

PFAS National Environmental Management Plan 3.0

National Chemicals Working Group
of the Heads of EPA
Australia and New Zealand

HEPA

© Copyright Commonwealth of Australia and each Australian State and Territory that has endorsed this version of the PFAS NEMP, 2025.

Ownership of intellectual property rights

Unless otherwise noted, copyright (and any other intellectual property rights) in this publication is owned by the Commonwealth of Australia (referred to as the Commonwealth) and each Australian State and Territory that has endorsed this version of the PFAS NEMP.

Creative Commons licence

PFAS National Environmental Management Plan Version 3.0 is licensed by the Commonwealth of Australia and each Australian State and Territory that has endorsed this version of the PFAS NEMP, for use under a Creative Commons Attribution 4.0 International Licence except content supplied by third parties, logos and the Commonwealth Coat of Arms.

Inquiries about the licence and any use of this document should be emailed to copyright@dcceew.gov.au.



Cataloguing data

This publication (and any material sourced from it) should be attributed as: HEPA 2025, *PFAS National Environmental Management Plan Version 3.0*, Heads of EPA Australia and New Zealand 2025. CC BY 4.0.

This publication is available at dcceew.gov.au/publications.

Department of Climate Change, Energy, the Environment and Water

GPO Box 3090 Canberra ACT 2601

Telephone 1800 900 090

Web dcceew.gov.au

Disclaimer

The Australian Government and each Australian State and Territory acting through the Heads of EPA Australia and New Zealand has exercised due care and skill in preparing and compiling the information and data in this publication. Notwithstanding, the Australian Government and each Australian State and Territory, its employees and advisers disclaim all liability, including liability for negligence and for any loss, damage, injury, expense or cost incurred by any person as a result of accessing, using or relying on any of the information or data in this publication to the maximum extent permitted by law.

Acknowledgement of Country

We acknowledge the Traditional Custodians of Australia and their continuing connection to land and sea, waters, environment and community. We pay our respects to the Traditional Custodians of the lands we live and work on, their culture, and their Elders past and present.

Contents

Introduction	1
Acknowledgements	2
1 Scope	4
1.1 What the PFAS NEMP does	4
1.2 An introduction to PFAS	6
2 Australia and New Zealand's international obligations	10
2.1 Introduction	10
2.2 International obligations in relation to PFOS, PFOA and PFHxS	11
3 Guiding principles	13
3.1 General environmental obligations concerning PFAS	15
3.2 Managing PFAS inputs – source control	16
4 Communication and engagement	19
4.1 Roles and responsibilities	19
4.2 Principles for effective engagement	20
4.3 Approaches for environmental regulators	21
5 PFAS monitoring	23
5.1 Planning and design of environmental monitoring programs	23
5.2 Ambient monitoring programs	25
5.3 Site-specific monitoring programs	30
6 PFAS inventory	33
6.1 Scope of a PFAS inventory	33
6.2 Conducting a PFAS inventory	34
6.3 Case study – firefighting foam survey	34
7 PFAS-contaminated site prioritisation	37
7.1 Site prioritisation process	37
7.2 Next steps after site prioritisation	38
7.3 Case study – preliminary PFAS prioritisation	38
8 PFAS environmental guideline values	41
8.1 Considerations for using guideline values	41
8.2 Basis for selection of the guideline values included in the PFAS NEMP	43
8.3 Exposure pathways for human health assessments	43
8.4 Exposure pathways for ecological assessments	44

8.5	Consideration of bioaccumulation	46
8.6	Health-based guideline values	47
8.7	Ecological guideline values	52
8.8	Information on alternative approaches to risk assessment and environmental management of PFAS compounds and mixtures ..	64
9	PFAS-contaminated site assessment	73
9.1	Site investigation process	74
9.2	Risk assessment	75
9.3	PFAS-specific considerations	76
10	On-site stockpiling, storage and containment	83
10.1	Risk-based management	85
10.2	Design considerations	87
10.3	Detailed guidance on design, construction and management of on-site stockpiling, storage and containment	90
11	Transport of PFAS-contaminated material	103
11.1	Waste code for PFAS-contaminated material	103
11.2	Considerations for transport	103
12	Reuse of PFAS-contaminated material including soils and water ..	106
12.1	Reuse of soil	106
12.2	Reuse with a detailed risk assessment	110
12.3	Reuse requiring consultation with the environmental regulator	111
12.4	Organic waste and resource recovery materials	112
12.5	Reuse of PFAS-contaminated water	118
13	PFAS site remediation and management	123
13.1	International obligations	123
13.2	Australian jurisdictional requirements	124
13.3	Why and when site remediation may be triggered	124
13.4	Considerations in setting remediation goals and objectives ..	125
13.5	Preferred remediation hierarchy and treatment options	128
13.6	Demonstrating remediation success	131
13.7	Long-term management strategies	132
14	PFAS disposal to landfill	135
14.1	Landfill siting and design	135
14.2	Landfill operation	136
14.3	Leachate management practices	136
14.4	Monitoring at landfills	137

14.5	Closure considerations	138
14.6	Landfill acceptance criteria	138
15	PFAS in the wastewater treatment system	143
15.1	PFAS management framework	144
15.2	Additional management tools	145
15.3	Case study – PFAS contamination of a wastewater treatment system	145
15.4	PFAS criteria in biosolids	146
16	Data sharing	153
17	PFAS notification	155
17.1	Case study – General environmental duty	155
18	PFAS sampling	157
18.1	Sampling and analysis quality plans	157
18.2	Sampling and quality assurance and quality control	161
18.3	Assessing PFAS leachability	166
19	PFAS analysis	176
19.1	Standard and non-standard analysis methods	176
19.2	Considerations for selecting an analysis method	180
19.3	Consideration of non-standard methods including relevance to site assessment and broader environmental assessment	184
19.4	Guidance on analysis of PFAS in solid organic waste and resource recovery materials	189
20	Future work	195
20.1	Theme 1 – The PFAS chemical family	195
20.2	Theme 2 – Environmental data and monitoring	195
20.3	Theme 3 – Water	195
20.4	Theme 4 – Soil	195
20.5	Theme 5 – Resource recovery and waste management	196
20.6	Theme 6 – Site-specific application of the PFAS NEMP guidance	196
21	Review	198
21.1	Informal review	198
21.2	Formal review	198
Appendix A		
	The PFAS chemical family	200

Appendix B	
PFAS ambient sampling guideline	208
B.1 Objectives	208
B.2 Background	208
B.3 Sampling design	209
Appendix C	
Activities associated with sources of PFAS contamination	223
Appendix D	
Treatment technologies potentially available in Australia	228
Appendix E	
Matters to inform selection of management and remediation options	233
E.1 Likelihood of hazard or risk occurring	233
E.2 Degree of harm that might result from hazard or risk, and/or level of protection that may be required	234
E.3 Availability and suitability of practical mechanisms to eliminate/minimise risk	235
E.4 Costs and benefits associated with available ways of eliminating/minimising risk	237
Appendix F	
Example stockpiling, storage and containment checklist and framework	240
Appendix G	
Example PFAS Management Framework for a water utility	244
G.1 Introduction	244
G.2 Governance	245
G.3 Purpose	245
G.4 Scope	246
G.5 Risks	246
G.6 Monitoring and analysis	248
G.7 Input stage	250
G.8 Processing stage	252
G.9 Outputs stage	254
Appendix H	
Overview of PFAS leaching methods	259
Appendix I	
Abbreviations and Glossary	270
References	282

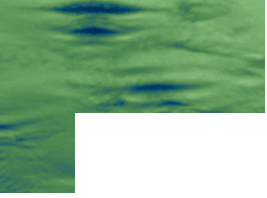
Tables

Table 1	PFAS ambient land use classes	28
Table 2	PFOS concentrations in water by ambient land use class in Victoria	29
Table 3	PFOS and PFOA concentrations in water by ambient land use classes in Queensland	30
Table 4	Health-based guideline values developed by health authorities	48
Table 5	Human health investigation levels for soil	50
Table 6	Ecological guideline values for soil	56
Table 7	Biota guideline values	57
Table 8	Ecological water quality guideline values	59
Table 9	Stockpiling, storage and containment infrastructure	85
Table 10	Hierarchy of levels of assessment and management required for some common organic waste types with respect to potential PFAS content	117
Table 11	Landfill acceptance criteria	141
Table 12	Criteria for PFOS + PFHxS and PFOA in biosolids and maximum allowable soil contaminant concentrations based on a 1-, 2- and 5-fold margin of safety	150
Table 13	General guidance on sampling environmental media and materials and reference to relevant PFAS NEMP sections by media	158
Table 14	Examples of laboratory-based leaching methods available to assess the release of PFAS from soils and solid material	170
Table 15	Examples of field-based leaching methods available to assess the release of PFAS from soils and solid material	172
Table 16	Methods of PFAS analysis: standard and selected non-standard methods*	177
Table A1	Common PFAS compounds	203

Table B1	Example sample location data	210
Table B2	Typical suite of PFAS compounds and LOR currently analysed by commercial laboratories (grouped by PFAS analyte)	211
Table B3	Guidance on the frequency of collection and purpose of quality control samples	216
Table C1	Activities associated with PFAS contamination due to fire risk	223
Table C2	Activities associated with PFAS contamination more broadly	224
Table D1	PFAS treatment technologies currently available in Australia	229
Table D2	PFAS treatment technologies in Australia currently on trial or require further development	231
Table F1	Example checklist for storage of unused chemicals containing PFAS	240
Table F2	Example framework for short-term stockpile management	241
Table G1	Example wastewater treatment plant risk assessment	248
Table H1	Overview of laboratory-based leaching methods commonly applied and commercially available in Australia	259
Table H2	Overview of field-based leaching methods commonly applied and commercially available in Australia	267
Table I1	Abbreviations	270
Table I2	Glossary	275

Figures

Figure 1	An example of potential human health pathways for PFAS exposure	44
Figure 2	An example of potential ecological pathways for PFAS exposure	45
Figure 3	Examples of key pathways to consider in a risk assessment for PFAS in (a) terrestrial ecosystems; (b) wetlands; and (c) coastal environments	45
Figure 4	Examples of plausible mechanistic pathways for PFAS toxicity	53
Figure 5	Chemical partitioning relationships between generalised environmental compartments, including sediments and biota	61
Figure 6	Example of a cap cover with several layers	94
Figure 7	Decision tree for soil reuse	109
Figure 8	Example of PFCA precursor oxidation in the TOP assay	187
Figure 9	Example of PFSA precursor oxidation in the TOP assay	187
Figure 10	TOP assay applied to groundwater	188
Figure A1	The PFAS chemical family with examples of individual compounds	201
Figure A2	Alkyl chain with a functional group at both ends	202
Figure A3	Cyclic compounds with and without a fully fluorinated alkyl side chain	202



Introduction

The environmental management of the group of manufactured chemicals known as PFAS (per- and polyfluoroalkyl substances) is a high priority for environmental regulators around Australia and in New Zealand. This reflects the widespread presence of PFAS in the environment, its unusual chemical properties, the uncertainties associated with its potential risks, and the resulting need for a precautionary approach to protect the environment and/or human health.

The PFAS National Environmental Management Plan (PFAS NEMP) provides nationally agreed guidance on the management of PFAS contamination in the environment, including prevention of the spread of contamination. It supports collaborative action on PFAS by the Commonwealth, state and territory and local governments around Australia and the government of New Zealand. The PFAS NEMP is an Appendix to the Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination (Australian Government 2018a).

The PFAS NEMP reflects the current state of knowledge and is updated periodically to reflect new scientific evidence and guidance.

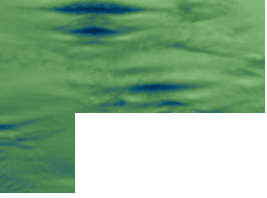
The first version of the PFAS NEMP, known as NEMP 1.0, was published in February 2018. It was developed by the Heads of EPA Australia and New Zealand (HEPA) at the request of Environment Ministers around Australia.

NEMP 2.0 was published in January 2020 and contained expanded and updated guidance on guideline values, soil reuse, wastewater management and on-site containment.

The widespread presence of PFAS in the environment in Australia and around the world is a result of their unique properties, which have led to them being widely used for many decades. PFAS are persistent and highly resistant to physical, chemical and biological degradation, and therefore PFAS are found in humans, animals and the environment around Australia.

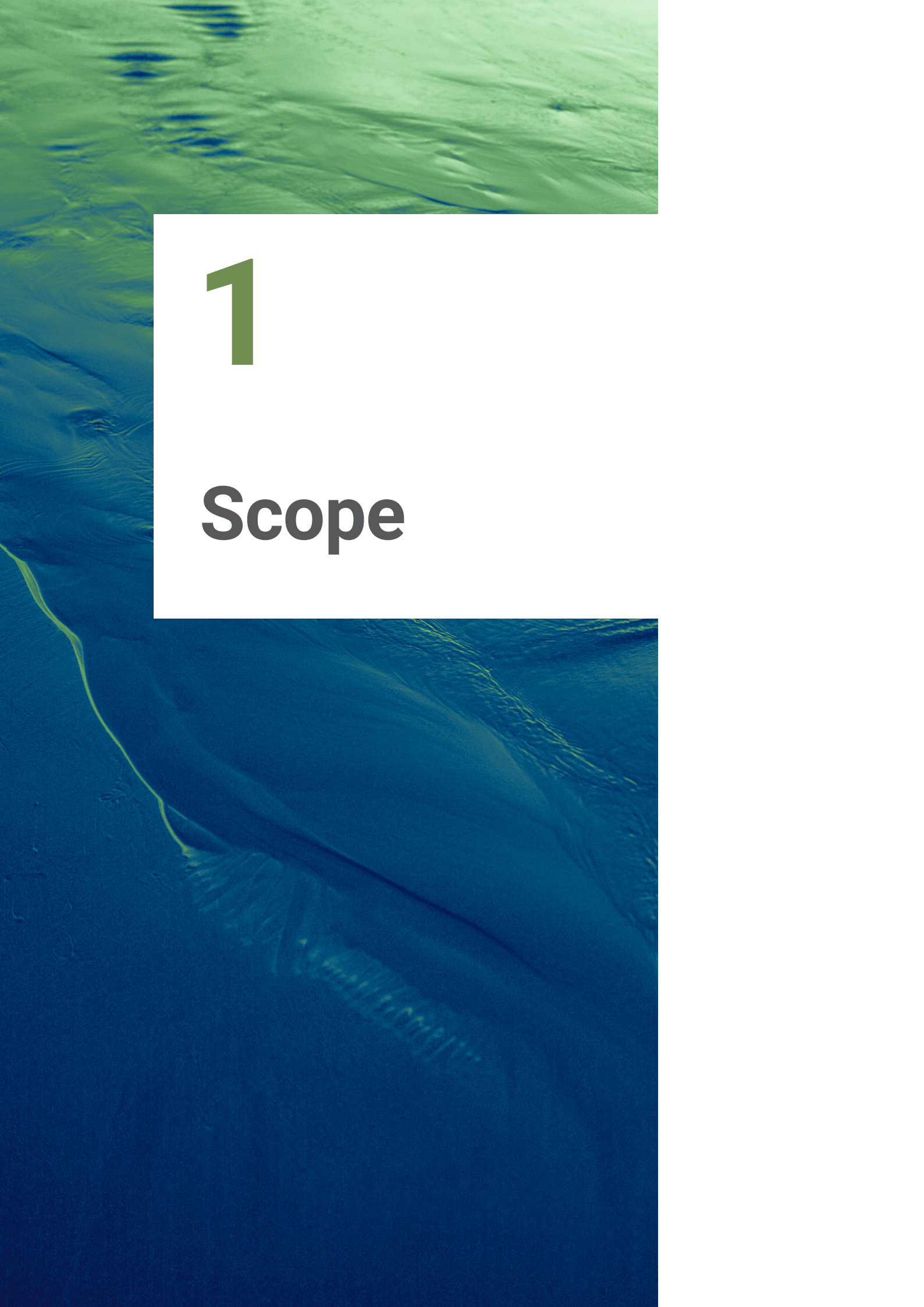
Addressing the wide range of issues associated with PFAS contamination, including the management of PFAS-contaminated material, represents a challenge for us as environmental regulators. These are challenges best dealt with collectively.

The PFAS NEMP recognises the need for sound regulation of PFAS by each jurisdiction in a way that can adapt to local circumstances and emerging priorities.



Acknowledgements

HEPA acknowledges the contributions of Commonwealth, State, Territory and New Zealand agencies to the PFAS NEMP 3.0. HEPA thanks agency representatives for their involvement, and everyone who has provided input and feedback to inform its ongoing development.

The background of the slide is a photograph of a river. The top portion of the image shows a wide, calm section of the river with a light greenish-brown hue. The bottom portion shows a narrower, faster-moving section with a deep blue hue and visible white rapids. A white rectangular box is positioned on the left side, overlapping both the top and bottom river sections. Inside this box, the number '1' is displayed in a large, bold, green font, and the word 'Scope' is displayed below it in a bold, dark grey font.

1

Scope

1 Scope

1.1 What the PFAS NEMP does

The PFAS National Environmental Management Plan (PFAS NEMP):

- provides guidance about the environmental management of per- and polyfluoroalkyl substances (PFAS), with a focus on preventing and managing PFAS contamination
- recognises that different PFAS production methods and subsequent transformation processes can create complex mixtures of many different intentionally produced and unintentionally generated PFAS compounds (see [Appendix A](#); see also Buck et al. 2011; ITRC 2017 and 2018a; OECD 2018 and 2021; NICNAS (for example, 2015a, 2015b, 2015c, 2017, 2019a and 2019b); Wang et al. 2018) requiring consideration, at least qualitatively
- recognises that production processes and products change over time and the definitions of what constitutes PFAS change to reflect this (see [Section 1.2](#) below)
- focuses on perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexane sulfonate (PFHxS), and their direct and indirect precursors, as these are the most widely studied PFAS
- recognises that the globally accepted definitions of PFOS, PFOA, and PFHxS, and long-chain perfluorocarboxylic acids (LC-PFCAs), include their salts and related compounds, including precursors, as established by the listing of PFOS, PFOA, and PFHxS and the proposed listing of LC-PFCAs under the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention)
- recognises that PFOS, PFOA, and PFHxS are usually primary indicators of the presence of a broad range of PFAS compounds, where contamination stems from the historic use of products formed by processes that a number of major manufacturers have phased out. Examples of PFAS formed by this chemistry are found in Barzen-Hanson et al. (2017)
- recognises that other types of PFAS, both long- and short-chain, are more likely associated with contamination caused by release of more modern and replacement PFAS-containing products, including compounds that transform into PFOA and homologues
- recognises that PFAS other than PFOS, PFOA, and PFHxS may also be present and in greater proportions in situations where historic contamination has not significantly dispersed and/or where modern replacement fluorotelomer-based PFAS products, which are not based on PFOS and PFHxS and related compounds, are predominant (Weiner et al. 2013; Backe et al. 2013)

- recognises that environmental standards for PFOS, PFOA and PFHxS encompass contributions from protonated acids and their conjugate bases, and that when considering chemical equivalence of precursors, where practicable, consideration of molar equivalence is desirable (for example, one mole 8:2 diPAP PFOA precursor potentially yields two moles of PFOA)
- recognises the need to respond to a rapidly evolving scientific understanding of PFAS characteristics, management techniques and environmental risks, including regular review of the guidance provided for specific PFAS
- recognises that in addition to primary sources (for example, contaminated sites where PFAS has been used), secondary sources for PFAS contamination may include facilities that receive waste and wastewater containing PFAS from a range of diffuse sources, such as landfills and wastewater treatment plants (WWTPs). The majority of PFAS diffused in the environment is attributed to a wide range of historic and current consumer, commercial and industrial products and articles in which PFAS have been used, with important entry points into the environment including sewage treatment outfalls, contaminated sites and landfills
- recognises the importance of managing PFAS contamination, including beneficial reuse of PFAS-contaminated material and wastes, in a way that maintains environmental values (including future land use options)
- considers the identification and implementation of site- and catchment-specific PFAS risk management actions
- recognises the role of Australia's health-based guidance on PFAS and ongoing research to better understand any human health effects, noting the recommendation that as a precaution, human exposure to PFAS be minimised since these chemicals remain in humans and the environment for many years (Department of Health and Aged Care 2024)
- does not address current use and management of PFAS-containing products and articles, except in supporting transition away from such use where practicable and managing environmental and waste contamination (Australian Government 2019a). Environmental regulators may take action to restrict and manage the use of PFAS-containing products and articles under national or their jurisdictional legislation, as well as promote public awareness of environmental issues associated with PFAS use
- recognises that managing PFAS is part of, and should be integrated into, the management of contaminants of concern more broadly.

1.2 An introduction to PFAS

PFAS is an abbreviation for per- and polyfluoroalkyl substances. PFAS are manufactured chemicals that have been used for more than 50 years. PFAS make products non-stick, oil- and water-repellent, and fire, weather- and stain-resistant. PFAS have been used in a range of consumer products, such as carpets, clothes, food packaging and paper, and have also been used in firefighting foams, pesticides and stain repellents. Some major manufacturers have agreed to voluntarily phase out PFOS and PFOA chemistry in making their products.

The most well-known PFAS are PFOS, PFOA and PFHxS. These three PFAS are part of a broader group of PFAS known as perfluoroalkyl acids (PFAAs), which resist physical, chemical and biological degradation, and are very stable. This stability creates a problem as these PFAS last for a long time. A wide range of other PFAS, known as precursors, can transform into PFAAs in products in the environment, and are also considered environmentally significant. [Appendix A](#) provides an overview of the PFAS chemical family. A number of PFAS compounds are listed on the [Australian Inventory of Industrial Chemicals](#) (Inventory search options include chemical name, molecular formula, registration number, etc) which is maintained by the [Australian Industrial Chemicals Introduction Scheme \(AICIS\)](#). Similarly, a number of PFAS compounds are listed on the New Zealand EPA's [Inventory of Chemicals \(NZIoC\)](#).

The Organisation for Economic Co-operation and Development (OECD) defines PFAS, from a chemical structure point of view, as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon (C) atom (without any hydrogen (H)/chlorine (Cl)/bromine (Br)/iodine (I) atom attached to it); that is, with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($-\text{CF}_3$) or a perfluorinated methylene group ($-\text{CF}_2-$) is a PFAS (OECD 2021).

This definition provides a broadly recognised scope which reduces confusion as to what constitutes a PFAS. Within this scope, it is possible to consider how the diverse molecular structures (for example, neutral, anionic, cationic or zwitterionic; with or without aromatic rings; non-polymers or polymers; low molecular weight or high molecular weight) and thus diverse physical, chemical and biological properties (for example, involatile or volatile; water soluble or water insoluble; reactive versus inert; bioaccumulative or non-bioaccumulative) may give rise to potential risks to the environment and/or human health, leading to the development of related environmental management measures.

1.2.1 Chemical structure and resulting environmental behaviour

The distinguishing characteristic of PFAS are a chain of carbon atoms bonded to fluorine (F) atoms. Some PFAS compounds, including PFOS, PFOA and PFHxS, have a hydrophilic functional group at the end of the chain.

The chemical structure of PFAS, including variations in chemical structure between different types of PFAS, is an important consideration for understanding the behaviour of PFAS in the environment. The high solubility of many PFAS in water means that PFAS may readily leach from soil and sediments into surface water and groundwater, where they can move long distances to enter creeks, rivers and lakes, estuaries, and marine ecosystems and become part of the food chain, being transferred from organism to organism. Research into the effects of PFAS on organisms, such as potential multigenerational effects on aquatic wildlife, is ongoing. Work is also underway to understand and predict the behaviour of different PFAS in the environment. [Section 8.3](#) and [Section 8.4](#) provide an overview of selected PFAS pathways in the environment.

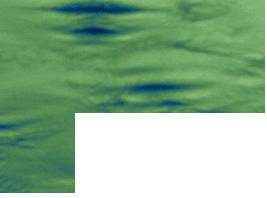
1.2.2 Use and resulting contamination

In Australia, PFAS have been used for a long time in a wide range of consumer products and industrial applications, including certain firefighting foams. There are now PFAS-contaminated sites around Australia resulting from these various uses. Over time, the chemicals have worked their way across and through the soil to contaminate surface water and groundwater, and have migrated into adjoining land areas. PFAS are also present in waste streams, including at landfills and wastewater treatment facilities, and more broadly in the environment.

In addition to the searchable Australian Inventory of Industrial Chemicals (see above), AICIS also provides information on [PFAS](#) for consumers and the community.

The PFAS NEMP uses terms including 'PFAS contamination' and 'PFAS-contaminated' when referring to environmental media in which detectable levels of PFAS are present. This reflects the fact that PFAS are synthetic organic compounds, for which there is no natural background (ambient) level. The presence of PFAS in environmental media does not necessarily constitute an unacceptable environmental and/or human health risk. Risk depends on a range of factors, including:

- PFAS compounds present
- PFAS leachability and concentration
- degree of exposure
- types of receptors exposed
- land use
- environmental values present

- 
- level of environmental protection
 - potential for bioaccumulation
 - environmental media in which the contamination occurs.

Section 9 provides further information on the assessment of PFAS contamination.



2

Australia and New Zealand's international obligations

2 Australia and New Zealand's international obligations

2.1 Introduction

Documents such as the PFAS National Environmental Management Plan (PFAS NEMP) should take into account international rules, standards, and guidelines, such as those established through international treaties.

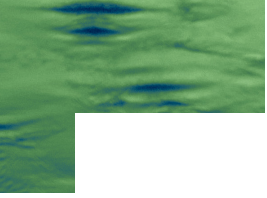
Australia and New Zealand are parties to the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention), a multilateral environmental agreement to protect the environment and/or human health from persistent organic pollutants (POPs). The Stockholm Convention sets globally accepted standards for the use and management of certain POPs. Parties to the Stockholm Convention participate in the listing process for identified chemicals of concern and consider the actions necessary to give effect to the final decision in each country.

