-	-	99 – sheep offal
^{65}Zn	3 month old	-	-	-	100 – milk
^{99}Tc	3 month old	-	-	-	100 – milk
^{125}Sb	Adult	96	-	-	4 – sheep offal
^{229}Th	3 month old	8	22	9	61 – milk
^{230}Th	Adult	19	5	72	4- cow offal
^{237}Np	Adult	23	-	9	68– sheep offal

D4.1 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. 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 also larger, dilution of disposed radionuclides is higher and, as a result, the predicted doses may be lower. However, there are other factors which may influence the doses, including the possibility of additional exposure pathways. The effect of different sizes of sewage treatment works on the GDCs was discussed in more detail previously (NRPB, 2000).

D5 REFERENCES

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

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APPENDIX E Methods and Data Used in the Calculation of Generalised Derived Limits

E1 INTRODUCTION

The methods and data used to calculate GDLs for ^{99}Tc, ^{229}Th, ^{230}Th, ^{234}Th and ^{237}Np are given in this section where they have differ from or supplement those given previously (NRPB, 2005). Methods and data for ^{99m}Tc were all as given previously. The main difference is the inclusion of progeny in-growth for the GDLs with multiple exposure pathways.

For ^{229}Th, ^{230}Th and ^{237}Np the in-growth of radiologically significant progeny over a 50 year period was considered for GDLs with multiple exposure pathways. For ^{229}Th, all progeny were included (^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Pb) for external exposure. However for the inhalation and ingestion exposure pathways only ^{225}Ra and ^{225}Ac were included. For GDLs for well mixed soil, sea washed pasture, marine and freshwater sediment and sewage (plant operator), the progeny were assumed to be in secular equilibrium with account taken of the food concentration factor for each member of the chain. However, for the sewage applied to land exposure pathway and the irrigation exposure pathways, in-growth of progeny was modelled explicitly for the food pathways over a 50 year period. For the freshwater GDL, the progeny were assumed to be in secular equilibrium for the ingestion of drinking water and freshwater fish pathways and account was taken of the element specific sediment and fish concentration factors for the chain members.

For ^{230}Th progeny, in-growth was more complex and depended on the particular GDL and related exposure pathways. For well mixed soil, marine and freshwater sediment and sea washed pasture GDLs, the in-growth of all progeny (^{226}Ra, ^{210}Pb, ^{210}Po) over a 50 year period was included. In this case the total GDLs for each chain member were added, accounting for the fraction of the progeny ingrown over 50 years in soil, ie,

$$\frac{1}{GDL_{Th230chain}} = \sum_{nuc=4} \frac{Act_{nuc}}{GDL_{nuc}} \qquad \text{(E1)}$$

Where:

for nuc =1 (^{230}Th) Act_{nuc} = 0.71

for nuc =2 (^{226}Ra) Act_{nuc} = 0.015

for nuc =3 (^{210}Pb) Act_{nuc} = 0.0075

for nuc =4 (^{210}Po) Act_{nuc} = 0.0074

For GDLs where a repeated application of the source occurred, eg, application of sewage sludge to land for GDLs for sewage, only in-growth of progeny in foods was included. No progeny in-growth was included for irrigation pathways for the freshwater

GDL or for the sewage plant operator exposure pathways for the sewage GDL, as the doses from the progeny were insignificant compared to those of the parent.

For ^{237}Np, ^{233}Pa was only included for external exposure from sediment and soil and also for ingestion of foods for the GDLs for well mixed soil and seawashed pasture. For ^{234}Th, short-lived ^{234m}Pa was included for all external exposure pathways.

E2 METHODS AND DATA USED

E2.1 External gamma exposure

External exposure is modelled as described previously (NRPB, 2005), with the effective dose, including doses from progeny in-grown over a 50 year period. The effective external dose rates 1 m above the various materials considered in calculating GDLS are given in Tables E1 and E2.

