



NSW Biosolids Guideline Review

Identification of key exposure pathways to assess risks from HHCB, triclosan, chlordane and PBDEs in biosolids

Department of Planning and Environment



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Abbreviations

µg	micrograms
%	per cent
<	less than
ASC NEPM	<i>National Environment Protection (Assessment of Site Contamination) Measure</i>
atm	standard atmosphere
BAF	bioaccumulation factor
BAS	biosolids-amended soil
BCF	bioconcentration factor
bw	body weight
C&R	Contaminants and Risk Team
d	day
DAF	dilution and attenuation factor
deca-BDE	decabromodimethyl ether
DI	daily intake
DPE	Department of Planning and Environment
dw	dry weight
ECCC	Environment and Climate Change Canada
ECHA	European Chemicals Agency
EHG	Environment and Heritage Group
EPA	Environment Protection Authority
EQS	environmental quality standard
ERA	ecological risk assessment
FSANZ	Food Standards Australia New Zealand
g	grams
ha	hectares
HHCB	4,6,6,7,8,8-hexamethyl-1,3,4,6,7,8-hexahydrocyclopenta[g]isochromene; Galaxolide
HHERA	human health and ecological risk assessment
HHRA	human health risk assessment
HIL	health investigation level
kg	kilograms
K _{OC}	organic carbon-water partition coefficient
K _{OW}	octanol-water partition coefficient
LOR	limit of reporting

mg	milligrams
mL	millilitres
MOS	margin of safety
na	not available
nd	not determined
ng	nanograms
OC	organic carbon
octa-BDE	octabromodiphenyl ether
PBDE	polybrominated diphenyl ether
penta-BDE	pentabromodiphenyl ether
PFAS	per- and poly-fluoroalkyl substances
PNEC	predicted no effect concentration
POPs	persistent organic pollutants
RfD	reference dose
RQ	risk quotient
RQ _{ECO}	ecological risk quotient
RQ _{HH}	human health risk quotient
RSL	regional screening level
SOM	soil organic matter
STP	sewage treatment plant
t	tonnes
TDI	tolerable daily intake
TF	transfer factor
UCL	upper confidence limit
US EPA	United States Environmental Protection Agency
ww	wet weight
WWTP	wastewater treatment plant

Executive summary

Background and scope

In 2016, the NSW Environment Protection Authority (EPA) funded a project to identify contaminants in biosolids which require further consideration due to potential ecological or human health risks (the Contaminants Review: WCA 2016). The Contaminants Review identified HHCB¹ (also known as Galaxolide), triclosan, polybrominated diphenyl ethers (PBDEs) and chlordane, as contaminants that need further investigation in Australia due to potential risks and a lack of Australian-specific data².

Following this work, the NSW EPA conducted a biosolids sampling program of 20 sewage treatment plants (STPs) in NSW to determine concentrations of a range of contaminants, including HHCB, triclosan, PBDEs and chlordane. The EPA provided these data to the Contaminants and Risk Team (C&R) in the Environment, Energy and Science (EES) Group of the NSW Department of Planning, Industry and Environment³ to undertake a risk assessment to help determine if the concentrations warranted regulation. The chlordane dataset collected from the 20 STPs had laboratory quality-control issues with recoveries, and therefore the EPA provided an alternative chlordane dataset which contained monitoring data from 33 STPs across NSW collected between 1996 and 2016. C&R used the chlordane data from 2016 in this dataset for the risk assessment, which included data from 24 STPs. The aim of the risk assessment was to determine if HHCB, triclosan, PBDEs and chlordane in biosolids require regulation and to identify key exposure pathways to derive thresholds for these contaminants in biosolids.

The type of risk assessment required for each contaminant was determined by the outcomes of the Contaminants Review (WCA 2016). Based on the Contaminants Review:

- HHCB, triclosan and chlordane were identified as contaminants with potential ecological risks, and therefore C&R undertook an ecological risk assessment (ERA) for these 3 contaminants.
- PBDEs and chlordane were identified as contaminants with possible dietary exposure and potential risks to human health, and therefore C&R undertook a human health risk assessment (HHRA) for these 2 contaminants.

The scope of this assessment was to:

- undertake an ERA (HHCB, triclosan and chlordane) and HHRA (PBDEs and chlordane) considering 4 scenarios of biosolids use requested by the EPA:
 - Scenario 1 – land application of ‘unrestricted use’ biosolids in residential gardens
 - Scenario 2 – land application of ‘unrestricted use’ biosolids for land rehabilitation⁴

¹ 4,6,6,7,8,8-hexamethyl-1,3,4,6,7,8-hexahydrocyclopenta[g]isochromene

² PFAS were another key group of contaminants identified in the Contaminants Review; these were assessed in a separate detailed risk assessment by C&R.

³ Now the Environment and Heritage Group (EHG) of the NSW Department of Planning and Environment.

⁴ Scenario 2 assumes land will not be used for agriculture in the future.

- Scenario 3 – land application of ‘restricted use’ biosolids in agriculture⁵, considering:
 - o a low and high application rate
 - o single and repeat applications
- Scenario 4 (additional scenario) – land application of ‘unrestricted use’ biosolids in agriculture
- use the results from the risk assessment to determine if HHCB, triclosan, PBDEs and chlordane require regulation in biosolids and identify key exposure pathways to derive biosolids thresholds for these contaminants
- make recommendations on suitable next steps.

Summary of available data

The NSW EPA sampled biosolids from 20 STPs, within Sydney and regional areas, to represent a range of different potential sources and treatment types. C&R used the HHCB, triclosan and PBDE data for the risk assessment presented in this report. As noted above, an alternative dataset from routine monitoring of 24 STPs was used for chlordane. For the risk assessment, C&R used the 95% upper confidence limit of the mean (95UCL)⁶ and the maximum concentrations⁷ for each contaminant. A summary of the data is provided below:

- HHCB was detected in all the biosolids samples collected by the EPA, and concentrations ranged from 420 to 68,000 µg/kg dry weight (dw) (95UCL = 30,000 µg/kg dw).
- Triclosan was detected in biosolids from all but one of the STPs sampled, and concentrations ranged from < 30 µg/kg (< limit of reporting) to 18,000 µg/kg dw (95UCL = 5,500 µg/kg dw).
- For the PBDE risk assessment, data were separated into 2 groups: Br1–Br9 (sum of PBDEs with between 1 and 9 bromine atoms) and Br10 (fully brominated deca-BDE). This was done due to differences in toxicity and environmental fate between these groups.
 - PBDE compounds in the Br1–Br9 group were detected in all biosolids samples collected by the EPA, and concentrations ranged from 17 to 240 µg/kg dw (95UCL = 110 µg/kg dw).
 - Deca-BDE (Br10) was detected in all of the biosolids samples, and concentrations ranged from 50 to 210,000 µg/kg dw (95UCL = 23,000 µg/kg dw). The maximum Br10 concentration occurred in one STP and was 300-fold higher compared to the next highest concentration (700 µg/kg dw). To address this, the risk assessment was conducted for Br10 using both the full dataset (i.e. maximum = 210,000 µg/kg dw and 95UCL = 23,000 µg/kg dw) and the dataset omitting the exceptionally high data from the one STP (i.e. maximum = 700 µg/kg dw and 95UCL = 360 µg/kg dw).

⁵ Scenario 3 includes rehabilitated land that will be used for agriculture in the future.

⁶ The 95UCL represents the upper limit of the true average concentration with 95% confidence. It is dependent on the number of samples and the variability.

⁷ For chlordane, the 95th percentile was used as the ‘maximum’ concentration due to the large dataset available (approx. 300 measurements).

- The chlordane dataset was extensive and included approximately 300 measurements. Chlordane was detected in approximately 40% of the samples and concentrations ranged from < 5 to 140 µg/kg dw (sum of *cis*- and *trans*-chlordane) (95UCL = 11 µg/kg dw). Due to the extensive chlordane dataset, C&R used the 95th percentile of chlordane concentrations as the 'maximum' concentration in the chlordane risk assessments (i.e. 27 µg/kg dw). This was done to represent a realistic maximum concentration but also remove any concentrations that were abnormally high. This approach was not used for the other contaminants due to the small dataset that did not account for temporal variability.

Human health and ecological risk assessment

Summary of the risk assessment method

The risk assessment approach for both ecological and human health was based on the draft report *Identification of key exposure pathways to assess risks from PFAS in biosolids* prepared by C&R (the PFAS biosolids report). The risk assessment was conducted according to current national guidance. This is a generic risk assessment and not linked to any specific biosolids land-application sites. To account for this and the uncertainties in the data and parameters, realistic but precautionary assumptions have been used in most cases. This level of conservatism is warranted in this case as the outcomes are used to determine if regulation is required. The risk calculations should not be used to conclude there is risk posed from biosolids land application at specific sites. This would require a site-specific risk assessment.

Ecological risks were assessed for HHCB, triclosan and chlordane by dividing the concentrations in biosolids-amended soil by relevant screening criteria to calculate an ecological risk quotient (RQ_{ECO}). Human health risks were assessed for chlordane and PBDEs by either dividing the concentration in biosolids-amended soil by relevant screening criteria or estimating daily intakes (DIs) relative to a tolerable daily intake (TDI) ('safe' doses). Both approaches resulted in a human health risk quotient (RQ_{HH}) and the approach used depended on the availability of relevant screening criteria.

An RQ above 1 indicates that either the concentration is above the screening criteria or the predicted DI is above a TDI. An RQ of 1 is commonly used in site risk assessments to determine if the risk is low (i.e. when RQ < 1). However, in this HHERA, if the RQ for the key pathway was above 0.2, C&R has recommended that thresholds in biosolids are derived. An RQ of 0.2 instead of 1 was used to allow for a margin of safety (MOS) of 5 and account for uncertainties in the data, for example:

- There are uncertainties in the biosolids contaminant concentrations – this risk assessment for HHCB, triclosan and PBDEs is based on contaminant concentrations from 20 STPs across NSW, and it is not known if, or the extent to which, these concentrations may vary over time and at other STPs not included in the EPA sampling program.
- There is a lack of endorsed Australian ecotoxicity data for these contaminants, adding to the uncertainty of potential ecological effects which are likely to be a risk driver in many instances.

The exposure pathway (human health or ecological) with the highest RQ was identified as the key exposure pathway for each of the scenarios 1 to 4. C&R has recommended that any threshold derivation process should be based on these key exposure pathways to ensure all relevant human health and ecological pathways are protected.

Where RQs were less than 0.2, C&R has concluded the risk from that pathway is low. If this was the case for all pathways for a scenario, C&R has concluded that a threshold is not necessary based on the available data. This may need to be reviewed if additional data shows a large variation in concentrations above the 5-fold MOS.

Results from each scenario

Scenario 1 – unrestricted use biosolids in residential gardens

Scenario 1 assessed the ecological and human health risk from use of unrestricted use biosolids in a residential garden. In this scenario it was assumed that biosolids are processed with another waste material (e.g. garden waste) containing none of the assessed contaminants to produce the unrestricted use biosolids. Based on information provided to C&R from the EPA, this is regularly done to produce unrestricted use biosolids in NSW. The assumed ratio in the unrestricted use biosolids was 1-part biosolids to 2-parts other waste, which is the highest ratio reported to be used for this purpose by a number of NSW water utilities (based on information provided to C&R from the EPA). In the risk assessment, it was assumed the unrestricted use biosolids product could be applied to a residential garden without any restrictions on the application rate. Therefore, contaminant concentrations in the unrestricted use biosolids were estimated and used as the biosolids-amended soil concentrations in the risk calculations.

The ecological assessment considered direct toxicity to terrestrial organisms as the only relevant ecological exposure pathway in this scenario. The RQ_{ECO} values exceeded 1 for HHCB and triclosan (30 and 92, respectively), and ranged up to 0.23 for chlordane.

Human health risks were assessed for PBDEs and chlordane for the following 5 exposure pathways:

- incidental ingestion of soil and dust
- incidental inhalation of dust
- dermal absorption
- consumption of homegrown fruit and vegetables
- consumption of home chicken eggs.

For Br1–Br9 and Br10, the highest RQ_{HH} values ranged up to 2 and 7.6, respectively, for the consumption of eggs. For chlordane, all RQ_{HH} values were less than 0.2.

Based on the Scenario 1 results, C&R recommends thresholds for HHCB, triclosan, PBDEs and chlordane are derived for unrestricted use biosolids. Overall, the key exposure pathway for HHCB, triclosan and chlordane was ecological toxicity to terrestrial organisms. For PBDEs (Br1–Br9 and Br 10), the key exposure pathway was the human health pathway for the consumption of home chicken eggs. Based on this, C&R recommends thresholds are derived for unrestricted use biosolids to protect these key exposure pathways.

Scenario 2 – unrestricted use biosolids for land rehabilitation

Scenario 2 assessed the ecological and human health risk from land application of unrestricted use biosolids for land rehabilitation. This scenario assumed the land will be used for public open space in the future and not used for agriculture. Similar to Scenario 1, the contaminant concentrations in unrestricted use biosolids (1-part biosolids to 2-parts other waste) were used as the biosolids-amended soil concentrations, as there are no restrictions on application rates.

Ecological risks were assessed for 3 exposure pathways:

- direct toxicity to terrestrial organisms
- toxicity to secondary consumers
- toxicity to offsite aquatic organisms.

For HHCB, triclosan and chlordane, RQ_{ECO} values exceeded 1 (RQ_{ECO} values up to 30, 92 and 2.3, respectively) in at least one of the assessed exposure pathways.

Human health risks were assessed for PBDEs and chlordane for the following exposure pathways:

- incidental ingestion of soil and dust
- incidental inhalation of dust
- dermal absorption
- consumption of drinking water.

All RQ_{HH} values for PBDEs and chlordane were less than 0.2 for all pathways, indicating risks to human health following land application of unrestricted use biosolids in land rehabilitation are low.

Based on the results for Scenario 2, C&R recommends thresholds for HHCB, triclosan and chlordane are derived for unrestricted use biosolids. For HHCB and triclosan, the key exposure pathway with the highest RQ value was direct toxicity to terrestrial organisms. For chlordane, the key exposure pathway with the highest RQ value was toxicity to secondary consumers. Thresholds for unrestricted use biosolids should protect these pathways.

Scenario 3 – restricted use biosolids in agriculture

Scenario 3 assessed ecological and human health risk from land application of restricted use biosolids in agriculture. This involved assessing 3 ecological exposure pathways (direct toxicity to terrestrial organisms, toxicity to secondary consumers and toxicity to offsite aquatic organisms) and several human health exposure pathways (including incidental exposure [ingestion, inhalation and dermal], home consumptions of produce [fruit and vegetables, beef and milk] and drinking water). Assessing the potential risk from market supply of agricultural products from biosolids-amended land was out of the scope of this HHERA, and risks specifically refer to consumption of homegrown/home-produced products.

This scenario assumed that biosolids are land applied and incorporated into the soil (i.e. biosolids-amended soil) as required by the NSW Biosolids Guidelines for agricultural use. For this scenario, risks were assessed based on estimated concentrations in the biosolids-amended soil and soil pore water for each of the following land application rates:

- 10 t/ha single application
- 10 t/ha repeat applications
- 50 t/ha single application
- 50 t/ha repeat applications.

The repeat applications assumed biosolids were applied every 5 years for 30 years. The land application scenario of 50 t/ha repeat application was considered as a realistic maximum biosolids application rate for agriculture.

For ecological risks, RQ_{ECO} values for HHCB exceeded 1 for direct toxicity to terrestrial organisms and toxicity to secondary consumers (RQ_{ECO} up to 24). For triclosan, all 3 assessed exposure pathways resulted in RQ_{ECO} values above 1 (RQ_{ECO} up to 72) and for

chlordane, exposure to secondary consumers resulted in RQ_{ECO} above 1 (maximum RQ_{ECO} = 1.8).

Human health risks were assessed for PBDEs (Br1–Br9 and Br10) and chlordane. For Br1–Br9, the consumption of beef and milk from grazing and fodder-fed cattle/dairy cows resulted in RQ_{HH} values above 1, ranging up to 12. For Br10 the maximum RQ_{HH} value was 1.1 for the consumption of beef from grazing cattle, although this value was driven by the high concentration of Br10 in one STP. Excluding this high value, all RQ_{HH} values for Br10 were below 0.2. For chlordane, all RQ_{HH} values were less than 0.2 (maximum RQ_{HH} = 0.1).

Based on the results for Scenario 3, C&R recommends thresholds for HHCB, triclosan, PBDEs and chlordane are derived for restricted use biosolids. The key exposure pathways for HHCB and triclosan were ecological direct toxicity to terrestrial organisms. For chlordane, the ecological pathways were also the most sensitive, with the key pathway identified as toxicity to terrestrial secondary consumers. The results from PBDEs, which were assessed only for human health risks, indicated that the key exposure pathway was beef consumption from grazing cattle for both Br1–Br9 and Br10. C&R recommends the derivation of thresholds for restricted use biosolids should be based on these exposure pathways.

Scenario 4 (additional scenario) – unrestricted use biosolids in agriculture

Although unrestricted use biosolids in NSW are unlikely to be used in this way, this additional scenario was assessed as it is permitted in the NSW Biosolids Guidelines. This scenario focused on human health pathways only, and the risk from the highest agricultural pathway only (determined from Scenario 3) is presented. The ecological pathways were not included as all relevant pathways for unrestricted use were already assessed in Scenarios 1 and 2. Scenario 4 was assessed to determine if the risks from unrestricted use biosolids via the agricultural pathways are potentially higher than those identified in Scenarios 1 and 2 and therefore would drive threshold derivation.

The maximum RQ_{HH} value for Br1–Br9 was 16 (beef from grazing cattle). This was higher than the RQ_{HH} values calculated for unrestricted use biosolids in Scenarios 1 and 2. In contrast, the RQ_{HH} values from Scenario 4 for Br10 and chlordane (maximum RQ_{HH} = 1.5 and 0.12, respectively) were not the highest. Therefore, this is not considered the key risk-driving scenario for these 2 compounds in unrestricted use biosolids.

Recommendations and next steps

This HHERA considered 4 different scenarios for biosolids use and assessed the ecological risks for HHCB, triclosan and chlordane and the human health risks for PBDEs and chlordane.

- C&R recommends thresholds are derived for HHCB, triclosan, PBDEs (Br1–Br9 and Br10) and chlordane in unrestricted use and restricted use biosolids to ensure land application of biosolids poses a low risk to ecology and human health.
- The key exposure pathways that threshold derivation should be based on are:
 - unrestricted use biosolids
 - o HHCB – ecological direct toxicity to terrestrial organisms
 - o triclosan – ecological direct toxicity to terrestrial organisms
 - o chlordane – ecological toxicity to terrestrial secondary consumers
 - o Br1–Br9 – consumption of beef from grazing cattle (human health)
 - o Br10 – consumption of chicken eggs (human health)
 - restricted use biosolids

- o HHCB – ecological direct toxicity to terrestrial organisms
 - o triclosan – ecological direct toxicity to terrestrial organisms
 - o chlordane – ecological toxicity to terrestrial secondary consumers
 - o PBDEs (Br1–Br9 and Br10) – consumption of beef from grazing cattle (human health).
- Where thresholds are derived based on agricultural applications of biosolids, C&R recommends the exposure assumptions used should be based on realistic maximum exposure. Thresholds derived this way will be protective but will not be over conservative. The derivation process using these assumptions should be transparent and applicable to other contaminants that are being considered as part of the NSW Biosolids Guideline review.

1. Project background and scope

1.1 Project information

In 2016, the NSW Environment Protection Authority (EPA) funded a desk-based project which reviewed contaminant concentrations in biosolids (the Contaminants Review: WCA 2016). The project compiled a list of contaminants that have been detected in biosolids worldwide and identified specific contaminants that required further consideration due to potential ecological and/or human health risks. Contaminants identified in the Contaminants Review included HHCB⁸ (Galaxolide), triclosan, polybrominated diphenyl ethers (PBDEs) and chlordane. HHCB, triclosan and chlordane were identified as priority contaminants due to a potential high risk to ecosystems. PBDEs and chlordane were identified due to possible dietary exposure and potential risks to human health.

Following this work, the NSW EPA conducted a one-off biosolids sampling program of 20 sewage treatment plants (STPs) in NSW in July 2017. The purpose of the program was to measure concentrations of the contaminants identified in the Contaminants Review (WCA 2016), which included these 4 contaminants of concern⁹.

The EPA asked the Contaminants and Risk team (C&R)¹⁰ to undertake a risk assessment for HHCB, triclosan, PBDEs and chlordane using these data. The aim was to determine if these contaminants in biosolids require regulation and to identify the key exposure pathways for threshold derivation. Based on the outcome of the WCA assessment, C&R undertook an ecological risk assessment (ERA) for HHCB, triclosan and chlordane and a human health risk assessment (HHRA) for PBDEs and chlordane¹¹.

This report presents preliminary outcomes of the ERAs and HHRA, together with an overview of the approach (scenarios, exposure pathways and assumptions) used in the risk calculations.