Australia and New Zealand are also parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) and the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (Rotterdam Convention).

It is important to note that technical guidance issued under a Convention may be adopted for the implementation of another Convention. For example, the Basel Convention produces technical guidelines for POPs that can be addressed cooperatively with the Stockholm Convention under its Article 6 – Measures to reduce or eliminate releases from stockpiles and wastes, including the:

- General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with POPs, that contain low POP content limits (LPCLs)
- Technical Guidelines on wastes consisting of, containing or contaminated with PFAS (PFOS, PFOA and PFHxS), that contain more specific guidance for these wastes.

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) is the lead agency in Australia on the Stockholm Convention, the Basel Convention and the Rotterdam Convention for provisions applying to chemicals that have an industrial use. In New Zealand, the Environmental Protection Authority Te Mana Rauhi Taiao is the lead operational agency on the Stockholm Convention, the Basel Convention and the Rotterdam



Convention, with Ministry for the Environment Manatū Mō Te Taiao being the policy lead.

2.2 International obligations in relation to PFOS, PFOA and PFHxS

To date, the PFAS compounds listed as POPs under the Stockholm Convention are:

- PFOS, its salts, and perfluorooctane sulfonyl fluoride (PFOSF). Listed on Annex B (restriction) in 2009. Note that the listing of PFOSF captures a wide range of PFOS-related compounds derived from PFOSF
- PFOA, its salts, and PFOA-related compounds. Listed on Annex A (elimination) in 2019
- PFHxS, its salts and PFHxS-related compounds. Listed on Annex A (elimination) in 2022.

As at July 2024, the Australian Government is considering the steps required to undertake the ratification process to adhere to the Stockholm Convention obligations for the listings of PFOS, PFOA and PFHxS.

New Zealand has ratified the listings of PFOS, PFOA and PFHxS. In the case of PFOA, New Zealand has registered for the specific exemptions provided for use in photographic coatings applied to films, and use in firefighting foam in installed systems. Both of these exemptions will expire on 3 December 2025.

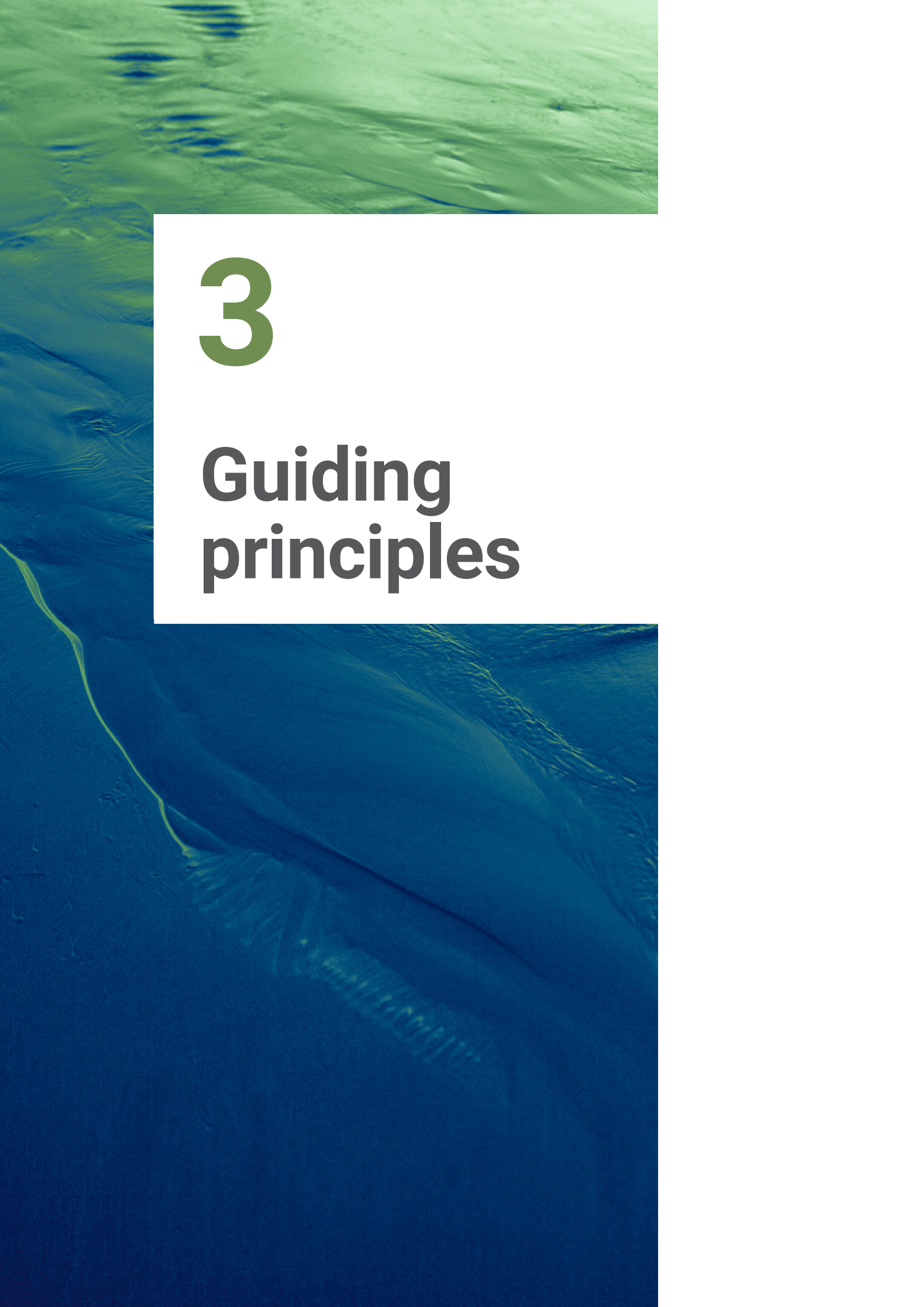
The Stockholm Convention is supported by a scientific body, the Persistent Organic Pollutants Review Committee (POPRC). The POPRC reviews proposals for listing POPs on the Stockholm Convention and makes recommendations to the decision-making body for the Convention (the Conference of the Parties) based on its analysis.

The POPRC assess listing proposals, which can include other PFAS, based on the following screening criteria:

- persistence
- bioaccumulation
- potential for long-range environmental transport
- evidence for adverse impacts.

Subject to recommendations from the POPRC, additional PFAS may be considered for listing on the Stockholm Convention in the future.

Note that references throughout the PFAS NEMP to the listing of PFOS, PFOA and PFHxS, and potential listing of other PFAS, include their respective salts and related compounds.

An aerial photograph of a river delta, showing a network of channels and distributaries. The water is a mix of green and blue, with the green areas likely representing shallower, vegetated regions and the blue areas representing deeper water. The land is visible as a light brown/tan color, forming a triangular shape at the river's exit into a larger body of water.

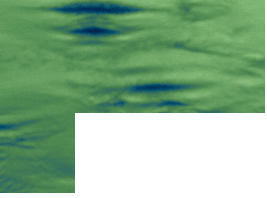
3

Guiding principles

3 Guiding principles

The following principles of sound environmental regulation guided the development of the PFAS National Environmental Management Plan (PFAS NEMP) and will continue to guide its further development and implementation:

- 1 A focus on protection of the environment, including flora and fauna, ecological communities and ecosystems and, as a precaution, protection of human health
- 2 Consideration of the principles established by the Intergovernmental Agreement on the Environment, which is a Schedule to the National Environment Protection Council Act 1994 (Cth) (NEPC Act), in all decision-making, including:
 - a) the precautionary principle. This principle states that where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation. In the application of the precautionary principle, public and private decisions should be guided by:
 - i) careful evaluation to avoid, wherever practicable, serious or irreversible damage to the environment
 - ii) an assessment of the risk-weighted consequences of various options
 - b) intergenerational equity. This principle states that the present generation should ensure that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations
 - c) conservation of biological diversity and ecological integrity. This principle states that conservation of biological diversity and ecological integrity should be a fundamental consideration
 - d) improved valuation, pricing and incentive mechanisms. This principle states that:
 - i) environmental factors should be included in the valuation of assets and services
 - ii) polluter pays; that is, those who generate pollution and waste should bear the cost of containment, avoidance or abatement
 - iii) the users of goods and services should pay prices based on the full life cycle costs of providing good and services, including the use of natural resources and assets and the ultimate disposal of any wastes

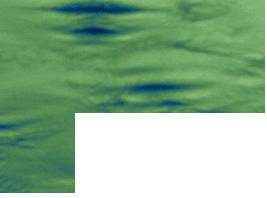
- 
- iv) environmental goals, having been established, should be pursued in the most cost-effective way, by establishing incentive structures, including market mechanisms, which enable those best placed to maximise benefits and/or minimise costs to develop their own solutions and responses to environmental problems
 - 3 Regulatory actions and decisions that are risk-based, informed by scientific evidence, focused on identified PFAS exposure pathways to ecological and human receptors, and meet national and international obligations
 - 4 Quantitative and qualitative PFAS assessment based on appropriate analytical methods and standards, with the required quality assurance and control
 - 5 Consistency across jurisdictions, supported by the PFAS NEMP, with consideration of accountability for pollution and for management actions
 - 6 Coordinated and cooperative action on cross-boundary issues, including within catchments
 - 7 Consideration of relevant legislative and policy frameworks for chemical and environmental management within and across jurisdictions and at the national and international level
 - 8 Integration with existing national governance mechanisms, including:
 - a) the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure 1998 (MCW NEPM) (Australian Government 1998)
 - b) the National Environment Protection (Assessment of Site Contamination) Measure 1999, (ASC NEPM), amended 2013 (Australian Government 1999a)
 - c) the National Water Quality Management Strategy (NWQMS) (Australian Government 2019b), including the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (WQG) (ANZG 2018)
 - d) the Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination (Australian Government 2018a)
 - 9 Where existing principles, guidelines, approaches or management options do not adequately foresee or address an identified environmental risk, responses guided by available scientific approaches, the precautionary principle and the understanding that action may be required to reduce risks
 - 10 Consideration of sustainability, including environmental, economic and social factors, when assessing the benefits and effects of management options, acknowledging the limited management options for PFAS currently available in Australia.

3.1 General environmental obligations concerning PFAS

Environmental legislation in many jurisdictions includes obligations and duties to understand and prevent or minimise risks of, and report occurrences of, environmental harm, nuisances, waste mismanagement and contamination. For example, a general environmental duty to prevent off-site dispersal of PFAS and on-site environmental harm should be complied with in jurisdictions where such a duty exists. These provisions are relevant to PFAS contamination, which can be environmentally significant due to its persistence, mobility and, for some PFAS, toxicity and potential for bioaccumulation in plants and animals.

The following actions will enable the responsible person or organisation to demonstrate compliance with these obligations and duties:

- understanding the PFAS content of products, articles and materials and/or the presence of PFAS contamination, for example, by determining the concentrations of PFAS present and/or the nature and location of PFAS sources
- where PFAS are present in products, articles and materials that present a risk to the environment and/or human health or more efficient resource usage through a circular economy, transitioning to use safer alternatives where practicable, excepting where PFAS usage is essential for health or safety, or critical for the functioning of society
- understanding the environmental values that may be impacted by the contamination, both on- and off-site, such as:
 - determining the surface water and groundwater environments, including any freshwater, estuarine and marine components, and any groundwater-dependent ecosystems
 - determining potential impacts of soil contamination on current and future land uses, and terrestrial ecosystems
 - determining what the water is used for, particularly its community values
 - considering important issues including any off-site movement, PFAS transformations, and exposure pathways to receptors
 - identifying and monitoring potential environmental sinks and receptors, such as soils, sediments and biota
- taking all reasonable and practicable measures to prevent or minimise potential environmental harm from PFAS-related activities and contamination, such as:
 - ensuring PFAS wastes, contaminated material and products are effectively stored and/or remediated to prevent release
 - having appropriate contingency plans to deal with leaks and spillage

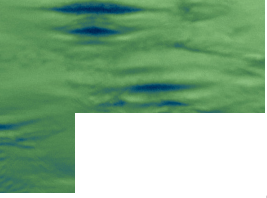
- 
- undertaking appropriate monitoring to check the effectiveness of management measures implemented and to assess the extent and impacts of any contamination
 - ensuring proper disposal of PFAS-contaminated waste by properly characterising waste and sending it to a facility licensed to accept it, noting dilution is not acceptable in soil, air, compost or other wastes or products
 - ensuring PFAS-contaminated material for reuse, including reused waste, are appropriately managed to prevent harm to land use, the environment, and/or human health
 - ensuring environmental regulators and any persons or organisations likely to be adversely affected by any releases are promptly advised of any incidents and contamination.

Non-compliance with these duties, including not taking actions such as those described above, may trigger a range of regulatory responses. Environmental regulators have produced guidance on how to meet these obligations for PFAS-containing products, articles and material.

3.2 Managing PFAS inputs – source control

A large body of work is underway internationally and across Australia and New Zealand to manage existing contamination and to increase our ability to prevent further contamination from PFAS and other industrial chemicals of concern. Transitioning away from the use of chemicals that cause irreversible or long-term contamination of the environment should be the ultimate goal for all users of PFAS in Australia (Australian Government 2019a) and New Zealand. Importers, sellers, and users of chemicals should inform themselves about the presence of PFAS in products and articles, due to their potential negative environmental, health and socio-economic impacts. Entities that currently sell or use long- (or short-) chain PFAS are encouraged to develop strategies that outline their current uses, and how and when they will transition away from these chemicals (Australian Government 2019a).

PFOA, PFHxS, their salts and related compounds are listed under Annex A of the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention) which stipulates their production and use in firefighting foams is to be eliminated. Specific exemptions are listed in Annex A but are only available to contracting parties that have registered for that exemption, and this does not include Australia. New Zealand has registered for the specific exemptions provided for use in photographic coatings applied to films, and use in firefighting foam in installed systems. Both of these exemptions will expire on 3 December 2025.



PFOS, its salts, and PFOSF are listed under Annex B of the Stockholm Convention which stipulates their production and use is restricted to those applicable acceptable purposes and/or specific exemptions listed in Annex B. In New Zealand's acceptance of the listing of PFOS, its salts, and PFOSF, none of the allowed acceptable purposes or specific exemptions have been adopted.

The Australian Government's National PFAS Position Statement (Australian Government 2019a) states that the ongoing sale or use of products that contain long-chain PFAS should be phased out, in line with the Stockholm Convention. Where short-chain PFAS are used in aqueous film-forming foam (AFFF), they should only be used in emergency situations and in accordance with all relevant regulations. Any releases should be fully contained and wastes managed in accordance with the PFAS NEMP.

PFOS, PFOA, PFHxS, and their related substances are listed in Schedule 7 of the Australian Government's Industrial Chemicals Environmental Management Standard (IChEMS) Register (see IChEMS Online Register). Schedule 7 chemicals are the highest concern and are likely to cause serious or irreversible harm to the environment with no essential uses. They are typically prohibited or severely restricted.

PFOS, PFOSF, PFOA, and PFHxS, their salts, and related compounds are listed in Schedule 2A of New Zealand's Hazardous Substances and New Organisms Act 1996 and are subject to the prohibitions and restrictions on persistent organic pollutants (POPs) in that legislation.



4

Communication and engagement

4 Communication and engagement

The following guidance provides advice for communication and engagement activities about PFAS contamination, particularly in areas impacted by point sources of PFAS contamination. It is designed to complement the PFAS Contamination Response Protocol (Appendix A) and the PFAS Information Sharing, Communication and Engagement Guidelines (Appendix C) to the Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination (Australian Government 2018a), and should be read in conjunction with Schedule B8 (Guideline on Community Engagement and Risk Communication) of the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM). This guidance has a particular focus on the role of environmental regulators. The aim is to support all environmental regulators in being a partner and a protector of the environment and/or human health in delivering the best outcomes for the community and the environment.

This guidance is divided into three sections. The first sets out roles and responsibilities. The second includes principles that should be considered when undertaking any PFAS-related communication and engagement activities. The third provides approaches for environmental regulators working with stakeholders on this issue.

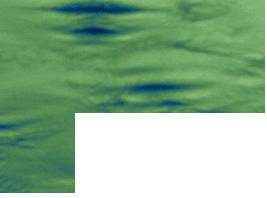
Clear and timely communication on PFAS, and the impacts and management of PFAS, benefits everyone and is vital to increasing the community's understanding of the PFAS issue. By communicating in a way that is open, transparent, tailored to community needs, and easy-to-understand, confusion, anxiety and distrust are reduced. The way in which information is conveyed is critical to building trust between those responsible, polluters, regulators and the community.

4.1 Roles and responsibilities

The roles and responsibilities of all government agencies, including which agency has the lead responsibility, along with inter-agency communication arrangements, should be clear from the outset. These steps will help to ensure that communication and engagement about PFAS contamination is evidence-based, consistent and accessible to the public.

When industry and government are engaging with the community about PFAS, the community needs to feel confident that:

- those responsible are focused on the wellbeing of people and their environment

- 
- their concerns are being heard, acknowledged and understood
 - information is tailored, easy to understand and available through multiple channels
 - they understand the uncertainties associated with risks of PFAS exposure, including the basis for precautionary measures and risks that PFAS pose relative to other risks
 - they understand what is happening in their area, how it will affect them and steps they can take to manage any issues
 - they trust the information being provided to them, such that there is confidence that conclusions are based on the most up to date and credible information and scientifically robust processes.

4.2 Principles for effective engagement

Early and well-considered engagement is important to establish a good foundation for working with communities and managing community expectations in relation to contaminated sites.

Industry and government should be transparent and clear in their communication about PFAS, accurately and swiftly communicating what is known and unknown, and presenting all relevant information and data. Where the data suggests that PFAS levels above the guidelines and exposure pathways are present, the government agencies responsible for providing health and environment advice should ensure the community receives advice as soon as possible to explain how to minimise their exposure. Communication should be in plain language wherever possible, with sufficient context provided to ensure that the information is easy to understand.

Where contamination crosses jurisdictional boundaries, all relevant jurisdictions should be involved in identifying stakeholders and planning engagement. Effective collaboration between all levels of government is critical to successful communication and engagement with communities affected by PFAS contamination.

Site-specific, and where applicable, catchment-wide strategies, including the identification of key stakeholders, should be developed. This is particularly important for sites that are complex, sensitive and pose an increased risk to human health. It is important to be clear about the purpose of engagement when creating these strategies.

In developing a site-specific strategy, identifying and mapping stakeholders will help to target activities, tailor messages and materials. Stakeholders include:

- primary – those who are directly affected

- secondary – those with a vested interest and/or ability to lobby decision makers
- influencers – media, respected and trusted community members or spokespeople, and decision makers.

4.3 Approaches for environmental regulators

The environmental regulator should be involved from the outset in planning and delivering communication and engagement activities. The environmental regulator should act as an accessible source of information for the community and ensure that polluters undertake appropriate engagement activities in accordance with the environmental legislation. It may also be appropriate to involve polluters in these discussions.

The role of the environmental regulator is to ensure the best outcome for the community and the environment. There are a number of measures that environmental regulators can use to ensure that the best outcomes for the community are achieved.

These measures range from supporting engagement by a polluter with the community, to regulatory action which instructs a polluter to engage with the community. It may be an environmental regulator's preference to work collaboratively with polluters to ensure that accurate, timely and consistent messaging is delivered to the community. Working with a polluter to engage with the community does not undermine the role of the environmental regulator; rather, it can achieve the best results. By working with, and supporting engagement among, those responsible, site owners, and occupants, the environmental regulator can ensure accurate and consistent messaging. Should the need arise to direct a polluter to undertake specific engagement activities, this option remains available.

Equally, while it is important for an environmental regulator to work with site owners and occupants to ensure effective community engagement, the environmental regulator must maintain a distinct and separate identity to perform its function, and to maintain the community's trust as effective and independent.

It is therefore important in all engagement and communications to distinguish and clearly communicate the roles and responsibilities of those responsible, the polluter, site owner and/or site occupant, and the environmental regulator.

An aerial photograph of a river, likely the Amazon, showing a wide, winding channel with varying shades of green and blue. A white rectangular box is overlaid on the left side of the image, containing the number 5 and the text 'PFAS monitoring'.

5

PFAS monitoring

5 PFAS monitoring

Environmental monitoring is used to determine if PFAS are present within an area of interest and to provide quantitative and qualitative data about the distribution, concentrations and types of PFAS within this area. This may include data on PFAS in environmental media including soil, sediment, water, air, and, if required, biota (see [Section 8.7](#)), and assessing potential for PFAS to leach from PFAS-contaminated material including soils, biosolids and construction materials (see [Section 18.3](#)). These data are used by site managers and environmental regulators to inform the assessment and management of PFAS contamination for the protection of the environment and/or human health.

For environmental regulators, monitoring also provides the evidence base for decision-making in relation to policy development, regulatory activities and site-specific management controls (for example, whether the PFAS concentration in water meets water quality guidelines or licence discharge limits). The following guidance should be read in conjunction with [Section 8](#) on environmental guideline values, [Section 9](#) on contaminated site assessment, [Section 10](#) on stockpiling and containment, [Section 18](#) on sampling, and [Section 19](#) on analysis.

5.1 Planning and design of environmental monitoring programs

The planning and design of an environmental monitoring program should reflect its specific aims and the expected uses of the data being collected.

There are two main types of monitoring programs:

- ambient monitoring programs provide data to assess the distribution, concentrations and types of PFAS, usually at broader scales than site-specific monitoring programs. Ambient data are attributed to a range of sources within a region, such as a catchment, urban area or jurisdiction. This also includes characterisation of locations remote from PFAS sources with minimal anthropogenic disturbance, such as reference sites. For PFAS, the term ‘ambient’ is used rather than ‘background’, as PFAS are not naturally occurring and so there are no natural ‘background’ concentrations of PFAS in the environment. Ambient monitoring programs may also provide screening information to assist in identifying previously unknown PFAS sources, sinks or pathways. Where known or suspected point sources are included in ambient datasets, they should be clearly flagged for comparison and reporting

- site-specific monitoring programs provide data to assess the distribution, concentrations and types of PFAS attributed to a source or sources at a specific site. This also includes the extent of off-site contamination caused or contributed to by contamination at the site, and the potential on- and off-site impacts on the environment and/or human health.

In general, ambient monitoring programs are undertaken by environmental regulators or by organisations with an interest in the area, and site-specific monitoring programs are undertaken by site managers.

Site-specific monitoring may be triggered by legacy contamination or by an incident (for example, a loss of containment of PFAS-contaminated material), or by a need to characterise baseline site conditions prior to a change of land use or development. It is important to note that site-specific monitoring programs are driven by, and should focus on, the specific information needs relevant to the site. This includes identifying off-site impacts from contamination at the site. Site-specific monitoring is not a replacement for a broader ambient monitoring program. For nationally agreed guidance on roles and responsibilities in responding to site-specific contamination, see the [Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination](#) (Australian Government 2018a) and particularly the [PFAS Contamination Response Protocol \(Appendix A\)](#). Typically, incident monitoring provides data to assess the source, cause, and extent of and the harm associated with a specific incident, such as a PFAS spill or inadvertent contamination of a resource being beneficially reused. It also includes clean-up monitoring.

It is essential to consider the likelihood of multiple PFAS sources within the same catchment, including point and diffuse sources, when designing monitoring programs. For example, the design of a site-specific monitoring program should account for the possibility of finding PFAS contamination that originates off-site or is of unknown origin. The results of this consideration should inform the scope, scale, and geographic focus of the monitoring program. A monitoring plan should include data tailored to identifying and evaluating PFAS distribution patterns attributable to different sources, areas of overlapping influence and ambient conditions.

To be fit for purpose, at a minimum data collection should be sufficient to:

- characterise the nature of PFAS that may be present
- map the distribution and spatial extent of PFAS in the area of interest
- characterise likely temporal variations associated with environmental patterns, including seasonal and intermittent weather variations
- inform the development of a catchment model or conceptual site model (CSM) identifying transport, fate and exposure pathways

- enable comparison against all relevant screening criteria (Section 8 provides guidance on PFAS environmental guideline values; Section 19 provides extensive guidance on PFAS testing (including standard analytes and consideration of the broader PFAS family including precursors))
- characterise the extent of any environmental impacts
- characterise the extent of human exposures.

Assumptions regarding the presence, concentration, dispersal and environmental attenuation of PFAS should be tested against site-specific data, as PFAS are mobile and persistent and some are bioaccumulative. The importance of site-specific data is heightened by the knowledge gaps that currently exist regarding the behaviour of PFAS in the environment. Research shows that the behaviour of PFAS in environmental media (for example, sorption in soil (Li et al. 2018) and uptake from soil (Bräunig et al. 2019)) is variable and relatively unpredictable across a range of spatial scales, based on current knowledge.

The starting assumption should be that PFAS will travel from its sources into environmental media downgradient within the catchment, or catchments, being monitored. The main pathway for movement of soluble PFAS compounds is expected to be in water along the hydrological gradient, with bioavailable PFAS taken up by aquatic biota and terrestrial plants and animals exposed to PFAS-contaminated water and, consequently, into the food chain. In the longer term, PFAS in water are likely to end up in a geological reservoir such as aquatic or marine sediments. A proportion of the PFAS in these sediments is likely to be remobilised by biota. Other emission pathways include air transport and sediment-laden runoff. For example, air transport may be relevant for volatile PFAS such as fluorotelomer alcohols and ketones, PFAS subject to thermal processes, and for PFAS bound to airborne particles. Sediment transport may also be relevant for PFAS such as longer-chain PFCAs that are strongly adsorbed to sediments. These varying pathways for environmental transport should inform the monitoring program for environmental media including soil sediments, water and biota.

