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NSW Biosolids Guideline Review

Identification of key exposure pathways to assess risks from PFAS in biosolids

Department of Planning and Environment

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Abbreviations

µg	micrograms
%	per cent
<	less than
>	greater than
ADI	acceptable daily intake
ASC NEPM	*National Environment Protection (Assessment of Site Contamination) Measure*
ASLP	Australian Standard Leaching Procedure
BAS	biosolids-amended soil
bw	body weight
C&R	Contaminants and Risk Team
conc	concentration
d	day
DAF	dilution and attenuation factor
DPE	Department of Planning and Environment
dw	dry weight
EHG	Environment and Heritage Group
EPA	Environment Protection Authority
FSANZ	Food Standards Australia New Zealand
g	grams
ha	hectares
HCV	health criteria value
HED	human equivalent dose
HHERA	Human health and ecological risk assessment
hr	hours
Kdes	solid-solution distribution coefficient
kg	kilograms
LOR	limit of reporting
mg	milligrams
mL	millilitres
MOS	margin of safety
na	not available
nd	not determined
ng	nanograms
NOAEL	no observed adverse effect level

NSW	New South Wales
OC	organic carbon
OEH	Office of Environment and Heritage
PEC	predicted environmental concentration
PFAA	perfluoroalkyl acids
PFAS	per- and poly-fluoroalkyl substances
PFAS NEMP	*PFAS National Environmental Management Plan*
PFCA	perfluorinated carboxylic acid
PFDA	perfluorodecanoic acid
PFHxS	perfluorohexane sulfonate
PFNA	perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
PFOS+PFHxS	sum of PFOS and PFHxS
PNEC	predicted no effect concentration
QA/QC	quality assurance and quality control
RfD	reference dose
RQ	risk quotient
RQ_{ECO}	ecological risk quotient
RQ_{HH}	human health risk quotient
SOM	soil organic matter
SSV	soil screening value
STP	sewage treatment plant
t	tonnes
TDI	tolerable daily intake
TF	transfer factor

Executive summary

Background and scope

In 2016, the NSW Environment Protection Authority (NSW EPA) funded a review to identify contaminants in biosolids which require further consideration due to potential ecological or human health risks (the Contaminants Review). As part of the Contaminants Review, several contaminants of concern were identified for further investigation. Two of these contaminants were perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), which belong to a large family of compounds referred to as per- and poly-fluoroalkyl substances (PFAS). 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 PFAS. The NSW EPA requested the NSW Office of Environment and Heritage (OEH)[1] Contaminants and Risk Team (C&R) to undertake a human health and ecological risk assessment (HHERA) for PFAS using the NSW EPA biosolids data. The aim of the HHERA was to determine if PFAS in biosolids require regulation and to identify the key exposure pathways for PFAS in biosolids for deriving thresholds[2].

The scope of this assessment was to:

- review PFAS data collected from 20 STPs in NSW and compare these to data used in the Contaminants Review (WCA 2016) to determine if concentrations in NSW are consistent with concentrations reported around the world
- undertake a HHERA for PFAS in biosolids considering 4 scenarios 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 rehabilitation[3]
    - Scenario 3 – land application of 'restricted use' biosolids in agriculture[4], considering:
        - a low and high application rate
        - single and repeat applications
    - Scenario 4 – land application of 'unrestricted use' biosolids in agriculture.
- use the results from the HHERA to determine if PFAS in biosolids require regulation and identify key exposure pathways for deriving biosolids thresholds for PFAS
- recommend next steps and any additional work to address knowledge gaps.

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[1] Now part of the Environment and Heritage Group (EHG) of the NSW Department of Planning and Environment.

[2] The other contaminants identified in the Contaminants Review have also undergone a similar assessment.

[3] Scenario 2 assumes land will not be used for agriculture in the future.

[4] Scenario 3 includes rehabilitated land that will be used for agriculture in the future.

Summary of available data

The NSW EPA sampled biosolids from STPs within Sydney and regional areas, to represent a range of different potential sources and treatment types. C&R used the PFAS data from these samples in the HHERA presented in this report. Although a number of PFAS were analysed for in the biosolids samples, the HHERA focused on PFOS, PFOA and perfluorohexane sulfonate (PFHxS) because these are the only PFAS compounds currently with criteria available in Australia and hence can be quantitatively assessed. A number of other PFAS were also detected in the biosolids that were not assessed in the HHERA as there are currently no Australian criteria or approaches for these compounds that are nationally supported (FSANZ 2017; HEPA 2020). On average, the concentrations of PFOS, PFOA and PFHxS made up 60% of the total PFAS concentrations[5] (see Appendix A).

PFOS was detected in all biosolids samples, with average concentrations ranging from 3.2 to 77 µg/kg. This maximum concentration was approximately 1.7-times lower than the 90th percentile concentration reported in studies around the world in the Contaminants Review (130 µg/kg) (WCA 2016). For PFOA, the average concentrations ranged from < 2.7 to 24 µg/kg, with the maximum concentration about 1.7-times higher than the 90th percentile concentration reported in the Contaminants Review (14 µg/kg) (WCA 2016). These results for PFOS and PFOA show that concentrations in NSW biosolids are in a similar range to concentrations that have been reported around the world. The concentrations of PFHxS were lower than PFOS and PFOA, ranging from < 0.1 to 3.8 µg/kg. This compound was not included in the Contaminants Review (WCA 2016), therefore, concentrations could not be compared.

Human health and ecological risk assessment (HHERA)

Summary of risk assessment method

The biosolids data from the EPA were used to estimate exposure concentrations or exposure doses of PFOS, PFOA and PFHxS. For example, estimated concentrations in biosolids-amended soil, agricultural produce (crops, beef, milk) and drinking or irrigation water were calculated. The estimated exposure concentrations/doses were used in risk calculations to identify key exposure pathways for PFAS in biosolids and to determine if regulation is warranted. These were generic risk calculations and are 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 only for PFOS and PFOA, as in Australia, endorsed screening criteria are available only for these compounds. To assess the risk, an ecological risk quotient (RQ_{ECO}) was calculated by dividing the estimated biosolids-amended soil concentrations by relevant screening criteria. In most cases, the soil screening criteria used were from the *PFAS National Environmental Management Plan* (PFAS NEMP) (HEPA 2020). However, for PFOA for the terrestrial secondary consumers

[5] 'Total PFAS' refers to the sum of individual PFAS analyte concentrations that were quantitatively measured in the chemical analysis (see Appendix A for the list of individual analytes).

pathway, a screening criterion from the United Kingdom (UK) adjusted to Australian conditions was used.

Human health risks were assessed for the sum of PFOS and PFHxS (PFOS+PFHxS) and PFOA. Assessing risks from PFOS+PFHxS is in accordance with current national guidance (FSANZ 2017). To assess human health risks, screening criteria from the PFAS NEMP (HEPA 2020) were used where available and human health risk quotients (RQ_{HH}) was calculated by dividing the estimated biosolids-amended soil concentrations by relevant screening criteria. If no screening criteria were available, exposures were estimated by calculating predicted daily intakes (μg/kg/d) and RQ_{HH} were derived using a toxicity reference value.

An RQ above 1 indicates that either the concentration is above the screening criteria or the predicted daily intake is above a toxicity reference value (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). However, in this HHERA, if the RQ for the key pathway was above 0.2, C&R has recommended that regulation is required and that a threshold in biosolids is derived. The exposure pathway (human health or ecological) that produced the highest RQ has then been identified 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.

An RQ above 0.2 instead of 1 was used, which allows for a margin of safety (MOS) of 5, to account for the following uncertainties:

- There is some uncertainty in biosolids PFAS concentrations – this risk assessment is based on PFAS concentrations from 20 STPs across NSW, and it is not known if, or the extent to which, these concentrations may vary overtime.
- The risk assessment focused on PFOS, PFOA and PFOS+PFHxS, and does not account for potential risk from other PFAS (see Appendix A) or precursors. Currently these cannot be accounted for quantitatively in risk assessments, and as such some additional conservatism is warranted.

Where RQs were equal to or less than 0.2, C&R has concluded that the risk from that pathway is low. If this was the case for all pathways for a scenario, C&R 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 risks from use of unrestricted use biosolids in a residential garden. For this scenario it was assumed biosolids are processed with another waste material (e.g. garden waste) containing no PFAS (other waste) 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 was the highest ratio reported 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 that unrestricted use biosolids could be applied to a residential garden without any restrictions on application rates. Therefore, concentrations of PFOS, PFOA and PFHxS in the unrestricted use biosolids were estimated, and these were 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. For both PFOS and PFOA, all RQs were less than 0.2, indicating that the risk is low.

Human health risks from PFOS+PFHxS and PFOA were assessed for 3 exposure pathways: incidental ingestion of soil/dust, consumption of homegrown fruit/vegetables and the consumption of home chicken eggs. For PFOA, all RQ_{HH} values were less than 0.2 indicating the risk is low. For PFOS+PFHxS, the RQ_{HH} values ranged up to 2.9. Based on this, C&R recommends a threshold for PFOS+PFHxS for unrestricted use biosolids is derived. Overall, the key exposure pathway for this scenario was incidental ingestion of soil/dust and consumption of homegrown fruit/vegetables (RQ_{HH} values up to 2.9).

Scenario 2 – unrestricted use biosolids for land rehabilitation

Scenario 2 assessed the ecological and human health risks from land application of unrestricted use biosolids for land rehabilitation. Similar to Scenario 1, the estimated concentrations of PFOS, PFOA and PFOS+PFHxS in unrestricted use biosolids (1-part biosolids to 2-parts other waste) were conservatively used as the biosolids-amended soil concentrations, as there are no restrictions on application rates.

Ecological risks from PFOS and PFOA were assessed for 3 exposure pathways: direct toxicity to terrestrial organisms, toxicity to secondary consumers and toxicity to offsite aquatic organisms. For direct toxicity to terrestrial organisms and toxicity to offsite aquatic organisms, all RQ_{ECO} values were less than 0.2, indicating that the risk is low. For the toxicity to secondary consumers pathway, the maximum RQ_{ECO} value for PFOS was 2.6 and for PFOA it was 0.8.

The assessment of human health risks for Scenario 2 considered 2 pathways: incidental ingestion of soil/dust and consumption of drinking water. All RQ_{HH} values were less than 0.2 indicating that risks to human health are low. C&R notes that the maximum PFOS+PFHxS RQ_{HH} for the drinking water pathway was 0.2. Considering this, and the uncertainties in estimating PFAS concentrations in drinking water, C&R recommends the EPA measures PFAS in groundwater and surface water in proximity to land rehabilitated with biosolids to confirm concentrations do not pose risk to human health.

Overall, the key exposure pathway for Scenario 2 was for ecological secondary consumers (RQ_{ECO} values up to 2.6 and 0.8 for PFOS and PFOA, respectively). Thresholds derived for unrestricted use biosolids should protect this pathway.

Scenario 3 – restricted use biosolids in agriculture

Scenario 3 assessed the ecological and human health risks from PFOS, PFOA and PFHxS following 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 11 human health exposure pathways (including incidental ingestion of soil/dust, home consumption of crops (fruit and vegetables), beef and milk). The potential risk from market supply of agricultural products from biosolids-amended land were 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.

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.

The ecological risks from direct toxicity to terrestrial organisms and offsite aquatic organisms were low for PFOS and PFOA (RQ_{ECO} < 0.2) for all application rates assessed. For indirect exposure to secondary consumers, the maximum RQ_{ECO} value for PFOS was 2.0, and for PFOA the maximum was 0.62.

Overall, the human health pathways posed a higher potential risk for PFOS+PFHxS compared to the ecological pathway. The beef and milk grazing and fodder pathways for PFOS+PFHxS resulted in the highest RQ_{HH} values ranging up to 18. For PFOA, there were no human health pathways that resulted in RQ_{HH} values above 1. However, for the milk grazing and fodder pathways, the maximum RQ_{HH} was 0.45.

Based on the results for Scenario 3, C&R recommends PFOS+PFHxS and PFOA thresholds for restricted use biosolids are derived. For PFOS+PFHxS the key exposure pathway for threshold derivation is milk consumption from dairy cows grazing on biosolids-amended soil (RQ_{HH} values up to 18). Whereas, for PFOA, the key exposure pathway for threshold derivation is ecological secondary consumers (RQ_{ECO} values up to 0.62).

In addition to the above recommendations for PFAS thresholds in biosolids, C&R also recommends the EPA measures PFAS in groundwater and surface water in the proximity of biosolids land applied in agriculture. This is due to uncertainties in predicting PFAS concentrations in water bodies from soils/biosolids. Information gained from measuring PFAS in the environment will provide more certainty in understanding the potential risks to drinking water and aquatic environments, and thereby inform management requirements for biosolids application.

Scenario 4 – unrestricted use biosolids in agriculture

Although unrestricted use biosolids in NSW are not currently used in this way, this additional scenario was assessed as it is permitted by the NSW Biosolids Guidelines. Only risk from the highest risk agricultural pathway (determined from Scenario 3) are presented. This was done to determine if the risks from unrestricted use biosolids via the agricultural pathways are potentially higher than those identified in Scenarios 1 and 2.

The maximum RQ_{HH} value for PFOS+PFHxS for Scenario 4 was 23. This is higher than the RQ_{HH} values calculated for unrestricted use biosolids in Scenarios 1 and 2. Therefore, this pathway should be used for threshold derivation for unrestricted use. In contrast, the maximum RQ_{HH} values for PFOA for Scenario 4 (0.58) was not the highest. Therefore, is not considered the key risk-driving pathway for PFOA in unrestricted use biosolids.

Recommendations and next steps

- C&R recommends that PFAS in unrestricted use and restricted use biosolids require regulation, and thresholds should be derived to ensure land application of biosolids poses a low risk to the environment and human health.
- The key exposure pathways that derivation should be based on are:
  - unrestricted use biosolids
    - PFOS+PFHxS – consumption of milk from grazing dairy cows (human health)

    - PFOA – ecological toxicity to secondary consumers
  - restricted use biosolids
    - PFOS+PFHxS – consumption of milk from grazing dairy cows (human health)
    - PFOA – ecological toxicity to secondary consumers.
- C&R recommends thresholds for unrestricted use biosolids apply to the final material ready for land application to ensure that additional contamination is not introduced if the biosolids are processed with another waste stream.
- C&R recommends threshold derivation should be based on realistic maximum exposures. Thresholds derived this way will be protective but will not be over-conservative. The assumptions used in the derivation process should be transparent and applicable to other emerging contaminants that are being considered as part of the NSW biosolids guideline review.
- C&R recommends that if PFAS toxicity reference values in Australia are changed in the future, or additional toxicity reference values for other PFAS are endorsed, this HHERA should be revised to ensure the key exposure pathways are still correct.
- C&R recommends the following additional work to address knowledge gaps due to uncertainties in estimating PFAS concentrations in water bodies based on soils/biosolids concentrations. This is important to validate as it will provide certainty that potential human health and ecological risks in water supplies and aquatic systems are low:
  - monitoring groundwater and surface water in proximity to areas where unrestricted use biosolids have been land applied for rehabilitation
  - monitoring groundwater and surface water in proximity to areas where restricted use biosolids have been land applied in agriculture.

Introduction

Background

In 2016, the NSW Environment Protection Authority (EPA) funded 3 projects to assist in the review of the NSW *Environmental Guidelines: Use and Disposal of Biosolids Products* (the NSW Biosolids Guidelines) (NSW EPA 2000). The 3 projects were desk-based reviews of current information on contaminants, stability and pathogens. The specific aims of the contaminants project were to:

- compile a current list of contaminants of concern for consideration with respect to biosolids in NSW, taking into account:
  - existing available data from sewage treatment plants (STPs) in NSW
  - current research into contaminants in biosolids, including contaminants of emerging concern
  - relevant existing policies and guidelines
  - any additional sources of information that were available
- provide recommendations to align NSW with current research and best practice on the management approaches for the identified contaminants of concern in biosolids
- comment on the relevance of the identified contaminants of concern in biosolids.

A report was completed by WCA Environment Ltd and submitted to the NSW EPA in October 2016 (WCA 2016) (the Contaminants Review). The report presented an evidence-based, precautionary screening risk assessment to prioritise potential contaminants of concern for routine measurements on NSW biosolids. The report provided a list of contaminants that have been measured and quantified in biosolids from around the world. A risk quotient (RQ) approach was used to identify priority contaminants that may pose an ecological risk. This involved comparing predicted environmental concentrations (PECs) (based on different land-application scenarios) with predicted no effect concentrations (PNECs). Contaminants that posed a potential human health hazard were identified by assigning potency scores to individual contaminants based on health criteria values (HCVs) (e.g. acceptable daily intakes (ADIs) and references doses (RfDs)). The report noted that very limited data were available from Australia and that most of the conclusions were based on international contaminant concentrations in biosolids.

Based on the assessment, WCA categorised individual contaminants as 'chemicals prioritised', 'chemicals for further consideration', 'chemicals parked' or 'chemicals presenting low potential environmental risks'. Two of the contaminants identified as requiring further consideration based on potential ecological impacts were perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), which belong to a large family of compounds, referred to as per- and poly-fluoroalkyl substances (PFAS). PFOS was also identified as a potential hazard to human health.

Following that work, the NSW EPA conducted a biosolids sampling program of 20 STPs in NSW to determine concentrations of a range of contaminants identified by WCA, including PFAS. The EPA asked NSW Office of Environment and Heritage (OEH) Contaminants and Risk Team (C&R)[6] to undertake a human health and ecological risk assessment (HHERA) for PFAS using the NSW biosolids data collected during its sampling program. The aim of the HHERA was to determine if PFAS in biosolids require

[6] Now part of the Environment and Heritage Group (EHG) of the NSW Department of Planning and Environment.

regulation and to identify the key exposure pathways for PFAS in biosolids for threshold derivation as part of the NSW Biosolids Guidelines review.

Introduction to human health and ecological risk assessment

Human health and ecological risk assessments are undertaken for a range of reasons. In this instance, the HHERA was undertaken to determine if PFAS in biosolids require regulation by the NSW EPA and to identify the key exposure pathways for consideration when deriving thresholds for these compounds in biosolids. Any thresholds should be derived based on the highest risk exposure pathway (human health or ecological) to ensure that land application of biosolids can be maintained while also posing a low risk to the environment and human health.

A key component to any HHERA is the conceptual model, which outlines the pathways that may expose people or ecosystems to contaminants. This is generally done using the source–pathway–receptor model (Figure 1), where:

- the source is the contaminant's origin (in this HHERA, the source is biosolids-amended soil)
- the pathway is the migration route for the contaminant away from the source (e.g. uptake into plants or transport with water)
- the receptor is the person or ecological community which may be exposed to the contaminant from the source that has been transported via a given pathway.

For there to be a potential risk, there needs to be an unbroken source, pathway and receptor linkage. If any of these elements are not present, then there is no risk.

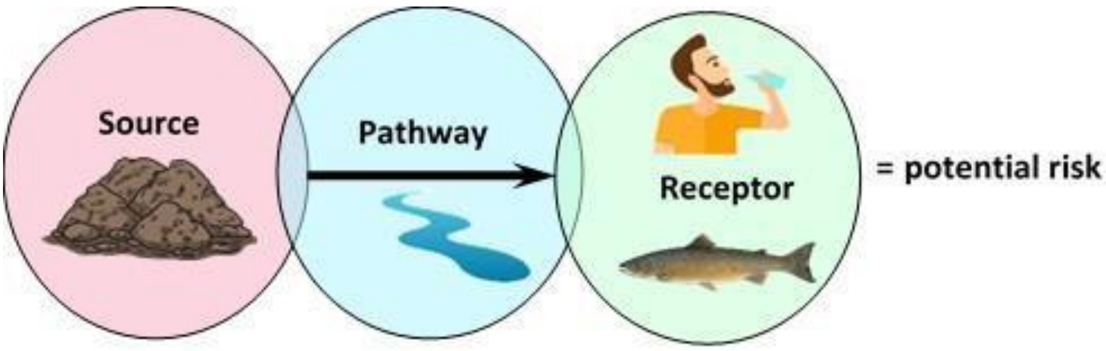

Figure 1: Source–pathway–receptor model

A quantitative HHERA, as presented in this report, can be used to identify key contaminants of concern and key exposure pathways that pose the highest risk to receptors. The process of identifying risks to receptors (human or ecological) involves:

1. an exposure assessment which estimates the magnitude, frequency, extent and duration of exposure to contaminants (the 'exposure')
2. a toxicity assessment which involves contaminant hazard identification and dose-response assessment which links the degree of exposure to a chemical and its potential effects (the 'toxicity').

To account for uncertainties in the data or parameters used to calculate the exposure, conservative assumptions are generally adopted to protect against worst-case scenario exposures. The HHERA presented in this report is generic and doesn't relate to any specific site or location. Due to this, generic assumptions have been used throughout. Further assessment on a site-specific basis can be conducted if required.

Risk characterisation is the final component of a HHERA, where the exposure and toxicity are compared to quantify the risk. This is done by calculating an RQ using Equation 1.

An RQ above 1 indicates the exposure concentration is above the 'safe' concentration/dose, and management options or further assessment may be required.

$$RQ = \frac{exposure}{toxicity} \qquad \text{Equation 1}$$

The key guidelines and frameworks C&R considered in this HHERA include:

- *Environmental Health Risk Assessment: Guidelines for assessing human health risks from environmental hazards* (enHealth 2012)
- *National Environment Protection (Assessment of Site Contamination) Measure* (ASC NEPM) (NEPC 2013a, 2013b)
- *PFAS National Environmental Management Plan* (PFAS NEMP) (HEPA 2020)
- *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZG 2018).

Scope of the report

The NSW EPA asked C&R to undertake a HHERA for PFAS using the NSW biosolids data collected during its sampling program. The primary aim of this assessment was to determine if PFAS in biosolids required regulation and to identify the key exposure pathways for PFAS in biosolids.

The scope of the assessment was to:

- review PFAS data collected from 20 STPs in NSW and compare these to data used in the Contaminants Review (WCA 2016) to determine if concentrations in NSW are consistent with concentrations reported around the world
- undertake a HHERA for PFAS in biosolids considering 4 scenarios:
  - land application of unrestricted use biosolids in residential gardens
  - land application of unrestricted use biosolids for land rehabilitation
  - land application of restricted use biosolids in agriculture, considering:
    - a low and high application rate
    - single and repeat applications
  - land application of unrestricted use biosolids in agriculture.
- use the results from the HHERA to determine if PFAS in biosolids require regulation and identify key exposure pathways that should be considered when deriving biosolids thresholds for PFAS
- recommend next steps and any additional work to address knowledge gaps.

Toxicity assessment for PFAS

Human health

A number of agencies have conducted extensive reviews of available epidemiological and toxicological studies for PFOS and PFOA including the European Food Safety

Authority (EFSA 2008), the Agency for Toxic Substances and Disease Registry (ATSDR 2015), and the United States Environmental Protection Agency (US EPA 2016a, 2016b). Epidemiological studies are based on data collected from human populations exposed to specific chemicals, often involving people working in chemical manufacturing plants or in other locations where they may have higher than normal exposure to those chemicals. Toxicological studies are laboratory studies conducted with test animals such as mice, rats, pigs, or monkeys. Assessment (safety) factors are usually applied to results of animal tests when extrapolating to possible human effects for regulatory purposes.

Food Standards Australia New Zealand (FSANZ 2017) reviewed the available major reviews noted above, along with other studies. FSANZ's conclusions, based on the epidemiological evidence, included that:

- associations between PFOS exposure and several health effects have been reported, notably increased serum cholesterol and decreased body weights at birth
- reasons for differences in serum cholesterol and body weights at birth were not clear, and other factors may be involved, apart from exposure to PFOS and PFOA
- findings for other health effects were 'inconsistent between studies and the biological significance of a number of the observed effects is questionable'
- associations between PFOA and some human cancers have been reported, but again 'a causal relationship cannot be established with reasonable confidence'.

FSANZ's conclusions based on the toxicological evidence included that:

- PFOS, PFOA and perfluorohexane sulfonate (PFHxS) persist in humans for much longer than in laboratory animals; half-life values for laboratory animals are generally days to weeks, but years in humans
- the primary target organ of repeat dose studies is the liver
- liver and testicular tumours were observed in rats but were likely caused by a mechanism not relevant to humans
- foetal and neonatal toxicity were observed including early embryonic loss, reduced bone formation, reduced heart size, decreased postnatal body weight gain, increased liver cell size and reduced fecundity of prenatally exposed females
- steep dose-response curves were reported, particularly in monkeys, with narrow dose range between the no observed adverse effect level (NOAEL) and treatment-related mortality.