TABLE E1 Integrated effective gamma dose rates per unit activity concentration above well-mixed soil, sediments and sewage sludge

	Effective gamma dose rates (Sv y^{-1} per Bq kg^{-1})		
Radionuclide	Well-mixed soil	Sediments	Sewage sludge in tanks
^{229}Th	2.73 10^{-7}	2.88 10^{-7}	5.30 10^{-7}
^{230}Th	2.63 10^{-10}	2.69 10^{-10}	1.48 10^{-9}
^{226}Ra [3]	2.50 10^{-6}	2.80 10^{-6}	Not considered [1]
^{210}Pb [3]	5.30 10^{-10}	4.90 10^{-10}	Not considered [1]
^{210}Po [3]	5.60 10^{-12}	6.10 10^{-12}	Not considered [1]
^{234}Th	Not considered [2]	Not considered [2]	3.60 10^{-9}
^{237}Np	2.19 10^{-7}	2.34 10^{-7}	4.31 10^{-7}

1 Not sufficient in-growth of progeny from parent ^{230}Th

2 Half life too small to allow for equilibrium in soil and sediments

3 Denotes progeny of ^{230}Th

Table E2 Activity concentrations and external dose rates in the 50th year above soil per unit deposit

	50th year activity concentration (Bq kg^{-1} per Bq m^{-2} y^{-1})		Effective gamma dose rates (Sv y^{-1} per Bq m^{-2} y^{-1})	
Parent	In top 0.30m of well mixed soil (irrigation)	In top 0.01m of undisturbed soil (sewage application)	Above well-mixed soil	Above undisturbed soil
^{99}Tc	1.13 10^{-1}	3.30 10^{-1}	-	-
^{229}Th	1.12 10^{-1}	3.29 10^{-1}	3.27 10^{-8}	6.98 10^{-8}
^{230}Th	1.13 10^{-1}	3.30 10^{-1}	2.89 10^{-9}	4.00 10^{-9}
^{234}Th	2.54 10^{-4}	7.44 10^{-3}	5.50 10^{-12}	3.41 10^{-11}
^{237}Np	1.13 10^{-1}	3.30 10^{-1}	2.73 10^{-8}	5.84 10^{-8}

The external gamma dose component of the multiple pathway GDLs is given by the following equations.

$$\mathrm{GDL}_{\mathrm{ex}} = \frac{D}{E} \qquad \text{(E2)}$$

where GDL_{ex} = GDL for external gamma exposure (Bq kg^{-1}),

D = effective dose limit of 10^{-3} Sv y^{-1},

E = effective dose from external irradiation from a unit activity concentration in the materials for each age group (Sv y^{-1} per Bq kg^{-1}).

For soils, E is given by

$$E = G\,(F_{\mathrm{ind}}\,T_{\mathrm{ind}} + F_{\mathrm{out}}\,T_{\mathrm{out}}) \qquad \text{(E3)}$$

where G = external effective dose 1 m above the materials, integrated over 1 year (Sv y^{-1} per Bq kg^{-1}),

F_{ind} = fraction of a year spent indoors (dimensionless),

T_{ind} = indoor location factor (dimensionless),

F_{out} = fraction of a year spent outdoors (dimensionless),

T_{out} = outdoor location factor (dimensionless).

The term location factor is defined as the ratio of the dose received in the protected location (indoors or outdoors) to that received outdoors over undisturbed pasture, for the period during which the person is in that location. The term location factor therefore describes the shielding offered at a particular location compared with a situation where no shielding is available.

E2.2 Inhalation of resuspended materials

The exposure from the inhalation of resuspended materials is modelled as described previously, (NRPB, 2005) except that for ^{229}Th, the progeny ^{225}Ra and ^{225}Ac are included in secular equilibrium as given in the following equations.

Mechanical and ambient resuspension for adult exposure is calculated for GDLs for well mixed soil, sewage sludge and freshwater as follows:

$$\mathrm{GDL}_{\mathrm{inh}} = \frac{D}{(O_{\mathrm{mech}}\,L_{\mathrm{mech}} + O_{\mathrm{wind}}\,L_{\mathrm{wind}})\,B\,(H_{e(inh)} + H_{e(inh)+n})} \qquad \text{(E4)}$$

where GDL_{inh} = GDL for inhalation of resuspended materials (Bq kg^{-1}),

D = effective dose limit of 10^{-3} Sv y^{-1},

$H_{e(inh)}$ = dose coefficient for inhalation (Sv Bq^{-1}),

$H_{e(inh)+n}$ = dose coefficient for inhalation for progeny, n (Sv Bq^{-1}),

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

O_{mech} = occupancy in air containing mechanically disturbed soil (h y^{-1})

L_{mech} = concentration of soil in air due to mechanical disturbance (kg m^{-3}),

O_{wind} = occupancy above materials for ambient resuspension (h y^{-1}),

L_{wind} = concentration in air due to ambient resuspension (kg m^{-3}).