5.2 Ambient monitoring programs

Ambient monitoring should test for a broad range of PFAS in environmental media to establish baseline information and identification of temporal and spatial trends in the concentration and presence of specific PFAS. The following environmental media should be considered for inclusion in an ambient monitoring program:

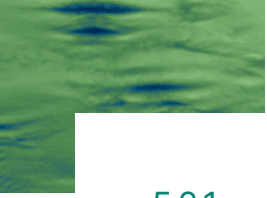
- soil – within different land use segments to assess the current status, changes to land use and soil over time, and monitor impacts from reuse of materials (for example, soils and biosolids)

- groundwater – within different land use segments to assess current status and changes to groundwater aquifers over time
- surface water – sampling of freshwater, estuarine and marine waters within different catchments and land uses to assess current status and changes in surface waters over time
- sediments – sampling of freshwater, estuarine and coastal sediments to assess current status and potential impacts on receiving environments
- biota – assessment of flora and fauna (for example, tissues from fish, crustaceans and molluscs) to inform bioaccumulation trends
- air – sampling of air (including gaseous phase, condensed phase, and particulates such as dust), particularly where there is a high potential for airborne emissions. Note that air sampling is not routine. Information on air sampling is covered in documents prepared by the Interstate Technology Regulatory Council (ITRC) (2018b).

It is useful to include general environmental monitoring parameters (for example, pH and electrical conductivity for water, and particle size for sediment) as this will allow sampling sites to be compared and ensure a diversity of sites are included. Some of this information may be available from existing programs in the area. See [Appendix B](#) for additional information and guidance on sampling for ambient programs.

Ambient monitoring should:

- consider where known and likely PFAS point sources are located and clearly flag these data so that reporting with and without point sources is possible. A distance of 1km from a point source should be used as a minimum distance for sites to be flagged as subject to point source impacts (see UNEP (2021a) for further information), although local movement pathways (groundwater, hydrology, soil movement) also need consideration. This is discussed further in the Victorian Case Study below ([Section 5.2.2](#)). Where the impacts of a PFAS point source are known to extend for a large distance (note that some are detectable for many kilometres), sampling locations should be flagged as subject to point source impacts. Point sources include known contaminated sites, but also other sources such as airports, wastewater treatment plants (WWTPs) and landfills
- include samples from a range of land uses across a catchment. This will help to eliminate bias and to provide information about PFAS concentration variation (for example, urban, industrial, and agricultural areas within a catchment). To assist with a consistent process for jurisdictions, a land use classification approach for ambient programs is further discussed in [Section 5.2.1](#) below.



5.2.1 Ambient land use classification

The purpose of this section is to provide a consistent but adaptable approach in setting land use categories in ambient programs, which enable PFAS concentrations to be compared across land use and jurisdictions.

In the absence of point sources, PFAS concentrations in the environment are likely to reflect the nature (type and intensity) of ambient land use (Sardiña et al. 2019; Baddiley et al. 2020). Ambient PFAS studies need to account for the nature of the land use surrounding, or upgradient of the studied area. Land use classification allows the assessment of the ambient data within its broader land use setting as well as the collation of comparable data across jurisdictions. The methods used to establish land use classes for ambient PFAS studies are briefly outlined below and are described in more detail by Environment Protection Authority (EPA) Victoria (2022).

The land use classification approach is based on the Australian Land Use and Management (ALUM) Classification (version 8) (ABARES 2016) system. This classification approach has been developed and applied within Victoria and Queensland (see [Section 5.2.2](#) and [Section 5.2.3](#)), with the aim to extend this to other jurisdictions for a nationally consistent approach. An equivalent land use classification system to ALUM exists for New Zealand – the Land Cover Database (LCDB) v5.0.

Once the proportions of primary land use are obtained from the ALUM or LCDB systems, a broader land use class can be assigned to the location as shown in [Table 1](#). The current five broad classes are:

- remote-ambient
- agricultural-ambient
- urban-ambient
- mixed-ambient
- marine-ambient.

To support sharing of data in Australia and New Zealand, it is recommended that these five broad land use classes are adopted for PFAS data compilation and assessment. It is likely that these land use classes will be refined over time, as more ambient studies are undertaken and the understanding on PFAS distribution improves. For some jurisdictions additional land use categories with finer resolution may apply, though it is recommended that they should sit under these five broad land use classes.

It also should be noted that in some cases, the allocation of sites to a primary land use needs to consider outliers due to potential PFAS point sources. For example, sites within the primary land use class of ‘Conservation and Natural’ areas should be clearly identified and flagged in ambient datasets, as they may have high historic levels of PFAS as a result of the use of aqueous film-forming foam (AFFF) for firefighting. Additionally,

point sources may not be limited to contaminated sites where AFFF has been used. Other potential sources should also be considered, such as WWTPs, landfills, and land where biosolids have been applied.

Table 1 PFAS ambient land use classes

Land use class	Proportion of land uses in the upstream catchment ^a
Remote-ambient	>85% remote (conservation areas, national and state parks) and <1% commercial and/or industrial and/or <5% residential and/or <2% high-intensity agriculture (for example, cropping, horticulture, feedlots) and/or <10% low-intensity agriculture (for example, grazing)
Agricultural-ambient	>60% high- or low-intensity agriculture and <10% commercial and industrial and/or <25% residential
Urban-ambient	>50% in Victoria, commercial and/or industrial and/or residential ^b >40% in Queensland, commercial and/or industrial and/or residential ^b
Mixed-ambient	Sites that do not fall within the remote, agricultural, urban, or marine land-use classes
Marine-ambient ^c	Coastal/bay sites with no dominant or definable contributing catchment

- a The methods to assign land use are described in EPA Victoria (2022). Spatial analysis was used to determine the upstream catchment proportion upstream of a location using ALUM spatial land use data.
- b Victoria has adopted a threshold of 50% commercial and/or industrial and/or residential land use to define Urban-ambient. Queensland has adopted a threshold of 40%. Each jurisdiction may need to review this threshold based on the density of its urban environments.
- c The marine-ambient land use category is not listed in EPA Victoria (2022) as there was insufficient data. The marine-ambient class has been included to cater for marine-ambient sample locations.

5.2.2 Case study – PFAS ambient environmental monitoring in Victoria

EPA Victoria have collected and analysed (Sardiña et al. 2024) PFAS data for ambient freshwater locations (rivers, lakes, streams) from 87 locations categorised into four land use classes (Table 2). Ambient sites in Victoria were selected to be more than >5km away from a known point source. This is further than the 1km recommended by Stockholm Convention guidance (UNEP 2021a), as there was evidence of transport of PFAS from known point sources beyond 1km.

The results of this analysis show that while PFAS is widely distributed in the environment, remote-ambient locations have no detectable (below the laboratory limit of reporting (LOR)) or low PFAS concentrations and

a low diversity of PFAS compounds. PFAS concentrations increased with land use intensity, with the maximum concentrations and frequency of detection following the pattern of: remote-ambient < agricultural-ambient < mixed-ambient < urban-ambient. This pattern is seen in water PFOS concentrations from Victoria (Table 2).

Table 2 PFOS concentrations in water by ambient land use class in Victoria

Land use class	Number of sites	PFOS min (µg/L)	PFOS max (µg/L)	PFOS detection (%)
Remote-ambient	5	<0.0002	0.0002	20
Agricultural-ambient	16	<0.0002	0.009	75
Urban-ambient	42	0.0007	0.081	100
Mixed-ambient	24	<0.0002	0.048	87

5.2.3 Case study – PFAS ambient environmental monitoring in Queensland

Ambient PFAS data from 54 sites in Queensland were categorised into five land use classes (Table 3). Ambient sites in Queensland were defined as >1km away from a known point source (UNEP 2021a). The majority of ambient sites sampled in Queensland were estuarine/tidal sites, whereas in Victoria they were freshwater sites. Note that for surface water assessment, consideration must be given as to whether the water type is freshwater, estuarine or marine. Tidal sites need to consider downstream land use and tidal movements.

The Queensland site categorisation also included a marine-ambient class for sites with no dominant or definable contributing catchment (Table 3). Marsh/wetland areas in the Queensland land use classification were assigned according to the dominant land use classification of the surrounding land use.

The 54 Queensland sites were sampled for six monitoring rounds over a one-year period (Baddiley et al. 2020). PFOS concentrations in water in Queensland appear to follow the same land use intensity gradient pattern seen in Victoria. In contrast to Victoria, Queensland had a larger proportion of sites with no detectable PFAS (see the PFOS data in Table 2). This may be due to larger river systems and catchments, lower population density, as well as tidal flushing at some sites. In both Queensland and Victoria, the highest PFOS concentrations were recorded in the urban-ambient land use class.

Table 3 PFOS and PFOA concentrations in water by ambient land use classes in Queensland

Land use class		Number of sites	Min (µg/L)	Max (µg/L)	Number of detections ^a	Detection (%) ^b
PFOS	Remote-ambient	3	<0.0001	0.0001	2	11
	Agricultural-ambient	18	<0.0001	0.0011	16	53
	Urban-ambient	8	<0.0001	0.037	8	83
	Mixed-ambient	19	<0.0001	0.018	15	55
	Marine-ambient	6	<0.0001	0.0004	4	24
PFOA	Remote-ambient	3	<0.001	< 0.001	0	0
	Agricultural-ambient	18	<0.001	<0.001	0	0
	Urban-ambient	8	<0.001	0.006	6	56
	Mixed-ambient	19	<0.001	0.005	4	9
	Marine-ambient	6	<0.001	<0.001	0	0

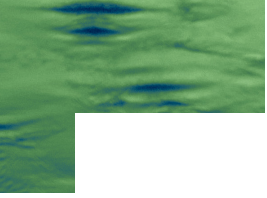
^a Detection in at least one sample at a site.

^b Overall detection frequency in all samples collected over the year at all sites.

5.3 Site-specific monitoring programs

In Australia, site-specific monitoring guidance is provided in the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM), and in New Zealand the Contaminated Land Management Guidelines 1, 2 and 5, as part of a nationally agreed process for characterising site contamination. This process is informed by the development of a robust conceptual site model (CSM), which takes into account the features of the surrounding land including other known or potential sources of PFAS contamination. Where other sources of PFAS contamination are known or potentially present, the site characterisation approach should be carefully considered with regard to effectiveness, efficiency, timeliness and sequencing. The ASC NEPM allows for both 'inside-out' and 'outside-in' approaches. In general, the same media and sinks should be assessed as in an ambient program, as described above.

Due to the bioaccumulative and biomagnifying nature of PFAS, additional PFAS-specific considerations include the need to sample aquatic, other biota, and animal/human food sources wherever a plausible transport



pathway from a known or potential contamination source exists. Note that sampling exposed aquatic biota may be necessary for effective assessment even if water concentrations are below the LOR (see NSW EPA (2022) for further information). In terrestrial settings, if reliable data on representative steady-state uptake factors for the PFAS and media relevant to the receptor being assessed are available (for example, for a livestock type), it may be possible to calculate potential uptake.

Some types of monitoring (for example, food items grown or eaten by ecological receptors and livestock testing) would be for the purpose of informing the conceptual site model and assessing risk to environmental values and receptors.

Well-designed site monitoring allows decision-makers to differentiate between ambient (diffuse) contamination and point source contamination originating from the site, and the extent to which on-site source(s) are contributing to off-site impacts.

An aerial photograph of a river, likely the Amazon, showing a wide, winding channel with varying shades of green and blue. A white rectangular box is overlaid on the left side of the image, containing the number '6' and the text 'PFAS inventory'.

6

PFAS
inventory

6 PFAS inventory

The purpose of a PFAS inventory is to collect local, jurisdictional and national information to quantify and characterise PFAS-containing products and PFAS-contaminated material.

Quantification and characterisation of PFAS-containing products and PFAS-contaminated material includes quantitative data (such as mass, volume and PFAS concentration) and qualitative data (such as PFAS type, storage and management arrangements, and planned use or disposal). For an environmental regulator undertaking a PFAS inventory, the objective is generally to use this information to identify areas or sites to prioritise regulatory action. The information required in a PFAS inventory includes:

- types, locations and quantities of PFAS-containing products or PFAS contaminated material
- management practices employed
- where available, extent of contamination present in the environment.

This information will assist those with management responsibilities for PFAS contamination, inform government policy development, and assist in evaluating the effectiveness of PFAS NEMP implementation.

[Appendix C](#) provides a list of activities that may be associated with PFAS, including a brief description of the relevant PFAS uses for each activity. This list can be used to support PFAS inventory activities.

6.1 Scope of a PFAS inventory

The scope of a PFAS inventory should include:

- liaising with other agencies to obtain government-held information on PFAS stocks or legacy issues
- identifying sites contaminated by PFAS, including the location, level and distribution of on- and off-site contamination, and catchment information
- identifying major primary sources (for example, major commercial, industrial and government facilities, infrastructure, and activities that historically or currently use or store PFAS-containing products). Note that all PFAS formulations should be considered (for example, surfactants used in chrome plating or firefighting, hydraulic fluids and lubricants, and wastes and waste liquids)
- identifying other primary sources (for example, sites where PFAS is or has been used, such as firefighting training facilities, foam deluge system installations, metal plating works, car washes, and electricity generation and distribution facilities)

- identifying secondary sources (for example, sites where diffuse PFAS inputs are or have been received such as landfills, wastewater treatment facilities, liquid waste treatment facilities, and biosolids stockpiles. Note that a PFAS inventory could, in some instances, include sites with a long history of repeated biosolids use).

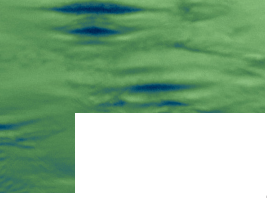
6.2 Conducting a PFAS inventory

The steps in conducting a PFAS inventory include:

- establish an inventory team. Depending on the objectives, this may include agencies responsible for chemicals management, customs services, representatives from major PFAS producers or consumers, research institutions, and non-government organisations
- identify key stakeholders. The involvement of appropriate stakeholders can help to clarify the relevant areas of industrial PFAS use, making the inventory process more practical and efficient
- define the scope of the inventory. This involves identifying the following:
 - industry and government sectors that should be considered further, based on the relevant areas of industrial use from the stakeholder identification stage
 - existing and potential waste sources
 - the resources available to perform the inventory
 - spatial priorities, such as where there are areas of environmental significance or other values of specific interest
- plan the inventory. This involves agreement on aims, objectives, timeframes, outputs, resources, stakeholder engagement, governance, probity and conflicts of interest
- data management. This involves arrangements for data acquisition, input, storage, integration, and issues such as quality assurance/quality control (QA/QC), probity and data security. Participant education should be considered where there is a risk that knowledge gaps may lead to misunderstanding or misrepresentation
- report, follow up, and review. This should include presenting the results of the inventory, legal and policy obligations and stakeholder communication.

6.3 Case study – firefighting foam survey

The Queensland Department of the Environment and Science (DES) effected the Environmental Management of Firefighting Foam–Operational Policy in response to growing concern regarding PFAS. A voluntary survey in early 2017 collected information on foam stocks, historical use, containment and waste management practices, and compliance with the policy.



Participants included sites likely to store high volumes of firefighting foam, such as bulk fuel storage, chemical storage, chemical manufacturing, mining and petroleum, locations handling dangerous goods, and major hazard facilities. Desktop identification of these included assistance from workplace health and safety authorities in addition to departmental records.

The survey received 468 responses. Approximately 425,000kg of foam was reported, mostly at bulk fuel and chemical storage facilities. PFAS-containing foams were reported at 98% of sites. It was estimated that 5% of sites were compliant.



7

PFAS- contaminated site prioritisation

7 PFAS-contaminated site prioritisation

Prioritising sites within a broader inventory of PFAS-contaminated sites involves determining which sites have a risk of causing harm to the environment and/or human health either on- or off-site or within the catchment. This gives agencies, site owners and managers the information they need to prioritise investigation, management and/or remediation actions. It also ensures environmental regulators focus on activities that address the highest risk sites.

7.1 Site prioritisation process

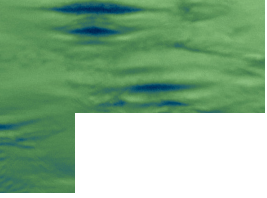
A risk-based prioritisation process involves an evaluation of both the likelihood and consequence of harm occurring. The likelihood of harm can be evaluated by accounting for the potential mass of PFAS likely to have been used at a site, taking into account any historical records and known incidents or discharges. If a PFAS inventory has been conducted (see [Section 6](#)), this will provide information on current PFAS stocks and/or contamination.

The likelihood of harm occurring is evaluated by the scale of PFAS contamination, the quantity of PFAS present, the physical features of the site, and the location of nearby receptors. Air, soil, surface water, and groundwater pathways connecting the site with receptors are important considerations. Other important considerations are the nature of the current and past site use and the efficacy of any measures already taken to minimise emissions.

The consequence of harm will be influenced by the environmental, social and economic values that are affected, or could be affected. For example, contamination of a wetland could affect environmental values (for example, biodiversity), social values (for example, First Nations or traditional custodians' cultural practices), and economic values (for example, access to wild foods or the income derived from nature tourism).

Initially, priority should be given to sites where contaminant concentrations exceed established criteria or guideline values for the protection of the environment and/or human health, where there are known or probable exposure pathways, and there are known or potential sensitive receptors.

As investigations proceed and as the conceptual site model (CSM) is reiterated or refined, the relative priority of a site may be revised (for example, as exposure pathways are confirmed or eliminated, or as further



data is gathered on the PFAS present on site) as the potential risks to the environment and/or human health are re-considered.

A similar prioritisation approach should be taken to determine the urgency of response when a PFAS-contaminated site is newly identified.

7.2 Next steps after site prioritisation

Once initial risks are assessed and site prioritisation is completed, a decision should be made on further actions, including:

- urgent investigation (known or highly probable pathways involving groundwater or surface water)
- high priority for investigation
- standard priority for investigation
- low priority for investigation
- no further site assessments or investigation required for PFAS contamination.

7.3 Case study – preliminary PFAS prioritisation

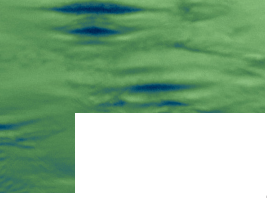
Completed in October 2016, EPA Victoria's preliminary PFAS inventory assessed major industries and sites that hold, use, or have used or received, PFAS, as well as a small number of sites where PFAS exist as a contaminant. The inventory first involved a desktop study of major industries that were likely to have PFAS stocks or contamination. This was followed by data collection in which EPA Victoria searched its own records, requested data from other government agencies, and sent questionnaires to identified sites.

This work identified fire training grounds, oil and gas industries, airports, and chemical manufacturers as the main sites of potential concern for PFAS contamination.

The inventory included over 14,000kg of PFAS-containing material.

The identified sites were prioritised based on the risk they posed to the environment and/or human health. An overall potential concern ranking was developed by assessing the proximity of sites to receptors and the likelihood of PFAS contamination, based on quantities historically used.

Scores were assigned by combining the PFAS inventory with geographic information system (GIS) data on nearby geographic features, surface water, groundwater, and land use. The consequence of harm from PFAS was determined by assessing the proximity of identified sites to sensitive receptors. The potential for complete exposure pathways for contamination was an important consideration.



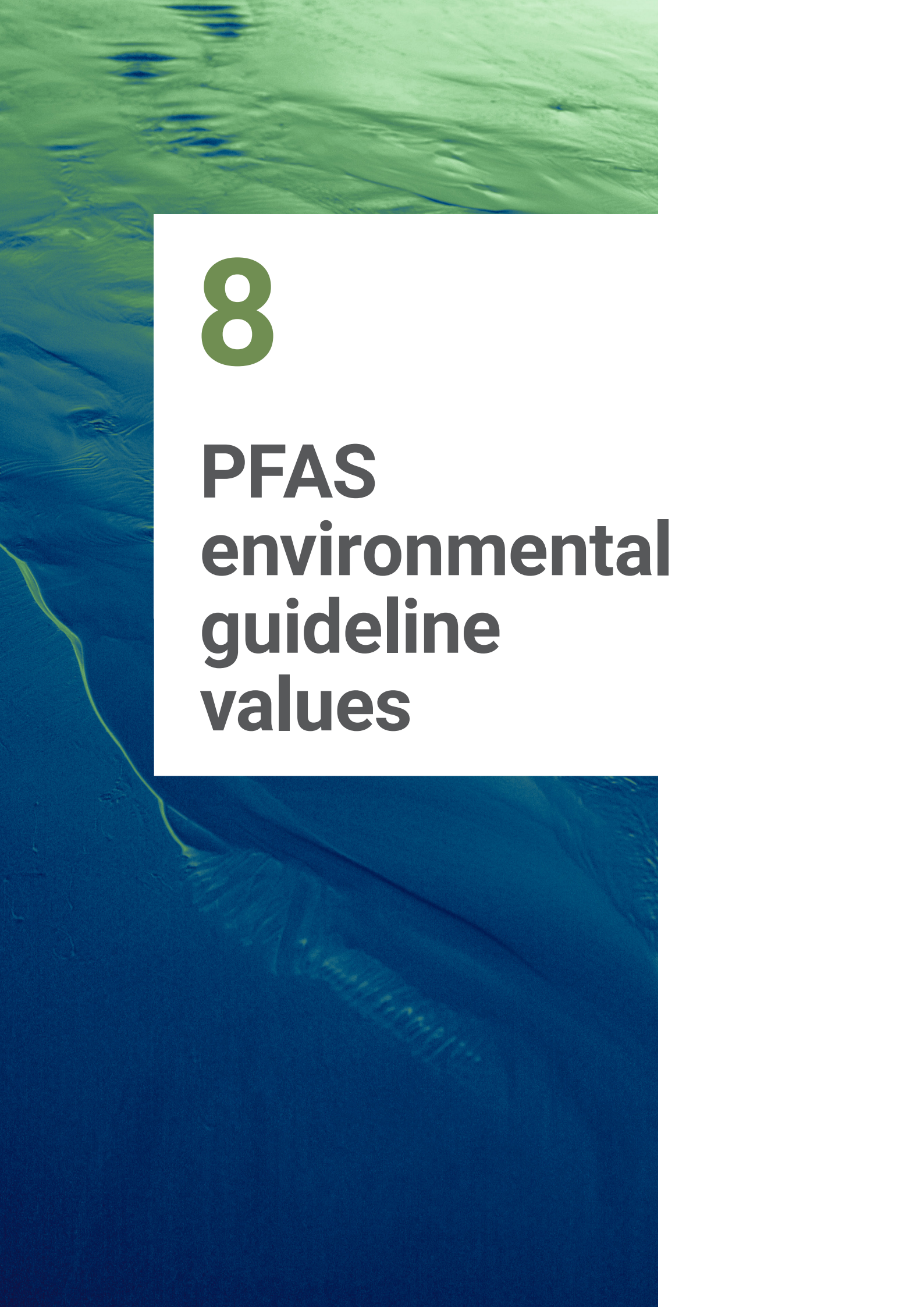
For human health, sensitive receptors included:

- residential areas, including home-grown produce
- schools and early childhood centres where risk has been identified
- aged care facilities and hospitals where risk has been identified
- agricultural areas, including aquaculture
- drinking water supply sources and infrastructure (such as stock and domestic bores, town water bores, and drinking water catchments and reservoirs)
- irrigation bores
- aquifer storage and recovery and reuse systems
- water used for recreation or fishing.

For ecological health, sensitive receptors included:

- areas identified with any of the nine Matters of National Environmental Significance (MNES) protected under the *Environment Protection and Biodiversity Conservation Act 1999 (Cth)* (EPBC Act), and areas of environmental significance as identified in specific jurisdictions
- protected areas, such as parks and other reserves
- aquatic and terrestrial ecosystems, such as Ramsar sites
- ecological receptors
- wetlands
- dams, bores, stockwater and irrigation water
- biota, such as aquatic flora and fauna, waterbirds, and those species at the top of affected food chains
- groundwater-dependent ecosystems
- predators of PFAS-affected aquatic fauna.

Assessing both the likelihood and consequence of PFAS contamination allowed the overall site priority to be determined and was used to inform priorities for regulatory action.



8

PFAS environmental guideline values

8 PFAS environmental guideline values

The purpose of a guideline value is to identify the level of a contaminant that will minimise human health and/or ecological risks, based on the best available scientific evidence. Guideline values are developed using methods designed to address the specific sensitivities of the receptors. For example, aquatic wildlife may experience continuous PFAS exposure from the water they live in, whereas for humans the main sources are usually food, consumer products and drinking water. In some cases, ecosystem guidance can be more stringent than human health guidance. This can arise due to some organisms being more sensitive to a contaminant than humans, and the different mechanisms by which PFAS accumulate (such as accumulation from water, sediment, food sources and trophic structures).

The following guideline values represent a nationally agreed approach that should be used to inform site investigations and environmental management. The purpose of the guideline values is not intended to be as clean-up criteria or an authorisation to pollute up to these values. The values include a degree of conservatism. This is necessary when deriving in-screening assessments to be protective of human health in circumstances where multiple exposure pathways may be present, and protective of ecological health in circumstances where there is variability in species sensitivity. This is especially important for bioaccumulative chemicals such as PFOS, PFHxS and PFOA.

8.1 Considerations for using guideline values

The identification of PFAS above relevant guideline values acts as a trigger to undertake further investigations (such as site-specific risk assessment), as opposed to the assumption that harm will have occurred. The guideline values can also prompt consideration of management action to meet the environmental values and mitigate, where practicable, human health and/or ecological risks.

When carrying out a contaminated site investigation, the following guidance should be considered:

- it is important that sufficient and appropriate characterisation of the contaminants is carried out when comparing site data with guideline values. This is required to ensure that the comparison is both meaningful and relevant for assessing potential risks to the environment and/or human health

- the selection of the appropriate guideline values at a site should consider current and potential (or future) uses of the site, and any catchment or groundwater management requirements, with reference to the conceptual site model (CSM).