Overall, although a clear understanding of potential human impacts is not available from the epidemiological evidence, the toxicological studies suggest that if exposure exceeds certain thresholds, health impacts to humans are possible. Due to the lack of consistent epidemiological evidence, the toxicology results have been used by various agencies including FSANZ to derive tolerable daily intakes (TDIs) for PFOS and PFOA. This is common for many other chemicals, but in the case of PFOS and PFOA, the widely differing elimination half-lives (toxicokinetics) between test animals and humans has caused additional difficulties in extrapolating results to humans. To account for this uncertainty, the derivation of the FSANZ TDI used a pharmacokinetic modelling approach and a default uncertainty factor to account for pharmacokinetic differences.

Detailed toxicological data are lacking for other PFAS except for PFHxS. Based on limited toxicological data and a half-life in humans for PFHxS similar to or greater than PFOS, enHealth (2016) recommended the TDI for PFOS be applied to the sum of PFOS and PFHxS (PFOS+PFHxS). FSANZ (2017) reaffirmed that approach. The adopted TDIs in Australia from FSANZ (2017) are listed in Table 1.

Based on these TDIs, a range of screening criteria that protect human health have been derived for use in Australia. These criteria are described in the PFAS NEMP (HEPA 2020) and those relevant to this report are listed in Table 2.

Table 1 Tolerable daily intakes (TDIs) for PFOS+PFHxS and PFOA (published in FSANZ 2017)

Compound	TDI (ng/kg-bw/d)	Comment
PFOS+PFHxS	20	Based on decreased parental and offspring body weight gains in a multigenerational reproductive toxicity study in rats. The TDI was derived by applying pharmacokinetic modelling to calculate human equivalent doses (HEDs) and applying an uncertainty factor of 30 to account for inter- and intra-species differences.
PFOA	160	Based on foetal toxicity in a developmental and reproductive study in mice. The TDI was derived by applying pharmacokinetic modelling to calculate HEDs and applying an uncertainty factor of 30 to account for inter- and intra-species differences.

Table 2 Soil and drinking water criteria for investigation – human health guideline values (from the PFAS NEMP) (HEPA 2020)

Exposure scenario	PFOS+PFHxS	PFOA	Comment
Drinking water	0.07 µg/L	0.56 µg/L	Australian Government Department of Health
Residential with garden/accessible soil	0.01 mg/kg	0.1 mg/kg	Based on 20% TDI (i.e. up to 80% of exposure is assumed to come from other pathways)
Soil in public open spaces	1 mg/kg	10 mg/kg	Based on 20% TDI (i.e. up to 80% of exposure is assumed to come from other pathways)

For other PFAS, there is a general lack of toxicological and epidemiological data, therefore no TDIs are available in Australia. In general, it is assumed that short chain perfluoroalkyl acids (PFAAs) are both less toxic and less bioaccumulative in animals than longer chain PFAAs (Ding and Peijnenburg 2013). However, short chain PFAAs are more bioaccumulative in plants, which could be relevant to human exposure. Long chain PFAAs other than PFOS, PFHxS and PFOA have been reported as bioaccumulating in numerous wildlife and laboratory studies (Ding and Peijnenburg 2013). Limited evidence suggests that some long chain perfluorinated carboxylic acid (PFCAs), such as perfluorononanoic acid (PFNA), are as or more toxic than PFOA, and therefore their hazard should not be ignored. For example, ATSDR (2018) set equivalent intermediate duration minimal risk levels for both PFOA and PFNA (3×10^{-6} mg/kg-bw/d). In general, measured concentrations of perfluorodecanoic acid (PFDA) in the biosolids were generally higher than PFOA concentrations, and similar to PFOS (Appendix A).

Further, toxicological data for PFAA precursors are very limited. The toxicity of precursors, themselves, and of their degradation intermediates, may be relevant when determining the overall risk from PFAS. For example, one research group has reported that toxicity of some intermediate precursors to some aquatic organisms is greater than the PFAA daughter products (Phillips et al. 2007).

C&R notes that based on the above information, although PFAS other than PFOS, PFOA and PFHxS cannot be quantitively assessed in Australia, they should not be overlooked in the interpretation of results from this HHERA. The approach used in this assessment to do this was the application of a margin of safety to the risk calculations when interpreting results.

Ecological

Toxicity data used to derive protective concentrations for ecosystems are generally calculated from laboratory experiments. Evaluation of any laboratory toxicity experiments needs to consider the ecological setting that can affect the health of species, and it is important to clearly identify the organisms that require protecting. Exposure pathways which may be relevant for ecological impacts include soil, surface waters, sediments and groundwater. Organisms may also be exposed though the food chain. Therefore, when assessing risk to ecosystems, it is important to consider terrestrial organisms, aquatic organisms and potential secondary and tertiary consumers (i.e. contaminant transfer through the food chain).

Detailed discussion on the different toxicity data is out of the scope of this review, though overall there are limited ecological data available for long term exposure of PFAS. The key criteria available for assessing risks from PFAS in Australia are detailed in the PFAS NEMP (HEPA 2020). C&R notes that at this stage, ecological criteria are only available in Australia for PFOS and PFOA.

Due to the relatively high water solubility and protein-binding characteristics of PFAS, it is critical to consider bioaccumulation[7] as part of a toxicity assessment. However, in Australia, the only endorsed approach to do this is to conduct direct measurements in organisms. Such data were not available for this HHERA. Conventional predictive models based on octanol-water partition coefficients (Kow) are not appropriate for predicting PFAS exposure (HEPA 2020), and therefore have not been used in this assessment.

Ecological soil screening criteria

Due to a lack of available toxicity data relevant to Australian species, international soil screening criteria have been adopted in the PFAS NEMP for terrestrial environments as an interim measure. Where relevant, these criteria have been used in this risk assessment (relevant ecological soil criteria are listed in Table 3).

[7] Bioaccumulation is the uptake of a contaminant from food and/or water by an organism resulting in an increase in concentration of the contaminant in that organism (HEPA 2020).

Table 3 **Soil screening criteria for investigation – ecological guideline values (adapted from the PFAS NEMP) (HEPA 2020)**

Exposure scenario	PFOS (mg/kg)	PFOA (mg/kg)	Comment and source
Ecological direct exposure	1	10	The human health screening value for public open space is used as an interim value (HEPA 2020)
Ecological indirect exposure	0.01	na	Based on dietary exposure of a secondary consumer* as the most sensitive exposure pathway (HEPA 2020)

na: not available

* 'Secondary consumers' refers to animals such as mammals and birds that consume smaller plant-eating animals and earthworms

PFOS and PFOA are known to bioaccumulate in terrestrial environments, and therefore exposure via the food chain needs to be considered. PFOS has also been shown to biomagnify in organism with lungs (e.g. mammals and birds), which is in contrast to organisms will gills (e.g. fish), where PFOS bioaccumulates but does not appear to biomagnify. The risks to terrestrial organisms from PFOS through direct and indirect exposure via the food chain are incorporated into the screening criteria listed in Table 3.

In the absence of ecological soil screening criteria for indirect exposure to PFOA, the assessment in this report used criteria from elsewhere. In this instance, the proposed soil screening value (SSV) for secondary consumers from the United Kingdom Environmental Agency (UK EA) was used. This value is 0.02 mg/kg (dry weight, dw), which is normalised to 3.4% soil organic matter) (UK EA 2017). C&R undertook a review of the suitability of this screening value for Australian conditions (Appendix B) and for the purposes of the assessment presented in this report, the value was reduced to 0.01 mg/kg (dw) to account for the lower organic matter content of Australian soils.

Ecological aquatic screening criteria

Draft water quality guidelines have been developed in Australia for PFOS and PFOA (Table 4), though these are currently under review. These values were derived using the standard approach for calculating water quality guidelines in Australia (ANZG 2018; Warne et al. 2018). Of importance is that long chain PFAAs have been shown to bioaccumulate in aquatic species. Based on the approach used to derive water quality guidelines in Australia (ANZG 2018; Warne et al. 2018), a higher level of species protection is used when assessing bioaccumulative contaminants. This generally means the 99% species protection level would be used as screening values for slightly to moderately impacted systems, instead of the 95% species protection value. However, for PFOS, the draft guideline value for 99% species protection is below the standard limit of reporting (LOR) used by laboratories. This presents challenges in applying this screening value. The PFAS NEMP notes that a water concentration below a LOR of 0.001 µg/L does not necessarily mean minimal risk to aquatic organisms. Therefore, to assess for direct toxicity, the 95% species protection level can be used. However, to assess bioaccumulation, aquatic biota should be sampled.

Table 4 **Aquatic screening criteria for investigation – ecological guideline values (adapted from the PFAS NEMP) (HEPA 2020)**

Exposure scenario	PFOS (µg/L)	PFOA (µg/L)	Comments and source
99% species protection – high conservation value systems	0.00023	19	Draft water quality guidelines
95% species protection – slightly to moderately disturbed systems	0.13	220	Note: the draft guidelines do not account for effects which result from biomagnification in air-breathing animals or animals that prey on aquatic organisms.
90% species protection – highly disturbed systems	2	632	

Biosolids use in NSW

Biosolids contain high contents of nutrients and organic matter, therefore, land applying 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, land rehabilitation, agriculture and forestry. There are no restrictions on land application rates for unrestricted use biosolids.
- Restricted use biosolids fall under lower contaminant and stability grades and are further divided into three subclassifications (restricted use 1, 2 and 3). 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 allowed in the biosolids and the receiving soil. There are currently no thresholds for PFAS compounds in biosolids or the receiving soil listed in the NSW Biosolids Guidelines.

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:

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

Conceptual model for exposure to PFAS in biosolids

C&R considered 4 scenarios of biosolids usage in this HHERA based on how most biosolids are used in NSW. These scenarios were agreed to with the NSW EPA before commencing the assessment:

- Scenario 1 – land application of unrestricted use biosolids in residential gardens
- Scenario 2 – land application of unrestricted use biosolids for land rehabilitation[8]
- Scenario 3 – land application of restricted use biosolids in agriculture[9].
- Scenario 4 – 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 products. However, as the NSW Biosolids Guidelines allow unrestricted use biosolids to be land applied in agriculture, and this is potentially a sensitive scenario for bioaccumulating compounds (e.g. PFAS), this scenario was added to the HHERA for completeness. Scenario 4 only considered human health risks as all potential ecological pathways from unrestricted use biosolids are already assessed in Scenarios 1 and 2 (i.e. for ecological receptors, the agricultural use of biosolids doesn't introduce any additional pathways). In addition, to streamline the Scenario 4 assessment, only the potential risks from the most sensitive agricultural pathway (as identified from Scenario 3) are presented in this report. The risks from other pathways can be provided if required.

For all scenarios, the primary source of the PFAS was assumed to be biosolids-amended soils and it was assumed that no PFAS were present in the soil at the time of land application.

The conceptual model considers the potential transport and exposure pathways, and the key receptors (people or ecosystems) that may be exposed under the scenarios listed above. Potential transport pathways for PFAS from biosolids-amended soil are:

- vertical migration through the soil profile via infiltration and leaching
- lateral migration of groundwater
- surface water runoff
- uptake into flora and fauna.

For the human health assessment, the following exposure pathways were considered (where relevant for a scenario):

- incidental ingestion of soil/dust
- consumption of plants (fruit and vegetables) exposed to contaminated soil and/or water
- consumption of animal produce (cattle, milk, poultry eggs etc) exposed to contaminated soil, water and/or crops
- direct or incidental ingestion of contaminated surface water and groundwater.

For the ecological assessment, the pathways considered included (where relevant for a scenario):

- direct contact and uptake from biosolids-amended soil

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[8] Scenario 2 assumes land will not be used for agriculture in the future.

[9] Scenario 3 includes rehabilitated land that will be used for agriculture in the future.

- direct contact and uptake from surface waters affected by migration of PFAS from biosolids-amended soil
- secondary consumers ingesting flora and/or fauna affected from exposure to PFAS from biosolids-amended soil.

Specific pathways considered for each scenario are discussed in detail in the scenario-specific sections of this report.

PFAS data available from NSW biosolids sampling

Concentrations of PFAS in NSW biosolids

In 2017, the NSW EPA collected biosolids samples from 20 STPs across NSW, to address recommendations from the Contaminants Review (WCA 2016). In NSW, the EPA currently licenses ~ 250 STPs, therefore approximately 8% of the facilities were sampled as part of this program. The aim of this sampling program was to measure concentrations of identified contaminants of concern in NSW biosolids. These concentrations could then be compared to those used in the risk assessment in the Contaminants Review to determine if concentrations are similar to those reported elsewhere.

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 processed biosolids that had completed treatment and were ready for land application. The samples were analysed for the suite of PFAS for which analytical methods were available at the time. For quality assurance and quality control (QA/QC), 5 duplicate samples and 2 blank samples were included in the analysis (frequency of QA/QC samples is consistent with guidance in the PFAS NEMP, HEPA 2020). As this risk assessment focused only on PFOS, PFHxS and PFOA, the average concentrations of these compounds measured in the 20 STPs in NSW are summarised in Table 5. For the purposes of this report, the STPs have been de-identified. The average concentrations of other PFAS compounds measured in the suite but not assessed in this report are provided in Appendix A.

The concentrations of PFOS were above the LOR in all biosolids samples, with averages ranging from 3.2 to 77 µg/kg. This maximum concentration was approximately 1.7-times lower than the 90th percentile concentration used in the preliminary screening risk assessment in the Contaminants Review (130 µg/kg) (WCA 2016). Average PFOA concentrations ranged from < 2.7 to 24 µg/kg, with the maximum concentration about 1.7-times higher than the 90th percentile concentration used in the preliminary screening risk assessment in the Contaminants Review (14 µg/kg) (WCA 2016). This indicates that concentrations of PFOS and PFOA in NSW biosolids are similar to those that have been reported elsewhere. The concentrations of PFHxS were lower than PFOS and PFOA, with average concentrations ranging from < 0.1 to 3.8 µg/kg. This compound was not included in the Contaminants Review and therefore the data could not be compared. Due to the low concentration of PFHxS, this compound had minimal contribution (< 5%) to the summed concentrations of PFOS+PFHxS.

Table 5 **Average[1] concentrations (µg/kg) of PFOS, PFOA and PFHxS from 20 sewage treatment plants (STPs) in NSW (n=2 for each STP)**

STP	PFOS	PFOA	PFHxS	PFOS+PFHxS[2]
A	20	12	0.75	20
B	3.2	1.8*	< 0.1	3.2
C	42	6.2	1.7	44
D	62	18	0.9	62
E	17	6.8	1.1	18
F	27	2.7	0.8	27
G	21	4.4	0.3	21
H	10	< 2.7	0.13*	11
I	18	< 2.7	0.28*	18
J	9.6	6.2*	0.28*	9.8
K	3.9	< 2.7	< 0.1	4.0
L	53	9.2	0.7	53
M	77	8.7	2.2	79
N	36	8.4	1.0	37
O	24	8.1	0.65	24
P	71	14	3.8	74
Q	45	24	0.55	46
R	8.7	1.9*	< 0.1	8.8
S	53	2.5	0.85	54
T	16	6.6	0.25	16
Maximum	77	24	3.8	79
Minimum	3.2	< 2.7	< 0.1	3.2
95th percentile	71	18	2.3	75
Average[1]	31	7.2	0.82	32

'<' indicates where concentrations were below the limit of reporting (LOR)

[1] Where concentrations were < LOR in one of the samples, half the LOR was used to calculate the averages

[2] To calculate the sum of PFOS and PFHxS, half the LOR was used if the reported concentration was <LOR

* Average concentrations include one sample that was < LOR

The NSW data were used in the HHERA presented in this report. Therefore, C&R has assumed these data are representative of the range of PFOS, PFOA and PFHxS concentrations in NSW biosolids. The sampling program did not account for possible temporal variation. If more PFAS data become available for NSW biosolids, these data can be assessed for consistency with data used in this risk assessment.

Concentrations of PFAS in leachates from NSW biosolids

Leachate testing was undertaken on the biosolids samples collected from NSW STPs to determine the potential for individual compounds to be mobilised from the material. This information is useful to determine potential exposure via groundwater or surface runoff pathways. The testing was done based on the Australian Standard Leaching Procedure (ASLP) (Standards Australia 1997) and involved extracting 2 g of biosolids with 40 mL of unbuffered ultrapure water (i.e. a solid to solution ratio of 1:20). The samples were shaken for 24 hrs. Following this, they were centrifuged, and the supernatant was analysed for a suite of PFAS. The PFOS, PFOA and PFHxS data from the leachate tests are shown in Table 6. Data for all other PFAS in the analytical suite are shown in Appendix A. For QA/QC, 4 duplicate samples and 4 blank samples were included in the analysis (frequency of QA/QC samples is consistent with guidance in the PFAS NEMP, HEPA 2020).

Table 6 Average[1] concentrations of PFOS, PFOA and PFHxS (µg/L) in biosolids leachates (n=2 for each STP)

STP	PFOS	PFOA	PFHxS	PFOS+PFHxS[2]
A	0.030	0.14	< 0.002	0.031
B	0.0053*	0.025	< 0.002	0.0063
C	0.12	0.14	0.047	0.17
D	0.073	0.24	0.013	0.086
E	0.047	0.12	0.020	0.067
F	0.031	0.022	0.0070	0.038
G	0.029	0.068	< 0.002	0.030
H	0.030	0.018	0.0045	0.034
I	0.029	0.0070	0.0075	0.037
J	0.093	0.18	0.0070	0.10
K	0.0028*	0.0095	0.002*	0.0048
L	0.061	0.13	0.010	0.071
M	0.25	0.12	0.034	0.28
N	0.053	0.11	0.019	0.072
O	0.053	0.11	< 0.002	0.054
P	0.23	0.33	0.094	0.32
Q	0.10	0.44	0.011	0.11
R	0.020	0.030	0.0045*	0.025
S	0.15	0.34	< 0.0020	0.15
T	0.12	0.065	0.0030*	0.015
Maximum	0.25	0.44	0.094	0.32
Minimum	0.003	0.007	< 0.002	0.005
95th percentile	0.23	0.33	0.049	0.28
Average[1]	0.079	0.12	0.014	0.093

'<' indicates where concentrations were below the limit of reporting (LOR)

[1] Where concentrations were < LOR in one of the samples, half the LOR was used to calculate the averages

[2] To calculate the sum of PFOS and PFHxS, half the LOR was used if the reported concentration was < LOR

* Average concentrations include one sample that was < LOR

Summary of methodology used to calculate risk and identify key exposure pathways

The concentrations of PFOS, PFOA and PFHxS in NSW biosolids were used to estimate exposure concentrations or exposure doses. For example, estimated concentrations in biosolids-amended soil, agricultural produce (crops, beef, milk) and drinking or irrigation water were calculated. The estimated exposure concentrations/doses were used in risk calculations to identify key exposure pathways for PFAS in biosolids and to determine if regulation is warranted. These were generic risk calculations and are 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 only for PFOS and PFOA due to the lack of screening criteria in Australia for other PFAS. To assess the risk, the estimated concentrations of each compound in a biosolids-amended soil were compared with screening criteria (Table 3 and Table 4). This comparison was used to calculate an ecological risk quotient (RQ_{ECO}) using Equation 2.

$$RQ_{ECO} = \frac{conc.\ in\ biosolids\ amended\ soil}{screening\ criterion} \qquad \text{Equation 2}$$

When RQ_{ECO} is less than 1, the screening criterion is not exceeded. When RQ_{ECO} is greater than 1, the criterion has been exceeded. The value of the RQ_{ECO} indicates how many times the criteria has been exceeded, for example, if the RQ_{ECO} is 2, the concentration in the biosolids-amended soil is double the criterion.

Human health risks were assessed for PFOS+PFHxS and PFOA, in accordance with current national guidance (FSANZ 2017). The detailed methods for assessing the human health risks for each scenario and pathway are outlined in Appendix C. For all pathways, the concentrations of PFOS and PFHxS were summed. Where relevant screening criterion were available for a specific pathway, a human health risk quotient (RQ_{HH}) was calculated using Equation 3.

$$RQ_{HH} = \frac{conc.\ in\ biosolids\ amended\ soil}{screening\ criterion} \qquad \text{Equation 3}$$

The interpretation of this RQ_{HH} is the same as that outlined for the RQ_{ECO} values (Equation 2).

For many of the human health exposure pathways, screening criteria were not available. In these cases, predicted daily intakes (µg/kg/d) were calculated using methods outlined in Appendix C. The daily intake was then used to calculate a RQ_{HH} using Equation 4.

$$RQ_{HH} = \frac{predicted\ daily\ intake}{TDI - background} \qquad \text{Equation 4}$$

where, the *TDI* is the tolerable daily intake (Table 1) and the background for both PFOS+PFHxS and PFOA was assumed to be 0.001 µg/kg/d (ToxConsult 2016). This approach of calculating RQ_{HH} values is likely to be less conservative than the approach using screening criteria due to additional conservatism built into derivation of the screening criteria (Table 2).

In most cases, daily intakes and RQ_{HH} values were calculated for children only. This is because children are the higher risk age group due primarily to a smaller body weight. The only exceptions to this were for 2 of the pathways assessed in Scenario 3 where RQ_{HH} values were calculated for adults instead of children. The details relating to this are provided in the relevant sections.

For Scenarios 1 and 2, risk calculations were completed for biosolids from each of the 20 STPs. For Scenario 3, risk calculations were initially conducted only based on the STP that had the highest concentration for each compound for the land application rates (i.e. 10 t/ha single application, 10 t/ha repeat applications, 50 t/ha single application, 50 t/ha repeat applications). If the maximum risk calculations resulted in an RQ above 1, additional calculations for biosolids from all STPs are reported in Appendix E. If additional STP-specific RQs are required, these can be provided.

For each scenario, if the maximum RQ was above 0.2, C&R has recommended that regulation is required and that a threshold in biosolids should be derived. This was done to account for the low margin of safety (MOS) at an RQ of 0.2 (i.e. less than 5) and considers the following uncertainties:

- There is some uncertainty in biosolids PFAS concentrations – this risk assessment is based on PFAS concentrations from 20 STPs across NSW, and it is not known if, or the extent to which, these concentrations may vary overtime.
- The risk assessment focused on PFOS, PFOA and PFOS+PFHxS, and does not account for potential risk from other PFAS (see Appendix A) or precursors. Currently these cannot be accounted for quantitatively in risk assessments based on Australian guidance, and as such some additional conservatism is warranted.

Where RQs were less than 0.2, C&R has concluded that 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.

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

Scenario 1 – unrestricted use biosolids in residential gardens

Scenario 1 considers the ecological and human health risks from unrestricted use biosolids land applied in the garden of a residential property. In NSW, unrestricted use biosolids need to meet stringent contaminant thresholds. The biosolids are often processed with other waste before land application, for example, garden waste, to produce a final product that meets the unrestricted use 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 ¼ to ⅓. To assess Scenario 1, measured concentrations of PFOS, PFOA and PFHxS in biosolids were divided by 3 to estimate concentrations in unrestricted use biosolids (Table 7). C&R used the factor of 3 as it represented the highest proportion of biosolids in the final product based on the survey information. This approach assumes there is no PFAS present in the other waste stream that the biosolids are processed with. For this scenario, the estimated concentrations in the unrestricted use biosolids were assumed to be the biosolids-amended soil concentrations, as unrestricted use biosolids can be applied at any rate and may be used to form a topsoil.

Table 7 Estimated concentrations of PFOS, PFOA, PFHxS and PFOS+PFHxS in unrestricted use biosolids (all concentrations in µg/kg)

STP	PFOS	PFOA	PFHxS	PFOS+PFHxS[1]
A	6.7	4.0	0.25	6.9
B	1.1	0.60	< 0.033	1.1
C	14	2.1	0.57	15
D	21	6.0	0.30	21
E	5.7	2.3	0.37	6.0
F	9.0	0.90	0.27	9.3
G	7.0	1.5	0.10	7.1
H	3.3	< 0.9	0.043	3.4
I	6.0	< 0.9	0.093	6.1
J	3.2	2.1	0.093	3.3
K	1.3	< 0.9	< 0.033	1.3
L	18	3.1	0.23	18
M	26	2.9	0.73	26
N	12	2.8	0.33	12
O	8	2.7	0.22	8.2
P	24	4.7	1.3	25
Q	15	8.0	0.18	15
R	2.9	0.63	< 0.033	2.9
S	18	0.83	0.28	18
T	5.3	2.2	0.0833	5.4

‘<’ indicates cases where concentrations were below the limit of reporting (LOR)

[1] To calculate PFOS+PFHxS, half the LOR was used if the reported concentration was < LOR

Ecological risk assessment

Ecological risks from PFOS and PFOA were assessed for the following pathway for Scenario 1:

- **Pathway 1** – biosolids-amended soil (BAS) → terrestrial organism.

This pathway assessed impacts to terrestrial organisms via direct toxicity only. Indirect ecological impacts were not assessed because it was considered unlikely that land application for this scenario would be on a sufficiently large scale to result in offsite impacts.