1.1.1 Contaminants

HHCB

HHCB (CAS number 1222-05-5), also known as Galaxolide (the trade name from International Flavors & Fragrances Inc), is a synthetic musk with a floral, woody odour used in fragrances, fabric softeners and detergents.

HHCB has a molecular formula of C₁₈H₂₆O (Figure 1) and a molecular weight of 258.4 g/mol. At room temperature, it occurs as a colourless highly viscous liquid. Its melting point is -10 to 0°C and its boiling point is 320°C at 1 atm. It tends to strongly associate with solids due to its low solubility in water (1.65 mg/L at 25°C, pH 7) and high

⁸ 4,6,6,7,8,8-hexamethyl-1,3,4,6,7,8-hexahydrocyclopenta[g]isochromene

⁹ The sampling program also included per- and poly-fluoroalkyl substances (PFAS), which are discussed in detail in a separate report.

¹⁰ Department of Planning, Industry and Environment – Environment, Energy and Science Group – Science, Economics and Insights Division (now the Department of Planning and Environment – Environment and Heritage Group).

¹¹ Note that C&R did not use the data for chlordane from the EPA sampling in the risk assessment due to uncertainties. An alternative dataset from routine biosolids monitoring from NSW STPs was used (outlined in Section 1.5).

octanol/water partitioning coefficient ($\log K_{ow} = 5.9$). This means that HHCB will be substantially removed by sorption to sludge in wastewater treatment plants (WWTPs), will have low mobility in soil, and will bind strongly to benthic and suspended sediment. HHCB has low persistence in water and is moderately persistent in soil and sediment, with half-life (DT_{50}) estimates of 10–69 hours in sludge, 100 hours for river water, 79 days in sediment, 95 days in forest soils, 239 days in agricultural soils, and 141–144 days in biosolids-amended soils (US EPA 2014).

HHCB has a low to moderate bioaccumulation potential. Bioconcentration factor values (BCF) of 1,584 (L/kg wet weight [ww]) for bluegill fish and 2,692 (L/kg ww) for earthworms indicate moderate bioconcentration potential, while bioaccumulation factors (BAF) for earthworms range from 0.01 to 39 kg dw/kg ww (calculated by C&R from the literature, see Appendix A).

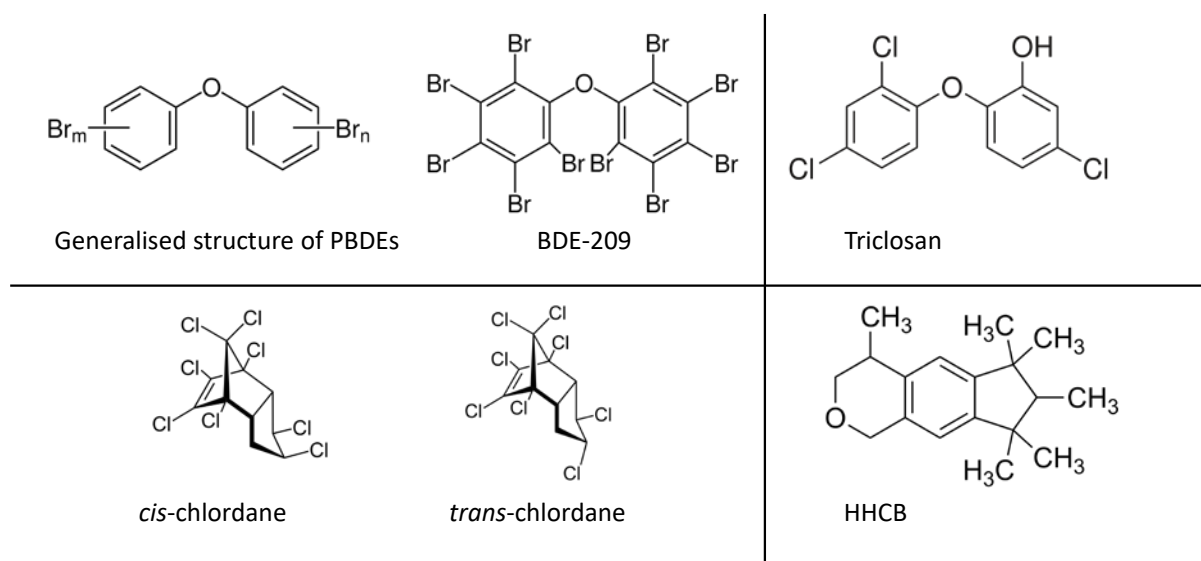


Figure 1 Chemical structures of PBDEs, triclosan, HHCB and chlordane

Triclosan

Triclosan (phenol, 5-chloro-2-(2,4-dichlorophenoxy; CAS number 3380-34-5) (Figure 1) is used as a material preservative and antimicrobial agent in a wide range of consumer and industrial products (e.g. toothpaste, soaps, cleaning products) where it acts to slow or stop the growth of bacteria, fungi, and mildew. It does not occur naturally in the environment. Triclosan is classed as a halogenated aromatic hydrocarbon with phenolic, diphenyl ether and polychlorinated biphenyl functionalities.

Triclosan is washed off from consumer products and enters the wastewater, where it tends to partition to the solids due to its low aqueous solubility (10 mg/L at 20°C). It has a high octanol-water partitioning coefficient ($\log K_{ow} = 4.8$) and has the potential to bioaccumulate and bioconcentrate. In fish, BCF values range between 16–90 L/kg ww for the common carp (*Cyprinus carpio*) and between 2,018 and 8,700 L/kg ww for zebrafish (*Danio rerio*) (ECCC 2017). In soil, triclosan biodegradation ranges from 2.9–58 days under aerobic conditions. Although this half-life is relatively short, exposure to triclosan can occur from the periodic land application of biosolids, and field dissipation half-lives measured are > 100 days, indicating exposure levels in soil can be constant (ECCC 2017).

PBDE

Polybrominated diphenyl ethers (PBDEs) are a group of aromatic chemicals that consist of 2 halogenated aromatic rings with 1 to 10 bromine atoms (Figure 1). There are 209

possible congeners, although most of them are not available as commercial products. PBDEs are used as flame retardants in plastics and textiles. Three commercial products have been on the market: pentabromodiphenyl ether (penta-BDE), octabromodiphenyl ether (octa-BDE), and decabromodimethyl ether (deca-BDE). Importation and manufacture of the first 2 has been prohibited in Australia since 2007, while the latter is not manufactured in Australia, but imported as the raw chemical (NICNAS 2019). These commercial products are mixtures of different PBDE congeners, for example, commercial penta-BDE tends to contain a combination of tetra-, penta- and hexa-BDE compounds. Therefore, a range of congeners can be found in biological matrices and the environment.

PBDEs are persistent environmental contaminants, the log K_{OW} of the commercial mixtures range from 6.29 (octa-BDE) to 6.9 (penta-BDE), with congener specific log K_{OW} in the range of 5.74 to 8.27 (Tittlemier et al. 2002). In the wastewater treatment process, PBDEs tend to sorb to solids, and are thereby regularly found in biosolids. Some PBDEs have the potential to bioconcentrate, typically with the lower brominated congeners accumulating more easily. Earthworms have been shown to bioaccumulate PBDEs from biosolids-amended soils, with earthworm BAFs ranging from 6.4–20 for BDE-47 and 4.8–18 for BDE-100 (Gaylor et al. 2013).

Chlordane

Chlordane (1,2,4,5,6,7,8,8-octachloro-2,3,3a,4,7,7a-hexahydro-4,7-methanoindene) is a synthetic broad-spectrum organochlorine insecticide which had been used to combat a variety of insect pests. It was available in many forms and formulations in approximately 70 different products¹². In Australia it was predominantly used to protect wooden structures against termites until 1995 (NHMRC 2011). Chlordane is listed on the Stockholm Convention on Persistent Organic Pollutants (POPs). In Australia it was phased-out of use in the mid-1990s, and in 2004 Australia placed strict controls on its import, manufacture and use.

Chlordane has several stereoisomers, but the 2 dominant isomers, *cis*- and *trans*-chlordane (Figure 1; CAS number *cis*-chlordane = 5103-71-9, CAS number *trans*-chlordane = 5103-74-2) comprised 60–85% of commercial formulations. In this assessment, the term ‘chlordane’ refers to a sum of both the *cis*- and *trans*- isomers (total chlordane). Chlordane has a low solubility in water (0.1 mg/L at 25°C) and a high octanol/water partitioning coefficient (log K_{OW} = 5.54) meaning it has a strong association with solid phases. In the aqueous environment, chlordane has been shown to bioconcentrate in both marine species (BCF = 3,000–12,000 L/kg) and freshwater species (BCF = 18,500 L/kg in rainbow trout) (ATSDR 2018). In soils, although there is not much data, earthworm BAFs ranging from 0.3–12 kg dw/kg ww were calculated by C&R for use in this risk assessment (see Appendix A).

Chlordane persists in soils and sediments for a long time, with a degradation half-life (DT_{50}) of approximately 1 year (ANZG 2018). It has also been detected within waters associated with agricultural runoff and near production and disposal facilities (ATSDR 2018).

¹² Australian Government Department of Agriculture, Water and the Environment – Organochlorine pesticides (OCPs) – Trade or common use names.

1.2 Biosolids use in NSW

Biosolids contain high contents of nutrients and organic matter, therefore land application of biosolids can be beneficial for soils. The annual production of biosolids in Australia in 2017 was approximately 327,000 dry tonnes. Of this, 20–25% was produced in NSW (PSD 2017). The NSW Biosolids Guidelines classify biosolids into different categories based on a contaminant grade (grades A to D) and a stabilisation grade (grades A to C). Biosolids with different classifications can be used for different purposes. Broadly these classifications are unrestricted use and restricted use.

- **Unrestricted use biosolids** must meet contaminant and stability grade A. These biosolids can be used for a wide range of purposes, including home lawns and gardens, public contact sites, urban landscaping, agriculture and forestry. There are no restrictions on biosolids land application rates for unrestricted use biosolids.
- **Restricted use biosolids** fall under lower contaminant (B, C or D) and stability grades (A or B) and are further divided into 3 subclassifications (restricted use 1, 2 and 3), depending on the contaminant and stability grades. Restricted use biosolids can be used for a range of purposes, including land application in agriculture, land rehabilitation and forestry, but not home gardens.

Specific requirements are provided in the NSW Biosolids Guidelines to determine maximum allowable application rates for restricted use biosolids. These generally depend on the concentrations of contaminants, nitrogen and phosphorus in the biosolids.

The NSW Biosolids Guidelines also contain threshold concentrations for a number of contaminants in the biosolids and the receiving soil. There are currently no thresholds for HHCB, triclosan and PBDEs in biosolids or the receiving soil listed in the NSW Biosolids Guidelines. For chlordane, threshold concentrations range from 0.02 mg/kg for Grade A biosolids, to 1 mg/kg for Grade D biosolids (NSW EPA 2000).

In NSW, 61% of the biosolids produced are used in agriculture (PSD 2017). The definition of agricultural land in the NSW Biosolids Guidelines is ‘land which is now or could be in the future used for agricultural purposes’. This therefore also includes mine sites or degraded lands whose rehabilitation plans indicate grazing or other agricultural uses.

The remaining biosolids produced in NSW are used for (PSD 2017):

- compost – 26%
- land rehabilitation – 5%
- ocean discharge – 4%
- stockpile – 2%
- landfill – 2%.

1.3 Conceptual models for exposure to contaminants in biosolids

The approach used to assess ecological and human health risks for this report was based on the draft report *Identification of key exposure pathways to assess risks from PFAS in biosolids* prepared by C&R (the PFAS Biosolids Report). General assumptions and parameters used in this risk assessment were consistent with the PFAS Biosolids Report, and chemical-specific parameters were sourced from relevant literature (e.g. toxicity reference values and transfer factors).

Four scenarios were assessed based on how most biosolids are used in NSW. These scenarios were agreed to with the NSW EPA before commencement of the assessment:

- Scenario 1 - unrestricted use biosolids in residential gardens
- Scenario 2 - unrestricted use biosolids for land rehabilitation¹³
- Scenario 3 - restricted use biosolids in agriculture¹⁴
 - a. for a low (10 t/ha) and a high (50 t/ha) land application rate
 - b. for single (1) and repeat (7) applications
- Scenario 4 (additional scenario) – land application of unrestricted use biosolids in agriculture.

Based on the way biosolids are currently used in NSW, Scenario 4 is not likely to be a common scenario as it is understood that biosolids application in agriculture tends to use restricted use biosolids. However, as the NSW Biosolids Guidelines allow unrestricted use biosolids to be land applied in agriculture, and this is potentially a sensitive pathway if compounds are known to bioaccumulate in food chains, this scenario was added to the risk assessment for completeness. Scenario 4 considered human health risks only as all potential ecological pathways for unrestricted use biosolids were already assessed in Scenarios 1 and 2 (i.e. for ecological pathways, the agricultural use of biosolids don't introduce any additional pathways). In addition, Scenario 4 is referred to as an 'additional scenario' as it was streamlined to present potential risks only from the most sensitive agricultural pathways in this report (as identified from Scenario 3). The risks from other pathways can be provided if required.

For all scenarios, the primary source of the contaminants was assumed to be biosolids-amended soils and it was assumed that no HHCB, triclosan, PBDEs or chlordane were present in the soil at the time of land application. For Scenarios 1, 2 and 4, it was assumed the biosolids were processed with an uncontaminated material (e.g. composted garden waste) to produce unrestricted use biosolids. For Scenario 3, it was assumed the biosolids were incorporated into the top 10 cm of soil. For each scenario, relevant ecological and human health pathways were assessed.

For the human health risk assessments, 10 distinct pathways were assessed. These included incidental exposure pathways, including incidental ingestion of soil and dust, incidental inhalation of dust and incidental dermal absorption. Further human exposure pathways that were assessed were linked to the consumption of home produce (fruit, vegetables, eggs, beef and milk) and the consumption of drinking water.

1.3.1 Ecological risk assessment exposure pathways

HHCB, triclosan and chlordane were identified in the Contaminants Review (WCA 2016) as contaminants with potential ecological risks, and therefore C&R undertook an ERA for these three contaminants for each scenario. Overall, 3 potential exposure pathways were considered:

- direct toxicity to terrestrial organisms (Pathway 1)
- indirect toxicity to terrestrial secondary consumers (Pathway 2)
- toxicity to offsite aquatic organisms (Pathway 3).

¹³ Scenario 2 assumes land will be rehabilitated to public open space/parklands and will not be used for agriculture in the future.

¹⁴ Scenario 3 includes rehabilitated land that will be used for agriculture in the future.

For Scenario 1, only Pathway 1 was assessed as it was assumed residential use of biosolids would not be at sufficient scale for Pathways 2 and 3 to occur. This is consistent with the PFAS Biosolids Report. For Scenarios 2 and 3, all 3 exposure pathways were assessed (Table 1).

Table 1 Exposure pathways assessed for HHCB, triclosan and chlordane in the ecological risk assessment

Ecological exposure pathways	Scenario 1	Scenario 2	Scenario 3
Pathway 1: direct toxicity to terrestrial organisms	✓	✓	✓
Pathway 2: indirect toxicity to terrestrial secondary consumers		✓	✓
Pathway 3: toxicity to offsite aquatic organisms via groundwater or surface runoff		✓	✓

1.3.2 Human health risk assessment exposure pathways

PBDEs and chlordane were identified in the Contaminants Review (WCA 2016) as contaminants with possible dietary exposure and potential risks to human health. Therefore C&R undertook an HHRA for these contaminants for each scenario. Overall, the HHRA considered 10 potential exposure pathways, which included:

- incidental exposure (ingestion of soil/dust) (Pathway 1)
- incidental inhalation of dust (Pathway 2)
- incidental dermal absorption (Pathway 3).
- consumption of homegrown produce (fruit and vegetables) (Pathway 4)
- consumption of eggs (Pathway 5)
- consumption of beef (pathways 6a and 6b)
- consumption of milk (pathways 7a and 7b)
- consumption of drinking water (Pathway 8).

Pathways were assessed only where they were relevant for a given scenario (Table 2) (discussed in more detail in the scenario-specific sections of this report).

Pathways 6 and 7 assessed the consumption of beef and milk from agricultural biosolids applications (Scenario 3). The pathways 'a' represent the contribution from soil only and the pathways 'b' represent the contribution from uptake into plants only. The sum of 'a' and 'b' indicates the risk from grazing beef cattle / dairy cows as they will consume both soil and plants. Pathway 'b' alone indicates the risk when fodder grown on biosolids-amended soil is consumed by beef cattle / dairy cows elsewhere.

Assumptions for the food-consumption pathways (i.e. eggs, fruit and vegetables, beef and milk) relate only to home consumption of produce. This risk assessment did not assess risks from market supply of agricultural products, noting that dilution of produce is likely to occur in commercial markets reducing the average exposure to the general public.

Table 2 Detailed exposure pathways considered in HHRA for PBDEs and chlordane

Human health exposure pathways	Scenario 1	Scenario 2	Scenario 3*
Pathway 1: incidental ingestion of soil/dust	✓	✓	✓
Pathway 2: incidental inhalation of dust	✓	✓	✓
Pathway 3: incidental dermal absorption	✓	✓	✓
Pathway 4: consumption of fruits and vegetables grown in biosolids-amended soil	✓		✓
Pathway 5: consumption of eggs from chickens exposed to biosolids-amended soil	✓		
Pathway 6a+b: consumption of beef cattle grazing on land applied with biosolids, which includes: a: consumption of beef from cattle ingesting biosolids-amended soil b: consumption of beef from cattle ingesting plants grown in biosolids-amended soil			✓
Pathway 6b: consumption of beef from cattle ingesting plants grown in biosolids-amended soil (i.e. beef cattle consuming fodder grown on biosolids-amended soil)			✓
Pathway 7a+b: consumption of milk from dairy cows grazing on land applied with biosolids, which includes: a: consumption of milk from dairy cows ingesting biosolids-amended soil b: consumption of milk from dairy cows ingesting plants grown in biosolids-amended soil			✓
Pathway 7b: consumption of milk from dairy cows ingesting plants grown in biosolids-amended soil (i.e. dairy cows consuming fodder grown on biosolids-amended soil)			✓
Pathway 8: consumption of drinking water based on transport of contaminants to groundwater through infiltration		✓	✓

* Scenario 3 pathways are also relevant to Scenario 4. However, only outcomes from the highest risk pathway are presented in this report for Scenario 4.

1.4 Assessment criteria

1.4.1 Ecological assessment criteria

The ERA (HHCB, triclosan and chlordane) used screening criteria relevant to each of the pathways outlined in Section 1.3.1. Where screening criteria from Australian sources (i.e. the *National Environment Protection (Assessment of Site Contamination) Measure* [the ASC NEPM] [NEPC 2013a] and Australian and New Zealand Water Quality Guidelines [ANZG 2018]) were available for a pathway, these were used. However, for the 3 compounds assessed, these were limited. If no Australian criteria were available, C&R included criteria from other sources such as predicted no effect concentrations (PNECs)

from the European Chemicals Agency (ECHA)¹⁵, United Kingdom Environment Agency (UK EA) and Environment and Climate Change Canada (ECCC). These other sources were selected as they have similar frameworks for deriving ecological screening criteria to those used in Australia. In cases where criteria were not available in any of these sources, C&R adopted criteria from other government jurisdictions or used data from peer-reviewed publications to derive interim criteria for use in this risk assessment. C&R notes that the selection or derivation of screening criteria in this risk assessment should be thoroughly peer reviewed before their implementation in any threshold derivation. All ecological screening criteria adopted for this assessment are shown in Table 3, and additional details on the selection process and calculations are provided in Appendix A. In Appendix A, C&R has noted where criteria in this risk assessment differ from those used in the Contaminants Review (WCA 2016).

Table 3 Screening criteria used to assess the ecological risk of HHCB, triclosan and chlordane

	Pathway	Screening criteria	Source
HHCB			
Direct terrestrial toxicity	1	750 µg/kg	Adjusted criterion based on ECHA PNEC of 1,500 µg/kg (see Appendix A)
Terrestrial secondary consumers	2	2,800 µg/kg	C&R derived (see Appendix A)
Aquatic organisms	3	6.8 µg/L	ECHA PNEC*
Triclosan			
Direct terrestrial toxicity	1	65 µg/kg	Adjusted criterion based on UK EA 2020 PNEC of 130 µg/kg (see Appendix A)
Terrestrial secondary consumers	2	1,050 µg/kg	Adjusted criterion based on UK EA 2020 PNEC of 2,100 µg/kg (see Appendix A)
Aquatic organisms	3	0.47 µg/L	ECCC 2017
Chlordane			
Direct terrestrial toxicity	1	40 µg/kg	Spanish Government 2014
Terrestrial secondary consumers	2	3.9 µg/kg	C&R derived (see Appendix A)
Aquatic organisms	3	0.03 µg/L	ANZG 2018

* ECHA webpage: echa.europa.eu/registration-dossier/-/registered-dossier/14504

1.4.2 Human health assessment criteria

Toxicity profiles for chlordane and PBDEs are available in Schedule B7 of the ASC NEPM (NEPC 2013b). The tolerable daily intakes (TDIs) for these compounds used in this risk assessment are summarised in Table 4.