The selection of guideline values should have regard to the specific environmental values and characteristics of the site, drawing on relevant guidance and in consultation with the environmental regulators. Relevant guidance could include:

- the National Environment Protection (Assessment of Site Contamination) Measure 1999 (ASC NEPM)
- the National Water Quality Management Strategy (NWQMS) (Australian Government 2019b), including the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (WQG) (ANZG 2018)
- New Zealand Resource Management (National Environmental Standards for Assessing and Managing Contaminants in Soil to Protect Human Health) Regulations 2011
- New Zealand Hazardous Activities and Industries List (HAIL) 2011
- New Zealand PFAS-related Notices and group standards under Hazardous Substances and New Organisms Act 1996
- jurisdictional tools such as Commonwealth, state/territory, New Zealand and regional council:
 - management plans for environment protection, catchments, groundwater basins, vegetation and biodiversity
 - contaminated sites registers
 - waste and wastewater management strategies
 - PFAS-specific guidance resources.

It is important to note that environmental regulators may specify, or environmental legislation may prescribe, the level of protection required.

For managing site-specific PFAS contamination, a site-specific CSM needs to consider the source area, off-site transport, relevant exposure pathways, potential receptors and any relevant environmental values. [Section 9](#) provides further guidance on risk assessment and evaluation in the context of contaminated site management, and [Section 13](#) discusses considerations for treatment and remediation. For sites where a PFAS Management Plan (PMP) or comparable management framework is already in place, this may include site-specific provisions in the PMP that have been agreed with the relevant environmental regulators. [Section 12.1.1](#) discusses the use of a PMP to agree a site-specific approach to soil excavation and reuse.

8.2 Basis for selection of the guideline values included in the PFAS NEMP

The guideline values in the PFAS National Environmental Management Plan (PFAS NEMP) are drawn from, and have been derived, with reference to existing nationally agreed and long-standing Australian frameworks, including the NWQMS and the ASC NEPM wherever possible. However, some of the guidance in these existing frameworks has not specifically covered PFAS and/or has limitations in effectively addressing the mobile, persistent and bioaccumulative nature of PFAS. As such, the guideline values in this PFAS NEMP are designed to be protective of environmental values given these unique circumstances, and are intended to complement and extend guidance to other existing guidelines and frameworks in Australia.

For guideline values where there are nationally recognised processes for the review and adoption of new criteria, such as the WQG, appropriate draft criteria are recommended below. The PFAS NEMP will be updated to align with subsequent updates as these are published.

In other instances, interim guideline values have been derived as part of the PFAS NEMP process using methods from the ASC NEPM and the Canadian methods for deriving environmental quality criteria. Some of these guideline values are expected to be subject to additional work in the future, including the addition of more recent literature as it becomes available.

Where the above options were not possible, internationally derived guideline values are provided.

8.3 Exposure pathways for human health assessments

Section 8.6 describes PFAS guideline values for human health assessments, including health-based guideline values (HBGVs) for drinking water and recreational guidelines from the National Health and Medical Research Council (NHMRC), and health investigation levels (HILs) for soil. Note that these screening values do not cover all potential exposure pathways for human health. Therefore, to assess risks for human health, site-specific exposures need to be considered as part of any assessment (see Section 9 on contaminated site assessment and Section 10, which includes discussion on the need to consider atmospheric emissions for specific circumstances). Figure 1 below indicates some of the key exposure pathways for a human health risk assessment (HHRA).

Due to the bioaccumulative nature of PFOS, multiple exposures may need to be considered. Guidance should be sought from the environmental regulator to confirm specific jurisdictional requirements.

Figure 1 An example of potential human health pathways for PFAS exposure

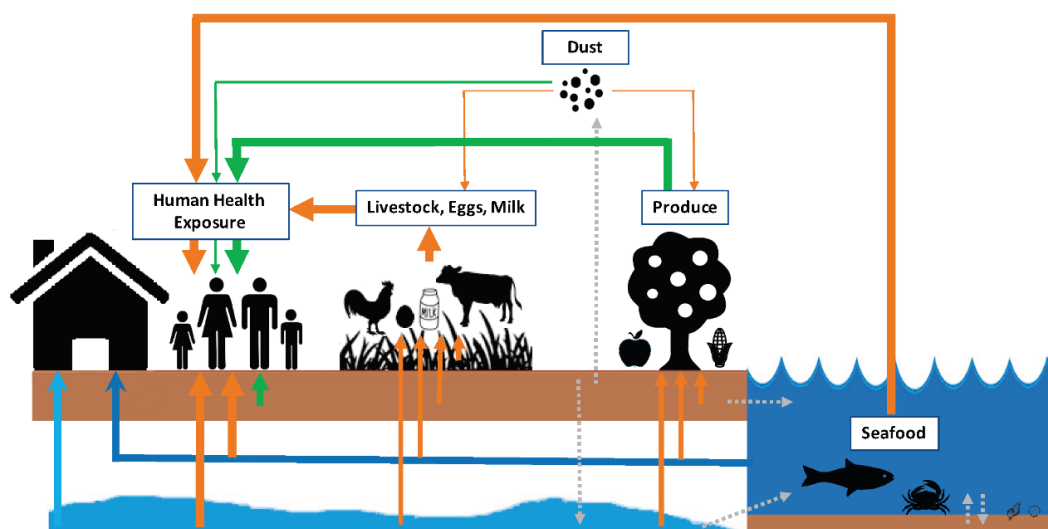


Figure 1 depicts potential exposure pathways affecting human health and is a general example of potential exposure pathways to be considered in a site assessment. Note that this is not intended as a comprehensive conceptual model covering all possible exposures.

Dotted grey arrows indicate PFAS transport mechanisms in the environment. Solid orange lines indicate potential PFAS uptake and exposure pathways to human receptors.

The green arrows indicate the exposure pathways that were considered in calculating the HILs for soil (see Table 5 below). These include exposure via soil, dust and consumption of home-grown garden produce (consistent with the derivation of the HIL A values in the ASC NEPM).

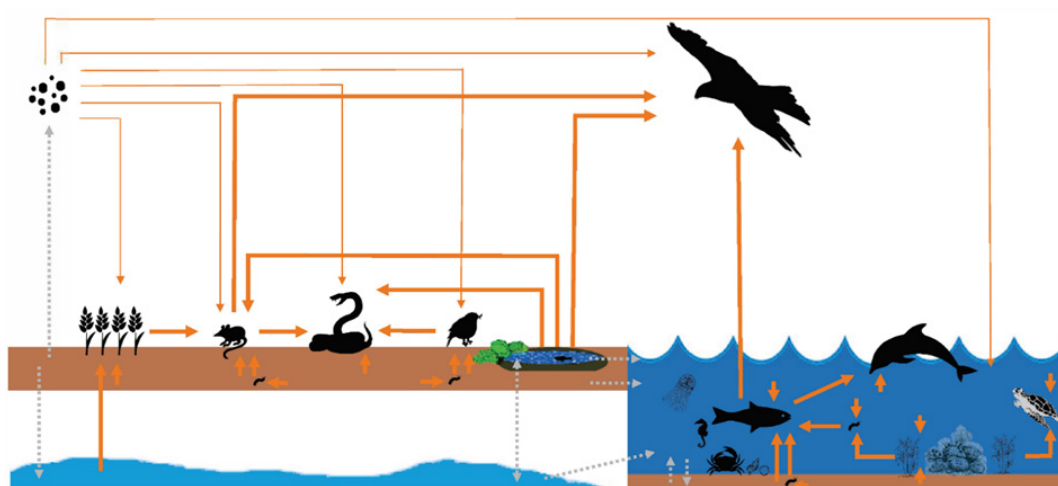
The arrow's thickness infers relative magnitude of assumed exposure, showing that dust inhalation is typically considered a minor pathway.

8.4 Exposure pathways for ecological assessments

Section 8.6 describes PFAS guideline values for ecological assessments. These include interim ecological soil guidelines for direct and indirect exposure, biota guideline values based on tissue samples, and interim ecological water quality guidelines.

The ecological guidelines need to be applied with consideration to the relevant receptors and pathways in the environment. Figure 2 below indicates some of the key exposure pathways for an ecological assessment. Figure 3 below provides examples of key pathways to consider in terrestrial, wetland and coastal environments. For additional guidance on contaminated site assessment for PFAS, see Section 9. Guidance should be sought from the environmental regulator to confirm specific jurisdictional requirements.

Figure 2 An example of potential ecological pathways for PFAS exposure



The conceptual model shown in Figure 2 is a general example of potential exposure pathways to be considered in a site assessment. Note that this is not intended as a comprehensive conceptual model covering all possible exposures.

Dotted grey arrows indicate PFAS transport mechanisms in the environment.

Solid orange lines indicate potential PFAS uptake and exposure pathways to ecological receptors.

The arrow thickness is relative to the significance of the PFAS exposure pathway.

Figure 3 Examples of key pathways to consider in a risk assessment for PFAS in (a) terrestrial ecosystems; (b) wetlands; and (c) coastal environments

a)



b)



c)

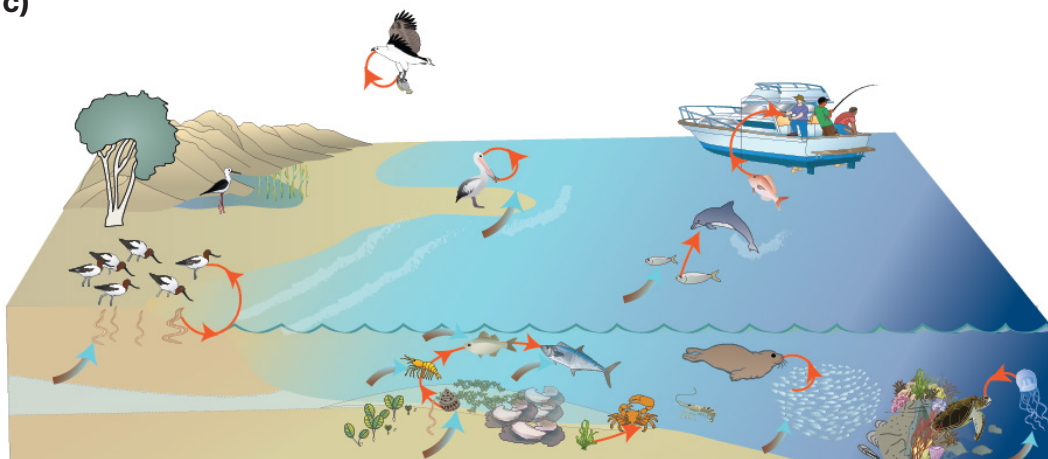


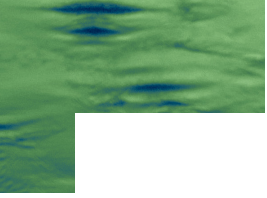
Figure 3 is an extension of pathways included in Figure 1 and Figure 2, and provides examples of pathways to consider in different environments such as terrestrial, freshwater, and marine ecosystems. These diagrams are intended as examples and are not comprehensive conceptual models covering all possible exposures.

Orange arrows indicate potential pathways for accumulation of PFAS.

Source: Lana Baskerville (2022); symbols courtesy of the University of Maryland Center for Environmental Science, Integration and Application Network ([Media Library | Integration and Application Network \(umces.edu\)](https://umces.edu)).

8.5 Consideration of bioaccumulation

For PFAS, bioaccumulation in aquatic species cannot currently be accurately predicted based on water concentrations. This is evident from site assessment data, where bioaccumulation in fish tissues has been measured, despite water concentrations being at or below the laboratory detection limits. Therefore, to consider risks as a result of bioaccumulation, direct measurement of aquatic biota is the preferred approach where



exposure pathways and sensitive receptors (ecological and/or human) exist. Taxonomic variability in PFAS elimination rates is an important consideration. For example, aquatic biota with gills (for example, fish) may have faster elimination rates compared with aquatic air breathing animals (for example, marine mammals (SA EPA 2017; Taylor et al. 2017)). Elimination rates may also differ in terrestrial animals (Lupton et al. 2014; Numata et al. 2014) which, when available, need to be considered when assessing risk to terrestrial ecosystems, and to humans through consumption of livestock products.

Any sampling program needs to consider if the assessment is for human health and/or ecological purposes, as there may be different sampling considerations. Sampling biota may reduce the uncertainty in assessing risks as a result of bioaccumulation. Additional details regarding consideration of PFAS bioaccumulation are discussed in [Section 9.3.2](#).

Where an assessment has to look forward in a predictive sense rather than investigate impact of existing contamination, multiple lines of evidence should be used. This can include:

- current data and studies on bioaccumulation in the area or similar areas of conservation and exposures
- use of published bioaccumulation data relevant to potential receptors and any relevant environmental values
- water and sediment quality data
- data on local environmental values and pressures
- use of passive samplers to monitor spatial and temporal trends and minimisation of PFAS flux from the site.

8.6 Health-based guideline values

The HBGVs are used to investigate and assess human health risks. The use of these values should take into account any additional guidance on human health protection from the relevant health and environmental regulators, along with guidance from [Section 5](#) on PFAS monitoring, [Section 9](#) on PFAS contaminated site assessment, [Section 18](#) on PFAS sampling, [Section 19](#) on PFAS analysis in the PFAS NEMP, and the ASC NEPM for monitoring, site assessment, sampling and analysis.

8.6.1 Health-based guideline values developed by health authorities

For humans, the main sources of PFAS are through ingestion of contaminated food and drinking water in a contaminated site setting. Health authorities have set HBGVs indicating the amount of a chemical intake a person can consume on a regular basis over a lifetime without any significant risk to health. The HBGVs for PFOS, PFHxS and PFOA were recommended by Food Standards Australia New Zealand (FSANZ) in the

form of a tolerable daily intake (TDI) (FSANZ 2017). The TDI was then used to calculate the HBGVs listed here.

The science and our understanding of these issues will continue to evolve. As a precaution, the [Environmental Health Standing Committee \(enHealth\)](#) continues to recommend exposure to PFAS be minimised wherever possible (Department of Health and Aged Care 2024).

As a precaution, the Department of Health and Aged Care has advised that the PFOS TDI should also apply to PFHxS. This means that the level of PFHxS exposure should be added to the level of PFOS exposure. The combined level should then be compared to the TDI for PFOS.

The methodologies used by national health agencies in deriving the values in [Table 4](#) include a level of conservatism in the drinking water (for example, NHMRC 2011) and recreational water (for example, NHMRC 2019) HBGVs. The methods assume only a minor portion (10%) of the TDI is allocated to this source.

For recreational water quality guidelines, [NHMRC \(2019\)](#) notes that there may be cases where recreational water may be used more frequently than the assumptions underpinning the guidelines. In such cases, more locally appropriate recreational guidance based on actual event frequency need to be considered in consultation with the state or territory health regulator.

Table 4 Health-based guideline values developed by health authorities

Description	Sum of PFOS and PFHxS ^a	PFOA	Comments and source
Tolerable daily intake (TDI)	0.02µg/kg _{bw} /day	0.16µg/kg _{bw} /day	FSANZ 2017
Drinking water quality guideline	0.07µg/L	0.56µg/L	NHMRC 2011 New Zealand Government Department of Internal Affairs 2022
Recreational water quality guideline ^{b c}	2µg/L	10µg/L	NHMRC 2019

a Where the criteria refer to the sum of PFOS and PFHxS, this means concentrations of PFOS only, PFHxS only, and the sum of the two.

b NHMRC (2019) notes that people's use of recreational water is not the same, given Australia's climate and geography. Some recreational water resources may be used less frequently than the assumed guidelines (150 days/year), and (in rare cases) some may be used more frequently. For example, surfing activities may be longer in duration and higher in ingestion risk, compared to NHMRC assumptions. In such cases more locally appropriate recreational guidance based on actual event frequency can be considered in consultation with the state or territory health regulator.

c The guidelines address natural fresh, estuarine and marine recreational water bodies but specifically exclude swimming pools, spas and hydrotherapy pools (NHMRC 2008).

8.6.2 Human health investigation levels for soil

The following HILs for soil were derived using the methodology consistent with the ASC NEPM for the HILs. Note that these values have not been derived under the ASC NEPM framework, nor published in the ASC NEPM. The PFAS HILs (Table 5) are to be used to assess potential human soil exposure in line with the same assumptions that underpin the ASC NEPM HILs. These values should be applied in conjunction with other lines of investigation to account for other relevant human health exposure risks outside the scope of the ASC NEPM HIL assumptions, for example:

- potential leaching and off-site transport resulting in other exposure scenarios
- bioaccumulation into home-grown produce
- consumption of livestock, poultry, eggs and fish
- land uses, such as agriculture.

For the 'residential with garden/accessible soil' land use category, the standard methodology under the ASC NEPM HIL A considers two exposure pathways: direct exposure to contaminated soil and dust, and indirect exposure from the consumption of home-grown fruit or vegetables. The default assumption is that home-grown produce makes up 10% of fruit and vegetables consumed. Note that these criteria do not account for potential home consumption of eggs from home-raised poultry, nor of milk or meat from livestock on the premises. These need to be assessed separately if such scenarios occur. The HILs calculations for the values listed in Table 5 are based on calculations considering a chemical intake from a contaminated source equal to 20% of the TDI. In other words, this allows for 80% of the chemical intake to be attributed to other exposure pathways (for example, consumption of other home-grown produce and recreational activities) as well as background exposure. This means that exceeding these values does not necessarily constitute a risk if other pathways are controlled.

The guideline values for PFOA and the sum of PFOS and PFHxS, for 'residential with garden/accessible soil' (using HIL A assumptions) were reviewed as part of the work program undertaken to inform the PFAS NEMP 3.0. As part of the work program, additional information on soil to plant transfer factors in the literature were identified and incorporated. Through the consultation process for PFAS NEMP 3.0, a plant transfer factor was updated, and this resulted in changes to the 'residential with garden/accessible soil' investigation levels listed in the previous version of the PFAS NEMP (PFAS NEMP 2.0). See Supporting Document 4 for details on the methods and transfer factors, specifically:

- relevant studies additional to those included in the derivation described in the calculation protocols and draft values document (OEH 2019) were considered, and a review of the additional literature for PFOA was

undertaken. Any additional data on PFOS in the review process was also considered and incorporated

- the soil to plant transfer factors were based on PFAS concentrations per wet weight (ww) plant. Where only data for dry weight (dw) were available these were converted to wet weights
- the uptake of PFOS and PFHxS from soils to plants has been explicitly accounted for, and the method described in OEH (2019) was considered appropriate and retained.

8.6.3 Comparison of PFOS and PFHxS concentrations

A review of soil to plant transfer factors for PFOS and PFHxS (OEH 2019) has shown that PFHxS accumulates more readily in plants compared with PFOS. This influences the total PFOS plus PFHxS concentration predicted in the plant. The sum of PFOS and PFHxS HIL A was derived assuming that PFOS and PFHxS are present in a soil at equal proportions. If a site has significantly more PFHxS in the soil than PFOS, a re-calculation of the criterion based on site-specific conditions is recommended as the HIL A may not be protective in such instances. For any additional calculations, the methodology is described in detail in OEH (2019) and the updated soil to plant transfer factors in Supporting Document 4.

Table 5 Human health investigation levels for soil

Land use	Sum of PFOS and PFHxS ^a (mg/kg)	PFOA (mg/kg)	Comments and source
Residential with garden/accessible soil (HIL A)	0.003	0.06	Assumes home-grown produce makes up to 10% of fruit and vegetable consumed (does not account for consumption of eggs from home poultry, milk or meat from stock on the premises). Also includes children's day care centres, preschools and primary schools. These values were derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL A. Note: if home-grown produce makes up more than the 10% of fruit and vegetable consumed, as assumed in the ASC NEPM generic example, a site-specific risk assessment is required. As an example, if home grown produce provides up to 50% of fruit and vegetable consumption, the screening value would be 0.001mg/kg for the sum of PFOS and PFHxS, and 0.01mg/kg for PFOA.

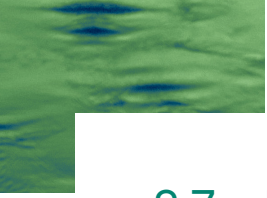
continues

Table 5 *continued*

Land use	Sum of PFOS and PFHxS ^a (mg/kg)	PFOA (mg/kg)	Comments and source
Residential with minimal opportunities for soil access (HIL B) ^b	2	20	The HIL B values assume soil is not used to grow and consume home-grown produce. Includes dwellings with minimal opportunities for soil access. These values were derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL B.
Public open space (HIL C) ^b	1	10	Relevant for public open space such as parks, playgrounds, playing fields (for example, ovals), secondary schools (except for soil used for agricultural studies) and footpaths. Excludes undeveloped public open space (such as urban bushland and reserves), which should be subject to a site-specific assessment where appropriate. These values were derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL C.
Industrial/commercial (HIL D) ^b	20	50	Assumes eight hours is spent indoors and one hour spent outdoors at a site such as a shop, office, factory, or industrial site. If these scenarios are not appropriate, a site-specific assessment is required. The PFOS + PFHxS value was derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL D. The industrial/commercial direct exposure criterion for PFOA (including its salts and related compounds) has been set as 50mg/kg, which is a proposed Basel Convention low persistent organic pollutant (POP) content limit (LPCL).

^a Where the criteria refer to the sum of PFOS and PFHxS, this means concentrations of PFOS only, PFHxS only, and the sum of the two.

^b Changes to waste thresholds due to the Basel Convention and Stockholm Convention LPCLs for PFOS, PFOA, PFHxS, and related compounds may result in values lower than the HIL values. As such, hazardous waste management requirements should be carefully considered when assessing PFAS concentrations in soil. These additional requirements may be a limiting factor when assessing site management options.



8.7 Ecological guideline values

The ecological guideline values are used to assess and investigate potential risks to aquatic and terrestrial ecosystems.

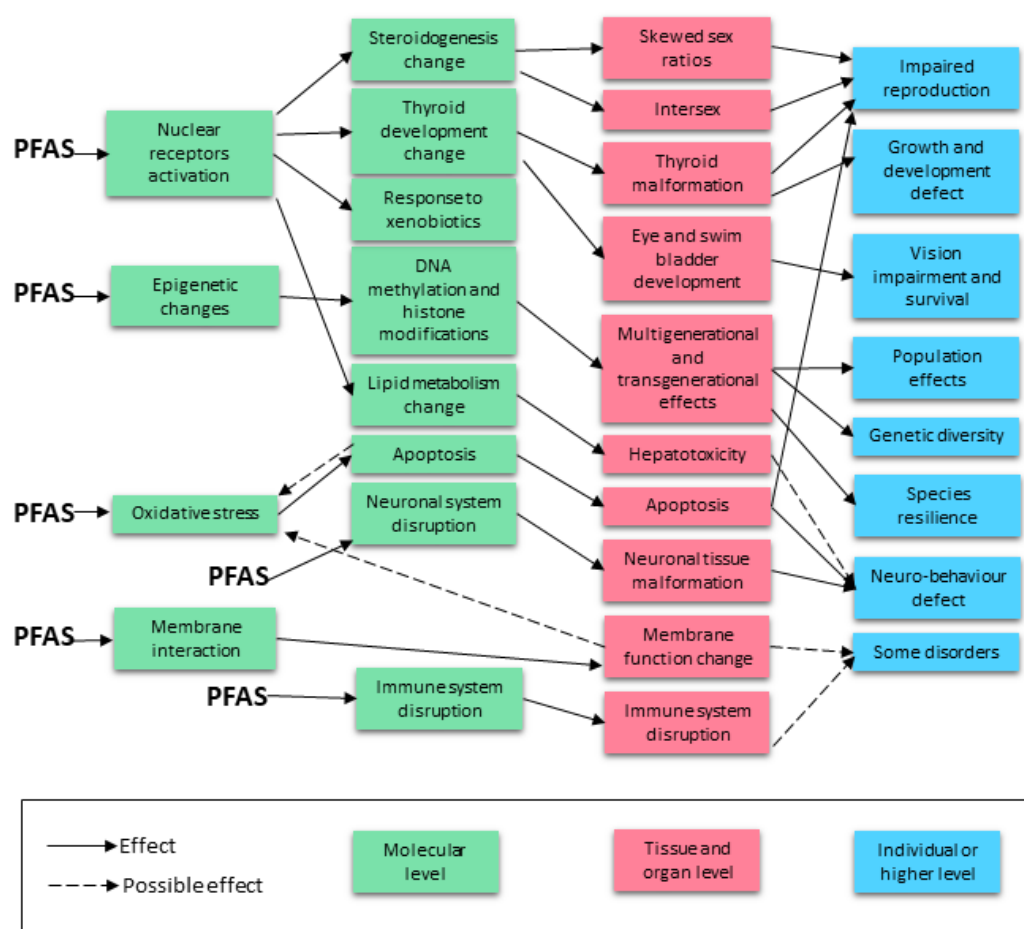
The use of ecological guideline values should take into account any additional guidance on ecological protection by relevant environmental regulators, along with the guidance provided in the PFAS NEMP and the WQG framework on considerations for monitoring, site assessment, sampling and analysis (see [Section 5](#) on monitoring, [Section 9](#) on contaminated site assessment, [Section 18](#) on PFAS sampling, and [Section 19](#) on PFAS analysis). The general environmental duty to prevent off-site dispersal of PFAS and protect relevant environmental values should also be taken into account in jurisdictions where such a duty exists.

The ecological guideline values in [Table 6](#) and [Table 7](#) are intended to be protective of wildlife, based on the current scientific evidence. The ecological water quality guideline values in [Table 8](#), and the sediment quality guidance, are likewise intended to be protective of receptors in aquatic ecosystems. These ecological guideline values are based on the current scientific evidence and should be used to inform an overall assessment of the environmental significance of PFAS concentrations for wildlife and trigger either appropriate management action or further investigation of risk.