Direct toxicity to terrestrial organisms (Pathway 1)

The ecological risks from PFOS and PFOA following land application of unrestricted use biosolids in residential gardens were assessed by comparing the estimated concentrations in unrestricted use biosolids (Table 7) with ecological direct toxicity screening criteria from the PFAS NEMP (Table 3) (1000 and 10,000 µg/kg, respectively)[10]. This was done to calculate an RQ_{ECO} as shown in Equation 2.

All RQ_{ECO} values were considerably lower than 1 for biosolids from all STPs (Table 8). They were the highest for PFOS, but in all cases the MOS was at least 40, indicating all values were at least 40-times lower than 1. In comparison, for PFOA the MOS was at least 1200. This suggests the ecological risk from unrestricted use biosolids in residential gardens is low.

Table 8 Ecological risk quotients (RQ_{ECO}) for the assessment of risks from unrestricted use biosolids in residential gardens via direct toxicity

STP	PFOS		PFOA	
	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{ECO}	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{ECO}
A	6.7	0.0067	4.0	4.0×10^{-4}
B	1.1	0.0011	0.60	6.0×10^{-5}
C	14	0.014	2.1	2.1×10^{-4}
D	21	0.021	6.0	6.0×10^{-4}
E	5.7	0.0057	2.3	2.3×10^{-4}
F	9.0	0.009	0.90	9.0×10^{-5}
G	7.0	0.007	1.5	1.5×10^{-4}
H	3.3	0.0033	< 0.9	$< 9.0 \times 10^{-5}$
I	6.0	0.006	< 0.9	$< 9.0 \times 10^{-5}$
J	3.2	0.0032	2.1	2.1×10^{-4}
K	1.3	0.0013	< 0.9	$< 9.0 \times 10^{-5}$
L	18	0.018	3.1	3.1×10^{-4}

[10] The PFAS NEMP outlines these criteria are interim and are based on protection of human health in a public open space scenario (HEPA 2020)

STP	PFOS		PFOA	
	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{ECO}	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{ECO}
M	26	0.026	2.9	2.9×10^{-4}
N	12	0.012	2.8	2.8×10^{-4}
O	8.0	0.008	2.7	2.7×10^{-4}
P	24	0.024	4.7	4.7×10^{-4}
Q	15	0.015	8.0	8.0×10^{-4}
R	2.9	0.0029	0.63	6.3×10^{-5}
S	18	0.018	0.83	8.3×10^{-5}
T	5.3	0.0053	2.2	2.2×10^{-4}
Maximum	26	0.026	8.0	8.0×10^{-4}

Grey indicates RQ ≤ 0.2

‘<’ indicates cases where concentrations were below the LOR

Human health risk assessment

Human health risks from PFOS+PFHxS and PFOA were assessed for Scenario 1 for the following exposure pathways:

- **Pathway 1** – BAS → incidental ingestion soil/dust
- **Pathway 2** – BAS → uptake into homegrown fruit and vegetables → consumption of homegrown fruit and vegetables
- **Pathway 3** – BAS → soil ingestion by chickens → consumption of chicken eggs.

The risk calculations for each of the pathways are explained in detail in Appendix C.

Residential exposure without chicken eggs (Pathways 1 and 2)

Pathways 1 and 2 were assessed together using soil screening criteria from the PFAS NEMP that protect exposure via incidental ingestion of soil/dust and consumption of homegrown fruit and vegetables (assumed 10% of total fruit and vegetable consumption comes from home gardens). These screening criteria are 9 and 100 µg/kg for PFOS+PFHxS and PFOA, respectively (HEPA 2020). The estimated concentrations of each compound in unrestricted use biosolids from each STP were assumed to be the biosolids-amended soil concentrations (Table 7). These concentrations were compared to the screening criteria to calculate an RQ_{HH} as shown in Equation 3.

The RQ_{HH} values for PFOS+PFHxS ranged from 0.12 to 2.9, with biosolids from 8 of the 20 STPs exceeding resulting in RQ_{HH} above 1 (Table 9). Based on this result, C&R recommends a threshold for PFOS+PFHxS in unrestricted use biosolids is derived. C&R notes that although the PFAS NEMP screening criteria used here combines risk for Pathways 1 and 2, the key risk-driving pathway is the consumption of homegrown fruit and vegetables (Pathway 2) (HEPA 2020). That is, if people are only exposed via incidental ingestion of home soil/dust, the risk would be considerably lower.

All RQ_{HH} values for PFOA for Pathways 1 and 2 were below 0.2 (Table 9). These values ranged from 0.006 to 0.08, which indicates that, even with the conservative assumptions used to derive the screening criteria (see Appendix C and Table 2 for details), the risk from these pathways is still low.

Table 9 PFOS+PFHxS and PFOA human health risk quotients (RQ_{HH}) for unrestricted use biosolids in a residential scenario without eggs (Pathways 1 and 2)

STP	PFOS+PFHxS		PFOA	
	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{HH}	Estimated conc. In unrestricted use biosolids (µg/kg)	RQ_{HH}
A	6.7	0.74	4.0	0.04
B	1.1	0.12	0.60	0.006
C	14	1.6	2.1	0.021
D	21	2.0	6.0	0.06
E	5.7	0.67	2.3	0.023
F	9.0	1.0	0.90	0.009
G	7.0	0.78	1.5	0.015
H	3.3	0.41	< 0.9	< 0.009
I	6.0	0.67	< 0.9	< 0.009
J	3.2	0.36	2.1	0.021
K	1.3	0.15	< 0.9	< 0.009
L	18	2.0	3.1	0.031
M	26	2.9	2.9	0.029
N	12	1.4	2.8	0.028
O	8.0	0.89	2.7	0.027
P	24	2.7	4.7	0.047
Q	15	1.7	8.0	0.08
R	2.9	0.33	0.63	0.0063
S	18	2.0	0.83	0.0083
T	5.3	0.59	2.2	0.022
Maximum	26	2.9	8.0	0.08

Red indicates RQ > 1, **Orange** indicates 1 ≥ RQ > 0.2, Grey indicates RQ ≤ 0.2
'<' concentration of PFOA in biosolids was below the LOR and the LOR was used in the calculations

Consumption of eggs from residential properties (Pathway 3)

Pathway 3 was assessed by estimating daily intakes of PFOS+PFHxS and PFOA, as no soil screening criteria are available for this pathway. A detailed description of these calculations is provided in Appendix C. In brief, initially concentrations of PFOS+PFHxS and PFOA in poultry eggs were calculated based on the estimated concentrations of PFOS+PFHxS and PFOA in unrestricted use biosolids, soil intake rates for chickens and egg transfer factors. These calculations assumed that chickens are directly ingesting unrestricted use biosolids. The egg concentrations were then used to calculate daily intakes for a child (years 0–5). These were then compared to the TDIs for each compound using Equation 4 to calculate an RQ_{HH}.

The estimated egg concentrations ranged from 0.23–5.5 µg/kg for PFOS+PFHxS, and < 0.095–0.84 µg/kg for PFOA (Table 10). The resulting RQ_{HH} values for PFOS+PFHxS were higher than those for PFOA. The maximum RQ_{HH} for PFOS+PFHxS was 1.4, with biosolids from 3 of the STPs resulting in RQ_{HH} values above 1 (Table 10). Based on this, C&R recommends a threshold for PFOS+PFHxS in unrestricted use biosolids is derived.

For PFOA, the maximum RQ_{HH} value for the residential egg consumption pathway was 2.5×10^{-2} (Table 10). This is a MOS of at least 40, indicating that the risk to human health via exposure to PFOA from chicken eggs is low.

Table 10 Estimated concentrations of PFOS+PFHxS and PFOA in eggs from chickens ingesting unrestricted use biosolids-amended soil and human health risk quotients (RQ_{HH}) for children

STP	PFOS+PFHxS			PFOA		
	Estimated egg conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}	Estimated egg conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}
A	1.5	7.0×10^{-3}	0.37	0.42	2.0×10^{-3}	1.3×10^{-2}
B	0.23	1.1×10^{-3}	0.058	0.063	3.0×10^{-4}	1.9×10^{-3}
C	3.2	1.5×10^{-2}	0.80	0.22	1.1×10^{-3}	6.7×10^{-3}
D	4.4	2.1×10^{-2}	1.1	0.63	3.0×10^{-3}	1.9×10^{-2}
E	1.3	6.1×10^{-3}	0.32	0.24	1.2×10^{-3}	7.3×10^{-3}
F	2.0	9.4×10^{-3}	0.49	0.095	4.5×10^{-4}	2.9×10^{-3}
G	1.5	7.2×10^{-3}	0.38	0.16	7.6×10^{-4}	4.8×10^{-3}
H	0.72	3.4×10^{-3}	0.18	< 0.095	$< 4.5 \times 10^{-4}$	$< 2.9 \times 10^{-3}$
I	1.3	6.2×10^{-3}	0.32	< 0.095	$< 4.5 \times 10^{-4}$	$< 2.9 \times 10^{-3}$
J	0.69	3.3×10^{-3}	0.18	0.22	1.1×10^{-3}	6.7×10^{-3}
K	0.27	1.3×10^{-3}	0.069	< 0.095	$< 4.5 \times 10^{-4}$	$< 2.9 \times 10^{-3}$
L	3.8	1.8×10^{-2}	0.96	0.33	1.6×10^{-3}	9.9×10^{-3}
M	5.5	2.6×10^{-2}	1.4	0.31	1.5×10^{-3}	9.2×10^{-3}
N	2.5	1.2×10^{-2}	0.64	0.29	1.4×10^{-3}	8.9×10^{-3}
O	1.7	8.3×10^{-3}	0.44	0.28	1.4×10^{-3}	8.6×10^{-3}
P	5.3	2.5×10^{-2}	1.3	0.49	2.4×10^{-3}	1.5×10^{-2}
Q	3.2	1.5×10^{-2}	0.80	0.84	4.0×10^{-3}	2.5×10^{-2}
R	0.61	2.9×10^{-3}	0.15	0.066	3.2×10^{-4}	2.0×10^{-3}
S	3.8	1.8×10^{-2}	0.96	0.087	4.2×10^{-4}	2.6×10^{-3}
T	1.1	5.5×10^{-3}	0.29	0.23	1.1×10^{-3}	7.0×10^{-3}
Maximum	5.5	2.6×10^{-2}	1.4	0.84	4.0×10^{-3}	2.5×10^{-2}

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

'<' concentration of PFOA in biosolids was below the LOR and the LOR was used in the calculations

Overview of risk assessment for Scenario 1

Scenario 1 assessed the risks to ecology and human health when unrestricted use biosolids are used in residential gardens. 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 waste material to produce unrestricted use biosolids. It was assumed the other material contained no PFAS. As there are no restrictions on application rates for this classification of biosolids, the assessment conservatively assumed 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. For both PFOS and PFOA, all RQs were less than 0.2, indicating the risk is low.

Human health risks from PFOS+PFHxS and PFOA were assessed for 3 exposure pathways: incidental ingestion of soil/dust, consumption of homegrown fruit/vegetables and the consumption of home chicken eggs. For PFOA, all RQ_{HH} values were less than 0.2 indicating the risk is low. For PFOS+PFHxS, the RQ_{HH} values ranged up to 2.9. Based on this, C&R recommends a threshold for PFOS+PFHxS for unrestricted use biosolids is derived. Overall, the key exposure pathway for this scenario was incidental ingestion of soil/dust and consumption of homegrown fruit/vegetables (RQ_{HH} values up to 2.9) (combined Pathways 1 and 2). The sensitivity of this pathway compared to the egg consumption pathway was driven partly by the conservative assumptions used in the derivation of the PFAS NEMP screening criteria (i.e. the soil screening criteria in the PFAS NEMP are based on 20% of the TDI, allowing for 80% of exposure via other pathways) (Table 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. Although currently only 5% of biosolids produced in NSW are used for land rehabilitation, based on information from the EPA, C&R understands that in the future this could increase. Similar to Scenario 1, this scenario assumed biosolids were processed with another waste product at a ratio of 1 part biosolids to 2 parts other (Table 7) to produce unrestricted use biosolids, which was used as a topsoil. As a result, the estimated concentrations in unrestricted use biosolids (Table 7) were used as the biosolids-amended soil concentrations in all calculations. It should be noted this assessment does not consider 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.

Ecological risk assessment

For this scenario, potential ecological risks from PFOS and PFOA were assessed by considering the following exposure pathways:

- **Pathway 1** – BAS → terrestrial organism
- **Pathway 2** – BAS → terrestrial organism → secondary consumer
- **Pathway 3** – BAS → groundwater/surface water runoff → surface water → aquatic organism.

Pathway 1 is consistent with the assessment shown for Scenario 1. Pathways 2 and 3 assessed potential risks that were not assessed for Scenario 1. Pathway 2 assessed indirect toxicity to secondary consumers, which is relevant as PFAS compounds are known to bioaccumulate. Pathway 3 assessed toxicity to offsite aquatic organisms via transport of PFAS to surface water through migration with groundwater or surface runoff.

Direct toxicity to terrestrial organisms (Pathway 1)

The assessment of Pathway 1 for this scenario is the same as that presented in Scenario 1 (unrestricted use biosolids in residential gardens). Therefore, the RQ_{ECO} values in Table 8 are also relevant here. In summary, all RQ_{ECO} values were considerably lower than 1, indicating the ecological risks to terrestrial organisms directly exposed to the biosolids-amended soil are low.

Indirect toxicity to secondary consumers (Pathway 2)

Pathway 2 assessed the potential for secondary consumers to be impacted following land application of unrestricted use biosolids for land rehabilitation. For PFOS this was done by comparing the estimated concentrations in unrestricted use biosolids (Table 7) with the interim soil screening criterion in the PFAS NEMP that protects this pathway (i.e. 10 µg/kg, Table 3). In the absence of a corresponding screening criterion for PFOA that is endorsed in Australia, the risks to secondary consumers for this compound were assessed using a criterion of 0.01 mg/kg, which was adjusted from UK EA (2017) (see Appendix B)[11].

The maximum RQ_{ECO} value for PFOS was 2.6 and biosolids from 8 of the 20 STPs resulted in a RQ_{ECO} above 1 (Table 11). Based on this, C&R recommends a threshold for PFOS in unrestricted use biosolids is derived. For PFOA, all RQ_{ECO} values were less than 1 (Table 12) but the MOS from one was less than 5 (i.e. $RQ_{ECO} > 0.2$). Based on this low margin of safety, C&R also recommends a threshold for PFOA in unrestricted use biosolids is derived.

Table 11 Ecological risk quotients (RQ_{ECO}) for PFOS risks to secondary consumers (Pathway 2) from unrestricted use biosolids in land rehabilitation

STP	Estimated conc. in unrestricted use biosolids (µg/kg)	Secondary consumer RQ_{ECO}
A	6.7	**0.67**
B	1.1	0.11
C	14	**1.4**
D	21	**2.1**
E	5.7	**0.57**
F	9.0	**0.90**
G	7.0	**0.70**
H	3.3	**0.33**
I	6.0	**0.60**
J	3.2	**0.32**
K	1.3	0.13
L	18	**1.8**
M	26	**2.6**
N	12	**1.2**
O	8	**0.80**
P	24	**2.4**
Q	15	**1.5**
R	2.9	**0.29**
S	18	**1.8**
T	5.3	**0.53**
Maximum	26	**2.6**

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

[11] C&R notes that the National Chemicals Working Group (NCWG) who draft the PFAS NEMP are currently working on derivation of an indirect soil criterion for PFOA. If this is implemented in the next version of the PFAS NEMP, the risk calculations in this assessment should be updated and the estimated risk may increase.

Table 12 **Ecological risk quotients (RQ_{ECO}) for PFOA risks to secondary consumers (Pathway 2) from unrestricted use biosolids in land rehabilitation**

STP	Estimated conc. in unrestricted use biosolids (µg/kg)	Secondary consumer RQ_{ECO}
A	4.0	**0.40**
B	0.60	0.060
C	2.1	**0.21**
D	6.0	**0.60**
E	2.3	**0.23**
F	0.90	0.090
G	1.5	0.15
H	< 0.9	< 0.090
I	< 0.9	< 0.090
J	2.1	**0.21**
K	< 0.9	< 0.090
L	3.1	**0.31**
M	2.9	**0.29**
N	2.8	**0.28**
O	2.7	**0.27**
P	4.7	**0.47**
Q	8.0	**0.80**
R	0.63	0.063
S	0.83	0.083
T	2.2	**0.22**
Maximum	8.0	**0.80**

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

Toxicity to offsite aquatic organisms (Pathway 3)

Pathway 3 assessed the potential for toxicity to aquatic organisms if surface water becomes impacted via transport of PFOS and PFOA with groundwater and/or surface runoff from areas where biosolids had been land applied. As there are no Australian-endorsed soil screening criteria for this pathway, it was assessed by predicting surface water concentrations based on solid-solution distribution coefficients for PFOS and PFOA. The predicted surface water concentrations were then compared to the 95% species protection aquatic screening criteria in the PFAS NEMP.

To estimate surface water concentrations, soil pore water concentrations were calculated. The procedure for doing this is outlined in Appendix D. Surface water concentrations were then estimated by applying a dilution and attenuation factor (DAF) of 10 to the pore water concentrations (Table 13). This DAF was used to account for dilution and attenuation that may occur between the land application site and the surface water. The estimated surface water concentrations for PFOS and PFOA were then compared to the aquatic screening criteria (0.13 and 220 µg/L, respectively) to calculate RQ_{ECO} values (Table 13).

Table 13 **Estimated pore water and surface water concentrations of PFOS and PFOA and corresponding ecological risk quotients (RQ_{ECO})**

STP	PFOS			PFOA		
	Estimated pore water conc. (ng/L)	Estimated surface water conc. (ng/L)	RQ_{ECO}	Estimated pore water conc. (ng/L)	Estimated surface water conc. (ng/L)	RQ_{ECO}
A	10	1.0	0.0079	61	6.1	2.8×10^{-5}
B	1.8	0.18	0.0014	10	1.0	4.4×10^{-6}
C	42	4.2	0.033	84	8.4	3.8×10^{-5}
D	25	2.5	0.019	110	11	4.9×10^{-5}
E	17	1.7	0.013	61	6.1	2.8×10^{-5}
F	11	1.1	0.0081	8.7	0.87	4.0×10^{-6}
G	9.9	0.99	0.0076	33	3.3	1.5×10^{-5}
H	11	1.1	0.0082	nd	nd	nd
I	10	1.0	0.0077	nd	nd	nd
J	38	3.8	0.019	150	15	6.8×10^{-5}
K	1.6	0.16	0.0014	nd	nd	nd
L	21	2.1	0.016	60	6.0	2.7×10^{-5}
M	89	8.9	0.068	55	5.5	2.5×10^{-5}
N	18	1.8	0.014	49	4.9	2.2×10^{-5}
O	18	1.8	0.014	50	5.0	2.3×10^{-5}
P	82	8.2	0.063	200	20	9.3×10^{-5}
Q	35	3.5	0.027	230	23	1.0×10^{-4}
R	7.0	0.70	0.0054	13	1.3	5.8×10^{-6}
S	53	5.3	0.041	na	na	na
T	47	4.7	0.036	27	2.7	1.2×10^{-5}
Maximum	89	8.9	0.068	230	23	1.0×10^{-4}

Grey indicates RQ ≤ 0.2

nd: not determined as either both biosolids or both leachates were < LOR which meant that pore water concentrations could not be calculated

na: not available due to solid-solution distribution coefficient (Kdes) calculation resulting in negative Kdes values (likely due to concentrations close to LOR) (see Appendix D for details)

The RQ_{ECO} values based on the estimated surface water concentrations ranged from 0.0014–0.068 for PFOS and 4×10^{-6} to 1×10^{-4} for PFOA. Although there is some uncertainty with this approach, the large margin of safety for these RQs suggests that the risk to aquatic organisms from PFOS and PFOA in biosolids land applied for rehabilitation is low. C&R notes that the potential risk from bioaccumulation in aquatic organisms cannot be determined at this stage, as there are no reliable bioaccumulation and biomagnification factors available for aquatic organisms that are accepted for use in Australia.

Human health risk assessment

For this scenario, human health risks were assessed for PFOS+PFHxS and PFOA by considering 2 exposure pathways:

- **Pathway 1** – BAS → incidental ingestion of soil/dust
- **Pathway 2** – BAS → groundwater/surface water → human consumption of water for drinking water purposes.

The risk calculations for each of the pathways are explained in detail in Appendix C.

Incidental ingestion of soil/dust (Pathway 1)

This pathway assessed the risk from incidental ingestion of soil/dust by someone using a rehabilitated area for recreational purposes. To do this, the estimated concentrations of PFOS+PFHxS and PFOA in unrestricted use biosolids (Table 7) were compared to the public open space soil screening criteria from the PFAS NEMP (1000 and 10,000 µg/kg, respectively) to calculate RQ_{HH} values.

All RQ_{HH} values for both PFOS+PFHxS and PFOA were considerably lower than 0.2 (Table 14) (maximum RQ_{HH} = 0.026). This indicates the risks posed to human health via this pathway are low.

Table 14 Human health risk quotients (RQ_{HH}) for incidental ingestion of soil/dust following land application of unrestricted use biosolids for land rehabilitation

STP	PFOS+PFHxS		PFOA	
	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{HH}	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{HH}
A	6.9	0.0069	4.0	4.0×10^{-4}
B	1.1	0.0011	0.60	6.0×10^{-5}
C	15	0.015	2.1	2.1×10^{-4}
D	21	0.021	6.0	6.0×10^{-4}
E	6.0	0.0060	2.3	2.3×10^{-4}
F	9.3	0.0093	0.90	9.0×10^{-5}
G	7.1	0.0071	1.5	1.5×10^{-4}
H	3.4	0.0034	< 0.9	$< 9.0 \times 10^{-5}$
I	6.1	0.0061	< 0.9	$< 9.0 \times 10^{-5}$
J	3.3	0.0033	2.1	2.1×10^{-4}
K	1.3	0.0013	< 0.9	$< 9.0 \times 10^{-5}$
L	18	0.018	3.1	3.1×10^{-4}
M	26	0.026	2.9	2.9×10^{-4}
N	12	0.012	2.8	2.8×10^{-4}
O	8.2	0.0082	2.7	2.7×10^{-4}
P	25	0.025	4.7	4.7×10^{-4}
Q	15	0.015	8.0	8.0×10^{-4}

STP	PFOS+PFHxS		PFOA	
	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{HH}	Estimated conc. in unrestricted use biosolids (µg/kg)	RQ_{HH}
R	2.9	0.0029	0.63	6.3×10^{-5}
S	18	0.018	0.83	8.3×10^{-5}
T	5.4	0.0054	2.2	2.2×10^{-4}
Maximum	26	0.026	8.0	8.0×10^{-4}

Grey indicates RQ ≤ 0.2

Drinking water (Pathway 2)

This pathway assessed exposure to someone downgradient from an area where biosolids have been land applied who may use impacted water for drinking water purposes. Similar to ecological Pathway 3 for this scenario, this risk was assessed by applying a DAF of 10 to estimated soil pore water concentrations (see Appendix D for details of soil pore water calculations). The resulting estimated drinking water concentrations were then compared to the drinking water guidelines for these compounds (0.07 and 0.56 µg/L for PFOS+PFHxS and PFOA, respectively) to calculate RQ_{HH} values.

The RQ_{HH} values for this pathway were all less than 1 for both PFOS+PFHxS and PFOA (Table 15 and Table 16). The highest RQ_{HH} for PFOS+PFHxS was 0.2, which provides a MOS from one of 5. For PFOA, the maximum RQ_{HH} was 0.048, which provides a MOS of 20. These results indicate the risks from impacted drinking water near a land rehabilitation area are low.

Despite the above outcome, C&R recommends EPA measures PFAS in groundwater and surface water in proximity to land rehabilitated with biosolids to better understand the potential transport and risks from these compounds. This recommendation is based on the uncertainties in the assumptions used to estimate drinking water concentrations and the large areas of land that may be rehabilitated using biosolids which may result in high loads of PFAS being mobilised from the sites.