The GDL for the inhalation of resuspended materials due to ambient resuspension is calculated as follows. This is used in the calculation of GDLs for well mixed soil, sewage sludge, freshwater, freshwater and marine sediment and sea-washed pasture and also to calculate GDLs for sewage in tanks at the sewage works.

$$\mathrm{GDL_{inh}} = \frac{D}{O_{\mathrm{mech}}\ L_{\mathrm{mech}}\ B\,(H_{e(inh)} + H_{e(inh)+n})} \qquad \text{(E5)}$$

where GDL_{inh} = GDL for inhalation of resuspended materials (Bq kg^{-1}),

D = effective dose limit of 10^{-3} Sv y^{-1},

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

O_{wind} = occupancy above materials for ambient resuspension (h y^{-1}),

L_{wind} = concentration in air due to ambient resuspension (kg m^{-3}).

$H_{e(inh)}$ = dose coefficient for inhalation (Sv Bq^{-1}),

$H_{e(inh)+n}$ = dose coefficient for inhalation for progeny, n (Sv Bq^{-1}),

E2.3 Inadvertent ingestion

For inadvertent ingestion the dose is modelled in the same way as described previously (NRPB, 2005) except that for ^{229}Th the progeny ^{225}Ra and ^{225}Ac are included in secular equilibrium as given in the following equation. This exposure pathway was included in the calculation of GDLs for marine and freshwater sediments, sea washed pasture, well-mixed soil, sewage sludge and freshwater.

$$GDL_a = \frac{D}{I_a\,(H_{\mathrm{e(ing)}} + H_{\mathrm{e(ing)}+n})\,O_m} \qquad \text{(E6)}$$

Where GDL_a = GDL for inadvertent ingestion of materials for each age group (Bq kg^{-1}),

D = effective dose limit of 10^{-3} Sv y^{-1},

I_a = inadvertent ingestion rate for each age group (kg h^{-1}),

$H_{e(ing)}$ = dose coefficient for ingestion (Sv Bq^{-1}),

$H_{e(ing)+n}$ = dose coefficient for ingestion for progeny, n (Sv Bq^{-1}),

O_m = number of hours per year each age group is exposed (h y^{-1}).

In some cases, eg, well-mixed soil, 100% occupancy of the area is assumed and allowance only has to be made for the time spent indoors. In these cases, I_a is replaced by the annual inadvertent ingestion rate (kg y^{-1}) taking into account indoor occupancy and O_m is no longer required.

The activity concentrations in soil of the progeny of ^{229}Th are assumed to be in secular equilibrium with the parent for both ingestion and inhalation pathways. For GDLs for sewage and freshwater, the soil concentration is modelled for a 50 year application of sewage sludge or irrigation water. This model is described in Appendix B of NRPB, 2005. The concentrations in soil for all radionuclides are given in Table E2.

E2.4 Ingestion of terrestrial foods

The GDLs for well-mixed soil, grass (^{99}Tc only), sea washed pasture and farmland treated with sewage sludge or irrigated with freshwater have contributions from ingestion of terrestrial foods. For ^{229}Th, the in-growth of the progeny ^{225}Ra and ^{225}Ac is included, while for ^{230}Th, the in-growth of the progeny ^{226}Ra, ^{210}Pb and ^{210}Po is included for all the above GDLs except for freshwater and grass. For ^{237}Np the in-growth of ^{233}Pa is only included for the GDLs for well mixed soil and sea washed pasture.