Environmental regulators acknowledge that understanding based on the scientific evidence is rapidly evolving. For example, understanding of plausible mechanistic pathways for PFAS toxicity changing as the linkages between molecular initiating events and apical endpoints, such as organism and species survival, resistance to disease, growth, development and reproduction, are becoming clearer (for example, Kumar et al. 2020a; Lee 2021).

Relevant scientific literature, environmental legislation, and government policies within jurisdictions should be consulted in evaluating applicable endpoints as additional lines of evidence where there are deviations from existing guideline values.

Figure 4 Examples of plausible mechanistic pathways for PFAS toxicity



Adapted from Kumar et al. (2020a) and Lee (2021).

The ecological guideline values are intended to indicate threshold concentrations which provide a defined degree of confidence that where concentrations are below these guidelines, specific risks are low and acceptable. Note that direct toxicity guidelines do not address bioaccumulation or secondary poisoning, nor do they address specific circumstances such as different food consumption ratios for groups such as migratory birds. The ecological guideline values are not intended to be generic contaminated site remediation criteria. Importantly, the NWQMS's principle of continual improvement means that where the concentration of a PFAS contaminant is below the appropriate guideline value, the over-riding objective should be to continue to improve, or at least maintain, water quality (that is, not to allow increases in concentration up to the guideline value) (ANZG 2018). Furthermore, disturbed or impacted systems should not be regarded as 'pollution havens', and the concepts of adaptive management and continual improvement should be implemented, to maximise future options for a waterway (ANZG 2018).

8.7.1 Ecological soil guideline values

The following interim ecological soil guideline values consider both direct exposure and indirect exposure to ecological receptors. It is acknowledged that these guideline values are interim and may be refined by future work as additional relevant research becomes available.

Soil ecological direct exposure guidance

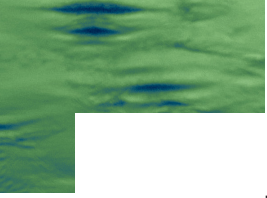
The direct exposure ecological soil guideline applies specifically to the protection of organisms that live within, or in close contact with soil, such as earthworms and plants. This direct exposure value can be used to assess the possibility of direct harm to these organisms. In the absence of acceptable and sufficient published guideline values for direct exposure, human health soil criteria for public open space (see [Table 5](#)) are recommended as an interim position.

Other factors important for assessing exposure, for example bioaccumulation, leaching and off-site transport, must be accounted for by including other lines of investigation.

Additionally, an interim direct soil guideline value for PFOA, protective of reptiles, has been included in [Table 6](#), and is intended to be used where reptiles are present or are potentially present.

The protection of reptiles is intrinsically important to Australian ecosystems. Australia is a hotspot for reptile diversity, hosting the largest number of species of any country in the world and accounting for approximately 10% of all known species globally (Tingley et al. 2019). Australian reptile fauna is also very distinctive with around 90% of species being endemic (Chapman 2009).

It is acknowledged that ecotoxicological research on impacts of PFAS on ecological health of reptilian fauna are scant although some studies of Australian environments are emerging (Lettooff et al. 2023; Beale et al. 2022). Rapid in vitro and in silico testing approaches could fill knowledge gaps left by traditional ecotoxicology tests, with reptile primordial germ cells (Golkar-Narenji et al. 2023) and isolated mitochondria (Haenel and Moore 2018) from reptile biopsies suitable for assessing animal fertility and organ toxicity. A transcriptomics points-of-departure (tPODs) assay developed by the US EPA offers another avenue for rapidly generating toxicity data at the gene level before an unwanted phenotype occurs (Alcaraz et al. 2022; Harrill et al. 2024). The tPODs can be extended to include other -omics measures, such as proteomics, lipidomics, and metabolomics. Biological features, such as genes and metabolites, will become increasingly vulnerable to changes (that is, one gene can regulate hundreds of metabolites).



The interim PFOA soil guideline value for reptiles is based on limited reptilian research (Zhang et al. 2020); see Supporting Document 3 for details on the methods considered for the PFAS NEMP 3.0.

Soil ecological indirect exposure guidance

The indirect exposure ecological soil guideline (Table 6) accounts for the various pathways through which organisms can be exposed whether or not they are in direct contact with PFAS-contaminated soil (for example, exposure through the food chain, such as animals consuming contaminated prey, plants and water). As discussed below, the values do not explicitly account for off-site environmental transport processes. The ecological soil guideline derivation approach for indirect toxicity and resultant values set by Environment and Climate Change Canada (ECCC) was considered and adapted for the Australian context (see Supporting Document 2 for details on the methods considered for the PFAS NEMP 3.0). The values calculated for exposure of a small secondary or tertiary consumer with large proportionate food intake are based on the most sensitive exposure pathway.

This guideline provides a default value to manage the potential level of exposure for wildlife feeding on organisms that have been exposed. For example, in an open space area, if plants and soil dwelling animals are present, it is likely that there will be birds, small mammals and/or reptiles present consuming these plants and animals (see Figure 2). It therefore recognises that traditional land use categories are not relevant to ecological risks, and therefore a single guideline value is applicable to all land use scenarios. This reflects the possibility of indirect PFAS exposure from any land use where PFAS may be present in a large area of soil.

The indirect exposure value may be over-protective if the area of exposed soil is too small to have any material impact on food chain transfer to secondary consumers such as invertivores and carnivores. In this situation, considering site-specific characteristics may justify the use of a higher value (up to 0.14mg/kg) as the trigger for a detailed site-specific investigation of risk. Examples of relevant considerations include:

- the site is intensively developed with greater than 80% of each hectare covered by hard surfaces (to be applied separately to each hectare)
- secondary and tertiary consumers are effectively absent from the site
- the site is situated in an extensively built-up urban setting
- the site is not in close proximity to waterways, drainage networks or groundwater.

These interim ecological soil guidelines do not consider the transport of soil, or PFOS or PFOA leaching from soil, into groundwater, surface water or onto adjacent sites. Therefore, these values do not cover impacts associated with PFAS transported into surface water on aquatic biota, or on wildlife that consume aquatic biota. Site-specific data should be considered

wherever possible, as environmental variability may lead to locally elevated ecological risks.

Table 6 Ecological guideline values for soil

Exposure scenario	PFOS (mg/kg)	PFOA (mg/kg)	Comments and source
Ecological direct exposure – all land uses	1	10 0.005 as an interim screening value if reptiles may be exposed ^a	Future work may be undertaken to review available soil guideline values proposed by Australian research and industry organisations.
Interim ecological indirect exposure – all land uses ^b	0.003	0.003	The guideline value is based on dietary exposure of secondary and tertiary consumers, and relevant Australian animals as the most sensitive exposure pathway assessed. For intensively developed sites with no secondary consumers and minimal potential for indirect ecological exposure, a criterion of up to 0.14mg/kg PFOS may be appropriate as outlined in the accompanying text in Section 8.7.1 .

- a PFOA ecological direct exposure for reptiles is based on a lowest observed adverse effect level (LOAEL) of 50µg/kg for reduced growth (Zhang et al. 2020), divided by a minimum uncertainty factor of 10 for inter-species differences (Australian Government 1999a). As this is based on a LOAEL, it may not be sufficiently protective of endangered, threatened or vulnerable reptiles and high ecological value sites. Application of an additional uncertainty factor, up to 10, is recommended in these cases. It also does not address effects that may occur via consumption of contaminated prey, plants and water. See Supporting Document 3 for additional information on the derivation of this value.
- b Ecological indirect exposure – guideline values have been updated since PFAS NEMP 2.0 to be more relevant to Australia-specific circumstances, based on consultation comments received and peer review of the guideline. See Supporting Document 2 for additional information on the derivation of this value.

8.7.2 Biota guideline values

The wildlife diet values for PFOA and the sum of PFOS and PFHxS in [Table 7](#) have been derived by using the approach in ECCC guidelines (2018) and adjusted to consider the Australian context by using wildlife consumption data for a representative mammalian Australian species. See Supporting Document 2 for details on the methods and data used, and Supporting Document 5 on the applicability of the Canadian ecological guidelines to Australia.

The tissue guideline for acceptable contaminant levels in bird egg is to assess potential risks to avian populations where these receptors may be relevant (see Supporting Document 2 for the bird tissue egg value). When assessing sensitive avian receptors, it is important to note that some birds

may be listed as endangered species, and therefore sampling eggs may not be appropriate. In such instances, if bird eggs were to be sampled, this would need to rely on samples of other species which have similar relevant ecological niches.

Table 7 Biota guideline values

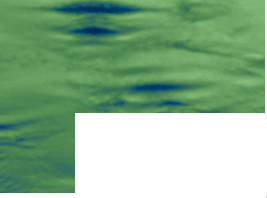
Exposure scenario	Sum of PFOS and PFHxS ^a	PFOA	Description
Ecological direct exposure for wildlife diet ^b	3.1µg/kg	2.8µg/kg	Mammalian diet – consumption of biota as wet weight food
	8.2µg/kg ^c	2.4µg/kg ^c	Avian diet – consumption of biota as wet weight food
Ecological exposure protective of birds ^d	0.2µg/g	0.015µg/g	Whole bird egg as wet weight

- a Where the criteria refer to the sum of PFOS and PFHxS, this means concentrations of PFOS only, PFHxS only, and the sum of the two. The ECCC (2018) guidelines refer to the criterion for PFOS only; in the PFAS NEMP the guideline values for ecological direct exposure for wildlife diet refer to the levels of PFOS and PFHxS in food consumed by mammals or birds. This has been adapted to allow for uncertainties and potential similar properties and toxicities of PFHxS with PFOS.
- b The guidelines for the sum of PFOS and PFHxS, and the guideline for PFOA, are based on the ECCC (2018) approach using representative local species. For the relevant TDIs and approach adopted, see Supporting Document 2. For reference, TDIs (µg/kg bw/day) used in deriving the guidelines are: Mammalian – PFOA 1, PFOS + PFHxS 1.1; Avian – PFOA 2.3, PFOS + PFHxS 7.7. As the PFOA mammalian toxicity derivation is based on adverse effects that occur during development and lactation, food intake rates are based on lactating females.
- c The avian diet value may not be protective of migratory wading birds that have a high food intake due to the need to gain weight rapidly.
- d Adapted from ECCC (2018) using an additional uncertainty factor. The adjusted uncertainty factor is 100 while the uncertainty factor used in ECCC (2018) was 10. This guideline value is to be used on sampled bird eggs to assess risk to sensitive avian ecological receptors. The guideline value for ecological exposure protective of birds refers to the levels of PFOS and PFHxS in bird eggs. Measurements are shown as micrograms per gram (µg/g) as reported in research on these issues.

8.7.3 Ecological water quality guideline values

The ecological water quality guideline values are developed through the WQG framework toxicant default guideline value (DGV) publication approval process, which is separate from the PFAS NEMP. Further information about the WQG framework, including the development and application of DGVs and site specific values, is available on the [Water Quality Australia website](#).

The WQG framework provides species protection DGVs that are protective of differing proportions of species, ranging from 80% to 99% of species. These DGVs are applied according to the current or desired aquatic ecosystem condition and associated level of protection. Importantly, the DGVs do not account for protection of terrestrial ecosystems dependent on the relevant aquatic ecosystem, nor air breathing aquatic predators from trophic transfer and bioaccumulation.



For contaminants that are not bioaccumulative, the relevant species protection DGV can be selected to reflect the conservation value of the aquatic ecosystem under consideration. However, the WQG framework recommends a different approach for contaminants that are bioaccumulative.

For bioaccumulative contaminants, which include many PFAS, the framework specifies that the 99% species protection DGV should be used in:

- assessing toxicity and bioaccumulation in high conservation value ecosystems
- assessing bioaccumulation in slightly to moderately disturbed ecosystems.

Additional guidance on assessing bioaccumulation for PFAS is also included in [Section 8.5](#). The species protection DGV may be below the ambient concentration. Actions to determine reliable ambient concentrations for organic chemicals with widespread (for example, global) contamination are discussed in the WQG and in [Section 5.2](#).

In short, jurisdictional guideline values may be developed, or site-specific guideline values for specific catchments based on reference sites, subject to the proviso that the concentrations at the reference site are unlikely to be causing adverse impacts on environmental values.

Contamination in specific waterways arising from diffuse sources is a separate issue that should be addressed with reference to the water quality management objectives set by the relevant jurisdiction.

The NWQMS advises against the use of mixing zones for toxicants that bioaccumulate (ANZG 2000). Therefore, due to the persistent and bioaccumulative nature of PFAS the use of mixing zones, sometimes known as exclusion zones, is not appropriate.

This approach is consistent with the established practice across most jurisdictions for substances associated with contaminant accumulation in aquatic species, chronic impacts or environmental risks outside the mixing zone.

Guidance should be sought from the environmental regulator to confirm specific jurisdictional requirements.

Table 8 Ecological water quality guideline values

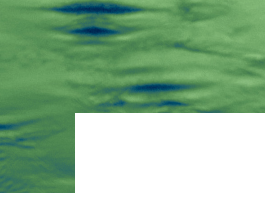
Exposure scenario	Guideline value	PFOS µg/L	PFOA µg/L
Freshwater ^a	99% species protection – high conservation value systems ^b	0.00023	19
	95% species protection – slightly to moderately disturbed systems ^c	0.13	220
	90% species protection – highly disturbed systems	2	632
	80% species protection – highly disturbed systems	31	1824
Interim marine ^d	99% species protection – high conservation value systems	0.00023	19
	95% species protection – slightly to moderately disturbed systems	0.13	220
	90% species protection – highly disturbed systems	2	632
	80% species protection – highly disturbed systems	31	1824

Data source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality – interim default guideline values for PFOS and PFOA (ANZG 2023).

- a The interim guidelines do not account for effects which result from the bioaccumulation and biomagnification of toxicants in air-breathing animals or in animals which prey on aquatic organisms.
- b The 99% species protection level for PFOS is close to the commercially available ultra-trace level of detection. Agencies may wish to apply an ‘ultra-trace detect’ threshold in such circumstances rather than a quantified measurement.
- c The WQG advise that the 99% level of protection be used for slightly to moderately disturbed systems. This approach is generally adopted for chemicals that bioaccumulate and biomagnify in wildlife. Environmental regulators may specify, or environmental legislation may prescribe, the level of species protection required, rather than allowing for case-by-case assessments.
- d Freshwater values are to be used on an interim basis until final marine guideline values can be set using the nationally agreed process under the WQG. The WQG advise that in the case of estuaries, the most stringent of freshwater and marine criteria apply, taking account of any available salinity correction. Marine guideline values developed by CRC CARE are under consideration through the nationally agreed water quality guideline development process.

8.7.4 Sediment quality

This guidance on sediment quality is intended to help site owners and managers better manage the risks of PFAS contamination at and near their site, particularly where PFAS contamination may be present in sediments. The sediments of many of the urban river systems, estuaries and near-shore coastal waters worldwide have higher contaminant loads, derived largely from past and present industrial discharges and urban drainage (Simpson and Batley 2016; Yang et al. 2011). Freshwater, estuarine, and marine sediments are an important component of aquatic ecosystems and can act as a potential source of contaminants to overlying waters and biota via benthic and other food webs (Simpson and Batley 2016).



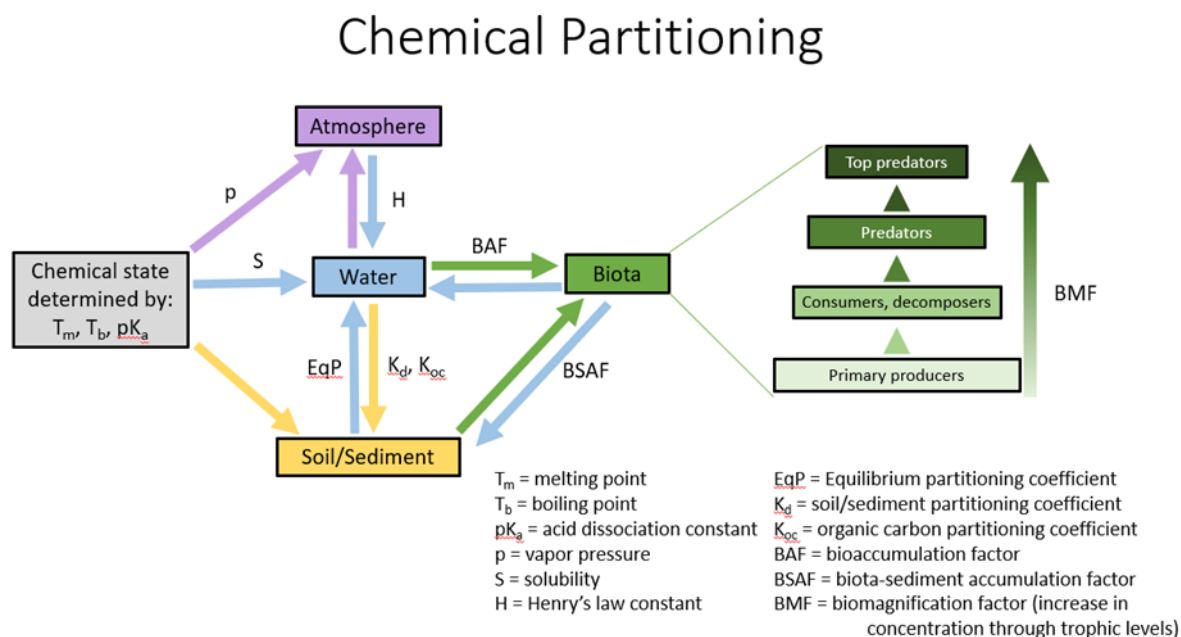
Contaminants in sediments, such as PFAS, behave differently depending on the freshwater, estuarine, or marine system that they are occurring in. For example, the fate and transport of PFAS in sediments is highly dependent on various environmental characteristics such as salinity, pH, the soil type and/or the soil profile. As there is insufficient ecotoxicity data pertaining to PFAS in the sediments of each aquatic system, specific guidance for the protection of each individual system cannot yet be provided.

PFAS contamination behaves differently depending on the medium (that is, in terrestrial, freshwater, estuarine or marine ecosystems). Marine sediments are, for example, often less varied in their physical characteristics and properties, such as salinity, temperature, pH, oxygen and other aquatic factors. These factors are likely to affect processes such as adsorption, desorption, deposition and remobilisation. These processes can directly affect exposure and biomagnification which can in turn impact on biota. It is therefore important that PFAS contamination in freshwater, estuarine, and marine sediments are investigated via co-located sampling of surface waters, sediments, and aquatic biota. This will help manage PFAS exposure and associated risks.

Sediments can act as a PFAS-sink through sorption to particulate matter that may consequently impact particle feeders through resuspension (that is, through dredging or natural events) or by desorption back to the water phase (Kumar et al. 2020a; Simpson and Batley 2016). This is likely to be the case for many PFAS (Simpson et al. 2021; Oliver et al. 2020; Zhu et al. 2014; Zareitalabad et al. 2013; Yang et al. 2011). Sediments may also act as secondary source zones or 'reservoirs' after the primary source zone at the point of emission has been managed. The management of PFAS-contaminated sediments can be complex and costly, while having significant technical limitations. Therefore, avoiding contamination by investing in the prevention of PFAS emissions is considered the most cost-effective way to manage the risk.

Generalised information regarding the fate and transport of PFAS in estuarine and marine environments is conceptualised in [Figure 1](#), [Figure 2](#) and [Figure 3](#) (see [Section 8.3](#) and [Section 8.4](#)). Chemical partitioning relationships between environmental compartments, including sediments and biota, are shown in [Figure 5](#).

Figure 5 Chemical partitioning relationships between generalised environmental compartments, including sediments and biota



Adapted from ITRC (2020)

8.7.5 Sediment quality guidance

Depositional environments such as wetlands, rivers, streams and estuaries have significantly different biotic and abiotic processes to terrestrial environments. Additionally, the type of ecosystem receptors also differ between sediments and soils. As a result, terrestrial soil guidelines or investigation values should not be used as ecological screening values for aquatic sediment contamination, particularly estuarine and marine sediments.

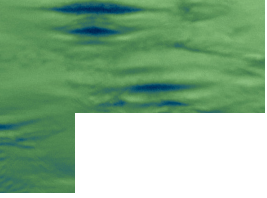
The following section focuses on PFAS contamination in aquatic sediments. However, there is currently insufficient relevant ecotoxicity data available to derive high confidence guideline values for PFAS in freshwater, estuarine and/or marine sediments. This guidance will be updated in future versions of the PFAS NEMP as more scientific information on estuarine and marine sedimentary ecosystems becomes available.

Freshwater sediment quality guidance

Currently, there is insufficient ecotoxicity data for PFAS in freshwater sediments to provide guideline values. The potential effects of PFAS in freshwater sediments is a priority for future work.

Estuarine and marine sediment quality guidance

Currently, there are no Australian or New Zealand sediment quality guideline values for PFAS such as PFOS, PFOA, and PFHxS, as ecotoxicity data is limited (Simpson et al. 2021; Kumar et al. 2020a and 2020b; Batley



et al. 2020; Oliver et al. 2020). As further scientific information becomes available, this guidance will be updated in future versions of the PFAS NEMP.

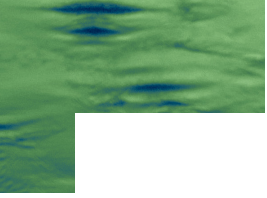
A lack of toxicity data for PFAS in estuarine and marine sediments has meant that international attempts to derive sediment quality screening or guideline values have used equilibrium partitioning (EqP) approaches (Batley et al. 2020; EC 2011; OECD 2002). The reported methods have been reviewed and limitations found in almost all studies (Kumar et al. 2020b).

Where criteria for PFAS in aquatic systems have been proposed, they have generally focused on fresh and marine waters and soils. Few international soil or surface water screening values for PFAS have been assessed as applicable to estuarine or marine sediments in Australia or New Zealand. Currently, sediment quality guideline values for toxicants typically use the lower 10th percentile of an empirical ranking of effects data (often involving a mixture of multiple toxicants (ANZG 2018)). This is because there are usually insufficient data to generate species sensitivity distribution (SSD) curves from sediment toxicity data for individual toxicants (Simpson and Batley 2016).

As the SSD approach currently cannot be applied to PFAS due to a lack of data, an alternative is to derive a sediment screening value based on EqP, namely, using a sediment-to-water partition coefficient (K_d) to convert a water quality guideline value or a predicted no effect concentration (PNEC) for water to a guideline value for sediments (Simpson and Batley 2016). The approach has previously been demonstrated for other contaminants, including metals, polycyclic aromatic hydrocarbons (PAHs) and POPs (EC 2011; US EPA 2003a, 2003b, 2003c, and 2003d).

A recent paper by Simpson et al. (2021) assesses the direct toxicity of PFAS to aquatic species in estuarine sediments. Simpson et al. (2021) used a combination of a SSD based on PFOS toxicity data for benthic marine species and measured K_d values, to derive a screening value for estuarine benthic sediments. The Simpson et al. (2021) study used a K_d value of 10 to derive a 99% species protection concentration (PC99) of 60µg/kg for PFOS (normalised to 1% organic carbon (OC)) in benthic marine sediment. It provides a line of evidence in considering direct toxicity. Note that the values do not yet fully account for long-term multi-generational effects, bioaccumulation or biomagnification (Section 8.7.7).

The long-term multigenerational effects were shown to be a sensitive endpoint in the derivation of the draft water quality guidelines set out in Table 8. For these reasons, and because the PC99 screening value proposed in the study is not currently endorsed as a single point of evidence by environmental regulators, the advice of environmental regulators should be sought if considering its use. The use of multiple lines of evidence, understanding the limitations on multi-generational effects, and including considerations for bioaccumulation as is undertaken for PFAS with the water quality guidelines is important. For the same



reasons discussed in regard to water quality guidelines (Section 8.7.3), a 99% aquatic toxicity value bears no relationship to bioaccumulation in air breathing fauna such as birds, or mammals. Evaluation of PFAS concentrations in the diet of those receptors is recommended to assess these risks.

8.7.6 Organic carbon and sediment adsorption coefficients

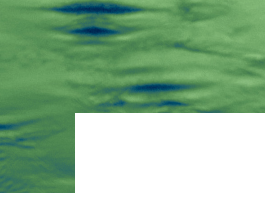
In estuarine and marine sediments OC has been identified as a strong predictor of PFAS (particularly PFOS) partitioning between the overlying water column and associated sediments (Simpson et al. 2021; Oliver et al. 2020; Zhu et al. 2014; Chen et al. 2012; Ahrens et al. 2011; Yang et al. 2011; You et al. 2010). As a result, OC concentrations are likely to influence the bioavailability of PFAS to benthic estuarine and marine sedimentary organisms. For example, where an OC value ranges between 0.1% to 5.6%, the resulting K_d ranges from 16–150L/kg. This relationship has been reported in some sedimentary systems (Simpson et al. 2021; Oliver 2020), whereas other studies did not show these strong relationships (Celis-Hernandez et al. 2021; Oliver 2020). How OC K_d relationships are used when assessing PFAS in sediments needs to be carefully considered given these conflicting findings. Until further scientific information becomes available, OC and other relevant data such as salinity, pH, sediment particle size, soil class, and chemical type should be collected when sampling sediments for site assessments. Some of these qualities are valuable modifying factors when considering sediment toxicity of other contaminants under the WQG.

8.7.7 Considerations for bioaccumulation

Multiple lines of evidence are an important consideration when assessing and monitoring sediment quality (ANZG 2018; Australian Government 2009; Simpson and Batley 2016). More detailed guidance is available in a range of publications including:

- National Assessment Guidelines for Dredging 2009 (Australian Government 2009)
- Monitoring and Sampling Manual: Environmental Protection (Water) Policy 2009 (DES 2018)
- Water quality – Sampling – Part 12: Guidance on sampling of bottom sediments from rivers, lakes and estuarine areas (ISO 2017)
- Field Manuals for Marine Sampling in Australian Waters, Version 2 (Przeslawski and Foster 2020)
- other jurisdictional or relevant authority's contaminant monitoring guidelines.