Table 15 Estimated drinking water concentrations of PFOS+PFHxS and human health risk quotients (RQ_{HH}) for drinking water exposure following application of unrestricted use biosolids for land rehabilitation

STP	Estimated conc. in unrestricted use biosolids (µg/kg)	Estimated soil pore water conc. (µg/L)	Estimated drinking water conc. (µg/L)	RQ_{HH}
A	6.9	0.010*	0.0010	0.015
B	1.1	0.0018*	0.00018	0.0026
C	15	0.076	0.0076	0.11
D	21	0.031	0.0031	0.044
E	6.0	0.027	0.0027	0.038
F	9.3	0.013	0.0013	0.019
G	7.1	0.0099*	0.00099	0.014
H	3.4	0.012	0.0012	0.017

STP	Estimated conc. in unrestricted use biosolids (µg/kg)	Estimated soil pore water conc. (µg/L)	Estimated drinking water conc. (µg/L)	RQ_{HH}
I	6.1	0.013	0.0013	0.018
J	3.3	0.043	0.0043	0.061
K	1.3	0.0018*	0.00018	0.0025
L	18	0.025	0.0025	0.036
M	26	0.11	0.011	0.15
N	12	0.028	0.0028	0.040
O	8.2	0.019*	0.0019	0.026
P	25	0.14	0.014	0.20
Q	15	0.041	0.0041	0.058
R	2.9	0.0070*	0.00070	0.010
S	18	0.053*	0.0053	0.076
T	5.4	0.048	0.0048	0.059
Maximum	26	0.14	0.014	0.20

Grey indicates RQ ≤ 0.2

* indicates that soil pore water concentrations were based on PFOS only, as Kdes could not be determined for PFHxS as either both biosolids or both leachates were < LOR

Table 16 **Estimated drinking water concentrations of PFOA and human health risk quotients (RQ_{HH}) for drinking water exposure following application of unrestricted use biosolids for land rehabilitation**

STP	Estimated conc. in unrestricted use biosolids (µg/kg)	Estimated soil pore water conc. (µg/L)	Estimated drinking water conc. (µg/L)	RQ_{HH}
A	4.0	0.061	0.0061	0.011
B	0.60	0.010	0.0010	0.0017
C	2.1	0.084	0.0084	0.015
D	6.0	0.11	0.011	0.019
E	2.3	0.061	0.0061	0.011
F	0.90	0.0087	0.00087	0.0016
G	1.5	0.033	0.0033	0.0058
H	< 0.9	nd	nd	nd
I	< 0.9	nd	nd	nd
J	2.1	0.15	0.015	0.027
K	< 0.9	nd	nd	nd
L	3.1	0.060	0.0060	0.011
M	2.9	0.055	0.0055	0.0098
N	2.8	0.049	0.0049	0.0088
O	2.7	0.050	0.0050	0.0089
P	4.7	0.21	0.021	0.037

STP	Estimated conc. in unrestricted use biosolids (µg/kg)	Estimated soil pore water conc. (µg/L)	Estimated drinking water conc. (µg/L)	RQ_{HH}
Q	8.0	0.23	0.023	0.041
R	0.63	0.013	0.0017	0.0023
S	0.83	na	na	na
T	2.2	0.027	0.0027	0.0048
Maximum	8.0	0.23	0.023	0.048

Grey indicates RQ ≤ 0.2

nd: not determined as PFOA concentrations in both biosolids were < LOR and Kdes values were not calculated

na: not available due to error in Kdes calculation resulting in negative Kdes values (likely due to concentrations close to LOR) (details of Kdes calculation provided in Appendix D)

Overview of the risk assessment for Scenario 2

Scenario 2 assessed the ecological and human health risks from PFOS, PFOA and PFHxS following land application of unrestricted use biosolids for rehabilitation. This assessment assumed the biosolids were processed with another waste material (e.g. garden waste compost) at a ratio of 1 part biosolids to 2 parts other to produce unrestricted use biosolids. It was assumed that the other material contained no PFAS. As there are no restrictions on application rates for this classification of biosolids, it was conservatively assumed the estimated concentration in the unrestricted use biosolids was equal to the biosolids-amended soil concentration following land application.

Ecological risks from PFOS and PFOA were assessed for 3 exposure pathways: direct toxicity to terrestrial organisms, toxicity to secondary consumers and toxicity to offsite aquatic organisms. For direct toxicity to terrestrial organisms and toxicity to offsite aquatic organisms, all RQ_{ECO} values were less than 0.2, indicating the risk is low. For the toxicity to secondary consumers pathway, the maximum RQ_{ECO} value for PFOS was 2.6 and for PFOA it was 0.8.

The assessment of human health risks for Scenario 2 considered 2 pathways: incidental ingestion of soil/dust and consumption of drinking water. All RQ_{HH} values were less than or equal to 0.2 indicating risks to human health are low. C&R notes the maximum PFOS+PFHxS RQ_{HH} for the drinking water pathway was 0.2. Considering this, and the uncertainties in estimating PFAS concentrations in drinking water, C&R recommends the EPA measures PFAS in groundwater and surface water in proximity to land rehabilitated with biosolids to confirm concentrations do not pose risk to human health.

Overall, the key exposure pathway for Scenario 2 was for ecological secondary consumers (RQ_{ECO} values up to 2.6 and 0.8 for PFOS and PFOA, respectively). A threshold derived for unrestricted use biosolids should protect this pathway.

Scenario 3 – restricted use biosolids in agriculture

Scenario 3 assessed risks from PFOS, PFOA and PFOS+PFHxS following land application of restricted use biosolids in agriculture. This scenario assumed that biosolids are land applied and incorporated into soil as required by the NSW Biosolids Guidelines for agricultural use. Before the assessment, estimated biosolids-amended soil and soil pore water concentrations were calculated based on the concentrations of these compounds in biosolids and biosolids leachates. This was done for 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.

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 that 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 maximum concentration of the compounds in biosolids from the 20 STPs were used to calculate the maximum estimated soil and pore water concentrations. In cases where an RQ_{ECO} or RQ_{HH} for the maximum concentrations exceeded 1 for any of the land application rates, the risks were calculated for biosolids from each of the 20 STPs. Results from these additional risk calculations are provided in Appendix E.

Estimated soil and pore water concentrations

Estimated soil concentrations for land application of biosolids in agriculture

Soil concentrations of PFOS, PFOA and PFOS+PFHxS were calculated for the 4 land application rates using Equation 5.

$$C_{BAS} = \left[C_B \times \left(\frac{M_B}{M_S + M_B}\right)\right] \times App \qquad \text{Equation 5}$$

where, C_{BAS} is the estimated concentration in the biosolids-amended soil (µg/kg), C_B is the concentration in biosolids (µg/kg), M_B is the mass of biosolids applied to land (dry t), M_S is the mass of soil the biosolids is incorporated into (dry t) and *App* is the number of repeat applications. The calculations assume an application area of 1 ha. Therefore, the mass of biosolids land applied was either 10 or 50 t, the mass of soil the biosolids were incorporated into was 1300 t and the number of repeat applications was either 1 or 7. The soil mass of 1300 t was determined by assuming a soil bulk density of 1.3 g/cm^3 and incorporation depth of 0.1 m. These assumptions were made based on feedback from government and industry stakeholders. These calculations do not account for any loss of contaminants from the soil following land application and assume the initial concentration in the soil is negligible. The calculated PFOS, PFOA and PFOS+PFHxS concentrations in the soil following land application of biosolids based on maximum concentrations in biosolids (from Table 5) are presented in Table 17. Estimated soil concentrations for biosolids from each of the 20 STPs are provided in Appendix F.

Table 17 **Maximum estimated biosolids-amended soil concentrations of PFOS, PFOA and PFOS+PFHxS (µg/kg) for each application rate of restricted use biosolids in agriculture**

Application rate	PFOS	PFOA	PFOS+PFHxS
10 t/ha single application	0.59	0.18	0.60
10 t/ha repeat applications	4.1	1.3	4.2
50 t/ha single application	2.9	0.89	2.9
50 t/ha repeat applications	20	6.2	21

Estimated soil pore water concentrations in biosolids-amended soil

The leachate concentrations reported in Table 6 were used to estimate soil pore water concentrations following land application of biosolids for the 4 land application rates. This was done using solid-solution distribution coefficients (Kdes) for each of the biosolids. Details about the Kdes calculations and the procedure for calculating soil pore water concentrations are provided in Appendix D. The maximum estimated soil pore water concentrations for each of the land application rates are summarised in Table 18. Estimated soil pore water concentration for biosolids from each of the 20 STPs are summarised in Appendix F.

Table 18 **Maximum estimated PFOS, PFOA and PFHxS soil pore water concentrations (µg/L) for each land application rate of restricted use biosolids in agriculture**

Application rate	PFOS	PFOA	PFOS+PFHxS
10 t/ha single application	0.0020	0.0052	0.0033
10 t/ha repeat applications	0.014	0.037	0.023
50 t/ha single application	0.0099	0.025	0.016
50 t/ha repeat applications	0.069	0.18	0.11

Ecological risk assessment

Ecological risks from PFOS and PFOA were assessed for the following pathways:

- **Pathway 1** – BAS → terrestrial organism
- **Pathway 2** – BAS → terrestrial organism → secondary consumer
- **Pathway 3** – BAS → groundwater/surface water runoff → surface water → aquatic organism.

Direct toxicity to terrestrial organisms (Pathway 1)

Direct toxicity risks to terrestrial organisms from use of restricted use biosolids in agriculture were assessed by comparing the maximum soil concentrations of PFOS and PFOA (from Table 17) with soil screening criteria for direct toxicity from the PFAS NEMP (1,000 and 10,000 µg/kg, respectively) to calculate RQ_{ECO} values.

For both compounds, the RQ_{ECO} values were all considerably lower than 0.2 (maximum $RQ_{ECO} = 2 \times 10^{-2}$) (Table 19). This indicates the ecological risk via direct toxicity to terrestrial organisms for both PFOS and PFOA in biosolids used in agriculture is low.

Table 19 **PFOS and PFOA ecological risk quotients (RQ_{ECO}) for direct toxicity to terrestrial organisms following land application of restricted use biosolids in agriculture**

Land application rate	PFOS			PFOA		
	Soil conc. (µg/kg)	Criteria (µg/kg)	RQ_{ECO}	Soil conc. (µg/kg)	Criteria (µg/kg)	RQ_{ECO}
10 t/ha single	0.59	1000	5.9×10^{-4}	0.18	10,000	1.8×10^{-5}
10 t/ha repeat	4.1	1000	4.1×10^{-3}	1.3	10,000	1.3×10^{-4}
50 t/ha single	2.9	1000	2.9×10^{-3}	0.89	10,000	8.9×10^{-5}
50 t/ha repeat	20	1000	2.0×10^{-2}	6.2	10,000	6.2×10^{-4}

Grey indicates RQ ≤ 0.2

Indirect toxicity to secondary consumers (Pathway 2)

To assess Pathway 2, the maximum PFOS and PFOA soil concentration at each land application rate were compared to screening criteria relevant for this pathway to calculate RQ_{ECO} values. For PFOS, the screening criterion of 10 µg/kg from the PFAS NEMP was used. In the absence of an Australian-endorsed corresponding soil screening criterion for PFOA, a value adjusted from the UK EA was used (10 µg/kg, UK EA 2017 and Appendix B).

The RQ_{ECO} values were less than 1 for all application rates, except for 50 t/ha repeat applications for PFOS (Table 20). Due to this, additional calculations were done for biosolids from each of the 20 STPs (Appendix E, Table E1). These showed that biosolids from 7 of the 20 STPs resulted in RQ_{ECO} values greater than 1 for this pathway at the 50 t/ha repeat application rate.

For PFOA, the RQ_{ECO} at the highest application rate was 0.62 (Table 20). Based on the outcomes from this pathway, C&R recommends thresholds for restricted use biosolids are derived for both PFOS and PFOA.

Table 20 **PFOS and PFOA ecological risk quotients (RQ_{ECO}) for secondary consumers following land application of restricted use biosolids in agriculture**

Land application rate	PFOS			PFOA		
	Soil conc. (µg/kg)	Criteria (µg/kg)	RQ_{ECO}	Soil conc. (µg/kg)	Criteria (µg/kg)	RQ_{ECO}
10 t/ha single	0.59	10	0.059	0.18	10	0.018
10 t/ha repeat	4.1	10	**0.41**	1.3	10	0.13
50 t/ha single	2.9	10	**0.29**	0.89	10	0.089
50 t/ha repeat	20	10	**2.0**	6.2	10	**0.62**

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

Toxicity to offsite aquatic organisms (Pathway 3)

To assess this pathway, surface water concentrations were estimated by applying a DAF of 10 to the soil pore water concentrations shown in Table 18. This DAF was used to account for any dilution and attenuation occurring from the land application site to the surface water. The surface water concentrations were then compared to the aquatic screening criteria for direct toxicity for PFOS and PFOA (0.13 and 220 µg/L, respectively) to calculate RQ_{ECO} values.

At all land application rates, the RQ_{ECO} values for PFOS and PFOA were less than 0.2 (maximum $RQ_{ECO} = 5.3 \times 10^{-2}$) (Table 21). This indicates the risk from PFOS and PFOA to offsite aquatic organisms from land-applied biosolids is low.

Table 21 PFOS and PFOA ecological risk quotients (RQ_{ECO}) for aquatic organisms using predicted surface water concentrations

Land application rate	PFOS			PFOA		
	Surface water conc. (µg/L)	Criteria (µg/L)	RQ_{ECO}	Surface water conc. (µg/L)	Criteria (µg/L)	RQ_{ECO}
10 t/ha single	0.00020	0.13	1.5×10^{-3}	0.00052	220	2.4×10^{-6}
10 t/ha repeat	0.0014	0.13	1.1×10^{-2}	0.0037	220	1.7×10^{-5}
50 t/ha single	0.00099	0.13	7.6×10^{-3}	0.0025	220	1.1×10^{-5}
50 t/ha repeat	0.0069	0.13	5.3×10^{-2}	0.018	220	8.2×10^{-5}

Grey indicates RQ ≤ 0.2

Human health risk assessment

Human health risks from PFOS+PFHxS and PFOA for Scenario 3 were assessed in detail due to the range of uses of agricultural land and the large proportion of biosolids used in agriculture in NSW. Overall, 11 exposure pathways were considered which included:

- **Pathway 1** – BAS → incidental ingestion of soil/dust
- **Pathway 2** – BAS → uptake into crops → human consumption of crops
- **Pathway 3** – BAS → groundwater/surface water → irrigation of crops → uptake into crops → human consumption of crops
- **Pathway 4** – BAS → ingestion of soil by grazing beef cattle → human consumption of beef
- **Pathway 5** – BAS → uptake into plants → ingestion of plants by beef cattle → human consumption of beef
- **Pathway 6** – BAS → groundwater/surface water → ingestion of water by beef cattle → human consumption of beef
- **Pathway 7** – BAS → ingestion of soil by grazing dairy cows → human consumption of milk
- **Pathway 8** – BAS → uptake into plants → ingestion of plants by dairy cows → human consumption of milk
- **Pathway 9** – BAS → groundwater/surface water → ingestion of water by dairy cows → human consumption of milk
- **Pathway 10** – BAS → groundwater/surface water → human incidental ingestion of water used for irrigation

- **Pathway 11** – BAS → groundwater/surface water → human ingestion of water for drinking water purposes.

The risk calculations for each of the pathways are explained in detail in Appendix C.

The human receptors considered for this scenario were residents consuming home produce. Therefore, this assessment should identify risks to the people with the highest exposure (i.e. the worst-case scenario). The results from this risk assessment are not relevant for the general public, as risks from produce supplied to the market were not assessed, noting dilution of produce is likely to occur in the commercial markets reducing the average exposure to the general public. Chickens and chicken eggs were not considered in Scenario 3 because the NSW Biosolids Guidelines do not allow use of biosolids for poultry farming.

All risk calculations presented in the following sections were done for exposure to children (aged 0–5 years) as this is the risk-driving age group due primarily to their lower body weight. The exceptions to this were Pathway 1 (incidental ingestion of soil/dust) and Pathway 10 (incidental ingestion of irrigation water), where only adult exposure was assessed as it was assumed that in an agricultural scenario, a child is unlikely to be directly exposed via these pathways on a regular basis.

In some cases, it may be possible that people (or livestock) are exposed to PFAS via more than one of the pathways listed above. If combinations of pathways are relevant, for example, a landowner is land applying biosolids for grazing cattle and using potentially impacted groundwater, the risks from each pathway can be summed together to determine the overall risk. This approach was used in the following sections for beef cattle/dairy cows grazing on biosolids-amended soil who will take up PFAS through ingestion of soil and plants (i.e. combined Pathways 4 and 5 and combined Pathways 7 and 8).

Incidental ingestion of soil/dust (Pathway 1)

This pathway assessed the incidental ingestion of soil/dust following land application of biosolids. As outlined above, this pathway was assessed for adults only. Daily intakes of PFOS+PFHxS and PFOA were estimated based on the estimated soil concentrations and a range of assumptions outlined in Appendix C. The daily intakes were then compared to background-adjusted TDIs to calculate RQ_{HH} values. For all land application rates, all RQ_{HH} values were considerably lower than 0.2 for this pathway (maximum $RQ_{HH} = 7.7 \times 10^{-4}$) (Table 22). This indicates the risk posed to people via incidental ingestion of soil/dust from biosolids-amended soil is low.

Table 22 Predicted daily intakes and human health risk quotients (RQ_{HH}) for PFOS+PFHxS and PFOA for incidental ingestion of soil/dust

Land application rate	PFOS+PFHxS		PFOA	
	Intake (µg/kg/d)	RQ_{HH}	Intake (µg/kg/d)	RQ_{HH}
10 t/ha single	4.3×10^{-7}	2.3×10^{-5}	1.3×10^{-7}	8.2×10^{-7}
10 t/ha repeat	3.0×10^{-6}	1.6×10^{-4}	9.2×10^{-7}	5.8×10^{-6}
50 t/ha single	2.1×10^{-6}	1.1×10^{-4}	6.3×10^{-7}	4.0×10^{-6}
50 t/ha repeat	1.5×10^{-5}	7.7×10^{-4}	4.4×10^{-6}	2.8×10^{-5}

Grey indicates RQ ≤ 0.2

Consumption of crops from biosolids-amended soil (Pathway 2)

The potential risks from consumption of home-produced crops grown in biosolids-amended soil were assessed by initially estimating concentrations of PFOS+PFHxS and PFOA in plants at the 4 biosolids application rates. Based on these concentrations, predicted daily intakes were calculated for children corresponding to each application rate (equations and assumptions provided in Appendix C). Calculations were done separately for fruits and vegetables due to variabilities in soil to plant transfer factors (TFs) and ingestion rates for these 2 plant groups. These data were then used to calculate RQ_{HH} values.

For the different land application rates, the estimated PFOS+PFHxS concentrations ranged from 0.00042 to 0.014 µg/kg (wet weight) in fruit and 0.18 to 6.1 µg/kg (wet weight) in vegetables (Table 23). In contrast, the estimated concentrations of PFOA ranged from 0.0055 to 0.19 and 0.018 to 0.62 µg/kg for fruit and vegetables, respectively. The lower concentrations in fruit are consistent with the lower transfer factors from soil into edible parts of fruit trees compared to vegetables.

At all application rates the RQ_{HH} values for both PFOS+PFHxS and PFOA were less than 1. However, for PFOS+PFHxS at the highest land application rate (50 t/ha repeat applications), there was a very low MOS of 1.2 (RQ_{HH} = 0.82). Based on this, C&R recommends a threshold for PFOS+PFHxS in restricted use biosolids is derived. In contrast, all PFOA RQ_{HH} values were considerably lower than 0.2 (maximum $RQ_{HH} = 1 \times 10^{-2}$), indicating the risk via this pathway for PFOA is low.

Table 23 PFOS+PFHxS and PFOA estimated plant concentrations (wet weights), predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of crops grown in biosolids-amended soil

Plant type	Application rate	PFOS+PFHxS			PFOA		
		Estimated plant conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}	Estimated plant conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}
Fruit	10 t/ha	0.00042	8.5×10^{-7}	4.5×10^{-5}	0.0055	1.1×10^{-5}	6.9×10^{-5}
	10 t/ha repeat	0.0030	6.0×10^{-6}	3.1×10^{-4}	0.039	7.7×10^{-5}	4.8×10^{-4}
	50 t/ha	0.0020	4.1×10^{-6}	2.2×10^{-4}	0.027	5.4×10^{-5}	3.4×10^{-4}
	50 t/ha repeat	0.014	2.9×10^{-5}	1.5×10^{-3}	0.19	3.8×10^{-4}	2.4×10^{-3}
Vegetable	10 t/ha	0.18	4.6×10^{-4}	0.041	0.018	4.6×10^{-5}	2.9×10^{-4}
	10 t/ha repeat	1.3	3.2×10^{-3}	0.17	0.13	3.3×10^{-4}	2.0×10^{-3}
	50 t/ha	0.88	2.2×10^{-3}	0.12	0.089	2.3×10^{-4}	1.4×10^{-3}
	50 t/ha repeat	6.1	1.6×10^{-2}	**0.82**	0.62	1.6×10^{-3}	1.0×10^{-2}

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

Consumption of crops irrigated with impacted water (Pathway 3)

Consumption of crops irrigated with groundwater or surface water impacted by biosolids-amended soil was assessed by initially estimating the concentration of PFOS+PFHxS and PFOA in irrigation water. To do this, a DAF of 10 was applied to the estimated soil pore water concentrations in Table 18 to account for some dilution and attenuation. Following this, plant concentrations were estimated using water-to-plant transfer factors. These were then used to calculate predicted daily intakes of PFOS+PFHxS and PFOA for children and RQ_{HH} values (see Appendix C for details of equations and assumptions).

The estimated concentrations of PFOS+PFHxS and PFOA in plants for this pathway (Table 24) were all considerably lower than the estimated concentrations in plants grown in biosolids-amended soil (Pathway 2, Table 23). The highest RQ_{HH} value for this pathway was 1.6×10^{-4} (Table 24), which provides a MOS from one of 6300. This indicates the risk from PFOS+PFHxS and PFOA to people consuming fruit and vegetables irrigated with water impacted by biosolids-amended soil is low.

Table 24 PFOS+PFHxS and PFOA estimated plant concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of crops irrigated with impacted water

Plant type	Application rate	PFOS+PFHxS			PFOA		
		Estimated plant conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}	Estimated plant conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}
Fruit	10 t/ha	3.8×10^{-5}	7.6×10^{-8}	4.0×10^{-6}	1.6×10^{-4}	3.1×10^{-7}	2.0×10^{-6}
	10 t/ha repeat	2.7×10^{-4}	5.3×10^{-7}	2.8×10^{-5}	1.1×10^{-3}	2.2×10^{-6}	1.4×10^{-5}
	50 t/ha	1.8×10^{-4}	3.7×10^{-7}	1.9×10^{-5}	7.5×10^{-4}	1.5×10^{-6}	9.4×10^{-6}
	50 t/ha repeat	1.3×10^{-3}	2.6×10^{-6}	1.3×10^{-4}	5.4×10^{-3}	1.1×10^{-5}	6.8×10^{-5}
Vegetable	10 t/ha	3.6×10^{-5}	9.2×10^{-8}	4.8×10^{-6}	1.5×10^{-4}	4.0×10^{-7}	2.5×10^{-6}
	10 t/ha repeat	2.5×10^{-4}	6.4×10^{-7}	3.4×10^{-5}	1.1×10^{-3}	2.8×10^{-6}	1.8×10^{-5}
	50 t/ha	1.8×10^{-4}	4.5×10^{-7}	2.4×10^{-5}	7.5×10^{-4}	1.9×10^{-6}	1.2×10^{-5}
	50 t/ha repeat	1.2×10^{-3}	3.1×10^{-6}	1.6×10^{-4}	5.4×10^{-3}	1.4×10^{-5}	8.6×10^{-5}

Grey indicates RQ ≤ 0.2

Consumption of beef from cattle grazing on biosolids-amended soil (Pathways 4 and 5)

To assess the risks from beef cattle grazing on biosolids-amended soil, Pathways 4 and 5 were combined because grazing livestock will always consume both soil and plants. To determine the risk from these pathways, beef cattle intake rates of PFOS+PFHxS and PFOA from soil and plants were estimated, followed by calculations of serum and beef concentrations. The beef concentrations were then used to calculate PFOS+PFHxS and PFOA predicted daily intakes for children consuming home-produce and corresponding

RQ_{HH} values (see Appendix C for equations and assumptions). This pathway does not consider sale of meat to market.

The estimated beef concentrations of PFOS+PFHxS for the different land application rates ranged from 1.8 to 60 µg/kg (Table 25). The corresponding RQ_{HH} values ranged from 0.26 to 8.9, with 50 t/ha single application and 10 and 50 t/ha repeat applications resulting in values above 1 (Table 25). Based on this, C&R recommends that a threshold for PFOS+PFHxS in restricted use biosolids should be derived.

Due to the elevated RQ_{HH} values for PFOS+PFHxS at the maximum soil concentrations for 50 t/ha single application, and 10 and 50 t/ha repeat applications, additional risk calculations were done for biosolids from all 20 STPs sampled (Appendix E, Table E2). These showed that biosolids sampled from 3 and 7 of the 20 STPs resulted in RQ_{HH} values above one at 50 t/ha single and 10 t/ha repeat applications, respectively. The exceedances were much higher for 50 t/ha repeat applications with biosolids from 17 of the 20 STPs resulting in RQ_{HH} values above 1.