For PBDEs, literature indicates the toxicity and environmental fate of fully brominated BDE (i.e. Br10) is different to the PBDEs that are not fully brominated (i.e. Br1–Br9). As a result, the Agency for Toxic Substances and Disease Registry (ATSDR) recommends separating Br10 from the other PBDEs (Br1–Br9) (ATSDR 2017) when assessing risks.

¹⁵ ECHA website: echa.europa.eu/

Therefore, in this risk assessment, C&R assessed Br10 and the sum of the other PBDEs (Br1–Br9) separately.

Table 4 Tolerable daily intakes (TDI) (µg/kg bw/d) used for the derivation of risk quotients for PBDEs and chlordane

Contaminant	TDI	Reference
Br1–Br9	0.1	US EPA 2008 a,b
Br10	7	US EPA 2008 c
Chlordane	0.5	OCS 2012; NHMRC 2011; WHO 2017

The TDI used in the risk assessment for Br1–Br9 was 0.1 µg/kg body weight (bw)/day (d), which is consistent with the United States Environmental Protection Agency (US EPA) reference doses (RfDs) for BDE-99 and BDE-47 (US EPA 2008a, 2008b). C&R notes the US EPA also provides RfDs for BDE-153 and octa-BDE (0.2 and 3 µg/kg bw/d, respectively). However, these were not used in the risk assessment as they will result in a less conservative assessment on the sum of Br1–Br9. The selection of the TDI used in this risk assessment is also consistent with the ASC NEPM.

In addition to the TDIs, there are also screening criteria available that are relevant to some of the pathways (or combinations of pathways) considered in this risk assessment (Table 5). The ASC NEPM lists health investigation levels (HILs) for different land uses, including residential with garden accessible soil (HIL A) and public open space (HIL C) for PBDE Br1–Br9 and chlordane. These HILs were derived using the same TDIs shown in Table 4, and therefore C&R has used these criteria for relevant pathways in scenarios 1 and 2.

- The HIL A is a screening value for residential areas with garden accessible soil, and considers multiple pathways, including incidental ingestion of soil/dust (Pathway 1), incidental inhalation of dust (Pathway 2), incidental dermal absorption (Pathway 3) and consumption of homegrown fruit/vegetables (Pathway 4).
- The HIL C is a screening value for public open space and considers the same pathways as HIL A, except for homegrown fruit/vegetables. This screening value considers shorter exposure duration for public open space compared with a residential setting, as well as a lower incidental soil ingestion rate.

Corresponding HILs are not available for deca-BDE (Br10). However, values similar to the HIL A values are available from the US EPA regional screening levels (RSLs)¹⁶, which were used in this assessment for Scenario 1 (Table 5). C&R notes the residential RSLs don't consider consumption of homegrown produce (Pathway 4). Therefore, in the Scenario 1 risk assessment for Br10, C&R has assessed Pathway 4 separately.

Drinking water guidelines are also relevant to this risk assessment for scenarios 2 and 3 (Table 5), for assessing if there are risks as a result of contaminants leaching into groundwater or surface waters used as a drinking water source. The *Australian Drinking Water Guidelines* (NHMRC 2011) present a criterion for chlordane (2 µg/L), which was used in this risk assessment. There are no corresponding values for PBDEs. Therefore, for use in this assessment, C&R adopted US EPA RSLs for tap water that protect human health. For Br1–Br9, C&R adopted 2 µg/L, which is the tap water RSL from US EPA for

¹⁶ *Regional Screening Levels (RSLs) - Generic Tables* webpage, US EPA website: www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

BDE-99 and BDE-47. These values are the most conservative and were selected to be consistent with the TDI adopted for Br1–Br9. For Br10, C&R adopted 110 µg/L which is the tap water RSL from the US EPA for Br10.

Table 5 Human health screening criteria for scenarios and pathways relevant to this risk assessment

Scenario/pathway	Compound	Value	Source/comment
Residential (Scenario 1: pathways 1, 2, 3 and 4)	PBDE Br1–Br9	1 mg/kg	HIL A from NEPM (NEPC 2013a)
	PBDE Br10	440 mg/kg	RSL from US EPA ^{A,B}
	Chlordane	50 mg/kg	HIL A from NEPM (NEPC 2013a)
Open space (Scenario 2: pathways 1, 2 and 3)	PBDE Br1–Br9	2 mg/kg	HIL C from NEPM (NEPC 2013a)
	PBDE Br10	880 mg/kg	Adjusted based on US EPA ^C
	Chlordane	70 mg/kg	HIL C from NEPM (NEPC 2013a)
Drinking water (scenarios 2 & 3: Pathway 8)	PBDE Br1–Br9	2 µg/L	RSL from US EPA ^A
	PBDE Br10	110 µg/L	RSL from US EPA ^A
	Chlordane	2 µg/L	NHMRC 2011

^A US EPA regional screening level (RSL): www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

^B The Br10 residential value does not consider Pathway 4. Therefore C&R has assessed this separately.

^C The US EPA residential RSL value was doubled as an interim screening criterion in this risk assessment. C&R assumed this is a conservative estimate due to the shorter exposure duration for public open space and the lower incidental soil ingestion rate.

1.5 Contaminant concentrations in biosolids

In July 2017, the NSW EPA collected duplicate biosolids samples from 20 STPs across NSW. Facilities were selected to ensure that STPs within Sydney and in regional areas were sampled, representing a range of different potential sources and treatment types. The samples were collected from biosolids that had completed treatment and processing for restricted use.

C&R has used this dataset to assess risks from HHCB, PBDEs and triclosan (the STPs have been de-identified in this report) (Table 6). For the PBDE dataset, 9 congeners (BDE-28, BDE-47, BDE-66, BDE-5, BDE-99, BDE-100, BDE-153, BDE-154, BDE-183) were summed to represent Br1–Br9, and fully brominated Br10 (BDE-209) was used as a single contaminant, as the environmental fate and toxicity of this compound is different to the PBDEs that are not fully brominated (see Section 1.4.2).

The dataset for chlordane from the 20 STPs had low laboratory recoveries, meaning the dataset was not suitable for a quantitative risk assessment. Therefore, the NSW EPA provided C&R with an extensive dataset (> 7,000 measurements) of routine biosolid monitoring data spanning 1996 to 2016 collected from 33 STPs across NSW. C&R used the 2016 data from this larger dataset in this risk assessment as the most recent data and to approximately match the timing of the other samples collected. The chlordane 2016 data were from 24 STPs in NSW and consisted of approximately 300 measurements.

Table 6 Duplicate measurements of HHCB, triclosan and PBDEs (Br1–Br9 and Br10) in biosolids collected from 20 STPs across NSW (concentrations (µg/kg dw) rounded to 2 significant figures)

STP	HHCB	Triclosan	Br1–Br9	Br10
A	16,000	1,400	100	160
	16,000	1,600	94	130
B	38,000	5,000	69	530
	40,000	6,700	69	700
C	56,000	13,000	130	300
	57,000	14,000	140	340
D	11,000	160	42	140
	5,600	100	69	190
E	28,000	1,200	74	170
	29,000	1200	73	180
F	23,000	2,300	120	280
	22,000	2,200	120	300
G	7,000	<30	22	530
	7,100	<30	21	590
H	64,000	9,900	85	450
	68,000	9,700	85	500
I	62,000	15,000	74	610
	63,000	16,000	77	590
J	420	60	34	50
	850	32	17	50
K	36,000	15,000	82	200,000
	43,000	18,000	81	210,000
L	31,000	1,500	130	250
	29,000	570	160	280
M	13,000	590	66	310
	13,000	570	67	270
N	3,600	170	70	200
	3,900	180	82	350
O	8,800	720	54	140
	8,700	780	52	150
P	3,100	180	90	230
	1,800	170	89	260
Q	1,000	91	240	280
	1,300	89	230	260
R	46,000	5,000	140	480
	51,000	5,400	150	630
S	36,000	5,900	110	210
	31,000	6,100	110	270
T	1,200	96	110	160
	1,400	78	110	200

The concentrations of HHCB in biosolids ranged from 420 to 68,000 µg/kg dw (Table 6), with the maximum concentration reported around 3.9-fold higher than the 90th percentile concentration reported in studies around the world in the Contaminants Review (17,500 µg/kg dw) (WCA 2016). Triclosan concentrations ranged from below the limit of reporting (LOR) (< 30 µg/kg) to 18,000 µg/kg dw, with the maximum concentration reported around 1.6-fold higher than the maximum concentration reported previously in Australia (11,200 µg/kg dw) (Langdon et al. 2011). Concentrations of Br1–Br9 ranged from 17 to 240 µg/kg dw, while Br10 ranged from 50 to 210,000 µg/kg dw (Table 6). The maximum BDE-209 concentration was 12-fold higher than the maximum BDE-209 concentration reported in the Contaminants Review (17,000 µg/kg dw) (WCA 2016). Concentrations of chlordane ranged from < 5 to 140 µg/kg (sum of *cis*- and *trans*-chlordane) in the dataset from 24 STPs sampled in 2016 (Table 7). The maximum reported *cis*-chlordane concentration reported in the Contaminants Review was 4 µg/kg dw.

For the risk assessment, C&R used the 95% upper confidence limit of the mean (95UCL)¹⁷ and the maximum concentrations for HHCB, triclosan and PBDEs (Table 7) as input concentrations. The maximum concentrations were used to determine if regulation is required, whereas the outcomes from the 95UCL concentrations were included for information.

For the PBDEs, the maximum Br10 concentration was measured from STP K (210,000 µg/kg dw). Samples from this STP were 300-fold higher than the next highest concentration (700 µg/kg dw) from STP B. STP K was not removed as an outlier because it was real data that may represent biosolids being land applied in some instances. However, the data from STP K skewed the summary statistics. Therefore, 2 sets of data were assessed for Br10:

- i. Br10 including data from STP K; and
- ii. Br10 without the STP K data (Table 7).

Table 7 Summary statistics for HHCB, triclosan, PBDE and chlordane concentrations (µg/kg dw) (concentrations rounded to 2 significant figures)

	HHCB	Triclosan	PBDEs Br1–Br9	PBDEs Br10	Chlordane
Minimum	420	<30	17	50	<5
Average	24,000	4,000	93	11,000	10
Median	19,000	1,300	84	280	<5
95UCL	30,000	5,500	110	23,000	360*
Maximum	68,000	18,000	240	210,000	700*
					27 [#]

Grey shaded cells = data used in risk assessment

* values exclude data from STP K

[#] 'maximum' concentration for chlordane is the 95th percentile concentration due to the large dataset available for this contaminant (approx. 300 measurements) (the actual maximum concentration was 140 µg/kg dw)

¹⁷ The 95UCL represents the upper limit of the true average concentration with 95% confidence. It is dependent on the number of samples and the variability.

The outcomes from the whole dataset using STP K were used to determine if regulation is required, whereas the outcomes from the reduced dataset without STP K are provided for information.

Due to the extensive chlordane dataset (approximately 300 measurements), the use of the maximum concentration in the risk assessment was considered overly conservative. Rather than using the maximum value and the 95UCL, the 95th percentile and the 95UCL were calculated¹⁸. This was done to represent a realistic maximum concentration, so not to inflate the assessment with concentrations that were abnormally high. The 95th percentile chlordane concentrations are termed as 'maximum' in the risk assessment and report tables. This approach was not applied to the other contaminants due to the significantly smaller dataset that did not account for temporal variability. The results from the 95th percentile concentrations were used to determine if regulation is required, whereas the 95UCL concentrations are provided for information.

1.6 Summary of method used to calculate risk and identify key exposure pathways

The risk assessment approach for both ecological and human health was based on the PFAS biosolids report and was conducted according to current national guidance (enHealth 2012; NEPC 2013c; NEPC 2013d; ANZG 2018). This is a generic risk assessment and not linked to any specific biosolids land-application sites. To account for this and the uncertainties in the data and parameters, realistic but precautionary assumptions have been used in most cases. This level of precaution is warranted in this case as the outcomes are used to determine if regulation is required. The risk calculations should not be used to conclude there is risk posed from biosolids land application at specific sites. This would require a site-specific risk assessment.

Ecological risks were assessed for HHCB, triclosan and chlordane by dividing exposure concentrations (e.g. biosolids-amended soil or estimated surface water concentration) by contaminant-specific screening criteria (Table 3). This comparison was used to calculate an ecological risk quotient (RQ_{ECO}) using Equation 1.

$$RQ_{ECO} = \frac{\text{exposure concentration}}{\text{ecological screening criterion}} \quad \text{Equation 1}$$

Human health risks were assessed for PBDEs and chlordane for each relevant exposure pathway (or combination of pathways) using either Equation 2 or 3 to calculate human health risk quotients (RQ_{HH}).

- Equation 2 was used where there were relevant human health screening criteria available for a pathway (or combination of pathways).
- If no screening criteria were available, RQ_{HH} was based on predicted daily intakes (DIs), which were calculated for each scenario and pathway (for details see

¹⁸ Due to the large number of measurements for chlordane that were below the limit of reporting (approximately 60%), the 95th percentile and 95UCL concentrations were calculated using the non-parametric method of maximum likelihood estimate (MLE) with a lognormal distribution and bootstrapping of n=10,000.

Appendix B). The DIs were compared to background adjusted TDI to calculate the RQ_{HH} for each pathway (Equation 3).

$$RQ_{HH} = \frac{\text{exposure concentration}}{\text{human health screening criteria}} \quad \text{Equation 2}$$

$$RQ_{HH} = \frac{\text{predicted daily intake}}{\text{TDI-background}} \quad \text{Equation 3}$$

The TDI is the tolerable daily intake (Table 4). The background for Br1–Br9 and Br10 was assumed to be 80% of the TDI (i.e. 0.08 and 5.6 µg/kg bw/d, respectively) (US EPA 2008a, 2008b, 2008c; NEPC 2013b). The background for chlordane was assumed to be 0% of the TDI, based on the ASC NEPM assumption that background exposure to chlordane is negligible (NEPC 2013b).

An RQ above 1 indicates that either the concentration is above the screening criteria, or the predicted DI is above a TDI (or ‘safe’ dose). An RQ of 1 is commonly used in site risk assessments to determine if the risk is low (i.e. when $RQ < 1$).

The RQ value also indicates how many times a criterion has been exceeded. For example, if the RQ is 2, the exposure concentration or predicted DI is double the criterion or background adjusted TDI. When the RQ is less than 1, the screening criterion is not exceeded.

C&R has presented all RQs in this report based on the 95UCL and maximum concentrations (95th percentile concentration for chlordane as outlined in Section 1.5). This will provide an indication of the range in the data available. The individual RQs that correspond to each of the STPs can be provided to the NSW EPA if required.

Use of risk quotients for recommendations

For each scenario, if the maximum RQ was above 0.2, C&R has recommended that regulation is required and that a threshold should be derived. An RQ above 0.2 was used, which allows for a margin of safety (MOS) of 5, to account for the following uncertainties:

- There are uncertainties in the biosolids contaminant concentrations – this risk assessment for HHCb, triclosan and PBDEs is based on contaminant concentrations from 20 STPs across NSW, and it is not known if, or the extent to which, these concentrations may vary over time and at other STPs not included in the EPA sampling program.
- There is a lack of endorsed Australian ecotoxicity screening criteria for these contaminants, adding to the uncertainty of potential ecological effects which are likely to be a risk driver in many instances.

Where RQs are equal to or below 0.2, C&R has concluded the risk from that pathway is low. If this was the case for all pathways for a scenario, C&R has concluded a threshold is not necessary based on the available data. This may need to be reviewed if additional data shows a large variation in concentrations above the 5-fold MOS.

C&R has identified the exposure pathway (human health or ecological) that resulted in the highest RQ as the key exposure pathway for that scenario. C&R has recommended the threshold derivation process should be based on these key exposure pathways to ensure all relevant human health and ecological pathways are protected.

2. Risk assessment outcomes

2.1 Scenario 1: unrestricted use biosolids in residential gardens

Scenario 1 considered the ecological and human health risks from unrestricted use biosolids used in the garden of a residential property. In NSW, unrestricted use biosolids need to meet stringent contaminant thresholds. To achieve this, biosolids are often processed with other waste streams, e.g. garden waste, to produce a final product that meets these requirements. Recently, the NSW EPA surveyed NSW water utilities to better understand the ratios used to produce unrestricted use products. The fraction of biosolids in the final product generally ranged from $\frac{1}{4}$ to $\frac{1}{3}$.

To assess risks for Scenario 1, measured contaminant concentrations in biosolids (from Table 7) were divided by 3 to estimate concentrations in unrestricted use biosolids (Table 8). This was done because only restricted use biosolids were sampled as part of the NSW EPA sampling program. The factor of 3 was used as it represented the highest proportion of biosolids in the final product based on the survey information. For this scenario, the estimated concentrations in the unrestricted use biosolids were used as the biosolids-amended soil (BAS) concentrations, as unrestricted use biosolids can be applied at any rate and may be used to form a topsoil. This approach also assumes that none of the assessed contaminants are present in the other waste stream the biosolids are processed with.

Table 8 Estimated 95UCL and maximum concentrations ($\mu\text{g/kg dw}$) of HHCB, triclosan, PBDEs and chlordane in unrestricted use biosolids (concentrations rounded to 2 significant figures)

Contaminant	95UCL concentration		Maximum concentration	
HHCB	10,000		23,000	
Triclosan	1,800		6,000	
Br1–Br9	35		79	
Br10	7,600	120*	70,000	230*
Chlordane	3.7		9.0 [#]	

* values exclude data from STP K (see Section 1.5)

[#] 'maximum' concentration for chlordane is the 95th percentile concentration due to the large dataset available for this contaminant (approx. 300 measurements)

2.1.1 Ecological risk assessment

For Scenario 1, ecological risks from HHCB, triclosan and chlordane were assessed for:

Pathway 1 – BAS → terrestrial organism

This pathway assessed impacts to terrestrial organisms via direct toxicity only. Indirect ecological impacts (i.e. terrestrial secondary consumers and offsite aquatic organisms) were not assessed because it was considered unlikely that land application of biosolids for this scenario would be on a sufficiently large scale to result in offsite impacts.

Potential ecological risks for direct toxicity to terrestrial organisms following land application of unrestricted use biosolids in residential gardens were assessed by

comparing the unrestricted use biosolids concentrations (Table 8) against the adopted ecological direct toxicity screening criteria (Table 3) to calculate RQ_{ECO} values (Table 9). The results for this pathway are summarised below:

- **HHCB** – the RQ_{ECO} values exceeded 1 based on both the maximum and 95UCL concentrations (maximum RQ_{ECO} = 30; 95UCL RQ_{ECO} = 13).
- **Triclosan** – the RQ_{ECO} values exceeded 1 based on both the maximum and 95UCL concentrations (maximum RQ_{ECO} = 92; 95UCL RQ_{ECO} = 28).
- **Chlordane** – the RQ_{ECO} value exceeded 0.2 based on the maximum concentration (maximum RQ_{ECO} = 0.23) but was below 0.2 based on the 95UCL concentration (95UCL RQ_{ECO} = 0.093).

Table 9 Scenario 1 ecological risk quotients (RQ_{ECO}) for exposure Pathway 1 (direct toxicity to terrestrial organisms) (rounded to 2 significant figures)

Scenario	HHCB	Triclosan	Chlordane
Scenario 1 (95UCL), Pathway 1	13	28	0.093
Scenario 1 (maximum), Pathway 1	30	92	0.23

Red indicates $RQ > 1$, Orange indicates $1 \geq RQ > 0.2$, Grey indicates $RQ \leq 0.2$

2.1.2 Human health risk assessment

For Scenario 1, human health risks from PBDEs (Br1–Br9 and Br10) and chlordane were assessed for:

Pathway 1 – BAS → incidental ingestion of soil/dust

Pathway 2 – BAS → incidental inhalation of dust

Pathway 3 – BAS → incidental dermal absorption

Pathway 4 – BAS → uptake into homegrown fruit and vegetables → consumption of homegrown fruit and vegetables

Pathway 5 – BAS → soil ingestion by chickens → consumption of chicken eggs.

The risk calculations for each of the pathways are explained in Section 1.6. Exposure pathways 1 to 4 were assessed together using the HIL A from the ASC NEPM (Table 5) for Br1–Br9 and chlordane. For Br10, the US EPA RSL was used (Table 5), which covers exposure pathways 1 to 3. Due to this, Pathway 4 was assessed separately for Br10.