Bioaccumulation and biomagnification issues may be quite significant in considering sediment exposure pathways. To evaluate these issues,



similar to aquatic exposure, biota sampling is generally preferred and may be needed where there is exposure of ecological receptors to PFAS in sediments, or where there is a plausible PFAS transport pathway from a contamination source to the sediments. For example, the Queensland ambient PFAS monitoring program (Baddiley et al. 2020) detected PFOS concentrations in sediment dwelling aquatic organisms at concentrations that exceed wildlife diet guideline values (Table 7). However, PFOS was not detected in co-located estuarine sediments (limit of reporting (LOR) 0.9–1µg/kg). Sampling of aquatic biota needs to be representative, comprehensive and sufficient to conceptualise PFAS contamination.

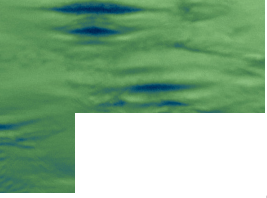
Exposure pathways to consider include sensitive ecological receptors such as aquatic flora and fauna, waterbirds, predators and higher trophic level organisms (see Section 8.4). Assessing and managing PFAS-contaminated sediments requires well designed monitoring and assessment programs. Accurately characterising both sediment properties and any PFAS contamination is important in developing a robust CSM and sampling and analysis quality plan (SAQP) (see Section 5.1 on planning and designing PFAS monitoring programs; Section 5.3 on site-specific monitoring programs; Section 8.1 on considerations for using guideline values; Section 9 on PFAS-contaminated site assessment; Section 9.2 on risk assessment; Section 9.3.1 on precursors and transformation products; Section 9.3.2 on the bioaccumulative nature of PFAS; and Section 18.1 on SAQPs).

8.8 Information on alternative approaches to risk assessment and environmental management of PFAS compounds and mixtures

The range of PFAS compounds measured in environmental media and wastes may be more extensive and in greater concentrations than just PFOS, PFHxS and PFOA. These three compounds can co-occur with or be absent from mixtures containing various homologues and PFAA precursors.

Although there is limited information and consensus around management of these other PFAS, the limited data emerging suggests that some of these or their precursors may be equally toxic, persistent, and/or bioaccumulative. For this reason, in accordance with the precautionary principle, it is important to consider their potential presence and possible ways to approach management and risk assessment. Given the large number of compounds and paucity of data on their properties and effects, risk assessment and management approaches are increasingly considering groups of compounds together on some basis to simplify assessment of media containing complex mixtures of PFAS.

The intention of the following section is to present some information on approaches that some overseas jurisdictions have taken to grouping PFAS.



It is provided to assist in understanding that approaches to deal with multiple PFAS are increasingly being employed, and outline some of the limitations and requirements associated with the approaches. Because there is currently no prescribed approach in Australia or New Zealand to assessing risks associated with complex PFAS mixtures, practitioners may need to consult with jurisdictional environmental regulators regarding the suitability of the various approaches in specific assessment scenarios.

In assessing and managing PFAS involving significant concentrations of PFAS outside of PFOS, PFHxS and PFOA, including complex mixtures, consideration should be given to implementing a monitoring and management approach appropriate for the contaminant profile, and environmental setting consistent with PFAS NEMP general environmental obligations and jurisdictional requirements.

A recent article (Goodrum et al. 2020) discusses issues related to assessing mixtures of PFAS. The discussion highlights the difficulties in choosing the most effective approach given the currently available information. Cousins et al. (2020) reviews pros and cons of various grouping approaches for PFAS management.

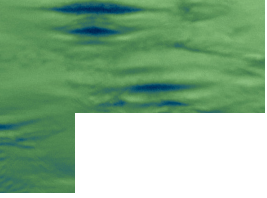
8.8.1 Simple additive approach

One approach is to develop guidelines for PFOS and apply these to the sum of a particular grouping of other PFAS. Advantages of this approach are that it is easy to understand, uses existing analytical methods and can be compared to environmental or human health guidelines. It assumes that a guideline value for the summated concentrations of all the group members is based on the value that would be acceptable if the total concentration was attributed to the member of the PFAS grouping with the most adverse effect of greatest concern, so it should be conservatively protective for that particular environmental or health risk. Uncertainties with this approach are whether all the PFAS in the group exert toxicity through the same mode of action and whether synergism or antagonism rather than additivity is relevant in the assessment of risk.

An example of this approach is the summation of PFOS plus PFHxS currently used for the derivation of criteria published in this section. Groupings used internationally differ across jurisdictions and reflect issues such as time of adoption and analysis techniques available, as well as what is considered relevant for the country.

Variations on the additive approach are dose addition and response addition. However, these rely on understanding of component toxicities unlikely to be available for the components of PFAS mixtures in many investigations:

- dose addition is applicable when the component chemicals share a similar adverse outcome pathway based on evidence of a common mode



of action or more broad evidence of impairment of the same target organ or biological systems

- response addition applies when components act on different systems or produce effects that do not influence each other (Goodrum et al. 2020).

Simple concentration addition should be considered a screening approach with inherent conservatism (that is, reasonable evidence that the compound against which the sum is compared is likely the most hazardous). Adopting this approach may result in conservative estimates of risk and consequently overconservative remediation. While a conservative approach can be consistent with the precautionary principle, it is important to consider the environmental context if setting management objectives.

8.8.2 Grouping based on environmental persistence

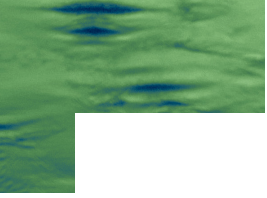
This approach includes compounds and homologues persistent in their own right. It also recognises that although PFAA precursors are not persistent, they transform in the environment and within biota, creating terminal products that are persistent. For example, the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention) refers to 'PFOA, its salts and PFOA-related compounds'.

This consideration has strong relevance when considering matters such as impact of an environmental release, the necessary duration of an environmental management measure and whether a fixation treatment is enduring. Compounds with a long environmental persistence necessitate more robust efforts in minimising release and maintaining effectiveness of management measures.

8.8.3 Grouping based on environmental persistence and another risk factor

This approach groups persistent compounds that exhibit another risk factor such as high mobility, high water solubility or bioaccumulation potential in either plants or animals or both. For example, the European Chemicals Agency groups compounds which are 'persistent, bioaccumulative and toxic' as well as substances that are 'very persistent and very bioaccumulative'. Germany has proposed a new regulatory grouping under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) of 'very persistent and very mobile' to protect water sources (Neumann and Schliebner 2017).

These approaches target groupings more closely to a specific risk factor. So far, they rely on 'read-across' principles and availability of information such as compound structure and solubility to inform grouping. The 'read-across' approach is used whereby human health effects and/or environmental effects or environmental fate may be inferred from data



for a reference substance(s) within the group by interpolation to other substances in the group.

This approach is likely to be useful when information is available on how relevant a potential PFAS group member is to the risk factor of interest. For example, if an objective was to reduce risks of plant uptakes, grouping of compounds with soil to plant transfer factors greater than a suitably low value could be considered whilst partition coefficient K_d values could be used to group compounds of higher risk of leaching.

8.8.4 Grouping per-fluoroalkyl acids together with their precursors

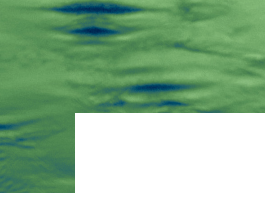
Under this approach, used in international regulation, a PFAS of concern is managed together with all its salts and precursors. The most well-known example is the Stockholm Convention, which lists PFOS, PFOA, and PFHxS this way by including 'related substances'. Similarly, a group of long-chain PFCA and associated precursors is also proposed for listing under the Stockholm Convention. Significantly, LPCLs for PFAS-related substances are generally based on a range of criteria, rather than toxicity alone.

This approach is useful when a PFAS compound is present together with its precursors in an exposure setting, waste or other circumstance under consideration. While comparing the sum of mass concentrations of the compound and its precursors to a relevant guidance value is one approach, it would be preferable if practicable to convert results to a chemical equivalent by considering the group on a molar basis.

8.8.5 Total organofluorine approaches

This relies on rapid and comparatively inexpensive analysis to measure the amount of fluorine in a sample, either total fluorine, which includes both organic and inorganic fluorine, or extractable/adsorbable organic fluorine (EOF/AOF), which more closely approximates total organofluorine and PFAS. A total fluorine analysis or criterion applied to soil lacks utility and is generally not recommended where soil minerals may contain fluorine. EOF and AOF avoid or mitigate the confounding effect of inorganic fluorine in sample matrices and are more useful for screening the presence of PFAS than for specific risk assessment, as they do not identify compounds contributing to the fluorine presence. These techniques may not be suitable where inorganic fluorine concentrations are orders of magnitude greater than the PFAS concentrations. Organic fluorine, measured by total organic fluorine (TOF) or EOF, is used in some countries regulating PFAS content in food contact material (Danish Veterinary and Food Administration 2020).

TOF analysis is further described in [Section 18.3.2](#). EOF and AOF are less specific techniques that measure the inorganic fluorine content of a sample broadly; this includes non-PFAS compounds, unidentified PFAS compounds



and known PFAS compounds that may or may not be the prime concern for the investigation.

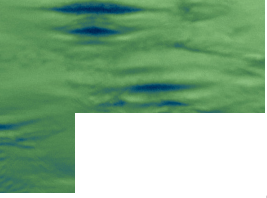
Subject to the above caveats, this approach is useful in screening potential presence of PFAS at comparatively high concentrations in circumstances when there is little information about available compounds potentially present in matter under investigation. Such analyses have been used as a screening tool estimating PFAS mass in samples, including products, articles and waste. In samples where there is a likely precursor presence identified by a total oxidisable precursor (TOP) assay, knowledge of extractable or adsorbable organic fluorine content by comparison of fluorine equivalent measured in the assay helps identify the extent to which the assay has accounted for precursor presence.

8.8.6 Total PFAS

A more recent overseas approach proposed is a drinking water guidance value for total PFAS (EU 2020), where 'PFAS Total' means the totality of per- and polyfluoroalkyl substances and is defined as substances that contain a perfluoroalkyl moiety with three or more carbons (that is, $-\text{C}_n\text{F}_{2n}-$, $n \geq 3$) or a perfluoroalkylether moiety with two or more carbons (that is, $-\text{C}_n\text{F}_{2n}-\text{O}-\text{C}_m\text{F}_{2m}-$, n and $m \geq 1$). The advantage of this approach is that one measurement could, if sufficiently conservative and appropriately relevant, account for numerous potential adverse effects of a large range of PFAS. The actual measurement approach is still to be decided.

It is more accurate and preferable to use the term 'sum of PFAS' rather than 'total PFAS' and specify the range of compounds within scope of the applicable analytical technique in recognition of the fact that commercially available techniques do not wholly account for the large range of fluorinated compounds that the term total PFAS implies. Use of this approach would necessitate an assessment of the range of PFAS potentially relevant to an exposure, waste or product circumstance, identification of an analytical technique applicable to detection and specification of the range of compounds included in the summation. This approach is similar to the use of TOF but can be more tailored to address the circumstances or issue being addressed, to reduce the degree of conservatism inherent in the TOF approach. The LORs may also be lower than those of TOF analysis, providing greater utility for screening at lower concentrations. As a grouping approach, the considerations discussed in [Section 8.8.1](#) are relevant.

Health Canada (2022) provides an example of a grouping approach that could be applied in an environmental protection context. The grouping is designed to ensure a stated PFAS exposure is maintained as low as reasonably achievable that could be adapted for addressing environmental issues. The compounds included and objective value developed by



Health Canada (2022) were determined by considering relevant treatment processes, available reporting levels using recognized analytical methods, relevant local monitoring data and the lowest treated concentrations technically achievable for a large number of quantifiable PFAS.

8.8.7 Relative potency factors

The Netherlands has developed potency factors for individual PFAS (Bil et al. 2021; Zeilmaker et al. 2018). This approach is similar to that applied in managing dioxins and PAHs. It is based on an observation that many PFAS commonly exert liver toxicity in animal studies. Comparative liver toxicities of 16 PFAS were determined with potency of PFOA assigned a value of 1 against which the others were scaled. An additional seven PFAS were also included in the scheme by using a read-across approach, which equated potency for these compounds to that of relevant similar homologues, giving a total of 23 compounds in the weighting scheme (Bil et al. 2021).

One potential application of potency factors is multiplying them against the reference dose for a common reference compound to allow estimation of reference doses for other PFAS in the scheme to allow risks to be determined. Another approach is to use these potency factors to provide an estimation of concentration in sediment, water, air or other media, of reference compound equivalents. The respective potency-based estimated reference doses and equivalent doses based on them could then be used in risk assessments or guideline formulation.

One limitation of this approach is that it is not evident that the common adverse effect (for example, liver toxicity in the above case), is the most toxic adverse effect out of those observed. For example, developmental effects in the case of PFOA and immunotoxicity in the case of PFOS may be more sensitive end points (Guruge et al. 2009; ATSDR 2021). A second limitation is that some evidence indicates that mixtures of PFOS with other PFAS show a synergistic toxicity; that is the effect caused when exposure to two or more PFAS results in a greater toxicity than the sum of the effects of the PFAS (Ojo et al. 2020; Ding et al. 2013). Synergistic toxicity is difficult to incorporate into a relative potency approach, as relative potency assumes toxicity is additive.

Some research on toxicity to biota has proposed that the differences in relative potency factors are chiefly an indication of accumulation potential due to differences in the PFAS elimination rates. Examination of the comparative potencies on an internal dose basis found little toxicity difference between compounds (Gomis et al. 2018).

At this stage, it is uncertain whether sufficient toxicological information is available to reliably use this approach for ecological risk assessment.

8.8.8 Development of specific toxicity reference values

Some international jurisdictions have developed toxicity values for a range of individual PFAS (for example, Danish Ministry of Environment 2015; US EPA 2021a). These involve selection of a relevant critical effect study, derivation of a point of departure for the chosen critical effect, conversion to a human equivalent dose if relevant and division by the product of uncertainty factors. As the studies chosen, critical effects, and uncertainty factors applied vary across jurisdictions, there can be a wide range of toxicity reference values derived for any one PFAS compound. When these are translated into guidance values for media such as drinking water or soil, exposure assumptions and relative resource allocations as a percentage of tolerable intakes add to the variation.

These sources may be helpful in contributing to risk assessment of specific compounds. It is not appropriate, however, to apply these without a strong understanding of their basis of derivation and review of applicability to the Australian or New Zealand context. For example, reviews of animal studies underpinning toxicity reference values may be helpful in reviewing ecological risk, but toxicity reference values based on human equivalent dose have no relevance to ecological assessment. Also note that HBGVs should not be used without confirmation they are appropriate by health regulators and adjustment of exposure assumptions to those relevant to the Australian or New Zealand context. The disadvantage of this chemical-by-chemical approach is the large amount of data required for relevant critical effect studies that is often not available. Also, as new PFAS chemicals come into use, there is an ongoing need for derivation of toxicity values.

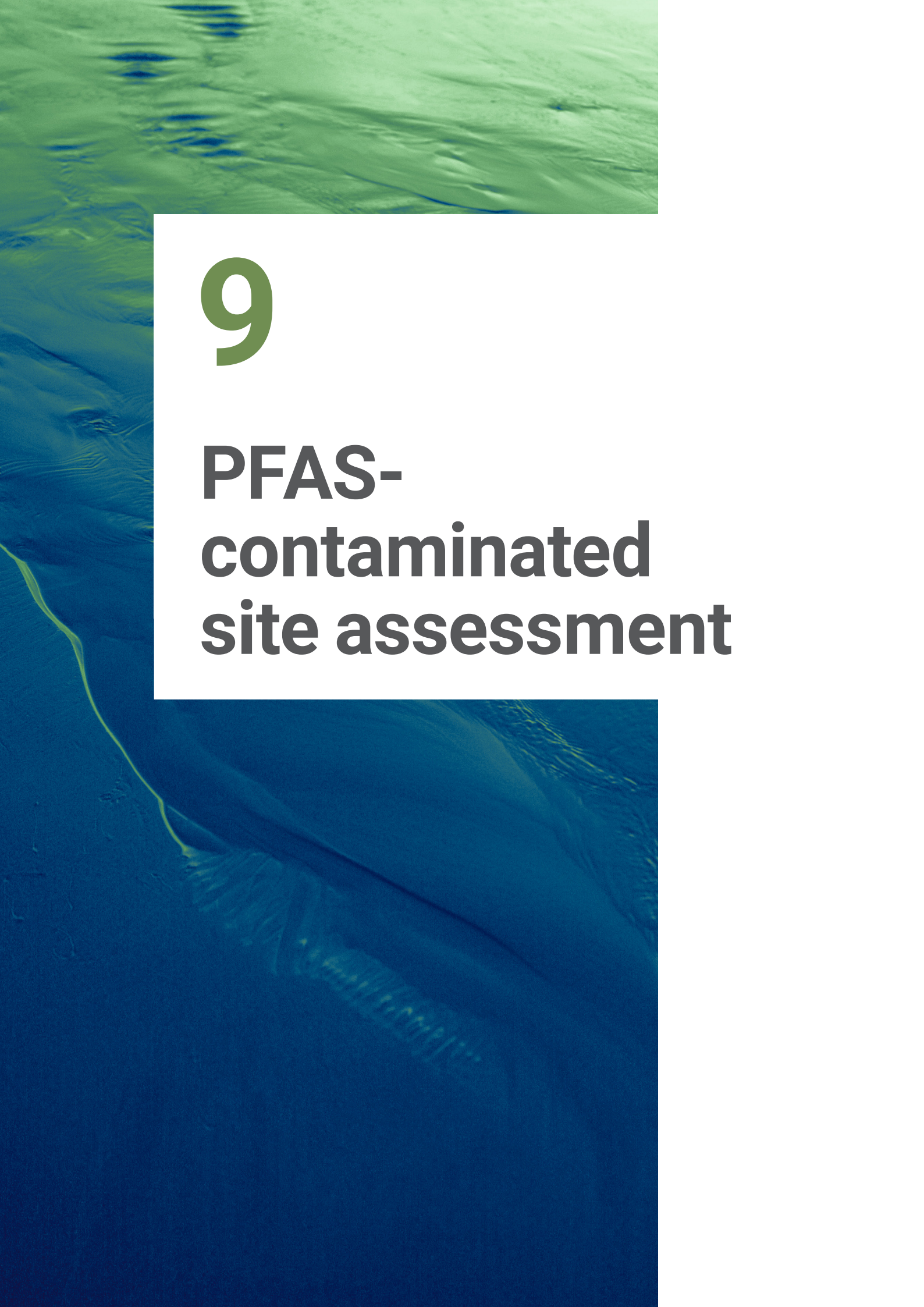
Some researchers have developed ecological toxicity reference values for PFAS mixtures by determining doses that cause ecologically relevant adverse effects using traditional toxicity testing. For example, Dennis et al. (2021) investigated reproduction, growth, and survival endpoints in breeding pairs of quail exposed for 90 days to different concentrations of perfluorohexanoic acid (PFHxA) and PFOS mixtures via drinking water and established oral lowest observed effect levels. The mixtures were chosen to reflect dominant PFAS commonly reported in environmental exposures.

Effect levels such as these reported in literature may be utilised in developing mixture-related specific toxicity reference values, which could be helpful in screening mixtures of similar complexion in environmental assessments. This approach would involve applying similar uncertainty factors to the chosen effect level as those underpinning PFAS NEMP environmental guidance to ensure consistency (see Supporting Document 2).

8.8.9 Emerging alternate testing approaches

Alternate testing approaches may help fill knowledge gaps left by traditional ecotoxicology tests. For example, for reptiles, rapid *in vitro* and *in silico* testing approaches with reptile primordial germ cells (Golkar-Narenji et al. 2023) and isolated mitochondria (Haenel and Moore 2018) from reptile biopsies are useful for assessing animal fertility and organ toxicity. tPOD assays developed by the US EPA offer another avenue for rapidly generating toxicity data at the gene level before an unwanted phenotype occurs (Alcaraz et al. 2022; Harrill et al. 2024). The tPODs can be extended to include other -omics measures, such as proteomics, lipidomics, and metabolomics. Biological features, such as genes and metabolites, will become increasingly vulnerable to changes (that is, one gene can regulate hundreds of metabolites).

If using new assessment methods, it is important to check if there is a reasonable basis to infer the observations are relevant to ecological health (refer to [Section 8.7](#)). Uncertainty may preclude use in quantitative risk assessment, although these are useful approaches to include as multiple lines of evidence and as indicators where traditional methods may not capture potential effects.



9

PFAS- contaminated site assessment

9 PFAS-contaminated site assessment

The complexity of PFAS contamination means that contaminated site assessment will commonly require a site-specific risk assessment to determine the risks associated with land and resource uses (that is, potential risks to the environment, to human health, and to environmental values).

The established national guidance document for the assessment of site contamination in Australia is the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM). In New Zealand, this guidance is provided by Contaminated Land Management Guidelines 1 and 5.

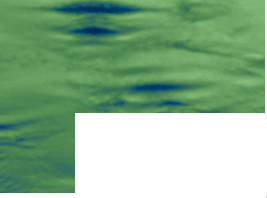
The general advice provided in the ASC NEPM and other established guidance may not always account for the specific considerations applying to PFAS assessment, particularly in relation to the protection of ecological values. The following advice is provided as a supplement to support the application of the ASC NEPM and other established guidance, such as jurisdiction-specific guidance, for PFAS management.

Specific considerations for assessment of PFAS-contaminated sites, reflecting the unique characteristics of PFAS, include:

- the persistence of PFAS in all environmental media (soil, sediment, surface water, groundwater)
- the high mobility of most PFAS in water, as well as in some soils and sediments
- the ability of some PFAS to bioaccumulate in humans, plants and animals, and biomagnify with each trophic level or step of a food chain, in a way that differs from other contaminants (for example, the lipophilic persistent organic pollutants (POPs)).

This means that particular attention should be given to the potential risks of PFAS contamination for ecological values, both on- and off-site. These potential risks may include risks to terrestrial and aquatic wildlife exposed through the food chain, and risks to aquatic wildlife exposed through the transport of PFAS into aqueous environments.

PFAS include a wide range of compounds with varying physico-chemical properties. PFAS are relatively soluble in water. Once PFAS have dissolved, most of the mass will be transported over time through surface drainage to surface water bodies and through leaching to groundwater, although sorbing to some extent to soils and sediment may also occur. Once dispersed in the aqueous phase, PFAS are highly bioavailable to aquatic organisms and plants.



If complete pathways of exposure to PFAS contamination are suspected or known to be present, including by ingesting contaminated water or produce, then immediate mitigation or management strategies should be implemented to minimise human exposure.

Therefore, if a credible source of PFAS contamination is identified (see [Appendix C](#)) it should be assumed that contamination can reach surface water bodies connected to the site by a viable surface water pathway. This can include drains and groundwater. The possibility of long-distance movement of contamination should be considered. Note that in Australia and overseas, groundwater plumes kilometres long have been identified.

When assessing contaminated sites, consideration should be given as soon as practicable to the potential for multiple exposure pathways affecting sensitive receptors, in order to develop a robust conceptual site model (CSM) and implement effective management controls. Early stakeholder engagement, including completion of water use and food surveys by people living and working in the area, is important to provide critical data for identifying complete exposure pathways. This will in turn inform decisions on precautionary measures to limit exposure and implement effective management controls.

9.1 Site investigation process

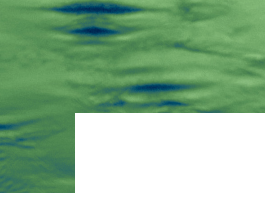
PFAS may come from a point source, from diffuse sources, or a combination of the two. The nature of the potential source(s) is an important consideration for the desktop component of the preliminary site investigation and when developing the CSM, and/or a sampling and analysis quality plan (SAQP).

Consideration should be given to the presence of both primary sources (such as firefighting training areas, landfills or wastewater treatment plants (WWTP)) and secondary sources (such as sediment in surface water bodies in retention ponds and dams at, or connected to, the site) as well as past use.

The scale and longevity of PFAS use, as well as the potential for complex PFAS contamination due to the use of different product formulations, should be considered (for example, a change in firefighting foam usage from an electrochemical fluorination-based aqueous film-forming foam (AFFF) to a fluorotelomer- or fluoropolymer-based AFFF).

9.1.1 Identification of off-site receptors

The ASC NEPM guidance allows for both the classic site assessment approach which starts with the on-site source, as well as where the



assessment starts with the identification of risks to off-site receptors and moving inward to determine the source.

The classic detailed site investigation approach would be to characterise on-site sources of PFAS followed by delineation of the contamination extent in affected media off-site in a systematic manner. However, this approach may cause significant delays in identifying and evaluating risk to off-site receptors, in informing affected communities, and in undertaking actions to mitigate unacceptable risks to sensitive receptors.

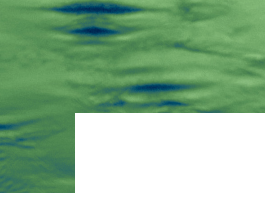
Following the identification of a credible source or sources of PFAS, priority should be given to early investigation of risks to sensitive off-site receptors. In practice, this should include targeted sampling of key PFAS migration pathways and receptors to inform a preliminary risk assessment and decision-making regarding precautionary risk management actions. The results of this targeted investigation should be used to inform the subsequent more detailed investigation and risk assessment.

9.2 Risk assessment

The ASC NEPM risk assessment process should be followed, giving due regard to the assumptions and limitations on use applicable to the available guideline values as discussed in [Section 8](#). In many cases the CSM is likely to be complex and include multiple exposure pathways and/or land uses which are not considered in the screening values. Consequently, site-specific risk assessment will be required where screening values are not available and/or are not appropriate to the site-specific circumstances.