The PFOA RQ_{HH} values for all land application rates were considerably lower than 0.2 (maximum $RQ_{HH} = 6.8 \times 10^{-3}$) (Table 25). This indicates the risk to human health from exposure to PFOA via consumption of beef from cattle grazing on biosolids-amended soil is low.

Table 25 **PFOS+PFHxS and PFOA estimated beef concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of beef from cattle grazing on biosolids-amended soil**

Land application rate	PFOS+PFHxS			PFOA		
	Estimated beef conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}	Estimated beef conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	1.8	5.0×10^{-3}	0.26	0.011	3.2×10^{-5}	2.0×10^{-4}
10 t/ha repeat	12	3.5×10^{-2}	1.8	0.080	2.3×10^{-4}	1.4×10^{-3}
50 t/ha	8.6	2.4×10^{-2}	1.3	0.055	1.6×10^{-4}	9.8×10^{-4}
50 t/ha repeat	60	1.7×10^{-1}	8.9	0.39	1.1×10^{-3}	6.8×10^{-3}

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

Consumption of beef from cattle ingesting impacted fodder (Pathway 5)

Assessing Pathway 5 alone gives an indication of the potential risks when fodder crops are grown on biosolids-amended soil and consumed by beef cattle in other areas. The process to assess this pathway was similar to that for the combined grazing scenario (Pathways 4 and 5) but only considered exposure via plant uptake (Pathway 5).

The estimated concentrations of PFOS+PFHxS in beef for this pathway ranged from 1.7 to 58 µg/kg for the 4 land application rates considered (Table 26). This is only marginally lower than the concentrations estimated for grazing beef cattle, indicating the majority of PFOS+PFHxS exposure from grazing is via the plant uptake pathway. This is also reflected in the RQ_{HH} values which ranged from 0.26 to 8.7 for Pathway 5 alone (Table 26). This demonstrates the plant pathway contributes to 95% of the exposure when the pathways are combined. Based on this, C&R recommends a PFOS+PFHxS threshold in restricted use biosolids should be derived.

Due to the exceedances for PFOS+PFHxS for the fodder consumption pathway at 50 t/ha single application, 10 and 50 t/ha repeat applications, additional risk calculations were conducted on biosolids from the 20 STPs sampled (Appendix E, Table E3). These showed that biosolids sampled from 2 and 6 of the 20 STPs had concentrations of PFOS+PFHxS that resulted in RQ_{HH} values above one at 50 t/ha single application and 10 t/ha repeat applications, respectively. At 50 t/ha repeat applications, this increased to 17 of the 20 STPs.

For PFOA, the beef concentrations and RQ_{HH} values were all considerably lower than those for PFOS+PFHxS (Table 26). All RQ_{HH} values for PFOA were considerably lower than 0.2 (maximum $RQ_{HH} = 6.8 \times 10^{-3}$). This indicates the risks to human health from PFOA when beef cattle are consuming fodder grown on biosolids-amended soil are low.

Table 26 **PFOS+PFHxS and PFOA estimated beef concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of beef from cattle ingesting fodder**

Land application rate	PFOS+PFHxS			PFOA		
	Estimated beef conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}	Estimated beef conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	1.7	4.9×10^{-3}	0.26	0.011	3.2×10^{-5}	2.0×10^{-4}
10 t/ha repeat	12	3.4×10^{-2}	1.8	0.079	2.2×10^{-4}	1.4×10^{-3}
50 t/ha	8.3	2.4×10^{-2}	1.2	0.055	1.6×10^{-4}	9.7×10^{-4}
50 t/ha repeat	58	1.7×10^{-1}	8.7	0.38	1.1×10^{-3}	6.8×10^{-3}

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

Consumption of beef from cattle ingesting impacted water (Pathway 6)

This pathway assessed the risks from using impacted groundwater or surface water for beef cattle drinking water. To do this, PFOS+PFHxS and PFOA concentrations in beef cattle drinking water were estimated by applying a DAF of 10 to the soil pore water concentrations in Table 18. Beef cattle daily intakes of PFOS+PFHxS and PFOA were then estimated, followed by calculations of serum and beef concentrations. The beef concentrations were used to calculate the PFOS+PFHxS and PFOA daily intakes for children consuming beef and corresponding RQ_{HH} values (equations and assumptions are provided in Appendix C).

For both PFOS+PFHxS and PFOA, the estimated beef concentrations for this pathway (Table 27) were considerably lower than those estimated for Pathways 4 and 5 (Table 25). As a result, the RQ_{HH} values were also considerably lower. For PFOS+PFHxS the maximum RQ_{HH} value was 0.018 at the highest biosolids application rate (50 t/ha repeat applications) (Table 27), indicating the risk from PFOS+PFHxS for this pathway is low. For PFOA, the highest RQ_{HH} value was 2.4×10^{-5}, indicating the risk posed to people from PFOA via this pathway is also low.

Table 27 **PFOS+PFHxS and PFOA estimated beef concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of beef from cattle ingesting impacted water**

Land application rate	PFOS+PFHxS			PFOA		
	Estimated beef conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}	Estimated beef conc. (µg/kg)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	0.0036	1.0×10^{-5}	0.00053	4.0×10^{-5}	1.1×10^{-7}	7.2×10^{-7}
10 t/ha repeat	0.025	7.1×10^{-5}	0.0037	2.8×10^{-4}	8.0×10^{-7}	5.0×10^{-6}
50 t/ha	0.017	4.9×10^{-5}	0.0026	2.0×10^{-4}	5.6×10^{-7}	3.5×10^{-6}
50 t/ha repeat	0.12	3.5×10^{-4}	0.018	1.4×10^{-3}	3.9×10^{-6}	2.4×10^{-5}

Grey indicates RQ ≤ 0.2

Consumption of milk from dairy cows grazing on biosolids-amended soil (Pathways 7 and 8)

To assess the risk from dairy cows grazing on biosolids-amended soil, Pathways 7 and 8 were combined considering grazing dairy cows will consume both soil and plants. To determine the risk from these pathways, dairy cow intake rates of PFOS+PFHxS and PFOA from soil and plants were estimated, followed by calculations of serum and milk concentrations. The milk concentrations were then used to calculate PFOS+PFHxS and PFOA daily intakes for children consuming home produce and corresponding RQ_{HH} values (see Appendix C for equations and assumptions). This pathway does not consider sale of milk to market.

The estimated milk concentrations of PFOS+PFHxS for the different land application rates ranged from 0.14 to 4.8 µg/L (Table 28). The corresponding RQ_{HH} values ranged from 0.52 to 18, with values from all land application rates, except 10 t/ha single application, exceeding 1 (Table 28). In addition, for the 10 t/ha single application rate, the MOS from one was very low at 1.9 (RQ_{HH} = 0.52). Based on this, C&R recommends a threshold for PFOS+PFHxS should be derived.

Due to the elevated RQ_{HH} values for PFOS+PFHxS at the maximum soil concentrations for 50 t/ha single application and 10 and 50 t/ha repeat applications, additional risk calculations were done for biosolids from all 20 STPs samples (Appendix E, Table E4). These showed that biosolids sampled from 8, 10 and 18 of the 20 STPs, respectively, had concentrations of PFOS+PFHxS that resulted in RQ_{HH} values above 1.

The estimated concentrations of PFOA in milk were lower than those for PFOS+PFHxS and ranged from 0.030 to 1.0 µg/L for the different land application rates (Table 28). The corresponding RQ_{HH} values were all less than 1 and ranged from 0.013 to 0.45. At the highest land application scenario (50 t/ha repeat applications) the RQ was above 0.2 (RQ_{HH} = 0.45). Therefore, C&R recommends a threshold for PFOA in restricted use biosolids is derived.

Table 28 **PFOS+PFHxS and PFOA estimated milk concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of milk from dairy cows grazing on biosolids-amended soil**

Land application rate	PFOS+PFHxS			PFOA		
	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	0.14	0.0099	0.52	0.030	0.0021	0.013
10 t/ha repeat	0.98	0.069	3.7	0.21	0.015	0.093
50 t/ha	0.68	0.048	2.5	0.14	0.010	0.064
50 t/ha repeat	4.8	0.34	18	1.0	0.072	0.45

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

Consumption of milk from dairy cows ingesting impacted fodder (Pathway 8)

Assessing Pathway 8 alone gives an indication of the potential risks when fodder crops are grown on biosolids-amended soil and consumed by dairy cows in other areas. The process to assess this pathway was similar to that for the combined grazing scenario (Pathways 7 and 8) but only considered exposure via plant uptake.

The estimated concentration of PFOS+PFHxS in milk for this pathway ranged from 0.14 to 4.6 µg/L (Table 29). For PFOA, the estimated concentrations were lower and ranged from 0.030 to 1.0 µg/L (Table 29). Similar to the beef consumption pathways these concentrations are only slightly lower than the estimated milk concentrations when Pathways 7 and 8 were combined. This indicates that for the combined pathway, the majority of PFOS+PFHxS and PFOA in the milk is coming via consumption of plants.

Table 29 **PFOS+PFHxS and PFOA estimated milk concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of milk from dairy cows ingesting impacted fodder**

Land application rate	PFOS+PFHxS			PFOA		
	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	0.14	9.7×10^{-3}	0.51	0.030	2.1×10^{-3}	0.013
10 t/ha repeat	0.96	6.8×10^{-2}	3.6	0.21	1.5×10^{-2}	0.092
50 t/ha	0.66	4.7×10^{-2}	2.5	0.14	1.0×10^{-2}	0.064
50 t/ha repeat	4.6	3.3×10^{-1}	17	1.0	7.1×10^{-2}	0.45

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

The RQ_{HH} values for this pathway were also very similar to the combined grazing pathway. For PFOS+PFHxS they ranged from 0.51 to 17 and for PFOA they ranged from 0.013 to 0.45. For PFOS+PFHxS, land application rates that showed RQ_{HH} values above 1 at the maximum concentrations were again used for additional risk calculations considering biosolids from all STPs sampled (Appendix E, Table E5). Due to the similarities in milk concentrations and RQ_{HH} values between this pathway and the combined dairy cow grazing pathway, either the same or similar proportions of STPs had biosolids that resulted in RQ_{HH} values above 1. Similar to the outcomes from the assessment of beef, based on this result, C&R recommends thresholds for PFOS+PFHxS and PFOA in restricted use biosolids are derived.

Consumption of milk from dairy cows drinking impacted water (Pathway 9)

This pathway assessed the risks from using impacted groundwater or surface water for dairy cow drinking water. To do this, PFOS+PFHxS and PFOA concentrations in dairy cow drinking water were estimated by applying a DAF of 10 to the soil pore water concentrations in Table 18. Dairy cow daily intakes of PFOS+PFHxS and PFOA were then estimated, followed by calculations of serum and milk concentrations. The milk concentrations were used to calculate the PFOS+PFHxS and PFOA daily intakes for children consuming milk and corresponding RQ_{HH} values (equations and assumptions are provided in Appendix C).

For both PFOS+PFHxS and PFOA, the estimated milk concentrations for this pathway (Table 30) were considerably lower than those estimated for Pathways 7 and 8 (Table 28 and Table 29). As a result, the RQ_{HH} values were also considerably lower (Table 30). For PFOS+PFHxS the maximum RQ_{HH} value was 0.036 at the highest biosolids application rate (50 t/ha repeat applications). For PFOA, all RQ_{HH} values were orders of magnitude below 1. These results indicate the risk posed to human health via this pathway is low.

Table 30 PFOS+PFHxS and PFOA estimated milk concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of milk from dairy cows ingesting impacted water

Land application rate	PFOS+PFHxS			PFOA		
	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	2.8×10^{-4}	2.0×10^{-5}	0.0011	1.1×10^{-4}	7.5×10^{-6}	4.7×10^{-5}
10 t/ha repeat	2.0×10^{-3}	1.4×10^{-4}	0.0074	7.4×10^{-4}	5.3×10^{-5}	3.3×10^{-4}
50 t/ha	1.4×10^{-3}	9.8×10^{-5}	0.0051	5.1×10^{-4}	3.6×10^{-5}	2.3×10^{-4}
50 t/ha repeat	9.7×10^{-3}	6.8×10^{-4}	0.036	3.6×10^{-3}	2.5×10^{-4}	1.6×10^{-3}

Grey indicates RQ ≤ 0.2

Incidental ingestion of irrigation water (Pathway 10)

This pathway assessed the risks from incidental ingestion of impacted irrigation water. To do this, irrigation water concentrations of PFOS+PFHxS and PFOA were estimated by applying a DAF of 10 to the soil pore water concentrations in Table 18. The irrigation water concentrations were then used to calculate daily intakes of PFOS+PFHxS and PFOA for adults only and corresponding RQ_{HH} values (children were not expected to be regularly exposed to irrigation water) (equations and assumptions are provided in Appendix C).

For both PFOS+PFHxS and PFOA, the RQ_{HH} values for this pathway were considerably lower than 0.2 (Table 31). The highest RQ_{HH} of 7.9×10^{-5} was for PFOS+PFHxS for the 50 t/ha repeat applications scenario, which provides a MOS of 12,500. This indicates the risks to human health via incidental ingestion of impacted irrigation water are low.

Table 31 **PFOS+PFHxS and PFOA predicted irrigation water concentrations, daily intakes and human health risk quotients (RQ_{HH}) for incidental ingestion of irrigation water**

Land application rate	PFOS+PFHxS			PFOA		
	Predicted irrigation water conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}	Predicted irrigation water conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}
10 t/ha	0.00033	4.7×10^{-9}	2.3×10^{-6}	0.00052	7.5×10^{-9}	4.7×10^{-7}
10 t/ha repeat	0.0023	3.3×10^{-8}	1.6×10^{-5}	0.0037	5.2×10^{-8}	3.3×10^{-6}
50 t/ha	0.0016	2.3×10^{-8}	1.1×10^{-5}	0.0025	3.6×10^{-8}	2.3×10^{-6}
50 t/ha repeat	0.011	1.6×10^{-7}	7.9×10^{-5}	0.018	2.5×10^{-7}	1.6×10^{-5}

Grey indicates RQ ≤ 0.2

Drinking water consumption (Pathway 11)

This pathway assessed the risks to people exposed to PFOS+PFHxS and PFOA via impacted drinking water, for example, if there is a drinking water bore that has become contaminated from an area where biosolids have been land applied in agriculture. To do this, drinking water concentrations of PFOS+PFHxS and PFOA were estimated by applying a DAF of 10 to the soil pore water concentrations in Table 18. These concentrations were then compared to the drinking water guidelines for these compounds from the PFAS NEMP (0.07 and 0.56 µg/L, respectively).

The estimated concentrations of PFOS+PFHxS and PFOA in impacted drinking water ranged up to 0.01 and 0.018 µg/L, respectively across the land application rates (Table 32). The RQ_{HH} values in all cases were below 0.2. The highest RQ_{HH} for PFOS+PFHxS was 0.16 and for PFOA was 0.032. These results suggest the risk via a drinking water pathway is low. Despite this, C&R recommends the EPA measures PFAS in groundwater and surface water in areas close to agricultural land that has received biosolids applications. This is because there is uncertainty in the DAF of 10 used to assess this pathway, the MOS for PFOS+PFHxS is only 6.3, and the importance of protecting drinking water. As PFAS, particularly the long chain PFAAs, are highly mobile in water and do not degrade under environmental conditions, they can travel long distances in ground and surface water. Information gained from such data will help better understand potential risks to drinking water and can inform management requirements for biosolids application.

Table 32 **PFOS+PFHxS and PFOA predicted water concentrations, daily intakes and human health risk quotients (RQ_{HH}) for consumption of impacted drinking water**

Land application rate	PFOS+PFHxS		PFOA	
	Predicted drinking water conc. (µg/L)	RQ_{HH}	Predicted drinking water conc. (µg/L)	RQ_{HH}
10 t/ha	0.00033	0.0047	0.00052	0.00094
10 t/ha repeat	0.0023	0.033	0.0037	0.0066
50 t/ha	0.0016	0.023	0.0025	0.0045
50 t/ha repeat	0.010	0.16	0.018	0.032

Grey indicates RQ ≤ 0.2

Overview of risk assessment for Scenario 3

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 11 human health exposure pathways (including incidental ingestion of soil/dust, home consumption of crops (fruit and vegetables), beef and milk). Each pathway was assessed at application rates of 10 and 50 t/ha, and 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 applications was considered as a realistic maximum biosolids application rate for agriculture. It was assumed that if no potential risks were identified at this application rate, the risks via that pathway were low.

The ecological risks from direct toxicity to terrestrial organisms and offsite aquatic organisms were low for PFOS and PFOA for all application rates assessed. For indirect exposure to secondary consumers, the maximum RQ_{ECO} value for PFOS was 2.0, and for PFOA the maximum was 0.62.

Overall, the human health pathways posed a higher potential risk for PFOS+PFHxS compared to the ecological pathway. The beef and milk grazing and fodder pathways (Pathways 4 and 5, Pathway 5, Pathways 7 and 8 and Pathway 8) for PFOS+PFHxS resulted in the highest RQ_{HH} values ranging up to 18. For PFOA, there were no human health pathways that resulted in RQ_{HH} values above 1. However, for the milk grazing and fodder pathways, the maximum RQ_{HH} was 0.45.

Based on the results for Scenario 3, C&R recommends PFOS+PFHxS and PFOA thresholds for restricted use biosolids are derived. For PFOS+PFHxS the key exposure pathway for threshold derivation is milk consumption from dairy cows grazing on biosolids-amended soil (RQ_{HH} values up to 18). Whereas, for PFOA, the key exposure pathway for threshold derivation is ecological secondary consumers (RQ_{ECO} values up to 0.62).

In addition to the above recommendations for PFAS thresholds in biosolids, C&R also recommends the EPA measures PFAS in groundwater and surface water in the proximity of biosolids land applied in agriculture. This is due to uncertainties in predicting PFAS concentrations in water bodies from soils/biosolids. Information gained from measuring PFAS in the environment will provide more certainty in understanding the potential risks to drinking water and aquatic environments, and thereby inform management requirements for biosolids application.

Scenario 4 – unrestricted use biosolids in agriculture

For Scenario 4, only risks from the highest human health risk 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). The highest human health risk pathway for both PFOS+PFHxS and PFOA was consumption of milk from grazing dairy cows (combined Pathways 7 and 8). This additional scenario 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.

Similar to the other unrestricted use biosolids scenarios (Scenarios 1 and 2), the estimated concentrations in unrestricted use biosolids (Table 7) were assumed to be the soil concentrations. The process for estimating the milk concentrations and daily intakes of the PFAS was the same as that outlined in the previous section and in Appendix C. Similar to other pathways, these are only presented for children as they are the highest risk age group, but risks to adults can be provided if required.

The estimated milk concentrations ranged from 0.26 to 6.0 µg/L for PFOS+PFHxS, and < 0.15 to 1.3 µg/L for PFOA (Table 33). For PFOS+PFHxS, biosolids from 19 of the 20 STPs resulted in RQ_{HH} values above 1, with a maximum of 23. This maximum RQ_{HH} value is higher than the other unrestricted use values from Scenarios 1 and 2, indicating this is the most sensitive unrestricted use pathway for PFOS+PFHxS which should be used for threshold derivation.

All RQ_{HH} values for PFOA were below 1, with a maximum of 0.58 (Table 33). This value is lower than the maximum that was identified for Scenario 2 of 0.8 for ecological secondary consumers (Table 12). Therefore, this is not the most sensitive pathway for threshold derivation.

Table 33 **PFOS+PFHxS and PFOA estimated milk concentrations, predicted daily intakes and human health risk quotients (RQ_{HH}) for consumption of milk from dairy cows grazing on biosolids-amended soil using unrestricted use biosolids**

STP	PFOS+PFHxS			PFOA		
	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}
A	1.6	0.11	**6.0**	0.65	0.046	**0.29**
B	0.26	0.018	**0.95**	0.10	0.0069	0.043
C	3.5	0.25	**13**	0.34	0.024	0.15
D	4.9	0.35	**18**	0.98	0.069	**0.44**
E	1.4	0.099	**5.2**	0.37	0.027	0.17
F	2.2	0.15	**8.1**	0.15	0.010	0.065
G	1.7	0.12	**6.2**	0.24	0.017	0.11
H	0.79	0.056	**2.9**	< 0.15	< 0.010	< 0.065
I	1.4	0.10	**5.3**	< 0.15	< 0.010	< 0.065
J	0.77	0.054	**2.9**	0.34	0.024	0.15
K	0.30	0.021	**1.1**	< 0.15	< 0.010	< 0.065

STP	PFOS+PFHxS			PFOA		
	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}	Estimated milk conc. (µg/L)	Intake (µg/kg/d)	RQ_{HH}
L	4.2	0.30	**16**	0.50	0.036	**0.23**
M	6.0	0.43	**23**	0.47	0.033	**0.21**
N	2.8	0.20	**10**	0.46	0.032	**0.20**
O	1.9	0.14	**7.1**	0.44	0.031	**0.20**
P	5.8	0.41	**22**	0.77	0.054	**0.34**
Q	3.5	0.25	**13**	1.3	0.092	**0.58**
R	0.67	0.048	**2.5**	0.10	0.0073	0.046
S	4.2	0.30	**16**	0.14	0.0096	0.060
T	1.3	0.089	**4.7**	0.36	0.025	0.16
Maximum	6.0	0.43	**23**	1.3	0.092	**0.58**

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

Key conclusions, recommendations and uncertainties

Key conclusions and recommendations

The HHERA presented in this report considered 4 different scenarios for biosolids usage:

- Scenario 1 – unrestricted use biosolids in residential gardens
- Scenario 2 – unrestricted use biosolids for land rehabilitation[12]
- Scenario 3 – restricted use biosolids in agriculture
- Scenario 4 – unrestricted use biosolids in agriculture

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

Scenario 1 – unrestricted use biosolids in residential gardens

Scenario 1 assessed the risks to ecology and human health when unrestricted use biosolids are used in residential gardens. 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 waste material to produce unrestricted use biosolids. It was assumed the other material contained no PFAS. As there are no restrictions on application rates for this classification of biosolids, the assessment conservatively assumed 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. For both PFOS and PFOA, all RQs were less than 0.2, indicating the risk is low.

Human health risks from PFOS+PFHxS and PFOA were assessed for 3 exposure pathways: incidental ingestion of soil/dust, consumption of homegrown fruit/vegetables and the consumption of home chicken eggs. For PFOA, all RQ_{HH} values were less than 0.2 indicating the risk is low. For PFOS+PFHxS, the RQ_{HH} values ranged up to 2.9. Based on this, C&R recommends a threshold for PFOS+PFHxS for unrestricted use biosolids is derived. Overall, the key exposure pathway for this scenario was incidental ingestion of soil/dust and consumption of homegrown fruit/vegetables (RQ_{HH} values up to 2.9) (combined Pathways 1 and 2). The sensitivity of this pathway compared to the egg consumption pathway was driven partly by the conservative assumptions used in the derivation of the PFAS NEMP screening criteria (i.e. the soil screening criteria in the PFAS NEMP are based on 20% of the TDI, allowing for 80% of exposure via other pathways).

Scenario 2 – unrestricted use biosolids for land rehabilitation

Scenario 2 assessed the ecological and human health risks from PFOS, PFOA and PFHxS following land application of unrestricted use biosolids for rehabilitation. This assessment assumed the biosolids were processed with another waste material (e.g. garden waste compost) at a ratio of 1 part biosolids to 2 parts other to produce

[12] Scenario 2 assumes land will not be used for agriculture in the future.

unrestricted use biosolids. It was assumed the other material contained no PFAS. As there are no restrictions on application rates for this classification of biosolids, it was conservatively assumed the estimated concentration in the unrestricted use biosolids was equal to the biosolids-amended soil concentration following land application.

Ecological risks from PFOS and PFOA were assessed for 3 exposure pathways: direct toxicity to terrestrial organisms, toxicity to secondary consumers and toxicity to offsite aquatic organisms. For direct toxicity to terrestrial organisms and toxicity to offsite aquatic organisms, all RQ_{ECO} values were less than 0.2, indicating the risk is low. For the toxicity to secondary consumers pathway, the maximum RQ_{ECO} value for PFOS was 2.6 and for PFOA it was 0.8.

The assessment of human health risks for Scenario 2 considered 2 pathways: incidental ingestion of soil/dust and consumption of drinking water. All RQ_{HH} values were less than 0.2 indicating risks to human health are low. C&R notes the maximum PFOS+PFHxS RQ_{HH} for the drinking water pathway was 0.2. Considering this, and the uncertainties in estimating PFAS concentrations in drinking water, C&R recommends the EPA measures PFAS in groundwater and surface water in proximity to land rehabilitated with biosolids to confirm concentrations do not pose risk to human health.

Overall, the key exposure pathway for Scenario 2 was for ecological secondary consumers (RQ_{ECO} values up to 2.6 and 0.8 for PFOS and PFOA, respectively). Thresholds derived for unrestricted use biosolids should protect this pathway.