For pathways without relevant screening criteria (Pathway 4 for Br10, and Pathway 5 for Br1–Br9, Br10 and chlordane) predicted DIs were calculated to derive risk quotients (using Equation 3, Section 1.6) (details on DI calculations and assumptions are explained in Appendix B). In summary, this was done by calculating the uptake of the contaminant into fruit, vegetables and eggs based on the estimated concentrations in unrestricted use biosolids (Table 8). The estimated fruit, vegetable and egg concentrations were then used to calculate predicted DIs ($\mu\text{g}/\text{kg}/\text{d}$) for children who may eat the homegrown produce. Calculations only for children are presented here as they represent the most sensitive age group. The RQs are listed in Table 10 and the results are summarised below:

- **PBDEs Br1–Br9** – all RQ_{HH} values were below 0.2 based on both the maximum and 95UCL concentrations for the combined pathways 1 to 4 (maximum RQ_{HH} = 0.079; 95UCL RQ_{HH} = 0.035). Whereas, for Pathway 5 (eggs) the RQ_{HH} based on the

maximum concentration exceeded 1 (maximum $RQ_{HH} = 2$) and exceeded 0.2 based on the 95UCL concentration (95UCL $RQ_{HH} = 0.89$).

- **PBDEs Br10** – all RQ_{HH} values were below 0.2, except when data from STP K were included. With the inclusion of the STP K data, the RQ_{HH} based on maximum concentrations exceeded 0.2 for pathways 1 to 4 (maximum $RQ_{HH} = 0.33$) and exceeded 1 for Pathway 5 (eggs) (maximum $RQ_{HH} = 7.6$).
- **Chlordane** - the RQ_{HH} values for all pathways were less than 0.2 indicating the risks from these pathways are low.

Table 10 Human health risk quotients (RQ_{HH}) for children for PBDEs and chlordane for unrestricted use of biosolids in residential gardens

Contaminant	Pathways 1 to 3 Ingestion & inhalation of soil/dust & dermal	Pathway 4 Fruit & vegetables	Pathways 1 to 4 Combined risk	Pathway 5 Eggs
Br1–Br9 95UCL	-	-	0.035*	0.89
Br1–Br9 max	-	-	0.079*	2.0
Br 10 95UCL	0.017*	0.018	0.035	0.81
Br 10 max	0.16*	0.17	0.33	7.6
Br 10 95UCL (excl STP K)	2.7×10^{-4} *	2.9×10^{-4}	5.6×10^{-4}	0.013
Br 10 max (excl STP K)	5.3×10^{-4} *	5.7×10^{-4}	0.0011	0.025
Chlordane 95UCL	-	-	7.4×10^{-5} *	0.018
Chlordane max	-	-	1.8×10^{-4} *	0.043

*assessed using residential human health screening criteria from Table 5

Red indicates $RQ > 1$, **Orange** indicates $1 \geq RQ > 0.2$, Grey indicates $RQ \leq 0.2$

Scenario 1 summary

Scenario 1 assessed ecological (HHCB, triclosan and chlordane) and human health (PBDEs and chlordane) risks when unrestricted use biosolids are used in residential gardens. It was assumed the biosolids were processed with another waste material (e.g. garden waste) at a ratio of 1-part biosolids to 2-parts other to produce unrestricted use biosolids, and that the other waste material contained none of the assessed contaminants. As there are no restrictions on application rates for this classification of biosolids, the assessment conservatively assumed that the unrestricted use biosolids were used in residential gardens as a topsoil.

The ecological assessment considered direct toxicity to terrestrial organisms as the only relevant ecological exposure pathway in this scenario. The RQ_{ECO} values exceeded 1 in all instances for HHCB and triclosan (maximum RQ_{ECO} 30 and 92, respectively), and ranged up to a RQ_{ECO} of 0.23 for chlordane.

The human health pathways assessed for Scenario 1 included incidental ingestion of soil/dust, incidental inhalation of dust, dermal absorption, ingestion of homegrown fruit/vegetables and consumption of eggs from chickens kept in residential backyards. The RQ_{HH} values were highest for the consumption of eggs and ranged up to 2 for Br1–Br9 and up to 7.6 for Br10. For chlordane, all RQ_{HH} values were less than 0.2.

Based on the results for Scenario 1, C&R recommends thresholds for HHCB, triclosan, PBDEs (Br1–Br9 and Br10) and chlordane should be derived:

- For HHCB, triclosan and chlordane, the key exposure pathway with the highest RQ values was ecological toxicity to terrestrial organisms.
- For PBDEs, the key exposure pathway with the highest RQ value was human health exposure via eggs.

Thresholds for unrestricted use biosolids should protect these pathways.

2.2 Scenario 2: unrestricted use biosolids for land rehabilitation

Scenario 2 assessed ecological and human health risks when unrestricted use biosolids are used for land rehabilitation. Similar to Scenario 1, it was assumed biosolids were processed with another waste at a ratio of 1 part biosolids to 2 parts other (Table 8) to produce unrestricted use biosolids, and that the final product was used as a topsoil. As a result, the estimated concentrations in the unrestricted use biosolids were used as the biosolids-amended soil (BAS) concentrations in all risk calculations. This scenario assumed the rehabilitated land is used as public open space/parklands. It should be noted this assessment is not protective of any land-use changes where the rehabilitated land is used for agricultural purposes. In cases where the intention is to use rehabilitated land for agricultural purposes, the NSW Biosolids Guidelines require land application to comply with the agricultural requirements which are addressed in Scenario 3.

2.2.1 Ecological risk assessment

All 3 exposure pathways listed in Section 1.3.1 were assessed for Scenario 2 for HHCB, triclosan and chlordane.

Pathway 1 – BAS → terrestrial organism

The assessment of Pathway 1 for this scenario results in the same RQ_{ECO} values as presented in Scenario 1 (Section 2.1.1). In summary, RQ_{ECO} values exceeded 1 based on both the 95UCL and maximum concentrations for HHCB and triclosan. For chlordane the RQ_{ECO} was above 0.2 for the maximum concentration but not the UCL95 (Table 9).

Pathway 2 – BAS → terrestrial organism → terrestrial secondary consumer

Pathway 2 assessed the potential for toxicity to terrestrial secondary consumers, which is relevant for chemicals known to bioaccumulate. The assessment was done by dividing the unrestricted use biosolids concentrations (95UCL and maximum concentrations) (Table 8) by the soil screening criteria for secondary consumers (Table 3). Resulting RQs are presented in Table 11 and summarised below:

- **HHCB** – the RQ_{ECO} values exceeded 1 for both the maximum and 95UCL concentrations (maximum RQ_{ECO} = 8.1; 95UCL RQ_{ECO} = 3.6).
- **Triclosan** – the RQ_{ECO} value exceeded 1 for both the maximum and 95UCL concentrations (maximum RQ_{ECO} = 5.7; 95UCL RQ_{ECO} = 1.7).
- **Chlordane** – the RQ_{ECO} value was above 1 for the maximum concentration (maximum RQ_{ECO} = 2.3) and was close to 1 for the 95UCL concentration.

Table 11 Scenario 2 ecological risk quotients (RQ_{ECO}) for Pathway 2, toxicity to terrestrial secondary consumers (rounded to 2 significant figures)

Scenario	HHCB	Triclosan	Chlordane
Scenario 2 (95UCL), Pathway 2	3.6	1.7	0.95
Scenario 2 (maximum), Pathway 2	8.1	5.7	2.3

Red indicates RQ > 1, Orange indicates 1 ≥ RQ > 0.2, Grey indicates RQ ≤ 0.2

Pathway 3 – BAS → groundwater/surface water runoff → surface water → aquatic organisms

Pathway 3 assessed the risk to offsite aquatic organisms by estimating potential leaching of HHCB, triclosan and chlordane into groundwater and surface runoff into receiving surface water bodies from areas where biosolids have been land applied.

This pathway was assessed by predicting surface water concentrations based on estimated soil pore water concentrations. Briefly, soil pore water concentrations were calculated for HHCB, triclosan and chlordane (and PBDEs for use in the human health assessment for this scenario) using solid-solution partition coefficients (K_d). Unlike the PFAS Biosolids Report, the K_d values were not experimentally determined as leachate data from the sampled biosolids for these compounds were not collected. Therefore, K_d values were estimated by multiplying organic carbon-water partition coefficients (K_{oc})¹⁹ by the fraction of organic carbon (f_{oc})²⁰ ($K_d = K_{oc} \times f_{oc}$). The estimated K_d values were then used to calculate the soil pore water concentrations (see Appendix C of the PFAS Biosolids Report for details on how these are calculated). The estimated soil pore water concentrations were then converted to estimated surface water concentrations by applying a dilution and attenuation factor (DAF) of 10 (Table 12).

Pathway 3 was assessed by dividing the estimated surface water concentrations (Table 12) by the aquatic toxicity screening criteria (Table 3). The resulting RQs are presented in Table 13 and summarised below:

- **HHCB** – the RQ_{ECO} values exceeded 0.2 for both the maximum and 95UCL concentrations (maximum RQ_{ECO} = 0.54; 95UCL RQ_{ECO} = 0.24).
- **Triclosan** – the RQ_{ECO} values exceeded 1 based on both the maximum and 95UCL concentrations (maximum RQ_{ECO} = 8.6; 95UCL RQ_{ECO} = 2.6).
- **Chlordane** – the RQ_{ECO} values for the maximum and 95UCL concentrations were below 1 but exceeded 0.2 (maximum RQ_{ECO} = 0.60; 95UCL RQ_{ECO} = 0.25).

¹⁹ HHCB K_{oc} = 38,600; triclosan K_{oc} = 9,260; Br1–Br9 K_{oc} = 37,200; Br10 K_{oc} = 6,310,000; chlordane K_{oc} = 3,090 (see Appendix C)

²⁰ A value of 0.016 was used as f_{oc} , which is approximately the 40th percentile of the f_{oc} of 14 agricultural soils used in the Australian National Biosolids Research Program (Broos et al. 2007) and provides a conservative estimate of K_d (Langdon et al. 2010). This is a very conservative assumption for f_{oc} for Scenario 2 as the unrestricted use biosolids will have a higher organic carbon content than a soil. This will result in a higher estimate of the pore water concentration and higher RQs.

Table 12 Estimated HHCB, triclosan, PBDEs and chlordane concentrations (µg/L) in pore water and surface water for Pathway 3, Scenario 2 (rounded to 2 significant figures)

	Estimated pore water conc.	Estimated surface water conc.
HHCB		
95UCL	16	1.6
Max	37	3.7
Triclosan		
95UCL	12	1.2
Max	40	4.0
Br1–Br9		
95UCL	0.059	0.0059
Max	0.13	0.013
Br 10		
95UCL	0.075	0.0075
Max	0.69	0.069
Br 10 excl STP K		
95UCL	0.0012	0.00012
Max	0.0023	0.00023
Chlordane		
95UCL	0.074	0.0074
Max*	0.18	0.018

*‘maximum’ concentration for chlordane is the 95th percentile concentration due to the large dataset available for this contaminant (approx. 300 measurements)

Table 13 Scenario 2 ecological risk quotients (RQ_{ECO}) for Pathway 3, toxicity to offsite aquatic organisms (rounded to 2 significant figures).

Scenario	HHCB	Triclosan	Chlordane
Scenario 2 (95UCL), Pathway 3	0.24	2.6	0.25
Scenario 2 (maximum), Pathway 3	0.54	8.6	0.60

Red indicates RQ > 1, Orange indicates 1 ≥ RQ > 0.2, Grey indicates RQ ≤ 0.2

2.2.2 Human health risk assessment

For Scenario 2, human health risks were assessed for PBDEs and chlordane by considering the following exposure pathways:

Pathway 1 – BAS → incidental ingestion of soil/dust

Pathway 2 – BAS → incidental inhalation of dust

Pathway 3 – BAS → incidental dermal absorption

Pathway 8 – BAS → groundwater/surface water → human consumption of water for drinking water purposes.

Scenario 2 assumed that biosolids are applied to land used for public open space and will not be returned to agriculture in the future. Therefore, the pathways considered for this scenario were for incidental exposure only and did not consider exposure via food consumption.

The risk calculations for each of the pathways are explained in detail in Section 1.6. For Br1–Br9 and chlordane, pathways 1 to 3 were assessed together using HIL C values for public open space from the ASC NEPM (Table 5). For Br10 an adjusted value based on the US EPA residential RSLs was used (Table 5). To assess Pathway 8, the estimated surface water concentrations from Table 12 were used as a conservative estimate of drinking water concentrations. These data were compared to the drinking water health screening criteria (Table 5). The RQs are presented in Table 14 and the results are summarised below:

- **PBDEs** – all RQ_{HH} values for all exposure pathways were below 0.2 (maximum RQ_{HH} = 0.08), indicating the risk is low.
- **Chlordane** – all RQ_{HH} values for all exposure pathways were below 0.2 (maximum RQ_{HH} = 0.009), indicating the risk is low.

Table 14 Human health risk quotients (RQ_{HH}) for PBDEs and chlordane for unrestricted use biosolids in land rehabilitation

Contaminant	Pathway 1, 2, 3* Ingestion of soil/dust, inhalation of dust & dermal	Pathway 8 Drinking water
Br1–Br9 95UCL	0.018	0.003
Br1–Br9 max	0.039	0.0066
Br 10 95UCL	0.0086	6.8×10^{-5}
Br 10 max	0.080	6.3×10^{-4}
Br 10 95UCL excl STP K	1.3×10^{-4}	1.1×10^{-6}
Br 10 Max excl STP K	2.7×10^{-4}	2.1×10^{-6}
Chlordane 95UCL	5.3×10^{-5}	0.0037
Chlordane max	1.3×10^{-4}	0.009

*assessed using open space screening criteria from Table 5.

Red indicates $RQ > 1$, Orange indicates $1 \geq RQ > 0.2$, Grey indicates $RQ \leq 0.2$

Scenario 2 summary

Scenario 2 assessed ecological risks (HHCB, triclosan and chlordane) and human health risks (PBDEs and chlordane) following land application of unrestricted use biosolids for land rehabilitation. Similar to Scenario 1, this assessment assumed the biosolids were processed with another waste material (e.g. garden waste) at a ratio of 1-part biosolids to 2-parts other to produce unrestricted use biosolids, and that this product was used as a topsoil.

Ecological risks for this scenario were assessed for 3 exposure pathways: direct toxicity to terrestrial organisms, toxicity to terrestrial secondary consumers and toxicity to offsite aquatic organisms. For HHCB, triclosan and chlordane RQ_{ECO} values exceeded 1 (RQ_{ECO} values up to 30, 92 and 2.3, respectively) for at least one of exposure pathways assessed.

The assessment of human health risks for Scenario 2 considered 4 pathways: incidental ingestion of soil/dust, incidental inhalation of dust, incidental dermal absorption and consumption of drinking water potentially contaminated from biosolids application. All RQ_{HH} values for PBDEs and chlordane were less than 0.2, indicating risks to human health following land application of unrestricted use biosolids in land rehabilitation are low (noting if the land use changes to agriculture, risk needs to be assessed as per Scenario 3).

Based on the results for Scenario 2, C&R recommends thresholds for HHCB, triclosan and chlordane are derived. For HHCB and triclosan, the key exposure pathway with the highest RQ values was direct toxicity to terrestrial organisms. For chlordane, the key exposure pathway with the highest RQ value was indirect toxicity to terrestrial secondary consumers. Thresholds for unrestricted use biosolids should protect these pathways.

2.3 Scenario 3: restricted use biosolids in agriculture

Scenario 3 assessed risks from HHCB, triclosan, PBDEs and chlordane following land application of restricted use biosolids in agriculture. This scenario assumed that biosolids are land applied and incorporated into soils as required by the NSW Biosolids Guidelines for agricultural use. This was done for the following land-application rates (and is in line with the assessment in the PFAS Biosolids Report):

- 10 t/ha single application
- 10 t/ha repeat applications
- 50 t/ha single application
- 50 t/ha repeat applications.

These application rates were selected to represent a ‘standard’ application rate (10 t/ha) and a ‘high’ application rate (50 t/ha) based on information from the biosolids industry in NSW. For repeat applications, it was assumed biosolids were applied to soil every 5 years for 30 years, which is a frequency consistent with the NSW Biosolids Guidelines. This equates to 7 applications of biosolids, including the initial year. This was assumed to represent a realistic maximum biosolids application in NSW.

The biosolids-amended soil concentrations used in Scenario 3 were estimated for each land application rate according to Equation 4 (Table 15).

$$C_{BAS} = C_B \times \frac{Mb}{Mb+Ms} \times App \quad \text{Equation 4}$$

where:

- C_{BAS} is the estimated contaminant concentration in biosolids-amended soils
- C_B is the contaminant concentration in biosolids
- Mb is the mass of biosolids applied to land (either 10 dry t/ha or 50 dry t/ha)
- Ms is the mass of soil the biosolids is incorporated into (1300 t/ha was used assuming a soil bulk density of 1.3 g/cm³ and an incorporation depth of 10 cm)
- App is the number of biosolids applications (i.e. single [1] or repeat [7]).

To assess risks via water (ecological Pathway 3 and human health Pathway 8), water concentrations were estimated using the approach outlined in Section 2.2.1. This was

done based on BAS concentrations in Table 15 for each land application rate (resulting pore water and estimated surface/drinking water concentrations are shown in Table 16).

Table 15 Estimated biosolids-amended soil concentrations (µg/kg dw) for HHCB, triclosan, PBDEs, and chlordane used in the ecological and human health risk assessments for Scenario 3 (rounded to 2 significant figures)

HHCB		Triclosan		Br1–Br9		Br10		Chlordane	
95UCL	Max	95UCL	Max	95UCL	Max	95UCL	Max	95UCL	Max [#]
10 t/ha single application									
230	520	42	140	0.80	1.8	170	1,600	0.084	0.21
						2.7*	5.3*		
10 t/ha repeat application									
1,600	3,600	290	960	5.6	13	1,200	11,000	0.59	1.4
						19*	37*		
50 t/ha single application									
1,100	2,500	200	670	3.9	8.8	840	7,800	0.41	1.0
						13*	26*		
50 t/ha repeat application									
7,800	18,000	1,400	4,700	27	61	5,800	54,000	2.9	7.0
						92*	180*		

* values exclude data from STP K

[#] 'maximum' concentration for chlordane is the 95th percentile concentration due to the large dataset available for this contaminant (approx. 300 measurements)

Table 16 Estimated water concentrations (µg/L) for HHCB, triclosan, PBDEs and chlordane at each application rate

HHCB		Triclosan		Br1–Br9		Br10		Chlordane	
95UCL	Max	95UCL	Max	95UCL	Max	95UCL	Max	95UCL	Max
10 t/ha single application									
0.037	0.084	0.028	0.093	1.4×10^{-4}	3.0×10^{-4}	1.7×10^{-4}	0.0016	1.7×10^{-4}	4.1×10^{-4}
						$2.7 \times 10^{-6*}$	$5.3 \times 10^{-6*}$		
10 t/ha repeat applications									
0.26	0.59	0.20	0.65	9.5×10^{-4}	0.0021	0.0012	0.011	0.0012	0.0029
						$1.9 \times 10^{-5*}$	$3.7 \times 10^{-5*}$		
50 t/ha single application									
0.18	0.41	0.14	0.45	6.6×10^{-4}	0.0015	8.3×10^{-4}	0.0077	8.2×10^{-4}	0.002
						$1.3 \times 10^{-5*}$	$2.6 \times 10^{-5*}$		
50 t/ha repeat applications									
1.3	2.9	0.96	3.1	0.0046	0.01	0.0058	0.054	0.0057	0.014
						$9.1 \times 10^{-5*}$	$1.8 \times 10^{-4*}$		

* values exclude data from STP K

2.3.1 Ecological risk assessment

All three exposure pathways listed in Section 1.3.1 were assessed for Scenario 3 for HHCB, triclosan and chlordane. The RQ_{ECO} values are presented in Table 17.

Pathway 1 – BAS → terrestrial organism

Toxicity to terrestrial organisms from the use of restricted use biosolids in agriculture was assessed by dividing the 95UCL and maximum BAS concentrations for the different application rates (Table 15) by the screening criteria for direct terrestrial toxicity (Table 3). The RQs are presented in Table 17 and the results are summarised below:

- **HHCB** – the maximum RQ_{ECO} values were above 1 for all land application rates (maximum $RQ_{ECO} = 24$), except for 10 t/ha single application which was above 0.2. The 95UCL RQ_{ECO} values were above 1 for all application rates (95UCL RQ_{ECO} up to 10), except 10 t/ha single application which was above 0.2.
- **Triclosan** – all maximum RQ_{ECO} values were above 1 for all land application rates (maximum $RQ_{ECO} = 72$). The 95UCL RQ_{ECO} values were also above 1 for all application rates (95UCL RQ_{ECO} up to 22), except for the 10/ha single application rate which was above 0.2.
- **Chlordane** – all RQ_{ECO} values were below 0.2 indicating the risk is low.