Considerations for both human health and ecological risk assessment include, but are not limited to:

- nature of the source and potential contribution from precursors to risk (qualitative assessment)
- mass load and flux of PFAS to, within and from the site
- leaching from soil to groundwater and surface water
- adsorption onto, and leaching from, sediments
- groundwater discharge to surface water
- bioaccumulation and biomagnification in the food chain
- wastewater discharge with potential for accumulation in biosolids and discharge in the treated effluent from wastewater treatment facilities
- reuse of biosolids and effluent, including recycled water
- irrigation with impacted surface water, groundwater, and/or treated effluent, and uptake by plants and possible accumulation in soil.



Considerations for human health risk assessment include, but are not limited to:

- ingestion of contaminated stockwater (surface water and/or groundwater) and of contaminated grazing material and soil by livestock
- human intake of contaminated water through drinking or cooking
- human exposure to contaminated water through activities such as cleaning, showering and swimming
- human consumption of foodstuffs (including seafood, meat, eggs, grains, milk, fruit and vegetables) produced in the impacted area.

Considerations for ecological risk assessment include, but are not limited to:

- exposure of terrestrial (including avian) and aquatic organisms to contaminated soil, sediments and/or water
- ingestion by terrestrial (including avian) and aquatic organisms of contaminated plants and/or animals
- types of species and trophic levels.

9.3 PFAS-specific considerations

Broadly, PFAS are produced from two processes:

- electrochemical fluorination (ECF)
 - products (for example, firefighting foam) produced by ECF were based on PFOS and sulfonamide-based surfactants, which are understood to be precursors to perfluorosulfonic acids (PFSA) such as PFOS
- telomerisation
 - products based on fluorotelomers are considered perfluorocarboxylic acid (PFCA) precursors (D'Agostino and Maybury 2014).

Therefore, sites where only one type of product was used are likely to have one type of dominant precursor, whereas sites where both have been used may have both PFSA and PFCA precursors.

Source characterisation can be assisted when the identity and composition of products that have caused the contamination are known. Some studies have identified the classes of compounds present in various firefighting foam product formulations (for example, Backe et al. 2013; D'Agostino and Maybury 2014; Place and Field 2012). In spill incidents, the products may be available for sampling and characterisation.

[Appendix A](#) provides more information about the PFAS family.

9.3.1 Precursors and transformation

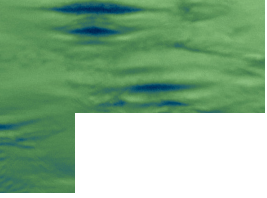
The characterisation of pathways and receptors should consider the likely or possible presence of a range of PFAS, including precursors (see the [Australian Industrial Chemicals Introduction Scheme \(AICIS\)](#) for information about PFAS compounds listed on the Australian Inventory of Industrial Chemicals).

The SAQP should investigate whether precursors and their transformation products, if present, have migrated along identified pathways and to receptor sites. If so, the CSM should also incorporate potential transformation products (for example, pathways and receptors affected by a fluorotelomer-based source zone should consider PFCAs rather than just fluorotelomers). It is therefore important that environmental assessments qualitatively consider the likely total mass and distribution of all PFAS present as well as PFOS, PFOA and PFHxS and other specific PFAS of concern.

A screening approach is useful for investigations, where appropriate analyses are applied to a representative number of samples to indicate whether detailed consideration of precursors is required.

Common commercially available analytical techniques based on liquid chromatography-tandem mass spectrometry (LC-MS/MS) generally include a range of perfluoroalkyl carboxylic acids, perfluoroalkyl sulfonic acids, perfluoroalkyl sulfonamides, and n:2 fluorotelomer sulfonates. These will, depending on the analysis requested, typically identify and measure up to approximately 33 PFAS compounds including the three most commonly known PFAS (PFOS, PFOA and PFHxS). However, this analytical suite may only incorporate a small proportion of the PFAS present, since compounds such as fluorotelomers other than n:2 sulfonates and fluoropolymers present in some formulations and intermediate transformation products (for example, fluorotelomer carboxylic acids and fluorotelomer alcohols) are not included within this typical analytical suite (Weiner et al. 2013).

Tools for screening for the presence of a broader range of PFAS include non-selective analytical techniques (for example, total oxidisable precursor (TOP) assay and total organic fluorine (TOF) assay). More recently, some laboratories have extended the scope of their analytical suites to include analytes that are potentially present in some wastes and/or include compounds that are emerging as replacements for withdrawn PFAS (for example, see [Appendix B.3.4](#), US EPA Method 1633). If precursors are present and further information is required on the specific PFAS (for example, discriminating between potential sources of PFAS emissions), more advanced analytical options are available such as untargeted high-resolution mass spectrometry (for example, orbitrap and liquid chromatography quadrupole time-of-flight mass spectrometry (LC-QToF-MS)). This approach is consistent with the ASC NEPM, which requires that site conceptualisation and characterisation is undertaken



to the extent necessary to reliably inform risk assessment and actions to manage unacceptable risks. These analytical options are discussed in greater detail in [Section 19](#).

As the knowledge base on PFAS transformation and behaviour is evolving, it is advisable to seek expert advice when investigating precursors and transformation products. Fully fluorinated end point perfluorinated compounds, such as PFOS and PFOA, will not degrade under typical environmental conditions. Polyfluorinated compounds can undergo transformation in the environment, during wastewater treatment processes and during some forms of remediation (for example, when using strong oxidants to remediate petroleum hydrocarbons). There is a risk that remediation for hydrocarbon contaminants may inadvertently lead to transformation of PFAS if site assessments do not investigate the presence of PFAS precursors (McGuire et al. 2014).

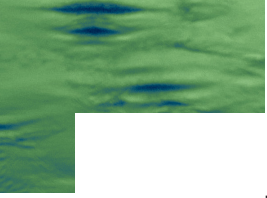
The degradation products of PFAS are often other measurable PFAS that contain a similarly sized (that is, equivalent length or one to two carbons shorter) perfluorinated group. Due to their potential to form more persistent perfluoroalkyl acids (PFAAs), these polyfluorinated compounds are often referred to as PFAA precursors or simply precursors, (for example, the transformation of 8:2 and 10:2 fluorotelomer compounds to form the persistent end point products PFOA and PFDA). Various PFAS transformation processes that occur in the environment are described in Washington et al. (2015).

Therefore, the biotransformation of precursors can contribute to the total concentration of PFAS of concern at a site even if no remedial actions are undertaken. Where PFAS are present in anoxic reducing conditions (that is, depleted of dissolved oxygen), such as when PFAS occurs along with hydrocarbon contaminants in groundwater at firefighting foam-affected fire-training grounds, this biotransformation process can take decades (Houtz et al. 2013).

However, if the source zone is not anoxic (for example, where firefighting foam has been spilt or used during equipment testing or has migrated into the wider environment), aerobic conditions (that is, in the presence of oxygen) are likely to markedly facilitate transformation of precursors. This is also the case if PFAS precursors are discharged to aerobic WWTPs.

9.3.2 Bioaccumulation

Bioaccumulation is the uptake of a contaminant from food and/or water by an organism which results in an increase in concentration of the contaminant in that organism. Further relevant information is provided in [Section 8](#) on PFAS environmental guideline values and [Section 18](#) on PFAS sampling.



The high water solubility and protein-binding characteristics of many PFAS contrast with the behaviour of many other persistent organic pollutants that accumulate in fatty tissues (for example, see Ng and Hungerbühler 2014). Therefore, using predictive models based on octanol-water partition coefficients (K_{ow}) to predict PFAS exposure is inappropriate.

Furthermore, PFAS bioconcentration factors for aquatic organisms have a high level of uncertainty. In evaluating risks to human health, it is important that sampling be of edible portions. For example, samples of fish fillets and prawns without heads would be required (preferably from legal size specimens), rather than the whole prey organisms used in ecological assessments. Sampling of specific organs (for example, the liver) may be required for either human health or ecological risk assessment depending on the site-specific issues being investigated.

Modelling uptake based on literature values may be incorporated into a multiple lines of evidence approach. The information should be evaluated, however, to check for the quality of the study and applicability to the site conditions being assessed.

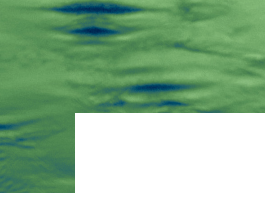
In relation to wildlife exposure to PFAS, there is a lack of available toxicity data relevant to Australian and New Zealand species, hindering quantitative risk assessment. Such information is unlikely to become available in the near future.

Bioaccumulative nature of PFAS in aquatic ecosystems

PFAS bioaccumulates in aquatic organisms. In Australia, the advice provided in the National Water Quality Management Strategy (NWQMS) (Australian Government 2019b) and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (WQG) (ANZG 2018) when assessing bioaccumulative contaminants is to use a higher degree of species protection than would normally be used (ANZG 2000; Warne et al. 2018).

In most situations, this means using the 99% species protection level as a screening value for slightly-to-moderately impacted systems, rather than the 95% value. This advice is intended as a practical measure to provide an additional level of protection to account for bioaccumulation. It is also important to note that the level of additional impact/disturbance permitted in aquatic ecosystems may be set by the environmental regulator. The use of a value providing a lower level of protection may not be permitted in such cases.

In the case of PFOS, the interim freshwater guideline value for 99% species protection is close to the trace limit of reporting (LOR) currently offered by commercial laboratories. As such, interpreting and applying this screening value may present challenges in some contexts. A point-in-time water concentration of PFAS below an LOR of 0.001 µg/L should not be assumed to mean that there is minimal risk to aquatic ecosystems, aquaculture, and wild-caught food species. It also does not mean that PFAS contamination is



not present, or that there is no need to sample sediments, water, or aquatic biota at levels appropriate for detection, quantification and reporting.

The recommended approach, if there is a PFAS source area or if it suspected to be present from historical use, is to sample and analyse aquatic biota to account for bioaccumulation and comparison with relevant criteria. Environmental regulators and/or local catchment managers should be consulted for additional jurisdiction-specific information and guidance.

Bioaccumulative nature of PFAS in terrestrial environments

Some PFAS are known to bioaccumulate in plants and animals in terrestrial environments, although the mechanisms and potential for bioaccumulation are not yet well characterised. When informing CSMs for contaminated sites, consideration should therefore be given to humans and predatory species (birds, terrestrial and semi-terrestrial mammals, reptiles, etc) that may be exposed to PFAS through their food chain. Humans, for example, may be exposed through drinking water, meat, fruit, vegetables, and eggs following exposure through PFAS-contaminated feed, soils, or groundwater.

In relation to human exposure to PFAS, direct measurement of PFAS in foodstuffs/produce is advisable for informing the CSM. Timely sampling should be prioritised to obtain produce that is representative of human exposure, as precautionary advice (for example, stopping bore water irrigation of vegetables and supply of bore water to stock) may result in a lack of suitable material to sample after the precautionary advice has been issued. This timely sampling should be done in a way that does not make exposure worse.

For the development of the CSM, modelling food uptake of contaminants may, in some instances, provide an alternative to field measurements in biota, direct measurement in foodstuffs/produce, or data from controlled environmental experimental systems (mesocosms). However, food web modelling can introduce significant uncertainties due to the multiple assumptions required and variation in the information available (for example, transfer factors to estimate PFAS uptake from water, soil, or vegetation into animals or food products such as meat, eggs and plants (ANZG 2000; Australian Government 1999a)).

Direct measurements can help reduce some of the uncertainties introduced by this modelling. These field studies should use recognised techniques and processes. Importantly, a food web assessment should not be undertaken without biota measurements. Where studies are used as the basis of the modelled assumptions, the rationale and evidence that this is the most appropriate reference for the objective should be included (see Supporting Documents for guidance on transfer factors from soil to plants for terrestrial environments). Note that there is limited information if plant uptake is related to soil exposure plus irrigation.

9.3.3 Biomagnification

Biomagnification occurs when the concentration of a contaminant is greater in an organism than in the food it eats, reflected in an increase in concentration with each trophic level of a food chain.

PFOS is unusual in that it can biomagnify through mechanisms that are different from the 'conventional' or hydrophobic POPs that are considered in the ASC NEPM. Conventional POPs biomagnify in a manner such that it is reasonable to assume that larger predatory fish will have higher concentrations than fish lower in the food chain or in most invertebrates.

PFOS has been shown to biomagnify in organisms with lungs (for example, mammals and birds). Therefore, in aquatic mammals and birds, PFOS concentrations are likely to be more elevated than in their prey, consistent with the other POPs. In organisms with gills (for example, fish), however, PFOS bioaccumulates but does not appear to biomagnify. Investigations in Australia and elsewhere have confirmed that concentrations of PFOS are highly variable between species and are not necessarily higher in predatory fish than in fish lower in the food chain or in crustaceans such as prawns and crabs. Concentrations in individual species are also highly variable.

As a result, the following issues should be considered when sampling aquatic biota:

- identification of key species for human exposure and ecosystem health
- sampling of a range of biota rather than focusing on 'sentinel' predatory species
- sampling of sufficient individuals (for ecosystem health) or combined samples (for human health) to adequately capture representative concentrations in key species
- obtaining samples of edible portions for human health assessment, preferably at animal sizes caught and harvested, for example:
 - fish – fillet, skin on
 - prawns – head and shell removed
 - crab – extracted meat
 - molluscs – edible flesh
- recognition that some ethnic communities may target less commonly sought species or less commonly consumed parts (for example, the liver or eyes), necessitating a broader suite of sampled organs
- recognition that birdlife (for example, wetland waders), may be particularly affected and require appropriate assessment.



10

On-site stockpiling, storage and containment

10 On-site stockpiling, storage and containment

Temporary on-site stockpiling, storage, and containment of PFAS-contaminated material can be undertaken at locations that are not intended to be for permanent reuse, storage or disposal.

The description of material as contaminated:

- is premised on a range of on-site processes such as:
 - site investigation
 - construction
 - demolition
 - remediation
 - care and maintenance
 - site management
- assumes that a decision has previously been made to manage this material due in whole or in part to its PFAS content.

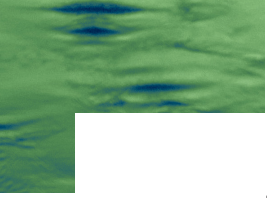
This description is not intended to cover soils, sediments, surface water, or groundwater that contain PFAS and remain in-situ and undisturbed.

This guidance is designed to assist governments, environmental regulators, developers, industry, and the community when considering on-site stockpiling, storage and containment options for PFAS-contaminated material during investigation, remediation and construction projects. It is not intended to apply to more permanent solutions such as:

- reuse of PFAS-contaminated material
- remediation approaches (such as capping)
- off-site disposal of PFAS-contaminated wastes in licenced landfill facilities
- destruction of concentrated PFAS wastes
- management of PFAS associated with wastewater treatment plants (WWTPs).

The advice set out below regarding design of on-site storage and containment infrastructure does not necessarily apply to remediation approaches such as in-situ or on-site capping. Additional technical guidance on the on-site containment of PFAS-contaminated soil is available in Guidelines for the Assessment of On-Site Containment of Contaminated Soil (ANZG 1999).

Additional information is provided in [Section 12](#) on the reuse of PFAS-contaminated material, in [Section 13](#) on the treatment, remediation and destruction of PFAS-containing wastes (including the preferred



hierarchy for treatment and remediation options), and in [Section 14](#) on the disposal of PFAS-contaminated wastes to landfill.

As set out in [Section 13](#), consideration should be given to the following hierarchy of PFAS waste management options:

- separation, treatment and destruction – this involves on- or off-site treatment of the PFAS-contaminated material so that it is destroyed, removed, or the associated risk is reduced to an acceptable level
- on-site encapsulation in constructed stockpiles or engineered storage and containment facilities, with or without chemical immobilisation – if the source site is hydrogeologically appropriate, on-site encapsulation may acceptably manage on- and off-site risks to direct and indirect beneficial uses and environmental values of soils, surface water, groundwater and biota
- off-site removal to a specific landfill cell – this may or may not include immobilisation prior to landfill disposal, noting that the conditions in the landfill may reverse or diminish the immobilisation chemistry in ways that are difficult to predict. Immobilisation prior to landfill disposal may require environmental regulatory approval. Leachate should be captured and treated to remove PFAS and the removed PFAS should be destroyed.

The management of PFAS-contaminated material often includes on-site stockpiling, storage and containment. The following types of material commonly involve large volumes:

- PFAS-containing firefighting foam stocks
- PFAS-contaminated solid material (for example, soil, sludge, sediment, biosolids, timber, asphalt, tarmac, rock, concrete, and rubble)
- PFAS-contaminated equipment (for example, appliances, pumps, pipes, fittings, nozzles, valves, extinguishers, filter material, membranes, and firefighting foam containers)
- PFAS-contaminated liquids, including firewater, water generated through flushing, construction water (groundwater, surface water runoff, etc), leachate and wastewater.

On-site storage and containment may be required during the investigation, remediation, construction, and/or demolition phases of a project, or where other treatment or remediation options are not yet available. Storage may be required for PFAS-contaminated material with a PFAS content below 50mg/kg. However, if ongoing containment presents unacceptable risks or unsustainable management requirements, it is generally expected that materials will be removed for treatment, environmentally sound disposal, or destruction.

Consistent with international approaches agreed under the [Stockholm Convention on Persistent Organic Pollutants](#) (Stockholm Convention) and the [Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal](#) (Basel Convention), if waste material

contains more than the low persistent organic pollutants (POPs) content limits (LPCLs) set for the POPs, the waste is to be treated using a technique that will destroy or irreversibly transform the PFAS. Destruction is the preferred option.

For example, techniques such as plasma arc or high temperature incineration (above 1200°C and with a high temperature resident burn time of 8 seconds (UNEP 2021b, 2023a; ITRC 2023; US EPA n.d.; Cement Australia 2018; MoE Japan 2013) are agreed technologies for destruction. In circumstances where destruction or irreversible transformation may not be environmentally preferable options due to environmental or human health impacts, the relevant environmental regulator should be consulted. See [Section 14.6](#) for further information.

10.1 Risk-based management

Timeframes and risks are important considerations in planning stockpiling, storage and containment infrastructure. As outlined in [Table 9](#), the design of infrastructure should be proportionate to the level of assessed risk (ANZG 1999).

Table 9 Stockpiling, storage and containment infrastructure

Description	Timeframe	Storage infrastructure for solid wastes and contaminated equipment ^a	Storage infrastructure for liquid wastes ^b
Transient	Less than 48 hours with no rain predicted	Covered stockpile or storage area on impervious bottom liner (for example, tarp, plastic sheeting, membrane)	Packaged liquid containers or self-bunded containment vessels on impervious bottom liner (for example, tarp, plastic sheeting, membrane)
Temporary	From 48 hours to 6 months	Managed stockpile, covered, on impervious, bunded hardstand, with effective stormwater controls (for example, diversion drains, banks) ^c	Self-bunded containment vessels covered, with lockable access, on impervious, bunded hardstand, with effective stormwater controls (for example, diversion drains, banks) ^c

continues

Table 9 *continued*

Description	Timeframe	Storage infrastructure for solid wastes and contaminated equipment^a	Storage infrastructure for liquid wastes^b
Short-term	From 6 months to 2 years	Constructed stockpile with robust anchored covers, impervious bottom liner, and effective stormwater controls ^c to ensure that rainwater and sheet flow do not contact impacted solids	Packaged, double-walled containment vessels or self-bunded containment vessels, covered, with lockable access, on impervious constructed storage area with effective stormwater controls ^c to ensure that rainwater and sheet flow do not contact contaminated liquids
Medium-term	From 2 to 5 years	Engineered containment facility, with effective stormwater controls ^c	Packaged, double-walled containment vessels or self-bunded containment vessels, resistant to UV degradation, in engineered containment facility, with effective stormwater controls ^c
Long-term	More than 5 years	Engineered containment facility, with effective stormwater controls ^c	Packaged, double-walled containment vessels or self-bunded containment vessels, resistant to UV degradation, in engineered containment facility, with effective stormwater controls ^c

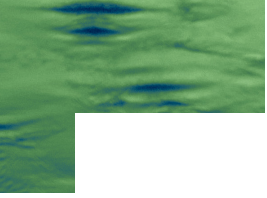
^a PFAS-contaminated equipment should be stored under cover on a sturdy impermeable, bunded surface that captures any seepage from equipment and any contaminated stormwater. Equipment, when demonstrated by monitoring to be clean following flushing or rinsing, is not subject to the requirement. Note that water used for flushing or rinsing is considered PFAS-contaminated and should be managed appropriately.

^b PFAS-contaminated liquids should be stored undercover within a secondary containment system so that any leakage due to spills, ruptures, crushing, or mishandling is effectively contained, preventing any release to soil, groundwater or surface waters.

^c A 'first flush' stormwater management system should not be used in conjunction with PFAS storage infrastructure.

For further guidance, see Sections 10.2.2, 10.2.3 and 10.3.2.

Importantly, environmental regulators in each jurisdiction may have specific regulatory requirements which should be considered in conjunction with this guidance. For example, there may be a requirement to have an environment protection licence or similar environmental approval, and this could include conditions on how stockpiles are stored. Similarly, environmental regulators may require that stockpiles comply with particular conditions on height, slope, quantity, duration and/or location. There may



also be requirements to immediately notify the environmental regulator if a loss of containment (LOC) is detected.

10.1.1 Considerations for specific circumstances

Where the volume of material is minimal (for example, less than 10m³ taken together or in aggregate), the proposed storage is transient (less than 48 hours) and rain is not predicted, then a practical approach to managing the material may be considered. This reflects the key design criterion of reducing or eliminating pathways for migration of PFAS contamination. For minimal volumes in transient stockpiles, particularly when rain is not predicted, implementation of the full range of recommended design criteria and engineering requirements may not be required.

In some circumstances, PFAS-contaminated material may be treated using chemical binding and immobilisation processes as part of on-site encapsulation within engineered containment facilities. There is limited information on the long-term effectiveness of these immobilisation techniques. Chemical immobilisation and on-site containment may be acceptable if:

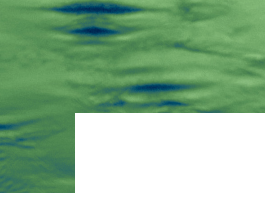
- the site is hydrogeologically appropriate
- the PFAS contamination is less than 50mg/kg of the sum of all PFOS-, PFOA-, and PFHxS-related compounds
- the facility is appropriately designed and engineered
- ongoing monitoring is guaranteed.

The full range of on- and off-site risks to soils, surface water, groundwater, and to direct and indirect receptors, and the potential for effective intervention in the event of a future LOC, should be considered in determining acceptability. The relevant environmental regulators should be consulted and a site-specific risk assessment may be required. See [Section 13](#) for more information on treatment and remediation, and [Appendix D](#) for more information on treatment technologies.

10.2 Design considerations

10.2.1 PFAS characteristics

The following guidance takes into account that there are a wide range of PFAS chemicals with varying chemical compositions, physical properties and molecular chain length. The presence of PFAS precursor chemicals and PFAS breakdown derivatives adds to this complexity. Consequently, PFAS exhibit differing characteristics and behaviours in different environmental settings. These considerations, which are discussed in more detail in [Section 9](#) and [Appendix A](#), are a critical input to effective on-site management. For example, PFAS are capable of long-range transport



through the environment, particularly in surface water and groundwater, and can migrate through soil and soil-based construction materials. Infiltration through some liners, such as clay and geosynthetic liners, is expected to occur at a significantly slower rate than for other media.

In addition, some PFAS (for example, fluorotelomer alcohols and ketones) are volatile. For these, air emissions need to be considered. Note that the options for air sampling of PFAS are not routine. Management options to reduce volatilisation or capture fugitive emissions may need to be considered.

10.2.2 Essential functional requirements

Stockpiling, storage and containment facilities should be designed to ensure they do not spread PFAS contamination or create any pathways for environmental and/or human health exposure. The development of a sound conceptual site model (CSM) can help to identify the functional requirements for the site and so inform the design process. Specific infrastructure and design requirements should be proportionate to the level of risk that is posed by the PFAS-contaminated material being stored or contained. The goal is to provide a robust interim storage solution that meets these requirements until a more effective treatment or disposal solution becomes available. Accordingly, facilities for the stockpiling, storage and containment of PFAS-contaminated material should be designed with a whole-of-life approach to construction, operation and decommissioning to meet the following essential functional requirements:

- avoid or minimise to the greatest practicable extent infiltration into the PFAS-contaminated material by precipitation, surface water and/or groundwater
- detect, monitor and collect any PFAS-contaminated liquid (leachate) generated during storage, to be extracted from the sumps for separate treatment or destruction
- ensure that the migration of leachate from sumps and other collection systems does not occur
- prevent seepage of leachate into groundwater or surface water
- avoid the release of PFAS-contaminated sediment as a result of erosion
- avoid the release of PFAS to the atmosphere
 - depending on the specific PFAS present, this may require measures to capture and manage potential emissions of PFAS to air. Misting, steaming, evaporative and other similar processes should also be avoided as PFAS is likely to be transferred by the water vapour into the atmosphere, unless the PFAS content is removed prior to emission
- mitigate dust generation
- enable future recovery of stored materials

- account for local climatic, fire, flood, geotechnical and groundwater conditions applicable to the site, property, area and region.

See also [Section 10.3.12](#) for guidance on design safety and verification.