Scenario 3 – restricted use biosolids in agriculture

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 11 human health exposure pathways (including incidental ingestion of soil/dust, home consumption of crops (fruit and vegetables), beef and milk). Each pathway was assessed at application rates of 10 and 50 t/ha, and 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 applications was considered as a realistic maximum biosolids application rate for agriculture. It was assumed that if no potential risks were identified at this application rate, the risks via that pathway were low.

The ecological risks from direct toxicity to terrestrial organisms and offsite aquatic organisms were low for PFOS and PFOA for all application rates assessed. For indirect exposure to secondary consumers, the maximum RQ_{ECO} value for PFOS was 2.0, and for PFOA the maximum was 0.62.

Overall, the human health pathways posed a higher potential risk for PFOS+PFHxS compared to the ecological pathway. The beef and milk grazing and fodder pathways (Pathways 4 and 5, Pathway 5, Pathways 7 and 8 and Pathway 8) for PFOS+PFHxS resulted in the highest RQ_{HH} values ranging up to 18. For PFOA, there were no human health pathways that resulted in RQ_{HH} values above 1. However, for the milk grazing and fodder pathways, the maximum RQ_{HH} was 0.45.

Based on the results for Scenario 3, C&R recommends PFOS+PFHxS and PFOA thresholds for restricted use biosolids are derived. For PFOS+PFHxS the key exposure pathway for threshold derivation is milk consumption from dairy cows grazing on biosolids-amended soil (RQ_{HH} values up to 18). Whereas, for PFOA, the key exposure pathway for threshold derivation is ecological secondary consumers (RQ_{ECO} values up to 0.62).

In addition to the above recommendations for PFAS thresholds in biosolids, C&R also recommends the EPA measures PFAS in groundwater and surface water in the proximity of biosolids land applied in agriculture. This is due to uncertainties in predicting PFAS concentrations in water bodies from soils/biosolids. Information gained from measuring PFAS in the environment will provide more certainty in understanding the potential risks to drinking water and aquatic environments, and thereby inform management requirements for biosolids application.

Scenario 4 – unrestricted use biosolids in agriculture

Although unrestricted use biosolids in NSW are not commonly used in agriculture, this additional scenario was assessed as it is permitted by the NSW Biosolids Guidelines. Risks from only the highest risk agricultural pathway (determined from Scenario 3) are presented. This was done to determine if the risks from unrestricted use biosolids via the agricultural pathways are potentially higher than those identified in Scenarios 1 and 2.

The maximum RQ_{HH} values for PFOS+PFHxS for Scenario 4 was 23. This is higher than the RQ_{HH} values calculated for unrestricted use biosolids in Scenarios 1 and 2. Therefore, this pathway should be used for threshold derivation. In contrast, the maximum RQ_{HH} values for PFOA for Scenario 4 (0.58) was not the highest. Therefore, is not considered the key risk-driving pathway for PFOA in unrestricted use biosolids.

Recommendations and next steps

- C&R recommends PFAS in unrestricted use and restricted use biosolids requires regulation, and thresholds should be derived to ensure land application of biosolids poses a low risk to the environment and human health.
- The key exposure pathways that derivation should be based on are:
  - unrestricted use biosolids
    - PFOS+PFHxS – consumption of milk from grazing dairy cows (human health)
    - PFOA – ecological toxicity to secondary consumers
  - restricted use biosolids
    - PFOS+PFHxS – consumption of milk from grazing dairy cows (human health)
    - PFOA – ecological toxicity to secondary consumers.
- C&R recommends thresholds for unrestricted use biosolids apply to the final material ready for land application to ensure additional contamination is not introduced if the biosolids are processed with another waste stream.
- C&R recommends threshold derivation should be based on realistic maximum exposures. Thresholds derived this way will be protective but will not be over-conservative. The assumptions used in the derivation process should be transparent and applicable to other emerging contaminants that are being considered as part of the NSW Biosolids Guideline review.
- C&R recommends if PFAS toxicity reference values in Australia are changed in future, or additional toxicity reference values for other PFAS are endorsed, this HHERA should be revised to ensure the key exposure pathways are still correct.
- C&R recommends the following additional work to address knowledge gaps due to uncertainties in estimating PFAS concentrations in water bodies based on soils/biosolids concentrations. This is important to validate, to provide certainty that potential human health and ecological risks in water supplies and aquatic systems are low:

- monitoring groundwater and surface water in proximity to areas where unrestricted use biosolids have been land applied for rehabilitation
- monitoring groundwater and surface water in proximity to areas where restricted use biosolids have been land applied in agriculture.

Uncertainties

Uncertainties that need to be considered when using the information presented in this report include:

- **Representativeness of biosolids PFAS data** – the risk assessment is based on one round of biosolids sampling from 20 STPs in NSW, therefore the data only represent a snapshot, and it is not known if, or the extent to which, these concentrations may vary overtime.
- **Risks posed by other PFAS including PFAA precursors** – the risk assessment focused on PFOS, PFOA and PFOS+PFHxS, and does not quantitatively account for potential risk from other PFAS or precursors. Currently these cannot be included in quantitative risk assessments due to lack of toxicity reference values. This HHERA has accounted for potential risk from other PFAS by using a MOS of 5 (i.e. RQ = 0.2). The level of conservatism to account for other PFAS and precursors will need to be considered when developing thresholds for biosolids.
- **Reliability of interim soil and water screening criteria** – ecological risks were assessed using the interim soil and water screening criteria from the PFAS NEMP (HEPA 2020), and if values change or new values are derived in the future, the risks will need to be re-evaluated. In addition, the ecological risks from PFOA to secondary consumers was assessed using a criterion from the UK. The relevance of this criterion has not been reviewed at this stage.
- **Risks related to offsite migration** – there is significant uncertainty in the understanding of offsite migration of PFAS from land-applied biosolids. This is mainly due to limited scientific understanding of PFAS mobility and transport. PFAS mobility will to a large extent be influenced by the site conditions including soil properties, groundwater conditions and surface water flows, resulting in variable results depending on site conditions. The uncertainty in predicting concentrations of PFAS in water based on soils/biosolids therefore results in significant uncertainty in assessing risks to human health and the aquatic environment from PFAS concentrations in waters. This uncertainty needs to be considered; therefore, monitoring groundwater and surface waters following application of biosolids is recommended.
- **Risks from bioaccumulation in aquatic organisms** – the potential risk from bioaccumulation in aquatic organisms cannot be determined at this stage, as there are no reliable bioaccumulation and biomagnification factors available that are endorsed in Australia. Therefore, the risks for consumption of seafood from water bodies impacted by biosolid-amended soil cannot be assessed. Based on PFAS contaminated sites assessments, this has been a significant issue in NSW and nationally and it is discussed in the PFAS NEMP (HEPA 2020). Biota sampling in water bodies near areas where biosolids have been land applied is necessary to further assess this risk.
- **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. Due to the unique bioaccumulative nature of PFAS this means thresholds developed for land rehabilitation will not protect agricultural pathways which include consumption

of produce (crops, livestock, milk) for the landowners/farmers. This needs to be considered in the review of the NSW Biosolids Guidelines.

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Appendices

Appendix A – Measured PFAS concentrations in NSW biosolids and biosolids leachates

Table A1 Concentrations of the suite of PFAS in biosolids from 20 STPs in NSW (all concentrations in µg/kg) (n=2 for each STP)

STP	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA	PFBS	PFHxS	PFOS
A	< LOR	0.7	2	< LOR	12	1.4	30	1.2	4	< LOR	0.7	20
	< LOR	0.7	2.1	0.7	12	1.7	25	1.2	4.5	< LOR	0.8	19
B	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	2.7	< LOR	< LOR	< LOR	< LOR	3.5
	< LOR	0.4	4.5	< LOR	2.2	< LOR	3.4	< LOR	< LOR	< LOR	< LOR	2.8
C	0.9	0.8	4.3	0.8	6.8	2.3	21	< LOR	2.5	0.8	1.9	39
	0.7	0.5	2.9	< LOR	5.6	2.5	22	< LOR	< LOR	0.6	1.5	45
D	1.7	2.7	11.5	4.1	23	5.5	96	7.3	22	1	0.9	60
	1.1	1.9	5.5	2.2	12	4.6	83	7.6	35	< LOR	0.9	63
E	< LOR	< LOR	2.1	< LOR	6.6	1.1	40	0.8	4	< LOR	1.1	17
	< LOR	0.3	2.1	< LOR	7	1.2	36	0.7	3.4	< LOR	1.1	17
F	< LOR	< LOR	3.6	< LOR	2.8	1	14	1.7	1.9	< LOR	0.7	27
	< LOR	< LOR	2.2	< LOR	2.6	1.2	15	1.8	2.2	< LOR	0.9	26
G	< LOR	0.3	< LOR	< LOR	4.8	1.7	25	3.3	7.7	0.3	0.4	23
	< LOR	0.4	< LOR	< LOR	4	1.7	24	3.4	6.9	< LOR	0.2	19
H	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	3.2	< LOR	< LOR	< LOR	< LOR	9.8
	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	3.2	< LOR	< LOR	< LOR	0.2	11
I	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	0.6	< LOR	17
	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	2.4	< LOR	< LOR	< LOR	0.5	19
J	< LOR	0.5	< LOR	< LOR	< LOR	< LOR	3.9	0.8	1.3	< LOR	< LOR	8.1
	1.2	4.7	6.4	1.8	11	2	7.5	1.8	2.1	0.9	0.5	11
K	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	2.5	< LOR	< LOR	< LOR	< LOR	4
	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	2.1	< LOR	< LOR	< LOR	< LOR	3.8
L	< LOR	0.6	5.8	0.9	8.3	2.5	22	1	2.7	0.3	0.7	51

STP	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA	PFBS	PFHxS	PFOS
	< LOR	0.7	11	0.9	10	2.8	25	2.4	5.3	< LOR	0.7	54
M	< LOR	2.8	2.3	0.8	8.7	2.3	21	2.5	4.6	0.6	2.3	76
	< LOR	2.2	2.5	< LOR	8.6	2.3	19	2	5	0.7	2.1	77
N	< LOR	2.3	3.7	0.8	8.5	1.6	11	1.4	3.4	1.4	1	35
	0.6	2.8	3.8	0.8	8.3	1.4	12	1.6	4.5	1.3	1	37
O	< LOR	3.1	2.7	0.8	7.7	2.4	22	3.1	7.6	0.4	0.6	23
	< LOR	3.9	2.9	0.9	8.5	2.5	23	3.1	7.9	0.5	0.7	24
P	< LOR	1.1	4.3	4	14	3.7	20	4.9	7.3	0.9	3.9	67
	< LOR	1.2	4.7	4.3	14	3.7	20	5.8	8.4	0.8	3.7	74
Q	0.7	3.7	9.9	6.4	27	7.5	49	7.6	17	1.2	0.8	49
	< LOR	0.7	3.3	3	20	5.9	31	5.2	11.5	< LOR	0.3	41
R	< LOR	< LOR	4.3	< LOR	2.5	< LOR	7.4	< LOR	< LOR	< LOR	< LOR	8.1
	< LOR	1.9	< LOR	< LOR	< LOR	1.2	7.1	< LOR	< LOR	< LOR	< LOR	9.3
S	< LOR	< LOR	< LOR	< LOR	2.2	1.2	13	1.1	1.4	< LOR	1	54
	< LOR	< LOR	2.1	< LOR	2.8	1.3	13	1.6	1.8	< LOR	0.7	52
T	< LOR	0.2	< LOR	1.3	8.1	2.1	11	1.5	3.3	< LOR	0.3	18
	< LOR	< LOR	< LOR	< LOR	5	1.3	11	1	2.2	< LOR	0.2	14

'LOR' is the limit of reporting

PFBA - perfluorobutanoic acid
PFPeA - perfluoropentanoic acid
PFHxA - perfluorohexanoic acid
PFHpA - perfluoroheptanoic acid
PFOA - perfluorooctanoic acid
PFNA - perfluorononanoic acid
PFDA - perfluorodecanoic acid
PFUnA - perfluoroundecanoic acid
PFDoA - perflurododecanoic acid
PFBS - perfluorobutane sulfonic acid
PFHxS - perfluorohexane sulfonate
PFOS - perfluorooctane sulfonate

Table A2 **Concentrations of the suite of PFAS in biosolids leachates from 20 STPs in NSW (all concentrations in µg/L) (n=2 for each STP)**

STP	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA	PFBS	PFHxS	PFOS
A	< LOR	< LOR	0.062	0.033	0.14	0.005	0.04	< LOR	< LOR	< LOR	< LOR	0.03
	< LOR	< LOR	0.062	0.024	0.14	0.006	0.039	< LOR	< LOR	< LOR	< LOR	0.03
B	< LOR	< LOR	0.03	< LOR	0.022	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
	< LOR	0.05	0.16	< LOR	0.027	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	0.01
C	0.058	0.1	0.17	0.027	0.14	0.012	0.043	< LOR	< LOR	0.033	0.045	0.12
	0.037	0.038	0.12	0.02	0.13	0.014	0.036	< LOR	< LOR	0.029	0.048	0.12
D	0.06	0.16	0.43	0.12	0.3	0.022	0.10	< LOR	< LOR	0.05	0.012	0.071
	0.057	0.16	0.2	0.072	0.18	0.023	0.086	< LOR	< LOR	0.015	0.013	0.075
E	< LOR	< LOR	0.064	< LOR	0.11	0.004	0.09	< LOR	< LOR	< LOR	0.018	0.043
	< LOR	< LOR	0.069	< LOR	0.13	0.006	0.089	< LOR	< LOR	< LOR	0.022	0.05
F	< LOR	0.025	0.12	0.012	0.019	0.002	0.008	< LOR	< LOR	< LOR	0.006	0.022
	< LOR	0.029	0.073	0.013	0.025	0.004	0.015	< LOR	< LOR	< LOR	0.008	0.04
G	0.02	0.031	0.024	< LOR	0.068	0.008	0.03	< LOR	< LOR	< LOR	< LOR	0.029
	0.016	0.027	0.022	< LOR	0.067	0.008	0.027	< LOR	< LOR	< LOR	< LOR	0.029
H	< LOR	< LOR	0.041	< LOR	0.019	< LOR	< LOR	< LOR	< LOR	< LOR	0.005	0.031
	< LOR	< LOR	0.034	< LOR	0.016	< LOR	0.006	< LOR	< LOR	< LOR	0.004	0.028
I	< LOR	< LOR	0.011	0.005	0.006	< LOR	< LOR	< LOR	< LOR	< LOR	0.006	0.021
	< LOR	< LOR	0.012	0.01	0.008	< LOR	< LOR	< LOR	< LOR	< LOR	0.009	0.037
J	0.004	0.013	0.017	0.014	0.027	0.011	0.041	< LOR	< LOR	0.002	0.001	0.1
	0.047	0.2	0.23	0.083	0.33	0.038	0.054	< LOR	< LOR	0.044	0.013	0.085
K	< LOR	< LOR	0.014	< LOR	0.009	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR	< LOR
	< LOR	< LOR	0.025	< LOR	0.01	< LOR	< LOR	< LOR	< LOR	< LOR	0.003	0.005

STP	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA	PFBS	PFHxS	PFOS
L	0.027	0.063	0.22	0.034	0.13	0.01	0.022	< LOR	< LOR	0.011	0.009	0.069
	0.032	0.06	0.44	0.035	0.13	0.009	0.02	< LOR	< LOR	0.008	0.011	0.052
M	< LOR	< LOR	0.073	0.032	0.098	0.011	0.048	< LOR	< LOR	0.027	0.028	0.22
	< LOR	< LOR	0.096	0.035	0.14	0.016	0.061	< LOR	< LOR	0.028	0.039	0.27
N	0.038	0.21	0.13	0.037	0.1	0.006	0.014	< LOR	< LOR	0.05	0.018	0.052
	0.31	0.23	0.14	0.033	0.11	0.006	0.017	< LOR	< LOR	0.052	0.02	0.054
O	0.25	0.4	0.094	0.023	0.099	0.011	0.036	< LOR	< LOR	0.012	< LOR	0.049
	0.29	0.6	0.11	0.035	0.12	0.013	0.044	< LOR	< LOR	0.018	< LOR	0.057
P	0.048	0.077	0.19	0.15	0.31	0.031	0.043	< LOR	< LOR	0.04	0.088	0.19
	0.04	0.13	0.18	0.16	0.34	0.038	0.061	< LOR	< LOR	0.037	0.1	0.26
Q	0.04	0.18	0.36	0.23	0.41	0.037	0.068	< LOR	< LOR	0.046	0.012	0.073
	< LOR	0.037	0.13	0.13	0.47	0.064	0.074	< LOR	< LOR	0.011	0.009	0.13
R	< LOR	< LOR	0.15	0.017	0.036	< LOR	0.01	< LOR	< LOR	< LOR	0.008	0.02
	< LOR	< LOR	0.035	< LOR	0.024	< LOR	0.009	< LOR	< LOR	< LOR	< LOR	0.02
S	0.7	< LOR	0.032	< LOR	0.03	0.007	0.022	< LOR	< LOR	< LOR	< LOR	0.15
	< LOR	< LOR	0.062	< LOR	0.038	< LOR	0.025	< LOR	< LOR	< LOR	< LOR	0.15
T	< LOR	0.009	0.018	0.034	0.082	< LOR	0.006	< LOR	< LOR	0.005	0.005	0.013
	< LOR	0.008	0.014	0.017	0.047	< LOR	0.007	< LOR	< LOR	0.005	< LOR	0.011

‘LOR’ is the limit of reporting

Appendix B – Review of the United Kingdom Environment Agency PFOA soil screening criterion for Australian conditions

United Kingdom Environment Agency soil screening value (SSV) derivation process

SSVs are defined in UK EA (2017) as 'concentrations of chemical substances found in soils below which there are not expected to be any adverse effects on wildlife such as birds, mammals, plants and soil invertebrates, or on the microbial function of soils'. The approach involves deriving a predicted no effect concentration (PNEC) for direct toxicity ($PNEC_{dt}$). If a chemical bioaccumulates, an additional PNEC is also derived for secondary poisoning ($PNEC_{sp}$). The final PNEC is the lowest of the 2 values. The final step in the process is determining if there is sufficient regulatory confidence in the underlying data to recommend a SSV from the PNEC.

The process for deriving a secondary poisoning PNEC is outlined in Section 3.5.3 of UK EA (2017). The terrestrial food chain considered in the derivation is soil → earthworm → worm-eating bird or mammal. Initially, a PNEC for secondary poisoning of birds or mammals is calculated based on a predicted no effect concentration for adverse effects via the diet ($PNEC_{oral}$) using an assessment factor. This is then converted into a $PNEC_{sp}$ as a soil concentration using a bioaccumulation factor for worms (BAF_{worm}). The PNEC can be normalised to a standard soil to reduce the inherent variability due to soil type. Normalisation of most non-ionic chemicals is based on soil organic matter (SOM). These values can be corrected based on site-specific SOM contents.

The PFOA SSV presented in UK EA (2017) is 0.02 mg/kg, which was derived using the secondary poisoning method (i.e. $PNEC_{sp}$) and has been normalised to a SOM content of 3.4% (standard value used for SOM in the UK). The value was calculated based on liver toxicity in rats and an assessment factor of 90. UK EA (2017) notes 'there is a moderate level of regulatory uncertainty associated with the recommended SSV due to limitations in the assessment methodology'.

Suitability of the UK EA (2017) SSV for Australian soils

Overall, the SSV is useful for screening in Australia but noting that there is moderate regulatory uncertainty. One of the key differences between UK and Australian soils is likely to be the SOM content. The SSV presented in UK EA (2017) is normalised to 3.4% SOM. The SOM content in Australian soils is likely to be lower than this, which means they tend to have lower sorption capacity. Accounting for this will reduce the SSV. The *National Environment Protection (Assessment of Site Contamination) Measure* (ASC NEPM) uses a soil organic carbon (OC) content of 1% for an Australian reference soil in the normalisation step for the ecological investigation levels. The SSV can be adjusted for variations in SOM as shown in equations B1 and B2 below (assuming SOM contains 58% OC) (UK EA 2017).

$$SOM = OC \times \frac{100}{58} \qquad \text{Equation B1}$$

where:

SOM = soil organic matter, % weight basis

OC = soil organic carbon, % weight basis.

This equation needs to be completed first as the carbon in the Australian reference soil is shown as OC rather than SOM. This results in a SOM content of 1.7%.

The SSV presented in UK EA (2017) (i.e. normalised to 3.4% SOM) can then be adjusted as follows:

$$SSV^* = SSV \times \frac{SOM^*}{SOM} \qquad \text{Equation B2}$$

where:

*SSV** = adjusted soil screening criteria

SSV = PFOA SSV from UK EA (2017) (0.02 mg/kg)

*SOM** = soil organic matter in the Australia reference soil (1.7%)

SOM = SOM used to normalise the UK EA (2017) PFOA SSV (3.4%).

Based on this calculation, the adjusted SSV for PFOA becomes 0.01 mg/kg.

C&R notes that recent literature indicates OC alone does not influence the partitioning of PFAS in soils and that other soil properties also contribute[13]. Changes in partitioning will also influence the bioavailability of these compounds. This means normalisation based only on OC or SOM may include some error, but at this stage there is insufficient data available to include other soil properties in the normalisation.

[13] Li Y, Oliver DP, Kookana RS (2018) 'A critical analysis of published data to discern the role of soil and sediment properties in determining sorption or per and polyfluoroalkyl substances (PFASs)', *Science of the Total Environment* 628-629: 110-120.

Appendix C – Method for calculating human health risks

Scenario 1 – unrestricted use biosolids in residential gardens

Pathway 1 (incidental ingestion of soil/dust) and Pathway 2 (consumption of homegrown fruit and vegetables)

Human health risks from Pathways 1 and 2 were assessed together using criteria from the *PFAS National Environmental Management Plan* (the PFAS NEMP) that are relevant for residential properties with gardens and accessible soil (HEPA 2020). The assumptions used to derive these criteria are consistent with those used to derive the low-density residential health investigation levels (HIL A) in the *National Environment Protection (Assessment of Site Contamination) Measure* (ASC NEPM) (NEPC 2013). Specifically, these criteria assume exposure via several routes, including:

- incidental ingestion of the soil
- consumption of homegrown fruit and vegetables (assuming up to 10% of a person's fruitand vegetable consumption comes from homegrown produce)
- inhalation of dust.

These criteria conservatively assume that a person may receive 80% of their PFOS+PFHxS and PFOA exposure from other sources. Therefore, the criteria are based on 20% of the tolerable daily intake (TDI). The dermal contact pathway which is normally considered in the HIL A derivation was not considered in the derivation of these criteria, because dermal uptake is not considered a major pathway given the low dermal absorption of PFOS, PFHxS and PFOA (ATSDR 2015).

Using the screening criteria, a RQ_{HH} was calculated for Pathways 1 and 2, using Equation C1.

$$RQ_{HH} = \frac{conc.\ in\ unrestricted\ use\ biosolids}{residential\ soil\ screening\ criteria} \qquad \text{Equation C1}$$

Pathway 3 (consumption of chicken eggs)

No relevant screening criteria are currently available for this pathway. Therefore, Pathway 3 was assessed by comparing daily intakes for children with background corrected TDIs for PFOS+PFHxS and PFOA. To calculate daily intakes, initially, concentrations in eggs (C_E) (µg/kg) were calculated using Equation C2 (parameters summarised in Table C1). This equation assumes the only source of PFOS+PFHxS and PFOA for chickens is the soil (in this case unrestricted use biosolids) and they get no input from water or food they ingest.

$$C_E = \frac{(C_{URbio} \times IR_S \times Bio_S) \times TF_{egg}}{LR \times E_W} \qquad \text{Equation C2}$$

Table C1 Summary of assumptions used to calculate PFOS+PFHxS and PFOA concentrations in eggs (Equation C2)

Parameter	Value	Units	Description
C_{URbio}	Variable	µg/kg	Estimated concentration in unrestricted use biosolids
IR_S	0.0105	kg/d	Chicken soil ingestion rate (AECOM 2017) (assumes all soil ingested is unrestricted use biosolids)
Bio_S	1	unitless	Bioavailable fraction – assumes all PFOS+PFHxS and PFOA is bioavailable

Parameter	Value	Units	Description
TF_{egg}	PFOS+PFHxS = 1 PFOA = 0.5	unitless	Transfer factor into egg (AECOM 2017) (Note: measured transfer factors based on a study where PFAS were fed to chicken via water in a controlled study)
LR	0.86	days	Laying rate (professional judgment, based on a chicken laying 6 eggs per week, 52 weeks per year)
E_W	0.058	kg	Edible weight of egg (AECOM 2017)

Egg concentrations were then used to calculate predicted daily intakes (µg/kg/d) for children who may eat eggs from home chickens, using Equation C3 (parameters summarised in Table C2).

$$Daily\ intake = \frac{C_E \times IR_{egg} \times AoF \times FI \times EF \times ED}{BW \times AT} \qquad \text{Equation C3}$$

Table C2 Summary of assumptions used to calculate predicted daily intakes of PFOS+PFHxS and PFOA from egg consumption for children

Parameter	Value	Units	Description
C_E	Variable	µg/kg	Concentration in egg (from Equation C2)
IR_{egg}	0.072	kg/d	Ingestion rate of eggs – 2-times 90th 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 all PFOS+PFHxS and PFOA in eggs is bioavailable
FI	1	unitless	Fraction ingestion from contaminated source – assumes all eggs consumed are from home chickens ingesting biosolids
EF	365	d/year	Exposure frequency
ED	6	years	Exposure duration (NEPC 2013)
BW	15	kg	Body weight (NEPC 2013)
AT	2190	days	Averaging time = EF × ED

A RQ_{HH} was then calculated using the predicted daily intakes and the TDIs (Table 1) (Equation C4).

$$RQ_{HH} = \frac{predicted\ daily\ intake}{TDI - background} \qquad \text{Equation C4}$$

where, the background for both PFOS+PFHxS and PFOA was assumed to be 0.001 µg/kg/d (ToxConsult 2016).