Pathway 2 – BAS → terrestrial organism → terrestrial secondary consumer

The risks to terrestrial secondary consumers from the use of restricted use biosolids in agriculture were assessed by comparing the 95UCL and maximum BAS for the different application rates (Table 15) with the screening criteria for secondary consumers (Table 3). The RQs are presented in Table 17 and the results are summarised below:

- **HHCB** – the maximum RQ_{ECO} values were above 1 for the repeat application rates (10 t/ha repeat $RQ_{ECO} = 1.3$; 50 t/ha repeat $RQ_{ECO} = 6.3$). For the 50 t/ha single application, the maximum RQ_{ECO} value was above 0.2 ($RQ_{ECO} = 0.9$). The 95UCL RQ_{ECO} values were all less than 1, except for 50 t/ha repeat application rate ($RQ_{ECO} = 2.8$).
- **Triclosan** – the maximum RQ_{ECO} value was above 1 only for the 50 t/ha repeat application rate ($RQ_{ECO} = 4.4$). For the 10 t/ha repeat applications and 50 t/ha single application, the maximum RQ_{ECO} values were above 0.2 (RQ_{ECO} values of 0.92 and 0.63, respectively). The 95UCL RQ_{ECO} values were all less than 1, except for the 50 t/ha repeat application rate ($RQ_{ECO} = 1.4$).
- **Chlordane** – the maximum RQ_{ECO} value was above 1 only for the 50 t/ha repeat application rate (maximum $RQ_{ECO} = 1.8$). The 10 t/ha repeat application and 50 t/ha single application were above 0.2. The 95UCL RQ_{ECO} value was above 0.2 only at the 50 t/ha repeat application rate ($RQ_{ECO} = 0.73$).

Pathway 3 – BAS → groundwater/surface water runoff → surface water → aquatic organisms

The risks from HHCB, triclosan and chlordane to offsite aquatic organisms following land application of restricted use biosolids in agriculture were assessed by comparing estimated surface water concentrations for the different biosolid application rates (Table 16) with the relevant aquatic toxicity screening criteria (Table 3). The RQs are presented in Table 17 and the results are summarised below:

- **HHCB** – all RQ_{ECO} values were less than 0.2 for 95UCL and maximum concentrations at all land application rates, except for the maximum concentration at 50 t/ha repeat applications which had an RQ_{ECO} of 0.42.

- **Triclosan** – the maximum RQ_{ECO} values were above 1 for the repeat application rates (10 and 50 t/ha) (maximum RQ_{ECO} values 1.4 and 6.7, respectively) and above 0.2 for the 50 t/ha single application rate ($RQ_{ECO} = 0.96$). All 95UCL RQ_{ECO} values were below 1, except for the 50 t/ha repeat application scenario where $RQ_{ECO} = 2.0$.
- **Chlordane** – all RQ_{ECO} values were below 1. The RQ_{ECO} value was above 0.2 only for the 50 t/ha repeat application rate (maximum $RQ_{ECO} = 0.47$).

Table 17 HHCB, triclosan and chlordane ecological risk quotients (RQ_{ECO}) for Scenario 3, restricted use biosolids in agriculture

	Single application (n=1)		Repeat application (n=7)	
HHCB	10 t/ha	50 t/ha	10 t/ha	50 t/ha
Pathway 1 (terrestrial organisms)				
95UCL	0.31	1.5	2.1	10
Maximum	0.69	3.4	4.8	24
Pathway 2 (terrestrial secondary consumer)				
95UCL	0.082	0.40	0.58	2.8
Maximum	0.19	0.90	1.3	6.3
Pathway 3 (offsite toxicity to aquatic organisms)				
95UCL	0.0055	0.027	0.038	0.19
Maximum	0.012	0.060	0.086	0.42
Triclosan	10 t/ha	50 t/ha	10 t/ha	50 t/ha
Pathway 1 (terrestrial organisms)				
95UCL	0.64	3.1	4.5	22
Maximum	2.1	10	15	72
Pathway 2 (terrestrial secondary consumer)				
95UCL	0.040	0.19	0.28	1.4
Maximum	0.13	0.63	0.92	4.4
Pathway 3 (offsite toxicity to aquatic organisms)				
95UCL	0.060	0.29	0.42	2.0
Maximum	0.20	0.96	1.4	6.7
Chlordane	10 t/ha	50 t/ha	10 t/ha	50 t/ha
Pathway 1 (terrestrial organisms)				
95UCL	0.0021	0.01	0.015	0.071
Maximum	0.0052	0.025	0.036	0.18
Pathway 2 (terrestrial secondary consumer)				
95UCL	0.022	0.10	0.15	0.73
Maximum	0.053	0.26	0.37	1.8
Pathway 3 (offsite toxicity to aquatic organisms)				
95UCL	0.0056	0.027	0.039	0.19
Maximum	0.014	0.067	0.10	0.47

Red indicates $RQ > 1$, Orange indicates $1 \geq RQ > 0.2$, Grey indicates $RQ \leq 0.2$

2.3.2 Human health risk assessment

For this scenario, human health risks were assessed for PBDEs and chlordane by considering 9 exposure pathways:

- **Pathway 1** – BAS → incidental ingestion of soil/dust
- **Pathway 2** – BAS → incidental inhalation of dust
- **Pathway 3** – BAS → incidental dermal absorption
- **Pathway 4** – BAS → uptake into homegrown fruit and vegetables → consumption of homegrown fruit and vegetables
- **Pathway 6a** – BAS → ingestion of soil by grazing beef cattle → human consumption of beef
- **Pathway 6b** – BAS → uptake into plants → ingestion of plants by beef cattle → human consumption of beef
- **Pathway 7a** – BAS → ingestion of soil by grazing dairy cows → human consumption of milk
- **Pathway 7b** – BAS → uptake into plants → ingestion of plants by dairy cows → human consumption of milk
- **Pathway 8** – BAS → groundwater/surface water → human consumption of water for drinking water purposes.

Pathways 6 and 7 assessed the home consumption of beef and milk. The pathways 'a' represent the contribution from soil only and the pathways 'b' represent the contribution from uptake into plants only. The sum of 'a' and 'b' indicates the risk from grazing beef cattle / dairy cows as they will consume both soil and plants. Pathway 'b' alone indicates the risk when fodder grown on biosolids-amended soil is consumed by beef cattle / dairy cows elsewhere.

The risk calculations for each of the pathways are explained in detail in Section 1.6, and predicted DI calculations and assumptions are explained in Appendix B.

For each exposure pathway, predicted DIs and risks (RQ_{HH}) were calculated for the following land application rate:

- 10 t/ha single application
- 50 t/ha single application
- 10 t/ha repeat applications
- 50 t/ha repeat applications.

The RQ_{HH} values for children for the 50 t/ha repeat application rate are listed in Table 18. These results only are presented here as they represent the worst case for human health risks for Scenario 3, and are the driver to determine if thresholds are required. This is in line with the process used in the PFAS Biosolids Report. For PBDE, RQs for the other application rates, adults RQs and the breakdown of the fruit and vegetable intakes refer to Appendix D (chlordane RQs are not provided in Appendix D as all RQs were less than 0.2, but values can be provided if needed). Results from the 50 t/ha repeat application rate are summarised below:

- **Br1–Br9** – the highest RQ_{HH} values were for the consumption of beef and milk (pathways 6 and 7). Based on both the 95UCL and maximum concentrations, the RQ_{HH} values for these pathways were above 1 (maximum RQ_{HH} of 12 for Pathway 6a+b), except for consumption of milk from dairy cows consuming fodder (Pathway 7b; 95UCL RQ_{HH} = 0.78). For Pathway 4, the consumption of homegrown fruit and vegetables, the maximum concentration resulted in a RQ above 0.2 (RQ_{HH} = 0.37).

- **Br10** – the highest RQ_{HH} was for the consumption of beef from grazing cattle (Pathway 6a+b) (maximum $RQ_{HH} = 1.1$). RQ_{HH} values were also above 0.2 for incidental ingestion of soil/dust (Pathway 1), consumption of homegrown fruit and vegetables (Pathway 4) and consumption of beef from cattle grazing on the land applied with biosolids (Pathway 7a+b) for the maximum Br10 concentrations. However, this was driven by the inclusion of data from STP K. When these data were excluded all RQ_{HH} values based on the maximum Br10 concentrations were considerably lower than 0.2.
- **Chlordane** – all RQ_{HH} values for all pathways were less than 0.2 (maximum $RQ_{HH} = 0.1$), indicating that the risks from these pathways are low.

Table 18 Human health risk quotients (RQ_{HH}) for children for PBDEs (Br1–Br9 and Br10) and chlordane assessed under Scenario 3 for the repeat application rate at 50 t/ha

Pathway	1 Soil/dust ingestion	2 Dust inhalation	3 Dermal absorption	4 Fruit and vegetables	6 a+b Beef – grazing	6b Beef – fodder	7 a+b Milk – grazing	7b Milk – fodder	8 Drinking water
Br1–Br9 95UCL	0.0091	2.2×10^{-9}	0.012	0.16	5.4	1.5	2.8	0.78	0.0023
Br1–Br9 max	0.020	4.8×10^{-9}	0.028	0.37	12	3.4	6.2	1.8	0.0051
Br 10 95UCL	0.028	8.1×10^{-9}	0.0038	0.028	0.12	0.0046	0.095	0.0036	5.3×10^{-5}
Br 10 max	0.26	7.5×10^{-8}	0.035	0.26	1.1	0.043	0.89	0.033	4.9×10^{-4}
Br 10 95UCL (excl STP K)	4.4×10^{-4}	1.3×10^{-10}	5.9×10^{-5}	4.5×10^{-4}	0.0019	7.3×10^{-5}	0.0015	5.6×10^{-5}	8.3×10^{-7}
Br 10 Max (excl STP K)	8.6×10^{-4}	2.5×10^{-10}	1.2×10^{-4}	8.8×10^{-4}	0.0038	1.4×10^{-4}	0.0030	1.1×10^{-4}	1.6×10^{-6}
Chlordane 95UCL	3.8×10^{-5}	4.0×10^{-9}	2.1×10^{-5}	0.0033	1.7×10^{-4}	1.4×10^{-4}	0.039	0.031	0.0029
Chlordane max	9.3×10^{-5}	9.8×10^{-9}	5.0×10^{-5}	0.0082	4.2×10^{-4}	3.3×10^{-4}	0.10	0.076	0.0070

Red indicates RQ > 1, Orange indicates $1 \geq \text{RQ} > 0.2$, Grey indicates $\text{RQ} \leq 0.2$

Scenario 3 summary

Scenario 3 was assessed in detail as most of the biosolids in NSW are land-applied in agriculture. This involved assessing 3 ecological exposure pathways and a combination of 9 human health exposure pathways (including incidental ingestion of soil/dust, incidental inhalation of dust, incidental dermal absorption, home consumption of crops [fruit and vegetables], beef and milk). Each pathway was assessed at application rates of 10 and 50 t/ha at single and repeat applications. The repeat applications assumed biosolids were applied every 5 years for 30 years. The land application scenario of 50 t/ha repeat application was considered a realistic maximum biosolids application rate for agriculture, and these results were presented in this report (other results are in Appendix D). It was assumed that if no potential risks were identified at this application rate, the risks via that pathway were low.

Ecological risks from HHCB, triclosan and chlordane were assessed for 3 exposure pathways (toxicity to terrestrial organisms, toxicity to terrestrial secondary consumers and toxicity to offsite aquatic organisms). RQ_{ECO} values exceeded 1 for HHCB for toxicity to terrestrial organisms and terrestrial secondary consumers (pathways 1 and 2). For triclosan, all 3 exposure pathways resulted in RQ_{ECO} values above 1, and for chlordane, exposure to terrestrial secondary consumers (Pathway 2) resulted in RQ_{ECO} above 1.

Human health risks from PBDEs and chlordane were assessed for 9 exposure pathways. For Br1–Br9, the consumption of beef and milk from grazing cattle / dairy cows resulted in RQ_{HH} values above 1, ranging up to 12. For Br10 the maximum RQ_{HH} value was 1.1 for the consumption of beef from grazing cattle, although this was driven by the high Br10 concentration from STP K. Excluding this value, all RQ_{HH} values for Br10 were below 0.2. For chlordane, all RQ_{HH} values were less than 0.2 (maximum $RQ_{HH} = 0.1$).

Based on the above results, C&R recommends thresholds for HHCB, triclosan, PBDEs and chlordane in restricted use biosolids are derived. The thresholds should protect the key exposure pathways:

- The key exposure pathway for HHCB and triclosan was ecological direct toxicity to terrestrial organisms (RQ_{ECO} up to 24 and 72, respectively).
- The key exposure pathway for PBDEs (both Br1–Br9 and Br10) was human health consumption of beef from grazing cattle (Pathway 7a+b) (RQ_{HH} up to 12 and 1.1, respectively).
- The key exposure pathway for chlordane was ecological toxicity to terrestrial secondary consumers (Pathway 2) (RQ_{ECO} up to 1.8).

C&R recommends the derivation of thresholds for restricted use biosolids should be based on these exposure pathways.

2.4 Scenario 4 (additional scenario) – unrestricted use biosolids in agriculture

For Scenario 4, risks from only the highest human health pathways determined from the Scenario 3 assessment (previous section) are presented in this section (risks from other pathways were assessed and can be provided if required). Therefore, this section refers

only to PBDEs and chlordane. Ecological risks from unrestricted use biosolids in agriculture do not need to be assessed here as all relevant pathways are already assessed for unrestricted use biosolids in scenarios 1 and 2.

The most sensitive pathways considered for this scenario were consumption of beef from grazing cattle for PBDEs (Br1–Br9 and Br10) (Pathway 6a+b) and consumption of milk from grazing dairy cows for chlordane (Pathway 7a+b). Similar to the other unrestricted use biosolids scenarios (scenarios 1 and 2), the estimated concentrations in unrestricted use biosolids (Table 8) were used as the soil concentrations. The process of estimating beef/milk concentrations and DIs of PBDEs and chlordane were the same as outlined for Scenario 3 and in Appendix B. Similar to other pathways, these are presented for children only as they are the most sensitive age group, but risks to adults can be provided if required.

For PBDEs, the assessment of unrestricted use biosolids in agriculture for Br1–Br9 resulted in a maximum RQ_{HH} of 16 (Table 19), which is the highest of all unrestricted use scenarios/pathways. Therefore, this pathway should be used to derive thresholds for Br1–Br9 in unrestricted use biosolids. This was not the case for Br10, where the maximum RQ_{HH} from the assessment of unrestricted use biosolids in agriculture ($RQ_{HH} = 1.5$, Table 19) was not higher than the highest RQ from other scenarios/pathways (maximum RQ_{HH} from Scenario 1 was 7.6 based on consumption of eggs, Table 10).

For chlordane, the assessment of unrestricted use biosolids in agriculture resulted in a maximum RQ_{HH} of 0.12 (Table 19). This value is lower than the RQ_{ECO} from Scenario 2 for ecological terrestrial secondary consumers of 2.3. Therefore, for chlordane the agricultural exposure scenario for unrestricted use biosolids is not the most sensitive pathway for threshold derivation.

Table 19 PBDE and chlordane human health risk quotients assessing key exposure pathways for unrestricted use biosolids in agriculture

Contaminant	Estimated soil conc. (µg/kg)	Key pathway	RQ_{HH}
Br1–Br9 95 UCL	35	Beef from grazing cattle	6.9
Br1–Br9 max	79	Beef from grazing cattle	16
Br10 95UCL	7,600	Beef from grazing cattle	0.16
Br10 max	70,000	Beef from grazing cattle	1.5
Br10 95UCL excl STP K	120	Beef from grazing cattle	0.0025
Br10 Max excl STP K	230	Beef from grazing cattle	0.0049
Chlordane 95 UCL	3.9	Milk from grazing cattle	0.051
Chlordane max	10 [#]	Milk from grazing cattle	0.12

[#] 'maximum' concentration of chlordane is the 95th percentile of concentrations due to the large dataset available for this contaminant

Red indicates $RQ > 1$, **Orange** indicates $1 \geq RQ > 0.2$, Grey indicates $RQ \leq 0.2$

3. Conclusions, recommendations and uncertainties

3.1 Key conclusions

This HHERA assessed the ecological risks for HHCB, triclosan and chlordane and the human health risks for PBDEs and chlordane. The type of risk assessment (ecological and/or human health) was based on the recommendations from the Contaminants Review (WCA 2016). Four different scenarios of biosolids use were considered:

- Scenario 1 – unrestricted use biosolids in residential gardens
- Scenario 2 – unrestricted use biosolids for land rehabilitation
- Scenario 3 – restricted use biosolids in agriculture
- Scenario 4 (additional scenario) – unrestricted use biosolids in agriculture.

For each scenario, relevant pathways for ecological and human exposure were assessed.

Based on the results of the HHERA, C&R recommends that HHCB, triclosan, PBDEs (Br1–Br9 and Br10) and chlordane require regulation and that thresholds for these contaminants in unrestricted use and restricted use biosolids are derived to protect ecology and human health.

The most sensitive exposure pathways, with the highest risk quotients (RQ) were identified for each type of biosolids (unrestricted or restricted use) (Table 20 to Table 24). C&R recommends these pathways are used to derive threshold concentrations for these contaminants in biosolids. This approach will result in thresholds that protect all other exposure pathways.

- **HHCB:** For HHCB, the most sensitive pathway was the ecological pathway for direct toxicity to terrestrial organisms (ecological Pathway 1), for both unrestricted use and restricted use biosolids.
- **Triclosan:** For triclosan, the most sensitive pathway was the ecological pathway for direct toxicity to terrestrial organisms (ecological Pathway 1), for both unrestricted use and restricted use biosolids.
- **Br1–Br9:** For Br1–Br9, the most sensitive pathway was consumption of beef from grazing cattle (human health Pathway 6a+b) for both unrestricted use and restricted use biosolids.
- **Br10:** For Br10, the most sensitive pathway was consumption of chicken eggs (human health Pathway 5) for unrestricted use biosolids and consumption of beef from grazing cattle (human health Pathway 6a+b) for restricted use biosolids.
- **Chlordane:** For chlordane, the most sensitive pathway for both unrestricted use and restricted use biosolids was the ecological pathway for toxicity to terrestrial secondary consumers (ecological Pathway 2).

Table 20 Summary of maximum risk quotients (RQs) for HHCB (only ecological risks assessed)

Ecological pathway	Biosolids type and scenario (Sc)		
	Unrestricted use		Restricted use
	Sc 1	Sc 2	Sc 3*
1 (direct terrestrial toxicity)	30	30	24
2 (terrestrial secondary consumers)	-	8.1	6.3
3 (aquatic organisms)	-	0.54	0.42

Grey shading indicates the most sensitive pathways for unrestricted and restricted use biosolids.

* only RQs for 50 t/ha repeat application shown

Table 21 Summary of maximum risk quotients (RQs) for triclosan (only ecological risks assessed)

Ecological pathway	Biosolids type and scenario (Sc)		
	Unrestricted use		Restricted use
	Sc 1	Sc 2	Sc 3*
1 (direct terrestrial toxicity)	92	92	72
2 (terrestrial secondary consumers)	-	5.7	4.4
3 (aquatic organisms)	-	8.6	6.7

Grey shading indicates the most sensitive pathways for unrestricted and restricted use biosolids

* only RQs for 50 t/ha repeat application shown

Table 22 Summary of maximum risk quotients (RQs) for Br1–Br9 (only human health risks assessed)

Human health pathway	Biosolids type and scenario (Sc)			
	Unrestricted use			Restricted use
	Sc 1	Sc 2	Sc 4 [#]	Sc 3*
1 (ingestion soil/dust)	0.079	0.039	-	0.02
2 (inhalation dust)			-	4.8×10^{-9}
3 (dermal absorption)			-	0.028
4 (fruit and vegetables)		-	-	0.37
5 (chicken eggs)	2.0	-	-	-
6a+b (beef from grazing cattle)	-	-	16	12
6b (beef from cattle consuming fodder)	-	-	-	3.4
7a+b (milk from grazing dairy cows)	-	-	-	6.2
7b (milk from dairy cows consuming fodder)	-	-	-	1.8
8 (drinking water)	-	0.0066	-	0.0051

Grey shading indicates the most sensitive pathways for unrestricted and restricted use biosolids.