The GDLs for each foodstuff produced on well-mixed soil and sea washed pasture for ^{229}Th and ^{237}Np are give in equation E7 (see Section E1 for approach used for ^{230}Th).

$$\mathrm{GDL_f} = \frac{D}{I_\mathrm{f}\ (H_{e(ing)} C_\mathrm{sf} + H_{e(ing)+n} C_{\mathrm{sf}+n})} \qquad \text{(E7)}$$

where GDL_f = GDL for the ingestion of food (f), grown on contaminated soil for each age group (Bq kg^{-1} or Bq l^{-1}),

D = effective dose limit of 10^{-3} Sv $y^{-}1$,

I_f = food ingestion rate (kg y^{-1} or l y^{-1}),

$H_{e(ing)}$ = dose coefficient for ingestion (Sv Bq^{-1}),

$H_{e(ing)+n}$ = dose coefficient for ingestion for progeny, n (Sv Bq^{-1}),

C_{sf} = concentration factor relating the radionuclide activity concentration in soil to the radionuclide activity concentration in food (Bq kg^{-1} or Bq l^{-1} in food per Bq kg^{-1} in the soil).

C_{sf+n} = concentration factor relating the radionuclide activity concentration in soil to the radionuclide activity concentration in food (Bq kg^{-1} or Bq l^{-1} in food per Bq kg^{-1} in the soil) for progeny n for ^{229}Th and ^{237}Np.

For animals C_{sf} is given by:

$$C_{sf} = \frac{A_f}{A_S} \qquad \text{(E8)}$$

And

$$C_{\mathrm{sf}} = C_{\mathrm{f(p-a)}} \left(C_{\mathrm{f(s-p)}} \, I_{\mathrm{p}} + I_{\mathrm{s}} \right) \qquad \text{(E9)}$$

where C_{sf} = concentration factor relating the activity concentration in the food to the activity concentration in the soil (Bq kg^{-1} or Bq l^{-1} per Bq kg^{-1} dry mass soil),

A_f = activity concentration in the plant (Bq kg^{-1} fresh mass),

A_s = activity concentration in the soil (Bq kg^{-1} dry mass),

$C_{f(s-p)}$ = equilibrium concentration factor relating the activity concentration in food crops to the activity concentration in soil (Bq kg^{-1} fresh mass plant per Bq kg^{-1} dry mass soil),

$C_{f(p-a)}$ = equilibrium concentration factor for the transfer of activity to animal products arising from a daily intake of activity in the animal diet (Bq kg^{-1} or Bq l^{-1} per Bq d^{-1}), (Note for milk products the factor is the value for milk multiplied by 11)

I_p = animal food intake (kg d^{-1} fresh mass),

I_s = intake of soil by cattle or sheep (kg d^{-1} dry mass).

The element-dependent equilibrium concentration factors between soil and plant, and between animal diet and animal products are given in Table E3. These values were obtained from a review of published data (Ewers et al, 2003). Other parameter values are as described previously (NRPB, 2005) except for ^{99}Tc where values were taken from Ewers, 2010. The values of C_{sf} for vegetables are the same as $C_{f(s-p)}$ and are also given in Table E3.

The GDLs for foodstuffs derived from land treated with sewage sludge or irrigated with freshwater used activity concentrations predicted by the dynamic foodchain model, FARMLAND (Brown and Simmonds, 1995) following deposition of the radionuclides. The general modelling approach adopted is described below. The following equation gives the activity concentration in foods from application of sewage or irrigation water to farmland.

$$A_{\mathrm{f}} = A_{\mathrm{f(u)}} \, R_{\mathrm{s}} \qquad \text{(E10)}$$

where A_f = food product activity concentration in the 50th year; from conditioning of farmland with sewage sludge (Bq kg^{-1} per Bq kg^{-1} of sludge) or from irrigating land (Bq kg^{-1} per Bq l^{-1} of water),

$A_{f(u)}$ = food product activity concentration in the 50th year per unit deposition (Bq kg^{-1} per Bq m^{-2} y^{-1}) (See Appendices B and C),

R_s = soil conditioning rate with sewage sludge (kg m^{-2} y^{-1}) or irrigation (l m^{-2} y^{-1} (taken to be 100 kg m^{-2} y^{-1})).