Scenario 2 – unrestricted use biosolids for land rehabilitation

Pathway 1 (incidental ingestion soil/dust)

The risk from incidental ingestion of soil/dust for this scenario was assessed by comparing the estimated concentration of PFOS+PFHxS and PFOA in unrestricted use biosolids to public open space soil screening criteria from the PFAS NEMP (1 and 10 mg/kg, respectively). This was done for concentrations corresponding to each of the STPs using Equation C5.

$$RQ_{HH} = \frac{conc.\ in\ unrestricted\ use\ biosolids}{public\ open\ space\ soil\ screening\ criteria} \qquad \text{Equation C5}$$

Pathway 2 (consumption of impacted drinking water)

Pathway 2 was assessed by comparing estimated downgradient drinking water concentrations of PFOS+PFHxS and PFOA to drinking water guidelines (Table 2). To do this, estimated soil pore water concentrations (Appendix D and Table 13) were divided by a dilution and attenuation factor (DAF) of 10, to account for any dilution and attenuation that may occur during transport from soil to groundwater or surface water. An RQ_{HH} was then calculated using Equation C6.

$$RQ_{HH} = \frac{estimated\ downgradient\ drinking\ water\ conc.}{drinking\ water\ guideline} \qquad \text{Equation C6}$$

Scenario 3 – restricted use biosolids in agriculture

Human health risks for Scenario 3 were assessed for 4 land application rates:

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

For each land application rate, the maximum soil concentration and pore water concentration were calculated. The results of these calculations are provided in Appendix F.

Pathway 1 (incidental ingestion soil/dust)

Pathway 1 was assessed for adults only, as it was assumed only adults would regularly be in areas where biosolids had been applied. The predicted daily intake (µg/kg/d) of PFOS+PFHxS and PFOA for Pathway 1 was calculated using Equation C7 (parameters described in Table C3). The daily intake of PFOS+PFHxS and PFOA was then compared to a background adjusted TDI to calculate an RQ_{HH} using Equation C4.

$$Daily\ intake = \frac{C_{BAS} \times IR_{BAS} \times CF \times AoF \times FI \times EF \times ED}{BW \times AT} \qquad \text{Equation C7}$$

Table C3 Summary of parameters used to calculate predicted daily intakes for PFOS+PFHxS and PFOA via direct ingestion of soil/dust (Equation C7)

Parameter	Value	Units	Description
C_{BAS}	Variable	µg/kg	Concentration in soils – maximum soil concentrations for the 4 land application rates
IR_{BAS}	50	mg/d	Soil ingestion rate – average outdoor soil and indoor dust incidental ingestion rates from enHealth (2012)

Parameter	Value	Units	Description
CF	10^{-6}	kg/mg	Unit conversion factor
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from contaminated source – assumes all soil/dust is ingested from areas where biosolids have been applied
EF	365	d/year	Exposure frequency
ED	29	years	Exposure duration (NEPC 2013)
BW	70	kg	Body weight (NEPC 2013)
AT	10585	days	Averaging time = ED × EF

Pathway 2 (consumption of crops grown in biosolids-amended soil)

To assess Pathway 2, initially the concentrations in plants were estimated for the 4 land application rates using Equation C8.

$$C_P = C_{BAS} \times TF_S \qquad \text{Equation C8}$$

where, C_P is the estimated concentration in the edible portion of a plant (µg/kg), C_{BAS} is the concentration in biosolids-amended soil (µg/kg), which will vary depending on the land application rate, and TF_S is the soil to plant transfer factor (TF). Calculations were done separately for fruits and vegetables as the soil-to-plant TFs for these groups of plants can vary.

OEH (2019) presented a summary of experimentally derived soil-to-plant TFs for PFOS and PFOA for different plant categories (green vegetables, root vegetables, tuber vegetables and fruit). For this study, the TFs for green vegetables and fruit were used, as biosolids cannot be used for contact agriculture (e.g. root vegetables). The relevant TFs from OEH (2019) are summarised in Table C4.

Table C4 Fruit and vegetable soil-to-plant transfer factors for PFOS, PFOA and PFOS+PFHxS

Compound	Fruit	Vegetable
PFOS	0.0005	0.2
PFOA	0.03	0.1
PFOS+PFHxS	0.0007	0.3

As the risks from PFOS and PFHxS are assessed together but the soil-to-plant transfer factors for these 2 compounds vary, the approach for calculating a combined TF from OEH (2019) was used. To do this, firstly the relative proportions of PFOS and PFHxS in the biosolids needs to be calculated. Based on the biosolids data in Table 5, the % contribution from PFOS to PFOS+PFHxS is considerable (ranges from 94 to 99%). As PFOS is not expected to transfer into plants as readily as PFHxS, the lowest of the range (i.e. 94%) was used as the proportion of PFOS in the combined TF calculation. Using this proportion, a combined transfer factor was calculated using Equation C9 (adapted from OEH 2019).

$$TF_{PFOS+PFHxS} = (TF_{PFOS} \times fraction_{PFOS}) + (TF_{PFOS} \times multiplier_{PFHxS}) \times (1 - fraction_{PFOS})) \qquad \text{Equation C9}$$

where:

$TF_{PFOS+PFHxS}$	= combined soil to plant TF for PFOS+PFHxS
TF_{PFOS}	= soil to plant TF for PFOS (Table C4)
$multiplier_{PFOS}$	= multiplier of 6.9 as reported in OEH (2019)
$fraction_{PFOS}$	= the fraction of PFOS in the sum of PFOS+PFHxS (i.e. 0.94)

The combined PFOS+PFHxS soil-to-plant TFs are shown in Table C4.

The child predicted daily intakes (µg/kg/d) of PFOS+PFHxS and PFOA from consumption of crops grown in biosolids-amended soil were then calculated using Equation C10 (parameters are described in Table C5). The daily intakes of PFOS+PFHxS and PFOA were then compared to a background adjusted TDI to calculate a RQ_{HH} using Equation C4.

$$Daily\ intake = \frac{C_P \times IR_P \times AoF \times FI \times EF \times ED}{BW \times AT} \qquad \text{Equation C10}$$

Table C5 Summary of assumptions used to calculate predicted daily intakes of PFOS+PFHxS and PFOA via consumption of crops grown in biosolids-amended soil (Equation C10)

Parameter	Value	Units	Description
C_P	Variable	µg/kg	Concentration in plant from Equation C8 – will vary for the different land application rates
IR_P	Fruit = 0.151 Vegetable = 0.190	kg/d	Ingestion rate for fruiting vegetables or root, tuber vegetables and leafy greens (FSANZ 2017)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	0.2	unitless	Fraction ingested from contaminated source[1]
EF	365	d/year	Exposure frequency
ED	6	years	Exposure duration (NEPC 2013)
BW	15	kg	Body weight (NEPC 2013)
AT	2190	days	Averaging time = ED × EF

[1] Assumes 20% of total amount consumed comes from areas where biosolids have been land applied

Pathway 3 (consumption of crops irrigated with impacted water)

To assess Pathway 3, groundwater/surface water concentrations of PFOS+PFHxS and PFOA were estimated by dividing the soil pore water concentrations from Table 18 by a dilution and attenuation factor (DAF) of 10. Following this, the plant concentrations (C_P) (µg/kg) were calculated for the 4 land application rates using Equation C11.

$$C_P = C_W \times TF_W \qquad \text{Equation C11}$$

where, C_W is the estimated groundwater/surface water concentration and TF_W is the water-to-plant TF. The TFs used in Equation C11 are summarised in Table C6. These values were based on experimentally derived data and were sourced from a literature review presented in ToxConsult (2016). The plant concentrations (C_P) for each application rate were used to calculate the predicted daily intake rate (µg/kg/d) and the RQ_{HH} using Equation C10 and Equation C4, respectively.

Table C6 Fruit and vegetable water-to-plant transfer factors for PFOS+PFHxS and PFOA

Compound	Fruit	Vegetable
PFOS+PFHxS	0.2	0.1
PFOA	0.3	0.3

Pathways 4 and 5 (consumption of beef from cattle grazing on biosolids-amended soil)

Pathways 4 and 5 were assessed together because it was assumed that grazing livestock would always ingest soil and plants rather than only one or the other. The livestock daily intakes (µg/kg/d) of PFOS+PFHxS and PFOA were calculated for each land application rate using Equation C12 (descriptions of parameters provided in Table C7).

$$Livestock\ daily\ intake = \frac{(C_{BAS} \times IR_{BAS} \times FI)+(C_P \times IR_P \times FI)}{BW} \qquad \text{Equation C12}$$

Table C7 Summary of assumptions used to calculate grazing livestock intakes for PFOS+PFHxS and PFOA from soil and plants (Equation C12)

Parameter	Value	Units	Description
C_{BAS}	Variable	µg/kg	Concentration in soils – maximum soil concentrations for the 4 land application rates
IR_{BAS}	0.5	kg/d	Livestock soil ingestion rate – based on US EPA (2005) and advice from NSW Dept of Primary Industries (DPI)
C_P	Variable	µg/kg	Concentration in plant/grass (explained in text below)
IR_P	13	kg/d (dry matter)	Livestock plant ingestion rate based on API (2004) and advice from NSW DPI
FI	1	unitless	Fraction ingested from the source – assumes 100% of soil and plants consumed by grazing livestock comes from areas where biosolids have been used (API 2004).
BW	500	kg	Livestock body weight (API 2004)

Equation C8 was used to calculate the plant/grass concentration (C_P) for the different land application rates (Table C8). The transfer factors used were 1.4 for PFOS and 4.3 for PFOA. These were selected by calculating that 95th percentile of transfer factors available in the literature (see Appendix G for details). The transfer factor for PFOS was also used for PFHxS. Although PFHxS is likely to be taken up more readily into plants, the contribution of PFHxS to PFOS+PFHxS was < 5%. Therefore, this is considered to have negligible impact on the estimated plant concentrations.

Table C8 **Estimated grass concentrations used to calculate beef concentrations in µg/kg**

Land application rate	PFOS+PFHxS	PFOA
10 t/ha	0.61	0.58
10 t/ha repeat	4.3	4.1
50 t/ha	3.0	2.8
50 t/ha repeat	21	20

The livestock daily intakes were then used to calculate the livestock serum concentration (C_{serum}) (µg/L) using Equation C13.

$$C_{serum} = \frac{livestock\ daily\ intake \times t1/2}{0.693 \times Vd} \qquad \text{Equation C13}$$

where, *t1/2* is the serum elimination half-life, which is chemical specific. The value for beef steer was 114 days for PFOS (Lupton et al. 2014) and 0.8 days for PFOA (Lupton et al. 2012). The value 0.693 in Equation C13 is based on pharmacokinetic models and *Vd* is the volume of distribution where 0.21 L/kg is assumed to be the extracellular fluid volume (ToxConsult 2016).

C_{serum} was then converted to a beef concentration (µg/kg) using Equation C14.

$$C_{beef} = TSR \times C_{serum} \qquad \text{Equation C14}$$

where, *TSR* is the tissues serum ratio, which was 0.1 (AECOM 2017).

The predicted daily intake (µg/kg/d) for these pathways was calculated using Equation C15 (descriptions of parameters provided in Table C9). The daily intakes of PFOS+PFHxS and PFOA were then compared to a background adjusted TDI to calculate a RQ_{HH} using Equation C4.

$$Daily\ intake = \frac{C_{meat} \times IR_M \times AoF \times FI \times EF \times ED}{BW \times AT} \qquad \text{Equation C15}$$

Table C9 **Summary of assumptions used to calculate predicted daily intakes of PFOS+PFHxS and PFOA for a child consuming beef from cattle grazing on biosolids-amended soil (Equation C15)**

Parameter	Value	Units	Description
C_{beef}	Variable	µg/kg	Concentration in beef – will vary for the different land application rates
IR_M	0.085	kg/d	Beef ingestion rate – high consumers of cattle (90th percentile) from FSANZ (2017)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	0.5	unitless	Fraction ingested from source[1]
EF	365	d/year	Exposure frequency
ED	6	years	Exposure duration (NEPC 2013)
BW	15	kg	Body weight (NEPC 2013)
AT	2190	days	Averaging time = ED × EF

[1] Assumes 50% of the beef consumed comes from cattle grazing on land where biosolids have been land applied (i.e. 50% of beef consumption comes from other areas)

Pathway 5 (consumption of beef from cattle ingesting fodder grown on biosolids-amended soil)

The equations used to assess Pathway 5 alone were the same as those used to assess the combined Pathways 4 and 5 (grazing beef cattle). The only difference was in the calculation of the livestock daily intake. This calculation considered only uptake into livestock via the plant pathway as shown in Equation C16 (description of parameters described in Table C7).

$$Livestock\ daily\ intake = \frac{(C_P \times IR_P \times FI)}{BW} \qquad \text{Equation C16}$$

Pathway 6 (consumption of beef from cattle drinking impacted water)

Pathway 6 considered consumption of beef cattle that have used impacted groundwater or surface water as drinking water. This pathway alone assumes livestock are not exposed to PFOS+PFHxS and PFOA via any other pathways. The livestock daily intakes (µg/kg/d) of PFOS+PFHxS and PFOA were calculated using Equation C17.

$$Livestock\ daily\ intake = \frac{(C_W \times IR_W \times FI)}{BW} \qquad \text{Equation C17}$$

where, C_W is the concentration in the water, which was estimated as the soil pore water concentration at the different land application rates (Table 18) divided by a DAF of 10. The parameter IR_W is the livestock water ingestion rate, which was assumed to be 70 L/d (DPI 2014) and *BW*, body weight, was 500 kg (API 2004). *FI* is the fraction ingested from the source, which was 1, assuming all water consumed by livestock contains contamination from soils where biosolids have been used.

Following this, the serum concentration, beef concentration and predicted daily intake for a person consuming beef were calculated using Equations C13, C14 and C15, respectively. The daily intake was then compared to the background adjusted TDI using Equation C4 to calculate an RQ_{HH}.

Pathways 7 and 8 (consumption of milk from dairy cows grazing on biosolids-amended soil)

Pathways 7 and 8 were assessed together as it was assumed that dairy cows would always ingest both soil and plants while grazing. This was done using the PFOS+PFHxS and PFOA livestock daily intake rates from Equation C12. Following this, dairy cow serum concentrations were calculated using Equation C13. In this instance, the serum elimination half-lives (*t1/2*) for PFOS and PFOA were 56 and 1.3 days, respectively (van Asselt et al. 2013; Vestergren et al. 2013). The volume distribution (*Vd*) for both compounds was 0.26 L/kg (Maksiri et al. 2005; Chaiyabutr et al. 2008). Following this, concentrations in milk were calculated using Equation C18.

$$C_{milk} = MSR \times C_{serum} \qquad \text{Equation C18}$$

where, *MSR* is the milk serum ratio, which was assumed to be 0.02 for PFOS+PFHxS and 0.2 for PFOA (ToxConsult 2016).

The child predicted daily intakes (µg/kg/d) of PFOS+PFHxS and PFOA was then calculated from Equation C19 (descriptions of parameters provided in Table C10). The daily intake was then compared to the background adjusted TDI using Equation C4 to calculate an RQ_{HH}.

$$Daily\ intake = \frac{C_{milk} \times IR_{MK} \times SG \times AoF \times FI \times EF \times ED}{BW \times AT} \qquad \text{Equation C19}$$

Table C10 Summary of assumptions used to calculate predicted daily intakes of PFOS+PFHxS and PFOA for a child consuming milk from dairy cows grazing on biosolids-amended soil

Parameter	Value	Units	Description
C_{milk}	Variable	µg/L	Concentration in milk – will vary for the different land application rates
IR_{MK}	1.1	kg/d	Milk ingestion rate – high consumers of milk (90th percentile) (FSANZ 2017)
SG	0.968	L/kg	Specific gravity of cow milk (ratio of density of milk to density of water) at 20°C is 1.0033. Therefore, 0.968 is the inverse (Sherbon 1988)
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from source – assumes 100% of milk is consumed from the areas where biosolids have been land applied
EF	365	d/year	Exposure frequency
ED	6	years	Exposure duration (NEPC 2013)
BW	15	kg	Body weight (NEPC 2013)
AT	2190	days	Averaging time = EF × ED

Pathway 8 (consumption of milk from dairy cows ingesting fodder grown on biosolids-amended soil)

Pathway 8 was assessed the same as the combined Pathways 7 and 8 but used the livestock daily intakes from Equation C16.

Pathway 9 (consumption of milk from dairy cows drinking impacted water)

Pathway 9 was assessed based on the livestock daily intakes of PFOS+PFHxS and PFOA calculated from Equation C17. From this, the serum concentration and milk concentration were calculated using Equation C13 and C18, respectively (using assumptions for dairy cows listed under the grazing dairy cow scenario). These data were then converted into predicted daily intakes for children for the 4 land application rates using Equation C19. The daily intake was then compared to the background adjusted TDI using Equation C4 to calculate a RQ_{HH}.

Pathway 10 (incidental ingestion of irrigation water)

Pathway 10 was assessed by calculating a daily intake (µg/kg/d) of PFOS+PFHxS and PFOA for someone who may be exposed to impacted groundwater or surface water used as irrigation water. This pathway was assessed only for adults as it was considered unlikely that a child would be regularly exposed to irrigation water. The daily intakes were calculated using Equation C20 (assumptions listed in Table C11), where the irrigation water concentration was equal to the estimated pore water concentration (Table 18) with a DAF of 10 applied. The RQ_{HH} was then calculated using Equation C4.

$$Daily\ intake = \frac{C_{irr} \times IR_{irr} \times AoF \times FI \times EF \times ED}{BW \times AT} \qquad \text{Equation C20}$$

Table C11 Summary of assumptions used to calculate predicted daily intakes of PFOS+PFHxS and PFOA for incidental ingestion of irrigation water by adults (Equation C20)

Parameter	Value	Units	Description
C_{irr}	Variable	µg/L	Concentration in irrigation water – will vary for the different land application rates
IR_{irr}	0.001	L/d	Irrigation water ingestion rate – based on incidental ingestion volumes from the *Australian Guidelines for Water Recycling* (NEPC 2006). Assumes majority of exposure is via contact with plants
AoF	1	unitless	Oral absorption factor – assumes 100% bioavailability
FI	1	unitless	Fraction ingested from the source – assumes all incidentally ingested irrigation water is impacted by biosolids-amended soil
EF	365	d/year	Exposure frequency
ED	29	years	Exposure duration (NEPC 2013)
BW	70	kg	Body weight (NEPC 2013)
AT	10585	days	Averaging time = ED × EF

Pathway 11 (consumption of impacted drinking water)

Pathway 11 was assessed by comparing an estimated drinking water concentration with the drinking water guidelines in the PFAS NEMP. The estimated drinking water concentrations were calculated by applying a DAF of 10 to the soil pore water concentrations in Table 18. Equation C21 was then used to calculate the RQ_{HH} values for PFOS+PFHxS and PFOA for this pathway.

$$RQ_{HH} = \frac{predicted\ conc.\ in\ drinking\ water}{drinking\ water\ guideline}$$ Equation C21

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Appendix D – Method for calculating soil pore water concentrations

Soil pore water concentrations were used to assess the risks from some pathways in Scenarios 2 and 3. These were calculated based on the concentrations in a biosolids-amended soil and solid-solution distribution coefficients (Kdes). The Kdes gives an indication of the amount of a contaminant that can desorb into solution from a solid matrix. This was calculated using Equation D1 (adapted from Sepulvado et al. 2011), using the leachate concentrations in Table 6 and the biosolids concentrations in Table 5.

$$K_{des} = \frac{C_B}{C_W} = \frac{m_b^0 - m_w}{m_w} \times \frac{V_w}{M_{biosolids}} \qquad \text{Equation D1}$$

where, C_B is the concentration of each contaminant in the biosolids (on a dry weight basis), C_W is the concentration of the contaminant in the leachate water, m_b^0 is the mass of the contaminant in the biosolids before desorption, m_W is the mass of the contaminant in leachate water after desorption, V_W is the volume of the water used for extraction and $M_{biosolids}$ is the mass of biosolids extracted. The Kdes values for biosolids from each STP are shown in Table D1. The larger the Kdes value, the less of the compound is desorbed into the leachate water. The use of this equation assumes there is no loss of any PFAS onto the vessels during the extraction and the distribution of the contaminants between the biosolids and water is at equilibrium. Kdes values were calculated only for biosolids that had concentrations above the LOR in paired samples for biosolids and leachates.

The Kdes values were used to estimate the pore water concentrations for Scenario 2 (land rehabilitation) and Scenario 3 (agriculture). The approach used was based on Langdon et al. (2010) and Chari and Halden (2012). This was done using 2 equations. The first was obtained by rearranging the equation used to experimentally determine solid-solution distribution coefficients (OECD 2000) to calculate the ratio between the solid and solution phases. This was done per given volume of biosolids-amended soil (i.e. 1.3 cm^3) (assuming soil bulk density of 1.3 g/cm^3) and is shown in Equation D2.

$$m_s/m_w = \frac{K_{des} \times M_{soil}}{V_w} \qquad \text{Equation D2}$$

where, m_s is the mass of the contaminant bound to the solid phase at equilibrium (µg) (i.e. starting total mass minus the solution phase mass), m_w is the mass of the contaminant in the solution phase at equilibrium (µg), *Kdes* is the solid-solution distribution coefficient reported in Table D1, M_{soil} is the mass of biosolids-amended soil in 1 cm^3 (i.e. 1.3 g dry weight) and V_w is the volume of pore water in 1 cm^3 soil (i.e. 0.5 mL). The use of 0.5 mL for V_w assumes the soil has a porosity of 50% and is at saturation. The use of Kdes calculated from biosolids and biosolids leachates for Scenario 3 (agricultural scenario) assumes the soil has no influence on the distribution of the contaminants between the solid and solution phases.

Table D1 **Solid-solution distribution coefficients (Kdes) for PFOS, PFOA and PFHxS from biosolids**

STP	PFOS	PFOA	PFHxS
A	650	66	nd
B	580	61	nd
C	330	24	16
D	830	55	49
E	340	37	35
F	850	100	94
G	700	45	nd
H	310	nd	30
I	600	nd	36
J	84	13	18
K	740	nd	nd
L	850	51	50
M	290	53	45
N	660	56	33
O	430	54	nd
P	290	22	20
Q	430	35	30
R	420	49	nd
S	330	-13[a]	nd
T	110	82	63
Maximum	850	100	94
Minimum	84	13[a]	16
Average	490	52[a]	40

nd: not determined as either both biosolids or both leachates were < LOR

[a] The value of -13 was not included in minimum and average calculations as this value was considered unreliable

The mass of each contaminant in the 0.5 mL of soil pore water was then calculated using Equation D3.

$$m_w = \frac{m_s^0}{\left({}^{m_s}/_{m_w}\right)+1} \qquad \text{Equation D3}$$

where, m_s^0 is equal to the total mass (µg) of the contaminant in 1 cm^3 of biosolids-amended soil, which was calculated from the concentration in the biosolids-amended soil. The ratio (m_s/m_w) was calculated from Equation D2. Therefore, m_w is the mass of the contaminant in 0.5 mL water (1 cm^3 of soil at saturation). This value was then converted to a concentration (µg/L) for use in the risk assessment (estimated pore water concentrations from these calculations are reported in the relevant section of the report and in Appendix F for Scenario 3).