* only RQs for 50 t/ha repeat application shown; [#] only the highest risk agricultural pathway was assessed for Scenario 4

Table 23 Summary of maximum risk quotients (RQs) for Br10 (only human health risks assessed)

Human health pathway	Biosolids type and scenario (Sc)			
	Unrestricted use			Restricted use
	Sc 1	Sc 2	Sc 4 [#]	Sc 3 [*]
1 (ingestion soil/dust)	0.16	0.080	-	0.26
2 (inhalation dust)			-	7.5×10^{-8}
3 (dermal absorption)			-	0.035
4 (fruit and vegetables)	0.17	-	-	0.26
5 (chicken eggs)	7.6	-	-	-
6a+b (beef from grazing cattle)	-	-	1.5	1.1
6b (beef from cattle consuming fodder)	-	-	-	0.043
7a+b (milk from grazing dairy cows)	-	-	-	0.89
7b (milk from dairy cows consuming fodder)	-	-	-	0.033
8 (drinking water)	-	6.3×10^{-4}	-	4.9×10^{-4}

Grey shading indicates the most sensitive pathways for unrestricted and restricted use biosolids

* only RQs for 50 t/ha repeat application shown; [#] only the highest risk agricultural pathway was assessed for Scenario 4

Table 24 Summary of maximum risk quotients (RQs) for chlordane (ecological and human health risks assessed)

Pathway	Biosolids type and scenario (Sc)			
	Unrestricted use			Restricted use
	Sc 1	Sc 2	Sc 4 [#]	Sc 3 [*]
Ecological 1 (direct terrestrial toxicity)	0.23	0.23	-	0.18
2 (terrestrial secondary consumers)	-	2.3	-	1.8
3 (aquatic organisms)	-	0.60	-	0.47
Human 1 (ingestion soil/dust)	1.8×10^{-4}	1.3×10^{-4}	-	9.3×10^{-5}
2 (inhalation dust)			-	9.8×10^{-9}
3 (dermal absorption)			-	5.0×10^{-5}
4 (fruit and vegetables)		-	-	0.0082
5 (chicken eggs)	0.043	-	-	-
6a+b (beef from grazing cattle)	-	-	-	4.2×10^{-4}
6b (beef from cattle consuming fodder)	-	-	-	3.3×10^{-4}
7a+b (milk from grazing dairy cows)	-	-	0.12	0.10
7b (milk from dairy cows consuming fodder)	-	-	-	0.076
8 (drinking water)	-	0.009	-	0.007

Grey shading indicates the most sensitive pathways for unrestricted and restricted use biosolids.

* only RQs for 50 t/ha repeat application shown; [#] only the highest risk agricultural pathway was assessed for Scenario 4

3.2 Recommendations and next steps

C&R recommends that HHCB, triclosan, chlordane and PBDEs (Br1–Br9 and Br10) in unrestricted use and restricted use biosolids require regulation and that thresholds are derived, to ensure land application of biosolids poses a low risk to ecology and human health.

Threshold derivation should be based on the key exposure pathways:

- Unrestricted use biosolids
 - HHCB – ecological toxicity to terrestrial organisms
 - Triclosan – ecological toxicity to terrestrial organisms
 - Chlordane – ecological toxicity to terrestrial secondary consumers
 - Br1–Br9 – consumption of beef from grazing cattle (human health)
 - Br10 – consumption of chicken eggs (human health).
- Restricted use biosolids
 - HHCB – ecological toxicity to terrestrial organisms
 - Triclosan – ecological toxicity to terrestrial organisms
 - Chlordane – ecological toxicity to terrestrial secondary consumers
 - PBDEs (Br1–Br9 and Br10) – consumption of beef from grazing cattle (human health).

Where thresholds are derived based on agricultural applications of biosolids, C&R recommends the exposure assumptions used should be based on realistic maximum exposure. Thresholds derived this way will be protective but will not be over conservative. The derivation process using these assumptions should be transparent and applicable to other contaminants that are being considered as part of the NSW Biosolids Guideline review.

3.3 Limitations and uncertainties

There are several limitations and uncertainties to consider when using the information presented in this report:

- **Representativeness of contaminant concentrations in biosolids** – the risk assessment for HHCB, triclosan and PBDEs is based on one round of biosolids sampling from 20 STPs in NSW, therefore the data represent only a snapshot and it is not known if, and to what extent, these concentrations may vary over time and at other STPs not included in the EPA sampling program.
- **Change of land use** – under the Biosolids Guidelines, the land use may change from land rehabilitation to agriculture (e.g. grazing) at a later stage. This means thresholds developed for land rehabilitation are not protective of agricultural pathways which include consumption of produce (crops, beef, milk) for the landowners/farmers. This needs to be considered in the review of the NSW Biosolids Guidelines.
- **Degradation of compounds** – the risk assessment did not take into account potential degradation or dissipation of the compounds over time. C&R notes the organic compounds assessed in this report are likely to show some degradation or dissipation in the field. However, the rate of degradation/dissipation can be difficult to estimate as it will be strongly influenced by the compound properties and environmental factors (e.g. temperature, moisture, sunlight, microbial activity). Therefore, C&R assumed no degradation or dissipation in this risk assessment.

- **Contaminant mobility** – the risk assessment estimated soil pore water, groundwater and surface water concentrations for several pathways using partitioning data sourced from the literature. To date, no validation/verification of these estimate concentrations has been conducted in NSW. However, C&R notes that these weren't key exposure pathways.

3.3.1 Limitations specific to some of the contaminants:

PBDEs

- The biosolids PBDE analysis included a limited suite of PBDEs in the Br1 to Br9 range. Since these congeners were summed to establish the exposure concentrations, this may result in an underestimation of exposure if other congeners are present. However, C&R notes the suite of PBDEs analysed in the biosolids samples is similar to the suite of PBDE congeners commonly analysed in environmental studies (i.e. BDE-28, BDE-47, BDE-99, BDE-100, BDE-138, BDE-153, BDE-154, BDE-183, and BDE-209). Additional congeners are usually found at trace concentrations (Fowles and Silver 2014, and references therein).
- Transfer factors for beef, milk and eggs were not available for PBDEs. As a surrogate, transfer factors for polychlorinated biphenyls (PCBs) and polychlorinated dioxins and furans were used. Refer to EnRiskS (2019) for a description of how these were used, and Appendix B of this report for details.
- There were data limitations for PBDE transfer factors into beef and milk. Transfer factors to estimate the PBDE concentrations in animal produce (i.e. beef and milk) were from OEHHA (2012). These transfer factors are expressed in d/kg since they reflect the ratio between the contaminant concentration in the produce ($\mu\text{g}/\text{kg}$) and the animal intake (kg/d). The transfer factors from OEHHA (2012) already consider the body weight of the animal, and therefore C&R could not use the same assumptions for body weight applied in the PFAS Biosolids Report. C&R notes that OEHHA (2012) does not clearly state what the animal body weights used were in deriving their transfer factors. C&R has assumed the beef cattle / dairy cow body weight does not differ significantly from the beef cattle / dairy cow weight of 500 kg used as a standard value throughout this risk assessment.

Chlordane

- The transfer factors for chlordane available in the literature were limited.
 - Transfer factors to estimate the chlordane concentrations in animal produce (i.e. egg, beef and milk) were from Leeman et al. (2007). The values presented in Leeman et al. (2007) were not chemical specific, but rather based on a group of pesticides which also included other pesticides such as DDT, aldrin, endrin and mirex (as well as others).
 - The transfer factors used to estimate transfer of chlordane from soil to root vegetables were calculated using soil and carrot concentrations reported in Mattina et al. (2000). The concentration of chlordane in carrots reported in the main text of the publication did not match the value reported in the accompanying supplementary data. C&R has used the value from the supplementary data, as it was presented together with a soil concentration, which enabled the derivation of a transfer factor. There is some uncertainty around this value, but it is unlikely to change the outcome of the risk assessment.
- Considering chlordane has been banned for use in Australia for a number of years, it is unclear how relevant the 2016 data used in this assessment are for current concentrations. C&R understands that the NSW EPA intends to undertake a

separate piece of work investigating this, which could be used to inform the conclusions from this report.

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Appendices

Appendix A: Selection of ecological screening criteria

HHCB

Direct toxicity to terrestrial organisms

In the absence of relevant Australian screening criteria for this pathway, C&R has adjusted a screening criterion from ECHA²¹ of 1,500 µg/kg to Australian conditions. The adjusted value is 750 µg/kg, which is explained below.

The ECHA value was based on the lowest available toxicity value of 45 mg/kg for earthworm reproduction (Gossmann 1997). The ECHA value was derived by normalising the toxicity value to 2% soil organic carbon and then applying an assessment factor of 10. The size of the assessment factor is based on the type of data available (i.e. short-term or long-term toxicity tests), the number of trophic levels tested, and the general uncertainties in predicting ecosystem effects from laboratory data (ECHA 2008).

C&R notes the soil organic carbon content in European soils is likely to be higher than that found in Australian soils. The ASC NEPM uses a soil organic carbon content of 1% for an Australian reference soil in the normalisation step for ecological investigation levels (NEPC 2013). Therefore, C&R adjusted the ECHA HHCB soil screening criterion of 1,500 µg/kg to this lower soil organic carbon content using Equation A1.

$$criterion^* = criterion \times \frac{OC^*}{OC} \quad \text{Equation A1}$$

where:

$criterion^*$ = adjusted criterion based on 1% soil organic carbon (OC)

$criterion$ = ECHA criterion normalised to 2% soil OC

OC^* = soil organic carbon content of the Australian reference soil (1%)

OC = soil organic carbon content used to normalise the ECHA criterion (2%).

This calculation results in an adjusted HHCB soil-screening criterion for direct toxicity to terrestrial organisms of 750 µg/kg. C&R notes this is higher than the value of 310 µg/kg that was used in the Contaminants Review (WCA 2016) which was sourced from the Netherlands (RIVM 2008).

Toxicity to terrestrial secondary consumers

No screening criteria were available for this pathway from any sources considered. Therefore, C&R derived an interim criterion of 2,800 µg/kg for use in this risk assessment. The derivation approach was based on the method used by ECHA (ECHA 2012) and involved deriving a predicted no-effect concentration for secondary poisoning ($PNEC_{sp}$) using Equation A2. In addition, C&R has adjusted the criteria to 1% soil OC to be consistent with the HHCB direct toxicity criterion presented above.

$$PNEC_{sp} = \frac{PNEC_{oral}}{BAF_{worm}} \quad \text{Equation A2}$$

where:

$PNEC_{sp}$ = predicted no effect concentration for secondary poisoning, mg/kg dry weight soil

²¹ 1,3,4,6,7,8-hexahydro-4,6,6,7,8,8-hexamethylindeno[5,6-c]pyran, ECHA webpage: echa.europa.eu/registration-dossier/-/registered-dossier/14504

$PNEC_{oral}$ = predicted no effect concentration for secondary poisoning mg/kg fresh weight food (the value used was 20.4 from ECHA)

BAF_{worm} = bioaccumulation factor for earthworms on a wet weight basis from empirical studies, kg dry weight (dw) soil / kg wet weight (ww) earthworm.

Table A1 presents soil and corresponding worm concentrations from the literature (Kinney et al. 2008; Kinney et al. 2012; Rivier et al. 2019). In each of these studies, concentrations of HHCB in soils and earthworms were reported on a dry weight basis. Therefore, to calculate the BAF_{worm} consistent with the procedure outlined above, the concentrations of HHCB in the worms were first converted to wet weights. This was done by applying a factor of 0.206 to the dry weight concentrations (UK EA 2009). The BAF_{worm} values were then calculated by dividing the wet weight concentration in the worms by the dry weight soil concentrations. The resulting $PNEC_{sp}$ (using Equation A2) were then adjusted to 1% soil OC using Equation A1, where the parameters '*criterion*' and '*OC*' were based on the individual studies listed in Table A1. The geometric mean of the adjusted $PNEC_{sp}$ (i.e. 2,800 $\mu\text{g/kg}$) was adopted as the HHCB soil screening criteria for terrestrial secondary consumers in this HHERA.

Table A1 HHCB worm bioaccumulation factors (BAF_{worm}), and adjusted terrestrial secondary poisoning predicted no effect concentrations ($PNEC_{sp}$) normalised to 1% soil organic carbon (OC)

Study	Soil conc. ($\mu\text{g/kg dw}$)	Worm conc. ($\mu\text{g/kg dw}$)	Worm conc. ($\mu\text{g/kg ww}$)	BAF_{worm}	$PNEC_{sp}$ (mg/kg) ^A	Soil OC % ^B	Adj. $PNEC_{sp}$ (mg/kg) ^C
Kinney et al. 2008	633	61	13	0.02	1,030	2.7	380
	1,050	3,340	688	0.66	31	1.2	26
	2,770	131	27	0.0097	2,090	2.2	950
Kinney et al. 2012	189	1,567	323	1.7	12	3.0	4.0
	165	2,310	476	2.9	7.1	3.0	2.4
	860	2,123	437	0.51	40	3.5	12
	235	2,697	556	2.4	8.6	3.5	2.5
	170	6,100	1,257	7.4	2.8	4.1	0.68
	190	4,500	927	4.9	4.2	4.1	1.0
Rivier et al. 2019	11.5	810	167	15	1.4	3.2	0.44
	5.4	120	25	4.6	4.5	3.2	1.4
	17	410	84	5.0	4.1	4.5	0.92
	11	2,090	430	39	0.52	3.2	0.16
	8.3	460	95	11	1.8	3.2	0.56
	35	1,460	301	8.5	2.4	4.5	0.53
	17	440	91	5.4	3.8	3.2	1.2
	8.3	80	16	2.0	10	3.2	3.2
	16	790	163	10	2.0	4.5	0.45

^A calculated from Equation A2 ($PNEC_{sp} = PNEC_{oral}/BAF_{worm}$), where $PNEC_{oral}$ was assumed to be 20.4 mg/kg fresh weight food;

^B where studies reported soil organic matter, values were converted to soil OC assuming soil OC is 58% of soil organic matter (UK EA 2017)

^C calculated as $Adj. PNEC_{sp} = PNEC_{sp} \times (1/OC)$

Aquatic toxicity

No screening criteria for aquatic toxicity were available from Australia. Therefore, C&R adopted a value from ECHA of 6.8 µg/L²². This value was derived by applying an assessment factor of 10 to the most sensitive toxicity value of 680 µg/L (chronic toxicity test with fathead minnow; Croudace et al. 1997). This value is also consistent with the PNEC reported in the draft Australian Government report *Galaxolide and a related polycyclic musk: Evaluation statement*, 28 May 2021 (AICIS 2021).

Triclosan

Direct toxicity to terrestrial organisms

No Australian criteria were available for this compound for this pathway. A value of 65 µg/kg was used for this assessment which was adjusted based on the value of 130 µg/kg from UK EA (2020). The UK EA (2020) value was derived by applying an assessment factor of 10 to the lowest toxicity value 1.96 mg/kg (dw) (survival/reproduction of *Hypoaspis aculeifer*; and normalised to a soil organic matter [SOM] of 3.4%). This value is consistent with the criteria used in the Contaminants Review (WCA 2016). C&R adjusted this value to 1.7% SOM, which is equivalent to a soil OC content of 1% (assuming OC = 0.58 × SOM, UK EA 2017). This adjustment to soil OC is consistent with the adjustment discussed above for HHCB. The resulting triclosan soil screening criterion for this pathway is 65 µg/kg.

Toxicity to terrestrial secondary consumers

No Australian criteria were available for this pathway. A value of 1,050 µg/kg was used in this assessment, which was adjusted based on the value of 2.1 mg/kg (dw) from UK EA (2020). The UK EA (2020) value is normalised to 3.4% organic matter and was derived using a PNEC_{oral} of 20 mg triclosan per kg food and a BAF_{worm} of 9.33 kg dw / kg ww. C&R adjusted this value to 1.7% SOM, which is equivalent to a soil content of 1% (assuming OC = 0.58 × SOM, UK EA 2017). This adjustment to soil OC is consistent with the adjustment discussed above for HHCB. The resulting triclosan soil screening criterion for this pathway is 1,050 µg/kg.

Aquatic toxicity

No Australian criteria were available for this pathway. C&R has adopted the value of 0.47 µg/L from Environment and Climate Change Canada (ECCC 2017). This value was derived using a species sensitivity distribution (SSD) with data for 20 species from 4 taxonomic groups. The value corresponds to the 5th percentile (i.e. should theoretically protect 95% of species).

C&R notes there are other guideline values available for aquatic toxicity of triclosan. ECHA used a similar approach as ECCC to derive an aquatic PNEC of 0.843 µg/L. A detailed review of the differences between the ECCC and ECHA values was out of scope of this assessment. However, as the ECCC value is more conservative, it was adopted for use in this assessment.

²² 1,3,4,6,7,8-hexahydro-4,6,6,7,8,8-hexamethylindeno[5,6-c]pyran, ECHA webpage: <https://echa.europa.eu/registration-dossier/-/registered-dossier/14504>

The UK has proposed an environmental quality standard (EQS) of 0.28 µg/L for the short-term toxicity of triclosan²³. This was derived using a deterministic approach where the EC₅₀ (median effective concentration) of the most sensitive organism (*Scenedesmus subspicatus*) was used together with an assessment factor of 10 to derive the final EQS. In the EU, a draft dossier has been prepared for an EQS for triclosan under the Water Framework Directive²⁴. An annual average (AA) QS of 0.02 µg/L has been proposed. The value was derived using the no observed effect concentration (NOEC) of a mesocosm study together with an assessment factor of 5. As both the UK and EU values are draft/proposed at this stage they have not been adopted for use in this assessment. The suitability of these values for inclusion in the assessment can be considered in more detail in the future when they are finalised.

Chlordane

Direct toxicity to terrestrial organisms

No criteria were available for this pathway from Australian sources, or the other key sources (ECHA, UK EA, ECCC). Therefore, to assess direct toxicity from chlordane to terrestrial organisms, C&R adopted the value of 40 µg/kg from the Spanish Government Royal Decree 9/2005 (Spanish Government 2014). This value was derived from ecotoxicological assessments considering exposures to soil microbes, terrestrial plants and soil invertebrates. C&R selected this value instead of the value of 0.253 µg/kg used in the Contaminants Review (WCA 2016), which was derived by INERIS (2011) using a partitioning coefficient method rather than ecotoxicological data. The preferred approach for deriving criteria in Australia is the use of ecotoxicity data over modelled data, and therefore C&R used the Spanish Government Royal Decree 9/2005 value as a preference.

Toxicity to terrestrial secondary consumers

No criteria were available from Australia or other jurisdictions to assess chlordane risks from this pathway. Therefore, C&R derived an interim criterion for use in the risk assessment. The approach was the same as that used for HHCB and was based on ECHA (2012). Three studies were used that presented corresponding soil and earthworm concentrations to allow BAF_{worm} values to be calculated. This was done by dividing the wet weight concentration in the worms by the dry weight soil concentrations (Table A2). The $PNEC_{sp}$ values were then calculated using Equation A2 using a $PNEC_{oral}$ of 0.03 mg/kg food (INERIS 2011). The $PNEC_{sp}$ values were then adjusted to 1% soil OC for consistency with the criteria discussed above. The geometric mean of the adjusted $PNEC_{sp}$ of 3.9 µg/kg was used in the risk assessment.

²³ Proposed EQS for Water Framework Directive Annex VIII substances: triclosan (For consultation), Water Framework Directive, United Kingdom Technical Advisory Group: www.wfduk.org/sites/default/files/Media/Triclosan%20-%20UKTAG.pdf

²⁴ European Commission, CIRCABC website, JRC_Draft EQS Dossier_Triclosan_21.12.2021_final.doc: <https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/fd7f81cf-397a-4efb-9415-00e6fa9f82a2/details>

Table A2 Chlordane worm bioaccumulation factors (BAF_{worm}), and adjusted terrestrial secondary poisoning predicted no effect concentrations ($PNEC_{sp}$) normalised to 1% soil organic carbon (OC)

Study	Soil conc. (mg/kg dw)	Worm conc. (mg/kg ww)	BAF_{worm}^A	$PNEC_{sp}$ (mg/kg) ^B	Soil OC % ^C	Adj. $PNEC_{sp}$ (mg/kg) ^D
Mukherjee et al. 2017	1.2	2.6	2.3	0.013	2.5	0.0052
Wågman et al. 1999 ^E	8.8×10^{-5}	5.2×10^{-5}	0.59	0.051	39	0.0013
	1.7×10^{-4}	7.2×10^{-5}	0.42	0.071	43	0.0017
	2.5×10^{-4}	8.0×10^{-5}	0.32	0.094	40	0.0023
Gish and Hughes 1982 ^F	0.27	0.93	3.5	0.0087	2.0	0.0043
	0.14	0.81	5.8	0.0052	2.1	0.0025
	0.15	0.33	2.2	0.014	1.8	0.0075
	0.11	0.54	4.9	0.0061	2.3	0.0027
	0.11	1.3	12	0.0024	2.2	0.0011
	0.12	0.29	2.4	0.012	2.2	0.0056
	0.2	0.31	1.5	0.020	2.6	0.0075
	0.11	0.34	3.1	0.0098	1.9	0.0052
	0.11	0.40	3.7	0.0082	2.1	0.0039
	0.14	0.28	2.0	0.015	2.6	0.0057
	0.27	0.13	0.48	0.062	2.4	0.026
	0.18	0.54	3.0	0.0099	2.6	0.0038

^A BAF_{worm} = conc. in worm (ww) / conc. in soil (dw)

^B $PNEC_{sp}$ = $PNEC_{oral}$ / BAF_{worm} (where the $PNEC_{oral}$ = 0.03 mg/kg food)

^C where studies reported soil organic matter, values were converted to soil OC assuming soil OC is 58% of soil organic matter (UK EA 2017)

^D adjusted $PNEC_{sp}$ = $PNEC_{sp} \times (1/OC)$

^E Wågman et al. (1999) study was done with compost samples. The chlordane data were presented for *trans*- and *cis*-chlordane, which have been summed together as total chlordane in the table

^F worm concentrations were converted from dry weights to wet weights using a conversion factor of 0.206 (UK EA 2009)

Aquatic toxicity

To assess potential for aquatic ecological toxicity, C&R used a value of 0.03 µg/L from the Australian Water Quality Guidelines (ANZG 2018). This value is for 99% species protection as recommended by ANZG for bioaccumulative substances such as chlordane (ANZG 2018).