Table E3 Element dependent transfer parameters

(a) Concentration factor from soil to plant (Bq kg^{-1} food per Bq kg^{-1} soil)

Food type	Element							
	Tc	Th	Ra	Ac	Pb	Po	Np	Pa
Domestic fruit	$5\ 10^{-1}$	$5\ 10^{-4}$	$3\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$	$4\ 10^{-3}$	$2\ 10^{-3}$	$4\ 10^{-2}$
Potatoes	$5\ 10^{-1}$	$5\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$2\ 10^{-3}$	$3\ 10^{-3}$	$1\ 10^{-3}$	$4\ 10^{-2}$
Green vegetables	$5\ 10^{-1}$	$5\ 10^{-4}$	$3\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$	$4\ 10^{-3}$	$2\ 10^{-3}$	$4\ 10^{-2}$
Pasture	$5\ 10^{0}$	$5\ 10^{-4}$	$1\ 10^{-2}$	$1\ 10^{-3}$	$1\ 10^{-2}$	$6\ 10^{-3}$	$1\ 10^{-2}$	$4\ 10^{-2}$

(b) Equilibrium factors for uptake of activity from animal intakes to animal products (Bq kg^{-1} or Bq l^{-1} food per Bq d^{-1} animal intake)

Food type	Element							
	Tc	Th	Ra	Ac	Pb	Po	Np	Pa
Cow meat	$1\ 10^{-2}$	$1\ 10^{-4}$	$5\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-3}$	$3\ 10^{-3}$	$1\ 10^{-4}$	$1\ 10^{-3}$
Sheep meat	$1\ 10^{-1}$	$1\ 10^{-3}$	$5\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$	$5\ 10^{-2}$	$4\ 10^{-4}$	$1\ 10^{-2}$
Cow offal	$4\ 10^{-2}$	$1\ 10^{-3}$	$5\ 10^{-4}$	$2\ 10^{-2}$	$2\ 10^{-3}$	$8\ 10^{-2}$	$2\ 10^{-2}$	$5\ 10^{-4}$
Sheep offal	$3\ 10^{-1}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$2\ 10^{-1}$	$9\ 10^{-2}$	$6\ 10^{-1}$	$3\ 10^{-2}$	$5\ 10^{-3}$
Milk	$3\ 10^{-4}$	$5\ 10^{-6}$	$7\ 10^{-5}$	$3\ 10^{-6}$	$3\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-6}$	$5\ 10^{-6}$
Milk products	$3.3\ 10^{-3}$	$5.5\ 10^{-5}$	$7.7\ 10^{-4}$	$3.3\ 10^{-5}$	$3.3\ 10^{-3}$	$1.1\ 10^{-3}$	$1.1\ 10^{-5}$	$5.5\ 10^{-5}$

(c) Fish concentration factors and sediment water distribution coefficients for freshwater (Bq kg^{-1} food per Bq $litre^{-1}$)[1]

Material	Element				
	Tc	Th	Ra	Ac	Np
Fish[2]	$1.5\ 10^{1}$	$3\ 10^{1}$	$5\ 10^{1}$	$3\ 10^{1}$	$1\ 10^{1}$
Sediment[3]	$2\ 10^{2}$	$5\ 10^{6}$	$5\ 10^{2}$	$1\ 10^{4}$	$3\ 10^{4}$

1 Tc, Th, Np using same references as Appendix B

2 Ra and Ac from Thompson et al, 1972

3 Ra from IAEA, 2001; Ac assumed high, based on NCRP, 1996.

Generalised derived limits for grass were calculated for ^{99}Tc only using the same methodology as described in NRPB, 2005 as given below.

$$\mathrm{GDL}_{f(grass)} = \frac{\mathrm{GDL}_f}{I_a C_{f(p-a)}} \qquad \text{(E11)}$$

Where $\mathrm{GDL}_{f(grass)}$ = GDL for each foodstuff (f) produced on contaminated grass for each age group (Bq kg^{-1} or Bq l^{-1})

GDL_f = GDL for each foodstuff (Bq kg^{-1} or Bq l^{-1})