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Appendix E – Additional risk calculations

Table E1 **PFOS ecological risk quotients (RQ_{ECO}) for secondary consumers at a land application rate of 50 t/ha repeat applications from 20 STPs sampled**

STP	Biosolids conc. (µg/kg)	Estimated soil conc. (µg/kg)	Criterion (µg/kg)	RQ_{ECO}
A	20	5.2	10	**0.52**
B	3.2	0.83	10	0.083
C	42	11	10	**1.1**
D	62	16	10	**1.6**
E	17	4.4	10	**0.44**
F	27	7.0	10	**0.70**
G	21	5.4	10	**0.54**
H	10	2.6	10	**0.26**
I	18	4.7	10	**0.47**
J	9.6	2.5	10	**0.25**
K	3.9	1.0	10	0.10
L	53	14	10	**1.4**
M	77	20	10	**2.0**
N	36	9.3	10	**0.93**
O	24	6.2	10	**0.62**
P	71	18	10	**1.8**
Q	45	12	10	**1.2**
R	8.7	2.3	10	**0.23**
S	53	14	10	**1.4**
T	16	4.1	10	**0.41**

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

Table E2 **PFOS+PFHxS estimated beef concentrations and human health risk quotients (RQ_{HH}) for beef consumption from beef cattle grazing on biosolids-amended soil at 10 t/ha repeat, 50 t/ha single and 50 t/ha repeat applications for biosolids from 20 STPs sampled (Pathways 4 and 5)**

STP	10 t/ha repeat applications		50 t/ha single application		50 t/ha repeat applications	
	Estimated beef conc. (µg/kg)	RQ_{HH}	Estimated beef conc. (µg/kg)	RQ_{HH}	Estimated beef conc. (µg/kg)	RQ_{HH}
A	3.3	0.49	2.3	0.34	16	2.4
B	0.52	0.077	0.36	0.053	2.5	0.37
C	6.8	1.0	4.7	0.71	33	4.9
D	9.8	1.5	6.8	1.0	48	7.1
E	2.8	0.42	2.0	0.29	14	2.1
F	4.4	0.65	3.0	0.45	21	3.1
G	3.3	0.50	2.3	0.34	16	2.4
H	1.6	0.24	1.1	0.16	7.7	1.1
I	2.9	0.43	2.0	0.30	14	2.1
J	1.6	0.23	1.1	0.16	7.5	1.1
K	0.63	0.093	0.43	0.065	3.0	0.45
L	8.4	1.3	5.8	0.87	41	6.1
M	12	1.8	8.6	1.3	60	9.0
N	5.8	0.86	4.0	0.60	28	4.2
O	3.9	0.58	2.7	0.40	19	2.8
P	12	1.7	8.1	1.2	57	8.5
Q	7.1	1.1	4.9	0.74	35	5.2
R	1.4	0.21	0.96	0.14	6.7	1.0
S	8.4	1.3	5.8	0.87	41	6.1
T	2.6	0.38	1.8	0.26	12	1.8

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

Table E3 **PFOS+PFHxS estimated beef concentrations and human health risk quotients (RQ_{HH}) for beef consumption from beef cattle consuming fodder grown on biosolids-amended soil at 10 t/ha repeat, 50 t/ha single and 50 t/ha repeat applications for biosolids from 20 STPs sampled (Pathway 5)**

STP	10 t/ha repeat applications		50 t/ha single applications		50 t/ha repeat applications	
	Estimated beef conc. (µg/kg)	RQ_{HH}	Estimated beef conc. (µg/kg)	RQ_{HH}	Estimated beef conc. (µg/kg)	RQ_{HH}
A	3.2	0.47	2.2	0.33	15	2.3
B	0.50	0.075	0.35	0.052	2.4	0.36
C	6.7	0.99	4.6	0.69	32	4.8
D	9.6	1.4	6.6	0.99	46	6.9
E	2.8	0.41	1.9	0.29	13	2.0
F	4.2	0.63	2.9	0.44	21	3.1
G	3.3	0.48	2.2	0.34	16	2.4
H	1.5	0.23	1.1	0.16	7.5	1.1
I	2.8	0.42	1.9	0.29	14	2.0
J	1.5	0.22	1.0	0.16	7.3	1.1
K	0.61	0.091	0.42	0.063	3.0	0.44
L	8.2	1.2	5.7	0.85	40	5.9
M	12	1.8	8.4	1.3	59	8.7
N	5.6	0.84	3.9	0.58	27	4.1
O	3.8	0.56	2.6	0.39	18	2.7
P	11	1.7	7.9	1.2	55	8.3
Q	6.9	1.0	4.8	0.72	34	5.0
R	1.3	0.20	0.93	0.14	6.5	0.97
S	8.2	1.2	5.7	0.85	40	5.9
T	2.5	0.37	1.7	0.26	12	1.8

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

Table E4 **PFOS+PFHxS estimated milk concentrations and human health risk quotients (RQ_{HH}) for milk consumption from dairy cows grazing on biosolids-amended soil at 10 t/ha repeat, 50 t/ha single and 50 t/ha repeat applications for biosolids from 20 STPs sampled (Pathways 7 and 8)**

STP	10 t/ha repeat applications		50 t/ha single applications		50 t/ha repeat applications	
	Estimated milk conc. (µg/L)	RQ_{HH}	Estimated milk conc. (µg/L)	RQ_{HH}	Estimated milk conc. (µg/L)	RQ_{HH}
A	0.26	**0.96**	0.18	**0.67**	1.3	**4.7**
B	0.041	0.15	0.028	0.11	0.20	**0.74**
C	0.54	**2.0**	0.38	**1.4**	2.6	**9.8**
D	0.78	**2.9**	0.54	**2.0**	3.8	**14**
E	0.22	**0.84**	0.16	**0.58**	1.1	**4.1**
F	0.35	**1.3**	0.24	**0.89**	1.7	**6.2**
G	0.26	**0.99**	0.18	**0.68**	1.3	**4.8**
H	0.13	**0.47**	0.087	**0.32**	0.61	**2.3**
I	0.23	**0.85**	0.16	**0.59**	1.1	**4.1**
J	0.12	**0.46**	0.085	**0.32**	0.60	**2.2**
K	0.050	0.19	0.034	0.13	0.24	**0.90**
L	0.67	**2.5**	0.46	**1.7**	3.2	**12**
M	0.98	**3.7**	0.68	**2.5**	4.8	**18**
N	0.46	**1.7**	0.32	**1.2**	2.2	**8.3**
O	0.31	**1.1**	0.21	**0.79**	1.5	**5.5**
P	0.93	**3.5**	0.64	**2.4**	4.5	**17**
Q	0.57	**2.1**	0.39	**1.5**	2.7	**10**
R	0.11	**0.41**	0.076	**0.28**	0.53	**2.0**
S	0.67	**2.5**	0.46	**1.7**	3.2	**12**
T	0.20	**0.75**	0.14	**0.52**	0.98	**3.7**

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

Table E5 **PFOS+PFHxS estimated milk concentrations and human health risk quotients (RQ_{HH}) for milk consumption from dairy cows consuming fodder grown on biosolids-amended soil at 10 t/ha repeat, 50 t/ha single and 50 t/ha repeat applications for biosolids from 20 STPs sampled (Pathway 8)**

STP	10 t/ha repeat applications		50 t/ha single applications		50 t/ha repeat applications	
	Estimated milk conc. (µg/L)	RQ_{HH}	Estimated milk conc. (µg/L)	RQ_{HH}	Estimated milk conc. (µg/L)	RQ_{HH}
A	0.25	0.94	0.17	0.65	1.2	4.5
B	0.040	0.15	0.028	0.10	0.19	0.72
C	0.53	2.0	0.37	1.4	2.6	9.6
D	0.76	2.8	0.53	2.0	3.7	14
E	0.22	0.82	0.15	0.57	1.1	4.0
F	0.34	1.3	0.23	0.87	1.6	6.1
G	0.26	0.96	0.18	0.67	1.2	4.7
H	0.12	0.46	0.085	0.32	0.59	2.2
I	0.22	0.82	0.15	0.57	1.1	4.0
J	0.12	0.45	0.083	0.31	0.58	2.2
K	0.048	0.18	0.034	0.13	0.23	0.87
L	0.65	2.4	0.45	1.7	3.2	12
M	0.96	3.6	0.66	2.5	4.6	17
N	0.45	1.7	0.31	1.2	2.2	8.1
O	0.30	1.1	0.21	0.77	1.4	5.4
P	0.90	3.4	0.63	2.3	4.4	16
Q	0.55	2.1	0.38	1.4	2.7	10
R	0.11	0.40	0.074	0.27	0.52	1.9
S	0.65	2.4	0.45	1.7	3.2	12
T	0.20	0.73	0.14	0.51	0.96	3.6

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

Appendix F – Estimated soil and pore water concentrations

Table F1 **Estimated soil and pore water concentrations for biosolids from each STP for the agricultural scenario (Scenario 3)**

Land application rate	STP	PFOS		PFOA		PFHxS	
		Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)
10 t/ha	A	0.15	0.24	0.092	1.4	0.0061	-
	B	0.024	0.041	0.014	-	< 0.00076	-
	C	0.32	0.97	0.047	1.9	0.013	0.78
	D	0.47	0.57	0.14	2.5	0.0069	0.14
	E	0.13	0.38	0.052	1.4	0.0084	0.24
	F	0.21	0.24	0.021	0.20	0.0061	0.064
	G	0.16	0.23	0.034	0.74	0.0023	-
	H	0.076	0.24	< 0.021	-	0.00076	-
	I	0.14	0.23	< 0.021	-	0.0023	-
	J	0.073	0.86	0.047	-	0.0023	-
	K	0.030	-	< 0.021	-	< 0.00076	-
	L	0.40	0.48	0.070	1.4	0.0053	0.11
	M	0.59	2.0	0.066	1.3	0.017	0.36
	N	0.27	0.42	0.064	1.1	0.0076	0.23
	O	0.18	0.42	0.062	1.1	0.0053	-
	P	0.54	1.9	0.11	4.7	0.029	1.4
	Q	0.34	0.80	0.18	5.2	0.0046	0.13
	R	0.066	0.16	0.015	-	< 0.00076	-
	S	0.40	1.2	0.019	-	0.0069	-

Land application rate	STP	PFOS		PFOA		PFHxS	
		Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)
	T	0.12	1.1	0.050	0.61	0.0023	0.028
10 t/ha repeat	A	1.1	1.7	0.64	9.7	0.043	-
	B	0.17	0.29	0.10	-	< 0.0053	-
	C	2.2	6.8	0.33	13	0.091	5.5
	D	3.3	4.0	0.96	17	0.048	0.97
	E	0.91	2.7	0.36	9.8	0.059	1.7
	F	1.4	1.7	0.14	1.4	0.043	0.45
	G	1.1	1.6	0.24	5.2	0.016	-
	H	0.53	1.7	<0.14	-	0.0053	-
	I	0.96	1.6	<0.14	-	0.016	-
	J	0.51	6.1	0.33	-	0.016	-
	K	0.21	-	<0.14	-	< 0.0053	-
	L	2.8	3.3	0.49	9.6	0.037	0.74
	M	4.1	14	0.46	8.8	0.12	2.5
	N	1.9	2.9	0.45	7.9	0.053	1.6
	O	1.3	3.0	0.43	8.0	0.037	-
	P	3.8	13	0.75	33	0.20	9.8
	Q	2.4	5.6	1.3	37	0.032	0.91
	R	0.46	1.1	0.10	-	< 0.0053	-
	S	2.8	8.5	0.13	-	0.048	-
	T	0.85	7.5	0.35	4.3	0.016	0.20

Land application rate	STP	PFOS		PFOA		PFHxS	
		Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)
50 t/ha	A	0.74	1.1	0.44	6.7	0.030	-
	B	0.12	0.20	0.067	-	< 0.0037	-
	C	1.6	4.7	0.23	9.3	0.063	3.8
	D	2.3	2.8	0.67	12	0.033	0.67
	E	0.63	1.8	0.25	6.8	0.041	1.2
	F	1.0	1.2	0.10	0.97	0.030	0.31
	G	0.78	1.1	0.16	3.6	0.011	-
	H	0.37	1.2	< 0.10	-	0.0037	-
	I	0.67	1.1	< 0.10	-	0.011	-
	J	0.36	4.2	0.23	-	0.011	-
	K	0.14	-	< 0.10	-	< 0.0037	-
	L	2.0	2.3	0.34	6.7	0.026	0.51
	M	2.9	9.9	0.32	6.1	0.081	1.7
	N	1.3	2.0	0.31	5.5	0.037	1.1
	O	0.89	2.1	0.30	5.6	0.026	-
	P	2.6	9.1	0.52	23	0.14	6.8
	Q	1.7	3.9	0.89	25	0.022	0.64
	R	0.32	0.78	0.070	-	< 0.0037	-
	S	2.0	5.9	0.093	-	0.033	-
	T	0.59	5.2	0.24	3.0	0.011	0.14

Land application rate	STP	PFOS		PFOA		PFHxS	
		Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)	Soil (µg/kg)	Pore water (ng/L)
50 t/ha repeat	A	5.2	8.0	3.1	47	0.21	-
	B	0.83	1.4	0.47	-	< 0.026	-
	C	11	33	1.6	65	0.44	27
	D	16	19	4.7	84	0.23	4.7
	E	4.4	13	1.8	48	0.29	8.1
	F	7.0	8.2	0.70	68	0.21	2.2
	G	5.4	7.7	1.1	25	0.078	-
	H	2.6	8.3	<0.70	-	0.026	-
	I	4.7	7.8	<0.70	-	0.078	-
	J	2.5	29	1.6	-	0.078	-
	K	1.0	-	<0.70	-	< 0.026	-
	L	13.7	16	2.4	47	0.18	3.6
	M	20	69	2.3	43	0.57	12
	N	9.3	14	2.2	38	0.26	7.9
	O	6.2	14	2.1	39	0.18	-
	P	18	64	3.6	160	0.99	47
	Q	12	21	6.2	180	0.16	4.5
	R	2.3	5.4	0.49	-	< 0.026	-
	S	14	41	0.65	-	0.23	-
	T	4.2	36	1.7	21	0.078	0.97

'<' indicates when the concentration in biosolids was below the limit of reporting (LOR) and the LOR was used to calculate soil concentrations

Appendix G – Selection of soil-to-plant transfer factors for grazing and fodder pathways

Pathways 4, 5, 7 and 8 in Scenario 3 consider risks to human health from beef and milk consumption from beef cattle/dairy cows grazing on biosolids-amended soil or consuming fodder grown in biosolids-amended soil. To estimate the concentrations in the plants/grass consumed by the animals, a soil-to-plant transfer factor (TF_S) was used.

To select a conservative TF_S for these calculations, C&R reviewed the available literature for PFOS and PFOA focusing on plant species most likely to be used for a grazing/fodder scenario (i.e. alfalfa, wheat, flax, rapeseed, oats and maize) (Tables G1 and Table G2, respectively). Only above-ground vegetative plant parts were considered in this review (i.e. not grains, roots, etc). The TF_S is the ratio of the concentration in the plant to the concentration in the soil as shown in Equation G1. All TF_S values are reported in Tables G1 and G2 on a dry weight basis as the plant ingestion rate for beef cattle/dairy cows is assumed on a dry matter basis (i.e. 13 kg/d). All references reported concentrations in a dry weight basis, except Braeunig et al. (2019) who reported plants concentrations on a wet weight basis. C&R converted these plant concentrations to dry weights and re-calculated TF_S values (details in Tables G1 and G2).

$$TF_S = \frac{conc.\ in\ plant\ (\mu g/kg\ dry\ weight)}{conc.\ in\ soil\ (\mu g/kg\ dry\ weight)} \qquad \text{Equation G1}$$

C&R notes there are a wide range of studies with a number of variables across the studies (e.g. plant species, concentration/treatment range, growing media, exposure duration). To account for this wide range of variability in selecting a conservative estimate of a TF_S, the 95th percentile from the PFOS and PFOA TF_S data has been used in the HHERA. These values are:

- PFOS – 1.4
- PFOA – 4.3.

Table G1 Summary of PFOS soil-to-plant transfer factors (TF_S) from the literature

Reference	Plant	Growing media	Transfer factor	Experimental details
Braeunig et al. (2019)*	Wheatgrass (shoots)	AFFF-impacted soils	0.53 1.2	• Two soils collected from AFFF-impacted airport sites and one uncontaminated soil • Soil properties: pH = 6.3–8.5, OC = 0.5–2.9%, sand = 54–92%, silt = 4–25%, clay = 5–33% • Plants harvested after 10 weeks
Brignole et al. (2003)	Alfalfa (vegetation)	Spiked artificial soil	1.6 0.27 0.18 0.064	• Soil spiked with PFOS at 5 concentrations ranging to 1,000 mg/kg • Soil properties: sand = 49%, silt = 30%, clay = 21%, organic matter = 2.1%, pH = 7.79 • Grown until fruit production
Brignole et al. (2003)	Flax (vegetation)	Spiked artificial soil	1.3 1.2 0.88	• Soil spiked with PFOS at 5 concentrations ranging to 1,000 mg/kg • Soil properties: sand = 49%, silt = 30%, clay = 21%, organic

Reference	Plant	Growing media	Transfer factor	Experimental details
				matter = 2.1%, pH = 7.79 • Grown until fruit production
Krippner et al. (2015)	Maize (straw)	Spiked soil	0.32 0.62	• Mixture of 10 PFAS spiked at 2 concentrations: 0.25 and 1 mg/kg • Soil properties: pH = 7.2, clay = 18%, silt = 34%, sand = 48% • Plants cultivated to maturity (128 days)
Lan et al. (2018)	Wheat (shoot)	Spiked soil	0.81 0.16	• Individually tested 6 PFAS spiked at 2 concentrations: 0.2 and 2 mg/kg • Soil properties: pH = 6.6, organic matter = 6.64%, sand = 25.6%, silt = 35%, clay = 39.4% • Shoots harvested after 4 weeks
Lasee et al. (2019)	Alfalfa (shoot)	Spiked sand	1.4	• Laboratory grade sand spiked with methanol stock solution containing 6 PFAAs • Plants grown for 2 months
Stahl et al. (2009)	Maize (straw)	Spiked soil-sand	0.13 0.10 0.21 0.20 0.16	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 5 months
Stahl et al. (2009)	Oats (straw)	Spiked soil-sand	0.22 0.15 0.27 0.76 0.83	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 3 months
Stahl et al. (2009)	Wheat (straw)	Spiked soil-sand	0.20 0.27 1.0 0.86 1.5	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 3.5 months
Stahl et al. (2009)	Wheatgrass (shoot)[#]	Spiked soil-sand	0.21 0.23 1.3 0.74 0.44	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • 4 grass cuttings over 6 weeks
Wen et al. (2014)	Wheat (straw)	Biosolids-amended soil	0.33 0.24 0.26 0.27	• Field collected biosolids-amended soil at 4 rates ranging from 4.5 to 36 dry t/ha (applied once a year since 2006) • Soil properties (control): pH = 8.11, organic matter = 0.78% • Plants harvested after 7 months
Wen et al. (2016)	Alfalfa (shoot)	Biosolids-amended soil	0.41	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, clay = 7.79%, silt =

Reference	Plant	Growing media	Transfer factor	Experimental details
				59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Wen et al. (2016)	Maize (shoot)	Biosolids-amended soil	0.17	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Wen et al. (2016)	Ryegrass (shoot)	Biosolids-amended soil	0.18	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Zhao et al. (2014)	Wheat (shoot)	Spiked soil	0.51 0.26 0.15 0.38 0.17 0.12	• Soil spiked with mixture of 11 PFAS at 3 concentrations: 200, 500 and 1,000 µg/kg (treatments with and without earthworms) • Soil properties: pH = 7.67, organic matter = 4.11%, CEC = 38.47 cmol/kg, clay = 24%, silt = 64%, sand = 12% • Plants harvested after 30 days
Zhao et al. (2017)	Rapeseed (shoot)	Spiked soil	0.65 0.55	• Soil spiked with PFOS and PFOA (300 µg/kg) with and without cadmium • Soil properties: pH = 7.51, OC = 1.81% • Plants harvested after 70 days
Zhao et al. (2017)	Wheat (shoot)	Spiked soil	0.28 0.13	• Soil spiked with PFOS and PFOA (300 µg/kg) with and without cadmium • Soil properties: pH = 7.51, OC = 1.81% • Plants harvested after 70 days

AFFF: aqueous film forming foams

CEC: cation exchange capacity

* Braeunig et al. (2019) reported plant concentrations on a wet weight basis. Transfer factors in the table were calculated by first converting the plant concentrations to a dry weight assuming 15% dry matter

The wheatgrass study by Stahl et al. (2009) investigated plant uptake of PFAS across 4 cuttings over a 6-week period. The transfer factors presented in the table from this study are the averages per concentration treatment across each of the cuttings

Table G2 Summary of PFOA soil-to-plant transfer factors (TF_S) from the literature

Reference	Plant	Growing media	Transfer factor	Experimental details
Braeunig et al. (2019)*	Wheatgrass (shoot)	AFFF-impacted soil	1.9 3.8	• Two soils collected from AFFF-impacted airport sites and one uncontaminated soil • Soil properties: pH = 6.3-8.5, OC = 0.5-2.9%, sand = 54-92%, silt = 4-25%, clay = 5-33% • Plants harvested after 10 weeks
Krippner et al. (2015)	Maize (straw)	Spiked soil	0.56 0.65	• Mixture of 10 PFAS spiked at 2 concentrations: 0.25 and 1 mg/kg • Soil properties: pH = 7.2, clay = 18%, silt = 34%, sand = 48% • Plants cultivated to maturity (128 days)
Lan et al. (2018)	Wheat (shoot)	Spiked soil	0.54 1.2	• Individually tested 6 PFAS spiked at 2 concentrations: 0.2 and 2 mg/kg • Soil properties: pH = 6.6, organic matter = 6.64%, sand = 25.6%, silt = 35%, clay = 39.4% • Shoots harvested after 4 weeks
Lasee et al. (2019)	Alfalfa (shoot)	Spiked sand	10	• Laboratory grade sand spiked with methanol stock solution containing 6 PFAAs • Plants grown for 2 months
Stahl et al. (2009)	Maize (straw)	Spiked soil-sand	0.27 0.13 0.21 0.31 0.31	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 5 months
Stahl et al. (2009)	Oats (straw)	Spiked soil-sand	0.88 0.69 0.18 3.6 4.3	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 3 months
Stahl et al. (2009)	Wheat (straw)	Spiked soil-sand	3.2 1.9 4.3 3.8 6.8	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • Plants harvested after approximately 3.5 months
Stahl et al. (2009)	Wheatgrass (shoot)[#]	Spiked soil-sand	2.3 2.9 3.0 1.6 1.1	• PFOS and PFOA spiked at 5 concentrations ranging from 0.25 to 50 mg/kg • Soil properties: pH = 7.0 • 4 grass cuttings over 6 weeks
Wen et al. (2014)	Wheat (straw)	Biosolids-amended soil	1.5 0.76 0.75 0.85	• Field collected biosolids-amended soil at 4 rates ranging from 4.5 to 36 dry t/ha (applied once a year since 2006) • Soil properties (control): pH = 8.11, organic matter = 0.78% • Plants harvested after 7 months

Reference	Plant	Growing media	Transfer factor	Experimental details
Wen et al. (2016)	Alfalfa (shoot)	Biosolids-amended soil	3.2	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Wen et al. (2016)	Maize (shoot)	Biosolids-amended soil	0.21	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Wen et al. (2016)	Ryegrass (shoot)	Biosolids-amended soil	1.3	• Field collected biosolids-amended soil received 20 dry t/ha for 9 years • Soil properties (control): pH = 7.36, OC = 1.01%, clay = 7.79%, silt = 59.1%, sand = 33.1%, CEC = 25 cmol/kg • Plants harvested after 45 days
Zhao et al. (2014)	Wheat (shoot)	Spiked soil	0.15 0.11 0.087 0.28 0.19 0.14	• Soil spiked with mixture of 11 PFAS at 3 concentrations: 200, 500 and 1,000 µg/kg (treatments with and without earthworms) • Soil properties: pH = 7.67, organic matter = 4.11%, CEC = 38.47 cmol/kg, clay = 24%, silt = 64%, sand = 12% • Plants harvested after 30 days
Zhao et al. (2017)	Rapeseed (shoot)	Spiked soil	0.052 0.042	• Soil spiked with PFOS and PFOA (300 µg/kg) with and without Cd • Soil properties: pH = 7.51, OC = 1.81% • Plants harvested after 70 days
Zhao et al. (2017)	Wheat (shoot)	Spiked soil	0.47 0.18	• Soil spiked with PFOS and PFOA (300 µg/kg) with and without cadmium • Soil properties: pH = 7.51, OC = 1.81% • Plants harvested after 70 days

* Braeunig et al. (2019) reported plant concentrations on a wet weight basis. Transfer factors in the table were calculated by first converting the plant concentrations to a dry weight assuming 15% dry matter

The wheatgrass study by Stahl et al. (2009) investigated plant uptake of PFAS across 4 cuttings over a 6-week period. The transfer factors presented in the table from this study are the averages per concentration treatment across each of the cuttings

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