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Appendix B: Human health risk calculations

For pathways and scenarios where no relevant screening criteria were available, human health risks were assessed by estimating daily intakes (DIs). The DIs were then divided by the background adjusted tolerable daily intakes (TDI) to calculate risk quotients. The approach to calculate the risk quotient from exposure to dust is slightly different as it involves calculating an air exposure concentration. This approach is summarised in the equations below for that pathway.

The human health risk calculations were done only for PBDEs (Br1–Br9 and Br10) and chlordane, as other contaminants in this report were assessed for ecological risks only. All assumptions shown in this section are relevant to children, which is consistent with the information provided in this report, as they are the most sensitive age group. The subsections below indicate which scenarios used the calculations presented. For cases where an Australian or international soil screening criteria was used to assess risks from a pathway, those assumptions have not been provided. Readers should refer to the cited source in the risk assessment for those details.

Pathway 1 – incidental ingestion of soil (Scenario 3)

Daily intake (human health) (DI)

$$DI \text{ (mg/kg/day)} = \frac{C_s \times IR_s \times AoF \times FI \times EF \times ED}{AT \times BW}$$

Parameter	Value	Units	Description
C_s	Variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
IR_s	0.0001	kg/day	Incidental soil ingestion rate (kg/day) – ASC NEPM, Schedule B7 (NEPC 2013a)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from contaminated source – assumes all soil/dust incidentally ingested is from areas containing biosolids
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	2,190	days	Averaging time = $EF \times ED$
BW	15	kg	Body weight (child) – ASC NEPM, Schedule B7 (NEPC 2013a)

Pathway 2 – incidental inhalation of dust (Scenario 3)

Particulate emission factor (outdoor air) (PEF_o)

$$PEF_o(m^3/kg) = \frac{Q/C \times 3600}{[0.036 \times (1 - V) \times (Um/Ut)^3 \times Fx]}$$

Parameter	Value	Units	Description
Q/C	90.8	g/m ² /s per kg/m ³	Air dispersion factor – ASC NEMP, Schedule B7, Appendix B (NEPC 2013b)
V	0	unitless	Fraction of outdoor surface cover – assumes bare ground
Um	2.4	m/s	Mean annual wind speed at a height of 10 m – ASC NEMP, Schedule B7, Appendix B (NEPC 2013b)
Ut	7.2	m/s	Threshold value of wind speed at a height of 10 m – ASC NEMP, Schedule B7, Appendix B (NEPC 2013b)
Fx	0.032*	unitless	Empirical function based on the ratio of means and threshold wind speeds – ASC NEMP, Schedule B7, Appendix B (NEPC 2013b)

* $Fx = 0.18 \times (8x^3 + 12x)\exp(-x^2)$ where $x = 0.886 (Ut/Um)$

Particulate emission factor (indoor air) (PEF_i)

$$PEF_i(m^3/kg) = \frac{1}{DL \times 10^{-6}}$$

Parameter	Value	Units	Description
DL	0.039	mg/m ³	Dust loading factor – ASC NEMP, Schedule B7, Appendix B (NEPC 2013b)
10^{-6}		kg/mg	Conversion factor for mg to kg

Concentration in dust (C_D)

$$C_D (mg/m^3) = \frac{C_s}{PEF}$$

Parameter	Value	Units	Description
C_s	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
PEF	variable	m ³ /kg	Particulate emission factor – calculated from previous equations

Inhalation exposure concentration (EC)

$$EC \text{ (mg/m}^3\text{)} = \frac{C_D \times RF \times ET \times EF \times ED}{AT}$$

Parameter	Value	Units	Description
C_D	variable	mg/m ³	Concentration in dust – calculated from previous equation
RF	0.375	unitless	Lung retention factor – ASC NEPM, Schedule B7 (NEPC 2013a)
ET	4 (outdoors) 20 (indoors)	hours/day	Exposure time outdoors and indoors – ASC NEPM, Schedule B7 (NEPC 2013a)
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	52,560	hours	Averaging time (child) = $EF \times ED \times 24$

Risk quotient (RQ)

$$RQ = EC / TRV_i$$

Parameter	Value	Units	Description
EC	variable	mg/m ³	Exposure concentration – from previous equation
TRV_i	0.00035 (Br1–Br9) 20,000 (Br10)* 0.00175 (chlordan)	mg/m ³	Inhalation toxicity reference value ASC NEPM, Schedule B7, Appendix A5 (NEPC 2013c) ASC NEPM, Schedule B7, Appendix A3 (NEPC 2013d)

* converted from the oral toxicity reference value of 0.007 mg/kg/d, assuming a person breathes 20 m³ per day, i.e. $(0.007 \times 70) / 20 = 0.0245$ mg/m³ (rounded down to 0.02 mg/m³)

Pathway 3 – dermal absorption (Scenario 3)

Daily intake (human health) (DI)

$$DI \text{ (mg/kg/day)} = \frac{C_S \times SAs \times AF \times DAF \times EF \times ED}{AT \times BW}$$

Parameter	Value	Units	Description
C_S	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
SAs	2,700	cm ²	Surface area of body exposed to soil (child) – assumes 44.3% of a total 6,100 cm ² for a child – ASC NEPM, Schedule B7 (NEPC 2013a)
AF	5×10^{-7}	kg/cm ² /d	Soil adherence factor – ASC NEPM, Schedule B7 (NEPC 2013a)
DAF	0.1 (Br1–Br9)	unitless	Dermal absorption factor

Parameter	Value	Units	Description
	0.01 (Br10)		ASC NEPM, B7 Appendix A5 (NEPC 2013c)
	0.04 (chlordane)		EU (2003)
			ASC NEPM, B7 Appendix A3 (NEPC 2013d)
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	2,190	days	Averaging time = EF × ED
BW	15	kg	Body weight (child) – ASC NEPM, Schedule B7 (NEPC 2013a)

Pathway 4 – consumption of homegrown fruit and vegetables (Scenario 1 [Br10 only] and Scenario 3)

Concentration in fruit and vegetables ($C_{f,v}$)

$$C_{f,v} \text{ (mg/kg)} = C_s \times TF_{f,v}$$

Parameter	Value	Units	Description
C_s	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
$TF_{f,v}$	variable	unitless	Transfer factor for fruit or vegetable (see table below)

Contaminant and plant type specific soil-to-plant transfer factors (all TFs are unitless)

Contaminant	Plant type	Value	Reference
Br1–Br9	Green vegetables	2.63×10^{-3}	EnRiskS (2019)
	Root vegetables	2.30×10^{-2}	EnRiskS (2019)
	Tuber vegetables	2.88×10^{-1}	EnRiskS (2019)
	Tree fruits	2.42×10^{-3}	EnRiskS (2019)
Br10	Green vegetables	2.84×10^{-4}	EnRiskS (2019)
	Root vegetables	1.80×10^{-3}	EnRiskS (2019)
	Tuber vegetables	1.59×10^{-2}	EnRiskS (2019)
	Tree fruits	1.07×10^{-4}	EnRiskS (2019)
Chlordane	Green vegetables	0.12	Mattina et al. (2003)
	Root vegetables	0.14	Calculated from data in Mattina et al. (2000) [#]
	Tuber vegetables	0.090	Calculated from data in Mattina et al. (2000)

Contaminant	Plant type	Value	Reference
	Tree fruits	0.18	Calculated from data in Mattina et al. (2000)

values for calculation of TF sourced from the supporting information

Daily intake (human health) from consumption of fruit and vegetables (DI)

$$DI (mg/kg/day) = \frac{C_{f,v} \times IR_{f,v} \times AoF \times FI \times EF \times ED}{AT \times BW}$$

Parameter	Value	Units	Description
$C_{f,v}$	variable	mg/kg	Concentration in fruit or vegetable from previous equations
$IR_{f,v}$	0.055 (green vegetables) 0.017 (root vegetables) 0.028 (tuber vegetables) 0.18 (tree fruits)	kg/d	Child fruit or vegetable ingestion rate – ASC NEPM, Schedule B7 (NEPC 2013a)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	0.1 (Scenario 1) 0.2 (Scenario 3)	unitless	Fraction ingested from contaminated source For Scenario 1, assumes 10% of fruit/vegetables are ingested from residential backyards where biosolids have been used. This is consistent with ASC NEPM Schedule B7 (HIL A) (NEPC 2013a) For Scenario 3, assumes 20% of fruit and vegetables are consumed from areas containing biosolids (assumption agreed with NSW Government agencies, May 2019)
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	2,190	days	Averaging time = $EF \times ED$
BW	15	kg	Body weight (child) – ASC NEPM, Schedule B7 (NEPC 2013a)

Pathway 5 – human consumption of chicken eggs (Scenario 1)

Concentration in eggs (C_{eggs}) (PBDEs)

$$C_{eggs}(mg/kg) = C_s \times IR_s \times FI \times AoF \times TF_{eggs}$$

Parameter	Value	Units	Description
C_s	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate

Parameter	Value	Units	Description
IR_s	0.0105	kg/day	Chicken soil ingestion rate (AECOM 2017)
FI	1	unitless	Fraction of soil ingested by chickens from contaminated source – assumes 100% of soil ingested by chickens is from areas containing biosolids
AoF	1	unitless	Oral absorption factor for chickens
TF_{eggs}	10 (Br1–Br9) 3 (Br10)	day/kg	Transfer factor from chicken into eggs* (OEHHA 2012, Appendix K)

* Transfer factors were not available for PBDEs. As a surrogate, transfer factors for polychlorinated biphenyls and polychlorinated dioxins/furans were used. Refer to EnRiskS (2019) for details.

Concentration in eggs (C_{eggs}) (chlordanes)

$$C_{egg}(mg/kg) = C_s \times TF_{egg} \times F_{soil}$$

Parameter	Value	Units	Description
C_s	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
TF_{egg}	5.5	unitless	Transfer factor into egg from feed (Leeman et al. 2007)
F_{soil}	0.1	unitless	Fraction of feed intake that is soil – assumes 10% of feed intake is soil (AECOM 2017 – Appendix I)

Daily intake (human health) from consumption of homegrown eggs (DI)

$$DI (mg/kg/day) = \frac{C_{eggs} \times IR_{eggs} \times AoF \times FI \times EF \times ED}{AT \times BW}$$

Parameter	Value	Units	Description
C_{eggs}	variable	mg/kg	Concentration in eggs (from previous equations)
IR_{eggs}	0.072	kg/day	Ingestion rate of eggs – 2-times 90 th percentile egg consumption rate from FSANZ (2017). Assumes people with their own chickens will eat a high rate of eggs (enHealth 2012). Equivalent to approx. 1.2 eggs per day for children.
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from the source – assumes all eggs consumed are from chickens ingesting biosolids
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	2,190	days	Averaging time = $EF \times ED$
BW	15	kg	Body weight (child) – ASC NEPM, Schedule B7 (NEPC 2013a)

Pathway 6 – human consumption of beef (Scenario 3)

Concentration in plants/fodder (C_P)

$$C_P \text{ (mg/kg dry weight)} = C_S \times TF_{plant} \times CF$$

Parameter	Value	Units	Description
C_S	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
TF_{plant}	0.1 (Br1–Br9) 0.01 (Br10) 0.12 (chlordane)	unitless	Yang et al. 2018 Yang et al. 2018 Mattina et al. 2003
CF^*	0.15	unitless	Convert TF from wet weight to dry weight. Assumes 15% dry matter (EnRiskS 2019)

* parameter not used for chlordane as TF presented on a dry weight basis

Concentration in beef (C_{beef}) for grazing cattle (PBDEs)

$$C_{beef} \text{ (mg/kg)} = [(C_S \times IR_S \times FI_S \times AoF) + (C_P \times IR_P \times FI_P \times AoF)] \times TF_{beef}$$

Parameter	Value	Units	Description
C_S	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
IR_S	0.5	kg/day	Cattle soil ingestion rate – based on US EPA (2005) and advice from NSW Dept of Primary Industries (DPI)
FI_S	1	unitless	Fraction of soil ingested from the area containing biosolids
C_P	variable	mg/kg (dry weight)	Concentration in plant (from previous equation)
IR_P	13	kg/day (dry matter)	Cattle plant ingestion rate based on API (2004) and advice from NSW DPI
FI_P	1	unitless	Fraction of plant ingested from the area containing biosolids
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
TF_{beef}	2 (Br1–Br9) 0.02 (Br10)	day/kg	Transfer factor into meat* (OEHHA 2012, Appendix K)

* Transfer factors were not available for PBDEs. As a surrogate, transfer factors for polychlorinated biphenyls and polychlorinated dioxins/furans were used. Refer to EnRiskS (2019) for details.

Concentration in beef (C_{beef}) from fodder (PBDEs)

$$C_{beef} \text{ (mg/kg)} = (C_P \times IR_P \times FI_P \times AoF) \times TF_{beef}$$

Parameter	Value	Units	Description
C_P	variable	mg/kg (dry weight)	Concentration in plant (from previous equation)

Parameter	Value	Units	Description
IR_p	13	kg/day (dry matter)	Cattle plant ingestion rate based on API (2004) and advice from NSW DPI
FI_p	1	unitless	Fraction of plant ingested from the area containing biosolids
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
TF_{beef}	2 (Br1–Br9) 0.02 (Br10)	day/kg	Transfer factor into meat* (OEHHA 2012, Appendix K)

* Transfer factors were not available for PBDEs. As a surrogate, transfer factors for polychlorinated biphenyls and polychlorinated dioxins/furans were used. Refer to EnRiskS (2019) for details.

Concentration in beef (C_{beef}) for grazing cattle (chlordanes)

$$C_{beef}(mg/kg) = (C_s \times TF_{beef} \times F_{soil}) + (C_p \times TF_{beef} \times F_{plant})$$

Parameter	Value	Units	Description
C_s	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
TF_{beef}	0.07	unitless	Transfer factor from feed into meat (Leeman et al. 2007)
F_{soil}	0.04	unitless	Fraction of feed intake that is soil – assumes 4% of intake for grazing cattle is soil, based on a soil ingestion rate of 0.5 kg/day and plant dry matter ingestion rate of 13 kg/day (API 2004 and advice from NSW DPI)
C_p	variable	unitless	Concentration in plant (from equation above)
F_{plant}	0.96	unitless	Fraction of feed intake that is plant dry matter – assumes 96% of intake for grazing cattle is plant, based on a soil ingestion rate of 0.5 kg/day and plant dry matter ingestion rate of 13 kg/day (API 2004 and advice from NSW DPI)

Concentration in beef (C_{beef}) from fodder (chlordanes)

$$C_{beef}(mg/kg) = C_p \times TF_{beef} \times F_{plant}$$

Parameter	Value	Units	Description
C_p	variable	mg/kg	Concentration in plant (from equation above)
TF_{beef}	0.07	unitless	Transfer factor from feed into meat (Leeman et al. 2007)
F_{plant}	1	unitless	Fraction of feed intake that is plant dry matter – assumes 100% of cattle diet is fodder grown in areas containing biosolids

Daily intake (human health) from consumption of beef (DI)

$$DI \text{ (mg/kg/day)} = \frac{C_{beef} \times IR_{beef} \times AoF \times FI \times EF \times ED}{AT \times BW}$$

Parameter	Value	Units	Description
C_{beef}	variable	mg/kg	Concentration in beef from previous equations
IR_{beef}	0.085	kg/day	Beef ingestion rate (child) – high consumers of cattle (90 th percentile) from FSANZ (2017)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	0.5	unitless	Fraction ingested from the source – assumes 50% of beef consumed comes from areas containing biosolids
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	2,190	days	Averaging time = $EF \times ED$
BW	15	kg	Body weight (child) – ASC NEPM, Schedule B7 (NEPC 2013a)

Pathway 7 – human consumption milk from dairy cows (Scenario 3)

Concentration in plants/fodder (C_P)

$$C_P \text{ (mg/kg dry weight)} = C_S \times TF \times CF$$

Parameter	Value	Units	Description
C_S	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
TF	0.1 (Br1-Br9) 0.01 (Br10) 0.12 (chlordane)	unitless	Yang et al. 2018 Yang et al. 2018 Mattina et al. 2003
CF^*	0.15	unitless	Convert TF from wet weight to dry weight. Assumes 15% dry matter (EnRiskS 2019)

* parameter not used for chlordane as TF presented on a dry weight basis

Concentration in milk (C_{milk}) for grazing cattle (PBDEs)

$$C_{milk} \text{ (mg/kg)} = [(C_S \times IR_S \times FI_S \times AoF) + (C_P \times IR_P \times FI_P \times AoF)] \times TF_{beef}$$

Parameter	Value	Units	Description
C_S	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
IR_S	0.5	kg/day	Cattle soil ingestion rate – based on US EPA (2005) and advice from NSW DPI
FI_S	1	unitless	Fraction of soil ingested from the area containing biosolids

Parameter	Value	Units	Description
C_P	variable	mg/kg (dry weight)	Concentration in plant (from previous equation)
IR_P	13	kg/day (dry matter)	Cattle plant ingestion rate based on API (2004) and advice from NSW DPI
FI_P	1	unitless	Fraction of plant ingested from the area containing biosolids
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
TF_{milk}	0.04 (Br1–Br9) 0.0006 (Br10)	day/kg	Transfer factor into milk* (OEHHA 2021, Appendix K)

* Transfer factors were not available for PBDEs. As a surrogate, transfer factors for polychlorinated biphenyls and polychlorinated dioxins/furans were used. Refer to EnRiskS (2019) for details.

Concentration in milk (C_{milk}) from fodder (PBDEs)

$$C_{milk} (mg/kg) = (C_P \times IR_P \times FI_P \times AoF) \times TF_{milk}$$

Parameter	Value	Units	Description
C_P	variable	mg/kg (dry weight)	Concentration in plant (from previous equation)
IR_P	13	kg/day (dry matter)	Cattle plant ingestion rate based on API (2004) and advice from NSW DPI
FI_P	1	unitless	Fraction of plant ingested from the area containing biosolids
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
TF_{milk}	0.04 (Br1–Br9) 0.0006 (Br10)	day/kg	Transfer factor into milk* (OEHHA 2021, Appendix K)

* Transfer factors were not available for PBDEs. As a surrogate, transfer factors for polychlorinated biphenyls and polychlorinated dioxins/furans were used. Refer to EnRiskS (2019) for details.

Concentration in milk (C_{milk}) for grazing cattle (chlordane)

$$C_{milk} (mg/kg) = (C_S \times TF_{milk} \times F_{soil}) + (C_P \times TF_{milk} \times F_{plant})$$

Parameter	Value	Units	Description
C_S	variable	mg/kg	Concentration in soil – variable based on biosolids concentration and land application rate
TF_{milk}	0.62	unitless	Transfer factor from feed into milk (Leeman et al. 2007)
F_{soil}	0.04	unitless	Fraction of feed intake that is soil – assumes 4% of intake for grazing cattle is soil, based on a soil ingestion rate of 0.5 kg/day and plant dry matter ingestion rate of 13 kg/day (API 2004 and advice from NSW DPI)

Parameter	Value	Units	Description
C_p	variable	unitless	Concentration in plant (from equation above)
F_{plant}	0.96	unitless	Fraction of feed intake that is plant dry matter – assumes 96% of intake for grazing cattle is plant, based on a soil ingestion rate of 0.5 kg/day and plant dry matter ingestion rate of 13 kg/day (API 2004 and advice from NSW DPI)

Concentration in milk (C_{milk}) from fodder (chlordane)

$$C_{milk} (mg/kg) = C_p \times TF_{milk} \times F_{plant}$$

Parameter	Value	Units	Description
C_p	variable	unitless	Concentration in plant (from equation above)
TF_{milk}	0.62	unitless	Transfer factor from feed into milk (Leeman et al. 2007)
F_{plant}	1	unitless	Fraction of feed intake that is plant dry matter – assumes 100% of cattle diet is fodder grown in areas containing biosolids

Daily intake (human health) from consumption of milk (DI)

$$DI (mg/kg/day) = \frac{C_{milk} \times IR_{milk} \times AoF \times FI \times EF \times ED}{AT \times BW}$$

Parameter	Value	Units	Description
C_{milk}	variable	mg/kg	Concentration in milk from previous equation
IR_{milk}	1.1	kg/day	Milk ingestion rate – high consumers of milk (90 th percentile) from FSANZ (2017)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from the source – assumes 100% of milk consumed comes from areas containing biosolids
EF	365	days/year	Exposure frequency – ASC NEPM, Schedule B7 (NEPC 2013a)
ED	6	years	Exposure duration (child) – ASC NEPM, Schedule B7 (NEPC 2013a)
AT	2,190	days	Averaging time = $EF \times ED$
BW	15	kg	Body weight (child) – ASC NEPM, Schedule B7 (NEPC 2013a)

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Appendix C: Organic carbon-water partition coefficients

The soil pore water calculations in this report used organic carbon-water partition coefficients (K_{OC}). The values that were used for each compound (group of compounds) are summarised below. For HHCB and triclosan, the K_{OC} was estimated from the more commonly reported octanol-water partition coefficients (K_{OW}). The relationship between $\log K_{OW}$ and $\log K_{OC}$ for various groups of organic compounds has been represented by numerous equations (e.g. Kenaga and Goring 1980; Briggs 1981; Schwarzenbach et al. 2003)²⁵. For compounds where only $\log K_{OW}$ values were available in the literature, Equation D1 (Kenaga and Goring 1980) was used to convert these values to $\log K_{OC}$. This equation was selected as it yielded more accurate predictions of $\log K_{OC}$ for compounds where experimental K_{OC} values were available. In addition, Equation D1 was derived using a relatively large dataset of 108 compounds that had a wide range of properties.

$$\log K_{OC} = 0.544 \log K_{OW} + 1.377 \quad \text{Equation D1}$$

HHCB ($K_{OC} = 38,600$)

A K_{OC} value for HHCB was not available in the literature. Therefore, the K_{OC} was estimated using a $\log K_{OW}$ of 5.9 sourced from PubChem²⁶. Using Equation D1, this $\log K_{OW}$ was converted to a $\log K_{OC}$ of 4.6, which equates to a K_{OC} of 38,600.