$C_{f(p-a)}$ = fraction of the daily activity intake via grazing animal diet transferred to a unit mass of foodstuff (Bq kg^{-1} or Bq l^{-1} of foodstuff per Bq d^{-1} ingested) (see Table E3)

I_a = amount eaten per animal per day (kg d$^{-1)}$

E2.5 Freshwater exposure pathways

For all radionuclides except for ^{229}Th, the freshwater exposure pathways were modelled as described previously (NRPB, 2005). The GDL for freshwater (expressed as whole water, for both dissolved and suspended fractions) has a unique method of derivation. The GDL is divided into two main components: exposure associated with aquatic exposure pathways and exposure due to irrigation (as given above). The GDLs from aquatic exposure pathways for ^{229}Th were derived from the GDLs calculated for each exposure pathway using the methods given below.

a) For inhalation and external exposure from shoreline sediments

The GDL for freshwater expressed in terms of the activity concentration in unfiltered water (ie, including the dissolved and solid phases) was derived using the following equation. For these pathways it is only necessary to consider the parent, ^{229}Th, as the contribution from the progeny is negligible.

$$GDL_{fwater} = \frac{GDL_{aqex}(1 + K_d S)}{K_d} \qquad \text{(E12)}$$

where GDL_{fwater} = GDL for freshwater (dissolved and suspended fraction) for parent ^{229}Th (Bq l^{-1}),

GDL_{aqex} = GDL for the aquatic exposure pathways: inhalation of and external exposure from shoreline sediment for parent ^{229}Th (Bq kg^{-1}),

K_d = freshwater sediment water distribution coefficient (Bq kg^{-1} per Bq l^{-1}) of parent ^{229}Th, (Table E3)

S = freshwater suspended sediment load (kg l^{-1}).

b) For ingestion of water and freshwater fish

It is assumed that for these exposure pathways ^{229}Th is in secular equilibrium with its progeny ^{225}Ra and ^{225}Ac and the GDLs are, therefore, summed over the progeny.

i) For drinking water:

The GDL for freshwater for the drinking water exposure pathway, expressed in terms of unfiltered water (ie, including the dissolved and solid phase) was derived using the following equation.

$$GDL_{fwater} = GDL_{dw}(1 + k_d S) + GDL_{dw+n}(1 + k_{d+n} S) \qquad \text{(E13)}$$

Where GDL_{dw} = GDL for the aquatic exposure pathways for unfiltered drinking water for ^{229}Th ($Bq\ kg^{-1}$),

GDL_{dw+n} = GDL for the aquatic exposure pathways for unfiltered drinking water for the progeny, n ($Bq\ kg^{-1}$),

K_d = freshwater sediment water distribution coefficient ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$) of parent ^{229}Th,

K d+n = freshwater sediment water distribution coefficient ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$) of progeny, n, (see Table E3).

ii) For freshwater fish:

The GDL for freshwater for the ingestion of fish exposure pathway, expressed in terms of unfiltered water (ie, dissolved and solid phase) was derived using equation E14.

$$GDL_{fwater} = \frac{GDL_{fwf}(1+k_d S)}{C_f} + \frac{GDL_{fwf+n}(1+k_{d+n} S)}{C_{f+n}} \quad \text{(E14)}$$

Where GDL_{fwf} = GDL for the ingestion of fish exposure pathway for the parent ^{229}Th ($Bq\ kg^{-1}$),

GDL_{fwf+n} = GDL for the ingestion of fish exposure pathway for the progeny, n ($Bq\ kg^{-1}$),

K_d = freshwater sediment water distribution coefficient ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$) of parent ^{229}Th,

K_{d+n} = freshwater sediment water distribution coefficient ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$) of progeny, n, (see Table E3).

C_f = concentration factor between fish and filtered water for parent ^{229}Th ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$), (see Table E3)

C_{f+n} = concentration factor between fish and filtered water for progeny, n ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$), (see Table E3).

E2.6 The transfer of technetium to food

As discussed in Appendix A, a review by Ewers, 2010, indicated that the appropriate value for the soil to plant transfer factor for technetium is 5 for fresh deposits and 0.5 for older deposits for transfer to crops. The soil to plant transfer factor for technetium remains as 5 for pasture for all situations. In calculating the GDLs, it is assumed that technetium will behave as an aged deposit for well mixed soil, seawashed pasture and sewage sludge applied to land, and a fresh deposit for freshwater when applied to land during irrigation.

E3 IMPORTANT EXPOSURE PATHWAYS FOR GDLS

Details of the limiting exposure pathways and age groups are presented here for the multiple exposure pathway GDLs. This supplements the information given previously (NRPB, 2005). Six tables (E4 to E9) are presented in this section, which give the percentage contribution of each exposure pathway to the overall GDL (note that the percentages are rounded to the nearest whole number so may not add up to 100% and 0 means less than 0.5%). The GDL for grass was only considered for ^{99}Tc and for this the most important exposure pathway and limiting age group was the ingestion of milk by infants. The information presented here will be of use if the screening level (10% of the GDL) is exceeded as discussed elsewhere (NRPB, 2005).

Table E4 Contributions of exposure pathways to the GDL for well- mixed soil

Nuclide	Limiting age group	Inhalation of resuspended material (%)	Ingestion of food produced on contaminated soil (%)	Inadvertent ingestion of soil (%)	External Irradiation (%)
^{99}Tc	1 year	0	100	0	0
^{229}Th	Adult	47	29	1	23
^{230}Th	1 year	3	82	11	4
^{237}Np	Adult	27	33	0	40

Table E5 Contributions of exposure pathways to the GDL for sea-washed pasture

Nuclide	Limiting age group	Inhalation of resuspended material (%)	Ingestion of food produced on sea-washed pasture (%)	Inadvertent ingestion of soil (%)	External Irradiation (%)
^{99}Tc	1 year	0	100	0	0
^{229}Th	3 month	0	100	0	0
^{230}Th	1 year	0	99	1	0
^{237}Np	Adult	5	41	1	53

Table E6 Contributions of exposure pathways to the GDL for fresh water sediment

Nuclide	Limiting age group	Inhalation of resuspended material (%)	Inadvertent ingestion of sediments (%)	External Irradiation (%)
^{99}Tc	1 year	0	100	0
^{229}Th	10 year	13	23	64
^{230}Th	10 year	10	28	62
^{237}Np	Adult	7	2	91

Table E7 Contributions of exposure pathways to the GDL for application of sewage sludge to farmland

Nuclide	Limiting age group	Inhalation of resuspended material (%)	Ingestion of animal products from pasture treated with sewage sludge (%)	Inadvertent ingestion of treated soil (%)	External Irradiation (%)
^{99}Tc	1 year	0	100	0	0
^{229}Th	Adult	14	40	33	13
^{230}Th	Adult	68	8	5	19
^{234}Th	Adult	0	1	1	98
^{237}Np	Adult	9	70	0	21

Table E8 Contributions of exposure pathways to the GDL sewage sludge based on exposure of the plant operator at the sewage works

Nuclide	Limiting age group	Inhalation of resuspended material (%)	Inadvertent ingestion of sewage materials (%)	External Irradiation (%)
^{99}Tc	Adult	19	81	0
^{229}Th	Adult	20	4	76
^{230}Th	Adult	68	28	4
^{234}Th	Adult	0	4	96
^{237}Np	Adult	8	1	91

Table E9 Contributions of exposure pathways to the GDL for freshwater

Nuclide	Limiting age group	Inhalation of resuspended material from sediment (%)	Ingestion of drinking water (%)	Ingestion of foods irrigated by freshwater (%)	Ingestion of freshwater fish	Inadvertent ingestion of irrigated soil (%)	Inhalation of resuspended material from irrigated soil (%)	External Irradiation from shoreline sediments (%)	External Irradiation from irrigated soil (%)
^{99}Tc	1 year	0	14	85	1	0	0	0	0
^{229}Th	10 year	9	25	5	17	0	0	44	0
^{230}Th	Adult	12	1	22	1	0	1	63	0
^{234}Th[1]	1 year		10	89	1	0	0		0
^{237}Np	Adult	6	12	4	4	0	0	73	1

1 Not considered for exposure from shoreline sediments.

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