Triclosan ($K_{OC} = 9,260$)

A K_{OC} value for triclosan was not available in the literature. Therefore, the K_{OC} was estimated using a $\log K_{OW}$ of 4.76 sourced from PubChem²⁷. Using Equation D1, this $\log K_{OW}$ was converted to a $\log K_{OC}$ of 3.97, which equates to a K_{OC} of 9,260.

Br1–Br9 ($K_{OC} = 37,200$)

The Agency for Toxic Substances and Disease Registry (ATSDR) reports $\log K_{OC}$ values for PBDEs with varying levels of bromination²⁸. For this assessment, the lowest $\log K_{OC}$ value in the range for tetra-BDEs was used (4.57). Tetra-BDE was selected to represent all compounds in the Br1–Br9 range. This was done because BDE-47, which is a tetra-BDE compound, overall had the highest concentration in the biosolids samples (other than deca-BDE which was assessed separately). This $\log K_{OC}$ equates to a K_{OC} value of 37,200.

²⁵ Kenaga E and Goring C (1980) 'Relationship between water solubility, soil sorption, octanol water partitioning and bioconcentration of chemicals in biota', in Eaton J, Parrish P and Hedricks A, editors, *Aquatic toxicology*, ASTM STP 707, Philadelphia (PA), American Society for Chemical Testing and Materials, pp 78–115; Briggs G (1981) 'Theoretical and experimental relationships between soil and adsorption, octanol-water partition coefficients, water solubilities, bioconcentration factors, and the parachor', *J. Agric Food Chem* 29:1050–1059; Schwarzenbach R, Gschwend P and Imboden D (2003) *Environmental organic chemistry*, 2nd edition, Hoboken (NJ), John Wiley & Sons, 302pp.

²⁶ <https://pubchem.ncbi.nlm.nih.gov/compound/Galaxolide#section=InChIKey>

²⁷ <https://pubchem.ncbi.nlm.nih.gov/compound/Triclosan#section=Vapor-Pressure>

²⁸ <https://www.atsdr.cdc.gov/ToxProfiles/tp207-c6.pdf>

Br10 ($K_{OC} = 6,310,000$)

The ATSDR reports²⁹ a log K_{OC} for deca-BDE of 6.8. This equates to a K_{OC} of 6,310,000.

Chlordane ($K_{OC} = 3,090$)

The ATSDR reports³⁰ a log K_{OC} for chlordane ranging from 3.49 to 4.64. Using the lowest value of this range equates to a K_{OC} value of 3,090.

²⁹ <https://www.atsdr.cdc.gov/ToxProfiles/tp207-c6.pdf>

³⁰ <https://www.atsdr.cdc.gov/toxprofiles/tp31.pdf>

Appendix D: PBDE human health risk quotients (RQ_{HH}) for Scenario 3

Table E1 Human health risk quotients (RQ_{HH}) for children for PBDEs (Br1–Br9 and Br10) for restricted use biosolids in agriculture

Contaminant	Pathway										
	1 Incidental ingestion soil	2 Incidental inhalation dust	3 Dermal absorption	4 Fruit & vegetables	4 Fruit	4 Vegetables	6a+b Beef – grazing	6b Beef – fodder	7a+b Milk – grazing	7b Milk – fodder	8 Drinking water
10 t/ha single application											
Br1-Br9 95UCL	2.7×10^{-4}	6.4×10^{-11}	3.6×10^{-4}	4.8×10^{-3}	2.3×10^{-4}	4.6×10^{-3}	1.6×10^{-1}	4.4×10^{-2}	8.2×10^{-2}	2.3×10^{-2}	6.8×10^{-5}
Br1-Br9 max	6.0×10^{-4}	1.4×10^{-10}	8.1×10^{-4}	1.1×10^{-2}	5.2×10^{-4}	1.0×10^{-2}	3.6×10^{-1}	1.0×10^{-1}	1.8×10^{-1}	5.1×10^{-2}	1.5×10^{-4}
Br10 95UCL	8.2×10^{-4}	2.4×10^{-10}	1.1×10^{-4}	8.4×10^{-4}	3.2×10^{-5}	8.1×10^{-4}	3.6×10^{-3}	1.4×10^{-4}	2.8×10^{-3}	1.1×10^{-4}	1.6×10^{-6}
Br10 max	7.6×10^{-3}	2.2×10^{-9}	1.0×10^{-3}	7.8×10^{-3}	2.9×10^{-4}	7.5×10^{-3}	3.4×10^{-2}	1.3×10^{-3}	2.6×10^{-2}	9.8×10^{-4}	1.4×10^{-5}
Br10 95UCL (excl STP K)	1.3×10^{-5}	3.8×10^{-12}	1.7×10^{-6}	1.3×10^{-5}	5.0×10^{-7}	1.3×10^{-5}	5.7×10^{-5}	2.1×10^{-6}	4.4×10^{-5}	1.7×10^{-6}	2.4×10^{-8}
Br10 max (excl STP K)	2.5×10^{-5}	7.4×10^{-12}	3.4×10^{-6}	2.6×10^{-5}	9.8×10^{-7}	2.5×10^{-5}	1.1×10^{-4}	4.2×10^{-6}	8.7×10^{-5}	3.3×10^{-6}	4.8×10^{-8}
10 t/ha repeat application											
Br1-Br9 95UCL	1.9×10^{-3}	4.5×10^{-10}	2.5×10^{-3}	3.4×10^{-2}	1.6×10^{-3}	3.2×10^{-2}	1.1	3.1×10^{-1}	5.7×10^{-1}	1.6×10^{-1}	4.7×10^{-4}
Br1-Br9 max	4.2×10^{-3}	1.0×10^{-9}	5.7×10^{-3}	7.6×10^{-2}	3.7×10^{-3}	7.2×10^{-2}	2.5	7.0×10^{-1}	1.3	3.6×10^{-1}	1.1×10^{-3}
Br10 95UCL	5.7×10^{-3}	1.7×10^{-9}	7.8×10^{-4}	5.9×10^{-3}	2.2×10^{-4}	5.6×10^{-3}	2.5×10^{-2}	9.5×10^{-4}	2.0×10^{-2}	7.4×10^{-4}	1.1×10^{-5}
Br10 max	5.3×10^{-2}	1.6×10^{-8}	7.2×10^{-3}	5.5×10^{-2}	2.1×10^{-3}	5.3×10^{-2}	2.4×10^{-1}	8.9×10^{-3}	1.8×10^{-1}	6.9×10^{-3}	1.0×10^{-4}
Br10 95UCL (excl STP K)	9.0×10^{-5}	2.6×10^{-11}	1.2×10^{-5}	9.2×10^{-5}	3.5×10^{-6}	8.9×10^{-5}	4.0×10^{-4}	1.5×10^{-5}	3.1×10^{-4}	1.2×10^{-5}	1.7×10^{-7}
Br10 max (excl STP K)	1.8×10^{-4}	5.2×10^{-11}	2.4×10^{-5}	1.8×10^{-4}	6.9×10^{-6}	1.8×10^{-4}	7.9×10^{-4}	3.0×10^{-5}	6.1×10^{-4}	2.3×10^{-5}	3.4×10^{-7}

Contaminant	Pathway										
	1 Incidental ingestion soil	2 Incidental inhalation dust	3 Dermal absorption	4 Fruit & vegetables	4 Fruit	4 Vegetables	6a+b Beef – grazing	6b Beef – fodder	7a+b Milk – grazing	7b Milk – fodder	8 Drinking water
50 t/ha single application											
Br1-Br9 95UCL	1.3×10^{-3}	3.1×10^{-10}	1.8×10^{-3}	2.4×10^{-2}	1.1×10^{-3}	2.2×10^{-2}	7.7×10^{-1}	2.2×10^{-1}	4.0×10^{-1}	1.1×10^{-1}	3.3×10^{-4}
Br1-Br9 max	2.9×10^{-3}	6.9×10^{-10}	3.9×10^{-3}	5.3×10^{-2}	2.5×10^{-3}	5.0×10^{-2}	1.7	4.8×10^{-1}	8.9×10^{-1}	2.5×10^{-1}	7.3×10^{-4}
Br10 95UCL	4.0×10^{-3}	1.2×10^{-9}	5.4×10^{-4}	4.1×10^{-3}	1.5×10^{-4}	3.9×10^{-3}	1.8×10^{-2}	6.6×10^{-4}	1.4×10^{-2}	5.1×10^{-4}	7.5×10^{-6}
Br10 max	3.7×10^{-2}	1.1×10^{-8}	5.0×10^{-3}	3.8×10^{-2}	1.4×10^{-3}	3.6×10^{-2}	1.6×10^{-1}	6.1×10^{-3}	1.3×10^{-1}	4.8×10^{-3}	7.0×10^{-5}
Br10 95UCL (excl STP K)	6.3×10^{-5}	1.8×10^{-11}	8.5×10^{-6}	6.4×10^{-5}	2.4×10^{-6}	6.2×10^{-5}	2.8×10^{-4}	1.0×10^{-5}	2.1×10^{-4}	8.0×10^{-6}	1.2×10^{-7}
Br10 max (excl STP K)	1.2×10^{-4}	3.6×10^{-11}	1.7×10^{-5}	1.3×10^{-4}	4.8×10^{-6}	1.2×10^{-4}	5.5×10^{-4}	2.0×10^{-5}	4.2×10^{-4}	1.6×10^{-5}	2.3×10^{-7}
50 t/ha repeat application											
Br1-Br9 95UCL	9.1×10^{-3}	2.2×10^{-9}	1.2×10^{-2}	1.6×10^{-1}	7.9×10^{-3}	1.6×10^{-1}	5.4	1.5	2.8	7.8×10^{-1}	2.3×10^{-3}
Br1-Br9 max	2.0×10^{-2}	4.8×10^{-9}	2.8×10^{-2}	3.7×10^{-1}	1.8×10^{-2}	3.5×10^{-1}	12	3.4	6.2	1.8	5.1×10^{-3}
Br10 95UCL	2.8×10^{-2}	8.1×10^{-9}	3.8×10^{-3}	2.8×10^{-2}	1.1×10^{-3}	2.7×10^{-2}	1.2×10^{-1}	4.6×10^{-3}	9.5×10^{-2}	3.6×10^{-3}	5.3×10^{-5}
Br10 max	2.6×10^{-1}	7.5×10^{-8}	3.5×10^{-2}	2.6×10^{-1}	1.0×10^{-2}	2.5×10^{-1}	1.1	4.3×10^{-2}	8.9×10^{-1}	3.3×10^{-2}	4.9×10^{-4}
Br10 95UCL (excl STP K)	4.4×10^{-4}	1.3×10^{-10}	5.9×10^{-5}	4.5×10^{-4}	1.7×10^{-5}	4.3×10^{-4}	1.9×10^{-3}	7.3×10^{-5}	1.5×10^{-3}	5.6×10^{-5}	8.3×10^{-7}
Br10 max (excl STP K)	8.6×10^{-4}	2.5×10^{-10}	1.2×10^{-4}	8.8×10^{-4}	3.3×10^{-5}	8.5×10^{-4}	3.8×10^{-3}	1.4×10^{-4}	3.0×10^{-3}	1.1×10^{-4}	1.6×10^{-6}

Table E2 Human health risk quotients (RQ_{HH}) for adults for PBDEs (Br1-9 and Br10) for restricted use biosolids in agricultural

Contaminant	Pathway										
	1 Incidental ingestion soil	2 Incidental inhalation dust	3 Dermal absorption	4 Fruit & vegetables	4 Fruit	4 Vegetables	6a+b Beef – grazing	6b Beef – fodder	7a+b Milk – grazing	7b Milk – fodder	8 Drinking water
10 t/ha single application											
Br1-Br9 95UCL	2.9 ×10 ⁻⁵	6.4 ×10 ⁻¹¹	1.8 ×10 ⁻⁴	0.0022	3.9 ×10 ⁻⁵	0.0022	0.065	0.018	0.021	0.0058	6.8 ×10 ⁻⁵
Br1-Br9 max	6.4 ×10 ⁻⁵	1.4 ×10 ⁻¹⁰	4.1 ×10 ⁻⁴	0.0049	8.7 ×10 ⁻⁵	0.0048	0.15	0.041	0.046	0.013	1.5 ×10 ⁻⁴
Br10 95UCL	8.8 ×10 ⁻⁵	2.4 ×10 ⁻¹⁰	5.5 ×10 ⁻⁵	3.9 ×10 ⁻⁴	5.3 ×10 ⁻⁶	3.8 ×10 ⁻⁴	0.001	5.6 ×10 ⁻⁵	7.1 ×10 ⁻⁴	2.7 ×10 ⁻⁵	1.6 ×10 ⁻⁶
Br10 max	8.2 ×10 ⁻⁴	2.2 ×10 ⁻⁹	5.2 ×10 ⁻⁴	0.0036	4.9 ×10 ⁻⁵	0.0035	0.014	5.2 ×10 ⁻⁴	0.0066	2.5 ×10 ⁻⁴	1.4 ×10 ⁻⁵
Br10 95UCL (excl STP K)	1.4 ×10 ⁻⁶	3.8 ×10 ⁻¹²	8.7 ×10 ⁻⁷	6.1 ×10 ⁻⁶	8.3 ×10 ⁻⁸	6.0 ×10 ⁻⁶	2.3 ×10 ⁻⁵	8.8 ×10 ⁻⁷	1.1 ×10 ⁻⁵	4.2 ×10 ⁻⁷	2.4 ×10 ⁻⁸
Br10 max (excl STP K)	2.7 ×10 ⁻⁶	7.4 ×10 ⁻¹²	1.7 ×10 ⁻⁶	1.2 ×10 ⁻⁵	1.6 ×10 ⁻⁷	1.2 ×10 ⁻⁵	4.6 ×10 ⁻⁵	1.7 ×10 ⁻⁶	2.2 ×10 ⁻⁵	8.3 ×10 ⁻⁷	4.8 ×10 ⁻⁸
10 t/ha repeat application											
Br1-Br9 95UCL	2.0 ×10 ⁻⁴	4.5 ×10 ⁻¹⁰	0.0013	0.015	2.7 ×10 ⁻⁴	0.015	0.46	0.13	0.14	0.041	4.7 ×10 ⁻⁴
Br1-Br9 max	4.5 ×10 ⁻⁴	1.0 ×10 ⁻⁹	0.0028	0.034	6.1 ×10 ⁻⁴	0.034	1.0	0.29	0.32	0.091	1.1 ×10 ⁻³
Br10 95UCL	6.2 ×10 ⁻⁴	1.7 ×10 ⁻⁹	3.9 ×10 ⁻⁴	0.0027	3.7 ×10 ⁻⁵	0.0027	0.010	3.9 ×10 ⁻⁴	0.0050	1.9 ×10 ⁻⁴	1.1 ×10 ⁻⁵
Br10 max	0.0057	1.6 ×10 ⁻⁸	0.0036	0.025	3.4 ×10 ⁻⁴	0.025	0.097	0.0036	0.046	0.0017	1.0 ×10 ⁻⁴
Br10 95UCL (excl STP K)	9.7 ×10 ⁻⁶	2.6 ×10 ⁻¹¹	6.1 ×10 ⁻⁶	4.3 ×10 ⁻⁵	5.8 ×10 ⁻⁷	4.2 ×10 ⁻⁵	1.6 ×10 ⁻⁴	6.2 ×10 ⁻⁶	7.8 ×10 ⁻⁵	2.9 ×10 ⁻⁶	1.7 ×10 ⁻⁷
Br10 max (excl STP K)	1.9 ×10 ⁻⁵	5.2 ×10 ⁻¹¹	1.2 ×10 ⁻⁵	8.4 ×10 ⁻⁵	1.1 ×10 ⁻⁶	8.3 ×10 ⁻⁵	3.2 ×10 ⁻⁴	1.2 ×10 ⁻⁵	1.5 ×10 ⁻⁴	5.8 ×10 ⁻⁶	3.4 ×10 ⁻⁷
50 t/ha single application											
Br1-Br9 95UCL	1.4 ×10 ⁻⁴	3.1 ×10 ⁻¹⁰	8.8 ×10 ⁻⁴	0.011	1.9 ×10 ⁻⁴	0.010	0.32	0.089	0.10	0.028	3.3 ×10 ⁻⁴
Br1-Br9 max	3.1 ×10 ⁻⁴	6.9 ×10 ⁻¹⁰	0.0020	0.024	4.2 ×10 ⁻⁴	0.023	0.71	0.20	0.23	0.063	7.3 ×10 ⁻⁴

Contaminant	Pathway										
	1 Incidental ingestion soil	2 Incidental inhalation dust	3 Dermal absorption	4 Fruit & vegetables	4 Fruit	4 Vegetables	6a+b Beef – grazing	6b Beef – fodder	7a+b Milk – grazing	7b Milk – fodder	8 Drinking water
Br10 95UCL	4.3×10^{-4}	1.2×10^{-9}	2.7×10^{-4}	0.0019	2.6×10^{-5}	0.0018	0.0072	2.7×10^{-4}	0.0034	1.3×10^{-4}	7.5×10^{-6}
Br10 max	0.0040	1.1×10^{-8}	0.0025	0.017	2.4×10^{-4}	0.017	0.067	0.0025	0.032	0.0012	7.0×10^{-5}
Br10 95UCL (excl STP K)	6.7×10^{-6}	1.8×10^{-11}	4.2×10^{-6}	2.9×10^{-5}	4.0×10^{-7}	2.9×10^{-5}	1.1×10^{-4}	4.3×10^{-6}	5.4×10^{-5}	2.0×10^{-6}	1.2×10^{-7}
Br10 max (excl STP K)	1.3×10^{-5}	3.6×10^{-11}	8.3×10^{-6}	5.8×10^{-5}	7.9×10^{-7}	5.7×10^{-5}	2.2×10^{-4}	8.4×10^{-6}	1.1×10^{-4}	4.0×10^{-6}	2.3×10^{-7}
50 t/ha repeat application											
Br1-Br9 95UCL	9.8×10^{-4}	2.2×10^{-9}	0.0062	0.075	0.0013	0.073	2.2	0.62	0.70	0.20	2.3×10^{-3}
Br1-Br9 max	0.0022	4.8×10^{-9}	0.014	0.17	0.0030	0.16	5.0	1.4	1.6	0.44	5.1×10^{-3}
Br10 95UCL	0.0030	8.1×10^{-9}	0.0019	0.013	1.8×10^{-4}	0.013	0.051	0.0019	0.024	9.1×10^{-4}	5.3×10^{-5}
Br10 max	0.028	7.5×10^{-8}	0.018	0.12	0.0017	0.12	0.47	0.018	0.22	0.0084	4.9×10^{-4}
Br10 95UCL (excl STP K)	4.7×10^{-5}	1.3×10^{-10}	3.0×10^{-5}	2.1×10^{-4}	2.8×10^{-6}	2.0×10^{-4}	8.0×10^{-4}	3.0×10^{-5}	3.8×10^{-4}	1.4×10^{-5}	8.3×10^{-7}
Br10 max (excl STP K)	9.3×10^{-5}	2.5×10^{-10}	5.8×10^{-5}	4.1×10^{-4}	5.5×10^{-6}	4.0×10^{-4}	0.0016	5.9×10^{-5}	7.5×10^{-4}	2.8×10^{-5}	1.6×10^{-6}

Red indicates RQ > 1