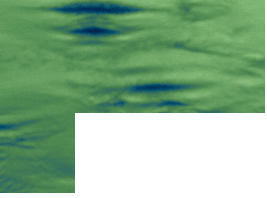
10.2.3 Additional operational requirements

In designing a storage or containment facility for PFAS-contaminated material, consideration should be given to the following operational requirements:

- making use, where appropriate, of suitable on-site materials
- access, loading/unloading and inspection
- segregated storage above and/or below ground of different material types and materials with different concentrations and, where relevant, types of PFAS contamination (for example, solids, liquids, firefighting foam concentrates, firewater, groundwater, soils, organic material, asphalt, tarmac, concrete, steel, timber)
 - the type of PFAS present may be a consideration (for example, consider future remediation and treatment). Liquids should generally be stored above ground in appropriate containment vessels/containers and in an appropriately bunded and covered area
- progressive or staged filling, capping, and/or extraction, if required
- monitoring, testing and verification.

Although not comprehensive, the following operational considerations apply to stockpiling, storage and containment of PFAS-contaminated material and should be taken into account in the design process:

- material should be stored or stockpiled, handled and transferred in a proper and efficient manner that minimises the likelihood of any leakage, spillage, or release to stormwater, surface water, groundwater, land or air
- unloading, loading and any internal transfer of liquids should be undertaken in a manner that minimises the possibility of spillage and occur on an area that is impervious to liquid, and sufficiently graded and bunded to retain any spillage or leakage
- unloading of solids should be carried out in a manner that minimises the creation of dust, and minimises or prevents emissions by any other manner
- smaller containers (for example, not exceeding 15L) should be stored within a secondary containment vessel/container
- larger packages, bulk containers and tanks must be stored in a bunded area at a sufficient distance from bund walls, unless splash shields or baffles of compatible, non-combustible materials, effective to prevent leakage or spillage, are installed which prevent any release beyond the bund wall

- 
- packages and bulk containers should be stored in a bunded area and handled so that they cannot fall or crush lower containers and cause spillage outside of the containment
 - storage and stockpiles should be placed on an impervious base or hardstand, sufficiently graded, bunded and drained to retain any spills or leaks and prevent infiltration
 - wherever practicable, roofing or other impervious cover should be placed over bunded areas, noting that tarpaulins may be appropriate for smaller transient stockpiles.

In addition, the following also apply to containment of PFAS-contaminated material:

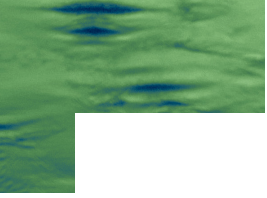
- stormwater management systems such as first flush systems should not be relied upon for containment
- storage and containment systems should be impervious to the materials stored, resistant to fire, and managed and maintained to prevent any release of liquids and leachate to sewer, stormwater drains, waters and land
- if co-located with flammable materials, allowance must be made in the design to contain firefighting water
- leachate management systems should be incorporated into the design of new facilities and existing containment facilities may also require review and/or upgrading, depending on the risks involved
- leachate that is extracted from the collection system should be sampled for laboratory analysis prior to treatment or disposal.

10.3 Detailed guidance on design, construction and management of on-site stockpiling, storage and containment

This detailed guidance applies to the design and construction of transient and temporary stockpiling and short- and medium-term storage of PFAS-contaminated material on-site during a range of on-site processes, including:

- site investigation
- construction
- demolition
- remediation
- care and maintenance
- site management projects.

This guidance also applies to the design and construction of medium- to long-term containment of PFAS-contaminated material on-site, where no



other options exist for management. Containment may include immobilising, capping or covering, or may require more significantly engineered containment facilities. In the medium- to long-term, particularly where ongoing storage or containment presents unacceptable risks, contained material should be removed for environmentally sound management or destruction.

The selection of suitable on-site storage and containment facilities should be considered as early as possible in the project planning process. It should consider the potential for PFAS to be released into the surrounding environment and the control measures required to prevent such a release. The assessment may be simple and straightforward where risks are low, and more detailed where there is a significant risk of PFAS release to the environment. Effective control measures should be implemented and monitored to ensure their ongoing effectiveness.

The design of storage, stockpile and containment facilities should include consideration of:

- the estimated mass, volume, and characteristics, including its leachability, of PFAS contamination (and co-contamination if it exists) in the material to be stored
- the type of PFAS-contaminated material to be stored at the site.

10.3.1 Key design criteria

The key design criterion is to reduce or limit the pathways for migration of PFAS contamination during and after the life of the project. This may require consolidating contaminated material in an engineered or otherwise designed facility. Where co-contamination by other hazardous, non-PFAS contaminants is known in advance, considered likely, or discovered, the design of the facility should consider the risks of each contaminant.

As PFAS are soluble in water, migration of PFAS contamination by infiltration, seepage, leakage and advection should be minimised.

Engineered facilities for storage, stockpiling and containment of PFAS-contaminated material should be designed to:

- limit the entry of rainfall, runoff, groundwater and surface water into the facility
- collect PFAS-contaminated leachate generated throughout the life of the facility, including construction.

To achieve the above, the following minimum design requirements should be considered:

- access, loading/unloading, inspection/monitoring, drainage and leachate capture, and stormwater management systems
- composite cap liner or equivalent to reduce infiltration into the facility
- composite side liner(s) to reduce infiltration into and out of the facility

- composite base liner or equivalent to maximise the collection of leachate (to reduce the potential for seepage from the facility), and to allow monitoring and measurement of leachate
- leak detection, drainage systems, sumps and other detention storages.

10.3.2 Stockpiling and storage

As outlined earlier in this section, stockpiling and storage infrastructure should be planned and implemented in accordance with a risk-based approach designed to:

- minimise the potential for the storage facility or the stockpile to release PFAS into the environment
- addressing operational requirements for differing durations of storage.

The essential criterion is to ensure all PFAS remain completely contained.

As noted above, storage and stockpiling of PFAS-contaminated material, including liquids, should be undertaken in such a way that PFAS cannot migrate into the surrounding soil or water and all runoff should be monitored for PFAS. This can often mean storage or stockpiling within a sealed and bunded area, where the material is in a suitable container or appropriately covered to minimise rainfall penetration and prevent runoff.

PFAS-contaminated material, particularly liquids, should be stored above ground in appropriately bunded storage areas or in containment vessels such as covered intermediate bulk containers (IBCs) and isotainers in bunded areas. The bunds or bunded tanks must be of low permeability and of a sufficient size to retain a major spill, including capacity for stormwater runoff. Unless otherwise required by the relevant environmental regulators, the capacity of the containment bunding should be at least 100% of the planned storage capacity plus 25% of the storage capacity up to 10,000L, together with 10% of the storage capacity between 10,000L and 100,000L, and 5% above 100,000L.

Along with ongoing monitoring, the condition of storage containers, stockpiles, covers and liners, on-site drainage systems, and the bunded area need to be monitored. Cracks or leaks in materials such as concrete may be difficult to detect and the integrity of bunding should never be assumed. If leaks are detected, further monitoring, assessment and action should be taken.

10.3.3 Containment

Key considerations for on-site containment include:

- physical characteristics of the site
- site assessment outcomes
- type of material that needs to be contained

- duration of storage
- PFAS chemicals present in the material
- their concentration, mass, volume, leachability and distribution
- ongoing storage requirements
- relevant approvals required by environmental regulators.

A comprehensive on-site environmental management plan (EMP) must provide for ongoing monitoring and management, including quality control and an auditable monitoring and management plan.

The volume of contaminated material at major sites may be very large, and this has implications for the options that are reasonable, practicable, or feasible.

On-site containment is subject to approval by environmental regulators and is only an option when:

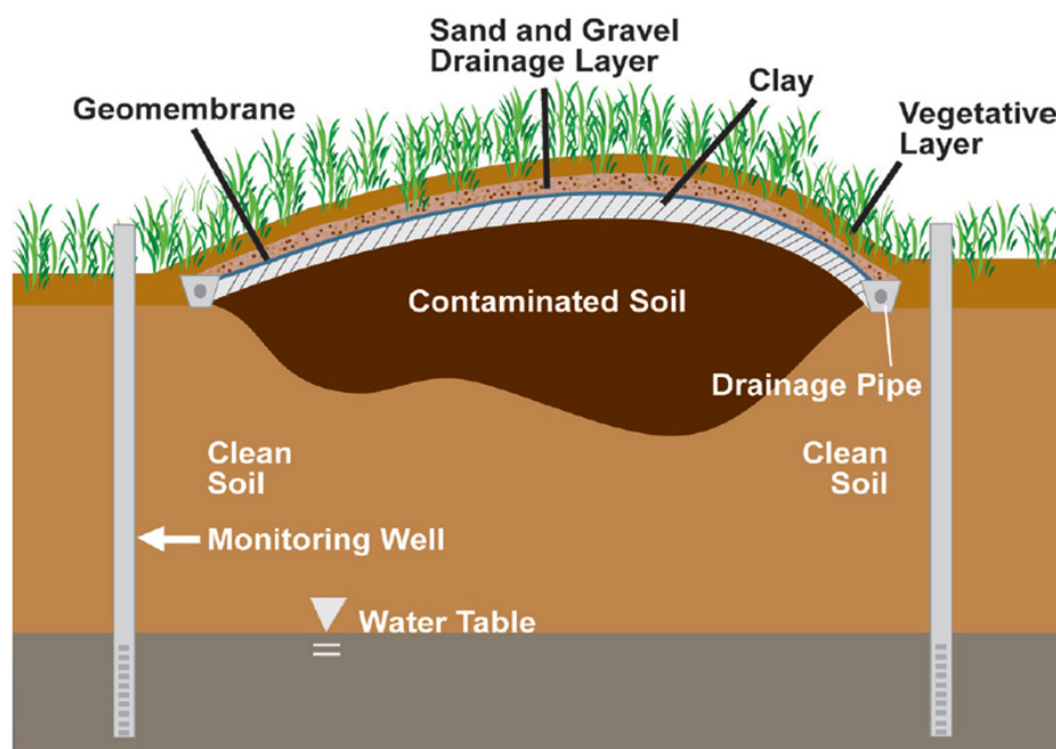
- the source site is hydrogeologically appropriate (with consideration of depth to water table and aquifer characteristics)
- it is possible to manage risks to on- and off-site beneficial uses (direct and indirect) and environmental values for soils, surface water, groundwater and biota
- there is capacity at the site for the proposed storage and any ancillary requirements
- the required environment and planning approvals have been obtained
- appropriate setback distances or buffer zones are available.

Methods for on-site containment may include, but are not limited to:

- engineered stockpiles for the containment of PFAS-contaminated material (for example, soil, concrete, asphalt)
- capping and covering to minimise the movement of PFAS off-site
- engineered containment facilities, with appropriate lining and cap or other barrier.

Capping and containment is a common technique in the remediation of contaminated sites. If properly engineered and maintained, capping can significantly reduce the infiltration of rainwater and can help protect local groundwater. Depending on site conditions, capping may be an effective remediation option for low levels of PFAS contamination in large quantities of soil and other solid materials (see [Section 10.3.7](#) for more information on capping).

Figure 6 Example of a cap cover with several layers



Source: USEPA (2012)

Engineered containment cells can be an appropriate long-term remediation option for mobile or reactive contaminants where off-site disposal or destruction are not viable. A containment cell may be appropriate where the contamination is of higher concentrations, more mobile, or less contained. The prevention of rainwater infiltration and groundwater through-flow are important management considerations and are discussed in more detail below.

When material is contained on-site, stormwater should be diverted away from the containment facility and its cap, and a leachate and stormwater runoff system should be implemented. Cap and cover systems should be designed and maintained to prevent intrusion by plant roots and animals into the PFAS-contaminated material (see [Figure 6](#)). Leachate and contaminated stormwater should be captured, analysed for PFAS, and if necessary, treated, removed and destroyed. However, if conditions are suitable for capping, then a robust and well-maintained impervious cover and suitable monitoring regime may be sufficient, making leachate management a less significant consideration.

10.3.4 Siting and location

The following considerations are relevant for selection of storage or stockpile sites:

- topography, geology and hydrogeology

- proximity to potential exposure pathways (for example, constructed drains, service trenches, natural rivers and streams, standing water bodies, groundwater and paleochannels)
- proximity to sensitive receptors (for example, key flora, fauna and ecological communities)
- matters of national environmental significance and those protected by state, territory, and local government legislation
- risks from extreme weather events and flooding
- risks from seismic events, bushfires, etc
- climatic, rainfall, and flood modelling to assess performance over the design life of the facility
- existing contamination (including baseline levels of contaminants within or near the storage pad footprint)
- infrastructure
- ownership of the land
- stakeholder interests and concerns
- local and state or territory regulations and controlling requirements.

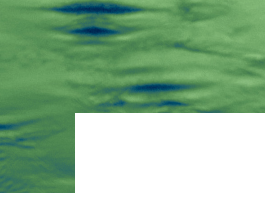
Note that a risk assessment undertaken by an appropriately qualified person may be required if potential exposure pathways to sensitive receptors are present.

Sites likely to include exposure pathways to potentially sensitive receptors would normally be considered unacceptable for storage or stockpiling of PFAS-contaminated material, based on risks to the environment and/or human health. See the [Guidelines for the Assessment of On-site Containment of Contaminated Soil](#) (ANZG 1999) and [Section 12.3](#) for further information.

Environmental regulators may consider sites such as those listed in [Section 12.3](#) on a case-by-case basis, based on an appropriate site-specific risk assessment and with consideration of applicable legislative requirements. Additional management and institutional controls, including monitoring, are likely to be required to ensure protection of the environment and/or human health. Contact with the environmental regulator must therefore be made before any proposal is made for storage, stockpiling, or containment facilities at the types of sites listed in [Section 12.3](#).

10.3.5 **Rainfall, stormwater, groundwater, flood and environmental management**

Risks associated with environmental variability, including weather events and natural disasters, should be carefully considered. The facility should not be located within floodplains with more than a 1:100 year annual exceedance probability (that is, > 0.01 AEP). Where this cannot be avoided due to site or operational constraints, or a lack of off-site alternatives,



relevant environmental regulators should be consulted and a site-specific risk assessment may be required. Careful consideration should also be given to local rainfall intensity frequency-duration information, including estimates of probable maximum precipitation for the site. A detailed risk assessment by a suitably qualified and experienced person should be conducted to ensure that safety, the integrity of the facility, and any environmental risks are comprehensively considered and mitigated. For example, the design should demonstrate that the PFAS-contaminated materials are protected from inundation and/or damage associated with an appropriate flood level for the designated site, its rainfall duration-intensity, and that a suitable height buffer between the facility's stored materials and local groundwater levels will have been achieved. Environmental regulators may require a commitment to the clean-up of any PFAS-contaminated material dispersed by a flood less than 0.01 AEP during the operating life of the storage infrastructure, and/or appropriate financial assurance.

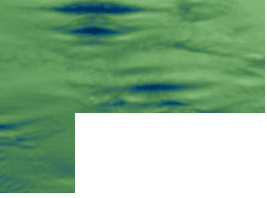
10.3.6 **Specific requirements for design and construction of containment infrastructure**

Importantly, environmental regulators may have specific regulatory requirements which must be considered in designing and constructing medium- to long-term containment facilities. Containment facilities should be designed in such a way that the PFAS-contaminated material is isolated from the surrounding environment by providing appropriate barrier systems. Depending on the type, mass and volume of PFAS-contaminated material, and considering the length of time storage will be required and the conditions likely to be encountered, the barrier system may include controls such as a primary (upper) and secondary (lower) composite liner, a primary leachate collection system, and a secondary leachate detection and collection system.

Should a containment facility be required, it should be built in accordance with appropriate regulatory approvals, design specifications and construction quality assurance planning. The approved plan provides a means of demonstrating to the regulatory authority and the public that the construction of the facility meets design requirements. Existing containment facilities may also require review and/or upgrading, depending on the risks involved.

Once the containment facility is filled with PFAS-contaminated material, it must be capped and rehabilitated. The following guidance applies to caps provided at the end of the operational life of the containment facility, and should be read in conjunction with the guidance below on caps and caps liners provided during the operational life of the facility prior to its closure ([Section 10.3.7](#)).

A visual marker layer between the contaminated material and the cap should be used to delineate the material from the cap. The cap should be



compatible with the liner system, provide an appropriate barrier to restrict water infiltration and provide separation between the PFAS-contaminated material and the surface. Following construction of the cap, the containment facility must be rehabilitated with an appropriate vegetative cover sufficient to maintain the integrity of the cap. A closure plan should be considered to monitor and maintain the ongoing effectiveness of the facility in containing the PFAS-contaminated material.

10.3.7 Caps and cap liners

The following guidance applies to caps provided during the operational life of the containment facility, and should be read in conjunction with the guidance above in [Section 10.3.3](#) on end-of-life caps.

Storage, stockpile, and containment facilities should always be designed to limit infiltration into the PFAS-contaminated material. Consequently, consideration should be given to cap and cap liner requirements during the operational life of the facility. This includes provision of temporary covers (that can be placed and removed on a daily basis) and thicker, less permeable interim caps if the facility is to remain open for longer periods.

If required, a cap liner or equivalent should meet the following minimum criteria:

- inclusion of a composite cap lining system designed to limit infiltration
- provision for protection from damage related to construction activities and vandalism
- inclusion of liner design considerations and a liner integrity survey to minimise the risk of installation defects in the completed liner system
- joining of the base liner to form a complete barrier system around the PFAS-impacted material
- promotion of runoff and inclusion of a surface water management system to limit the head of water on the cap lining system
- inclusion of measures to minimise permanent wrinkles within the geosynthetic layers.

Cap liner criteria may also apply to any side liner design.

10.3.8 Base liner

Facility design should limit seepage of leachate to the groundwater and surface water, and the infiltration of groundwater into the facility. In order to limit seepage through the base liner, the design should meet the following minimum criteria:

- inclusion of a composite base lining system designed to limit the medium- to long-term seepage rate through the base liner
- consideration of the suitability and stability of the sub-base

- provision for protection from damage related to construction and filling activities
- inclusion of liner design considerations and a liner integrity survey to minimise the risk of installation defects in the completed liner system
- grading and drainage towards a sump to limit the hydraulic head of leachate on the lining system
- inclusion of a leachate collection layer to convey leachate to a sump
- consideration of the potential for interaction with groundwater in a manner that may compromise the performance of the liner
- inclusion of measures to minimise permanent wrinkles within the geosynthetic layers.

Base liner considerations should also apply to any side liner design.

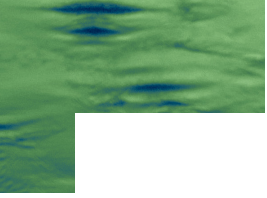
10.3.9 Sump and leachate collection

The base liner is required to include a sump with an extraction system in which the seepage rate can be periodically measured and any leachate extracted. Consideration should be given to inclusion of a leak detection system. The leak detection system is intended to provide a second line of protection against the potential migration into the environment. The leak detection system should be installed where leachate may be periodically retained before being pumped out. Leachate should not be discharged directly to sewerage or the environment.

The sump is a critical component of the facility and should be designed for the temporary retention of leachate between stages of leachate extraction. The sump is intended to collect leachate and the design levels and volume of leachate within the sump should be kept to a practical minimum amount during and following the filling of the engineered facility. Leachate should be pumped out to an enclosed tank. Potential transmission to other environmental media (for example, to air from aerosols or volatile PFAS, or into food webs through bioaccumulation through birds foraging in the pond) is considered a risk and should be avoided. Similarly, on-site evaporation processes are not generally supported as they may lead to the transfer of volatile PFAS to the atmosphere. Non-volatile PFAS may also be transferred into the atmosphere through water vapour, mist, steam, or similar processes.

The sump construction should allow for accurate leachate volume detection and an appropriate response procedure for when the maximum specified design storage depth in the sump is reached. Monitoring should include, amongst other things, data measured at the bottom of the leak collection layer below the sump as well as in the sump itself.

The depth of stored leachate in the sump should be minimised, its depth monitored, and the subject of appropriate controls. The minimum thickness



of the sump enclosure should be designed to limit the diffusion rate of PFAS through the sump system.

Any on-site leachate containment and/or treatment activities (for example, the use of leachate ponds, passive or active evaporation, filtration, aeration, ozonation, recirculation) require careful consideration by environmental regulators to ensure potential emissions to the environment are avoided and any subsequent exposures are effectively minimised. The chemical characteristics of PFAS suggest a robust precautionary approach by environmental regulators.

10.3.10 Side liner

Facility design should limit seepage through the side walls of the storage, stockpile or containment facility. Side liner design should consider the following minimum criteria:

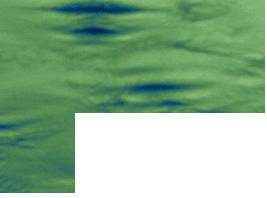
- inclusion of a composite side lining system designed to limit seepage through the side walls of the facility
- consideration of the suitability and stability of the sub-base
- provision of protection from damage related to construction activities and vandalism
- inclusion of liner design considerations and a liner integrity survey to minimise the risk of installation defects in the completed liner system
- above and below ground requirements, including slope and batter; rigid, flexible, piled, and/or modular side wall construction
- grading and drainage to promote runoff and limit hydraulic head, hydrostatic pressure, etc
- consideration of the potential for interaction with groundwater in a manner that may compromise the performance of the liner.

10.3.11 Maintenance and management planning

An environmental management, maintenance, and operating plan should be prepared and implemented to manage the containment and stockpiling facility. The plan should cover all aspects of maintenance and operation over the life of the facility, including after closure and during decommissioning.

The environmental management, maintenance and operating plan should include information on, amongst other things:

- key management roles, responsibilities and stakeholders
- stocks and flows of stockpile volume and material types, including:
 - details of material types
 - PFAS concentrations, masses, and volumes
 - source locations

- 
- hazardous waste transport tickets
 - any other relevant information
 - periodic monitoring, sampling, inspection, and maintenance, including triggers and contingency 'actions on' the identification of an issue
 - specified thresholds and actions to be taken if liquid or PFAS contamination are detected by the leak detection system above these specified thresholds
 - protocols and procedures for monitoring the effectiveness of the containment
 - environmental monitoring
 - reporting of monitoring and inspection records (see [Appendix F](#) for examples of simple stockpile inspection checklists)
 - facility performance review
 - relevant documentation (for example, construction records, inventories, safety data sheets (SDSs), supplier manuals for major components, and maintenance of equipment)
 - commissioning, handover-takeover and decommissioning processes.

The plan should also address stormwater management, indicating projected stormwater flows for the area at, and around, the containment facility.

The objective of the stormwater management is to avoid contamination of stormwater flows and to contain and manage any contaminated stormwater. This must include provision for leachate and contaminated stormwater to be captured, analysed for PFAS, and appropriately managed.

The integrity of the containment facility must be maintained at all times. This means the leachate collection and management system should be kept in good condition with a regular inspection and maintenance program in place to monitor the integrity of the cap of the containment facility.

Ongoing monitoring of the site will also need to be undertaken to ensure risks to receptors are minimised, and there are no unacceptable off-site impacts. Where a containment facility is expected to be maintained over the long term, the potential for ongoing leaching from the contained materials must be considered because the long-term mass of PFAS to a receiving environment may represent a significant risk, even if point-in-time PFAS concentrations in leachate are low.

Some jurisdictions may require additional regulatory approvals and controls including:

- listing of waste containment facilities on contaminated land registers and/or land titles
- regulatory approval/permits/controls for activities such as construction, ongoing management and monitoring.

10.3.12 Design safety and verification

The design of storage, stockpile, and containment facilities should consider relevant hazards and associated risks. The following design issues should be considered during design or construction verification processes:

- human health, public health and worker safety
- environment
- construction
- operations and maintenance, including the potential for leachate extraction and longer-term decontamination/remediation
- durability
- monitoring systems, including leak detection for emissions to air, soils, groundwater surface water and, where relevant, stormwater and sewerage systems.

Design, procurement, construction, installation, commissioning, operation (including monitoring) and decommissioning of the facility should satisfy all Work Health and Safety (WHS) and environmental considerations in accordance with relevant Commonwealth, national, state/territory, regional and local requirements.

Technical documentation, such as:

- design specifications
- construction drawings
- design reports
- site investigations
- impact assessments
- site-specific risk assessments
- EMPs
- PFAS Management Plans (PMPs)
- verification documentation
- QA/QC documents

should be developed and endorsed by relevant key stakeholders prior to construction commencing. Examples of simple stockpile inspection checklists are provided at [Appendix F](#).



11

Transport of PFAS- contaminated material

11 Transport of PFAS-contaminated material

The transport of PFAS-contaminated material should be planned in consultation with the environmental regulator, with regard to the characteristics, environmental risks and destination of the material. This planning process may not apply where the environmental regulator has issued standing guidance to cover transport arrangements.

11.1 Waste code for PFAS-contaminated material

The transport and tracking of PFAS-contaminated material (including PFAS-containing products that are waste) within and between jurisdictions are best managed with a single waste code. This provides clarity when regulating transport, tracking, treatment and disposal of this material.

Until the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure 1998 (MCW NEPM) is reviewed, environmental regulators will adopt the following PFAS-specific waste code within their legislative frameworks based on the following:

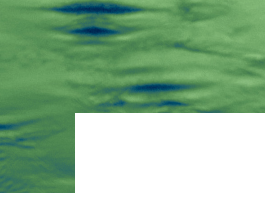
- Category: Organic chemical (M)
- Description: Per- and polyfluoroalkyl substances (PFAS)-contaminated materials, including waste PFAS-containing products and contaminated containers
- Waste Code: M270

The associated waste descriptions must include a reference to the PFAS present, in sufficient detail to accurately reflect the nature of the waste. Where multiple waste codes apply, the waste must be reported using the description 'Per- and polyfluoroalkyl substances (PFAS)-contaminated materials, including PFAS-containing waste products and contaminated containers'.

PFAS-contaminated material, including waste PFAS-containing products, are considered to be Dangerous Goods Class 9.

11.2 Considerations for transport

PFAS-contaminated material must be transported in accordance with the requirements of the environmental regulator. Decisions regarding authorisations for the transport of PFAS-contaminated material, including interstate transport, must consider whether the receiving facility can lawfully receive this material in relation to all the physical and chemical

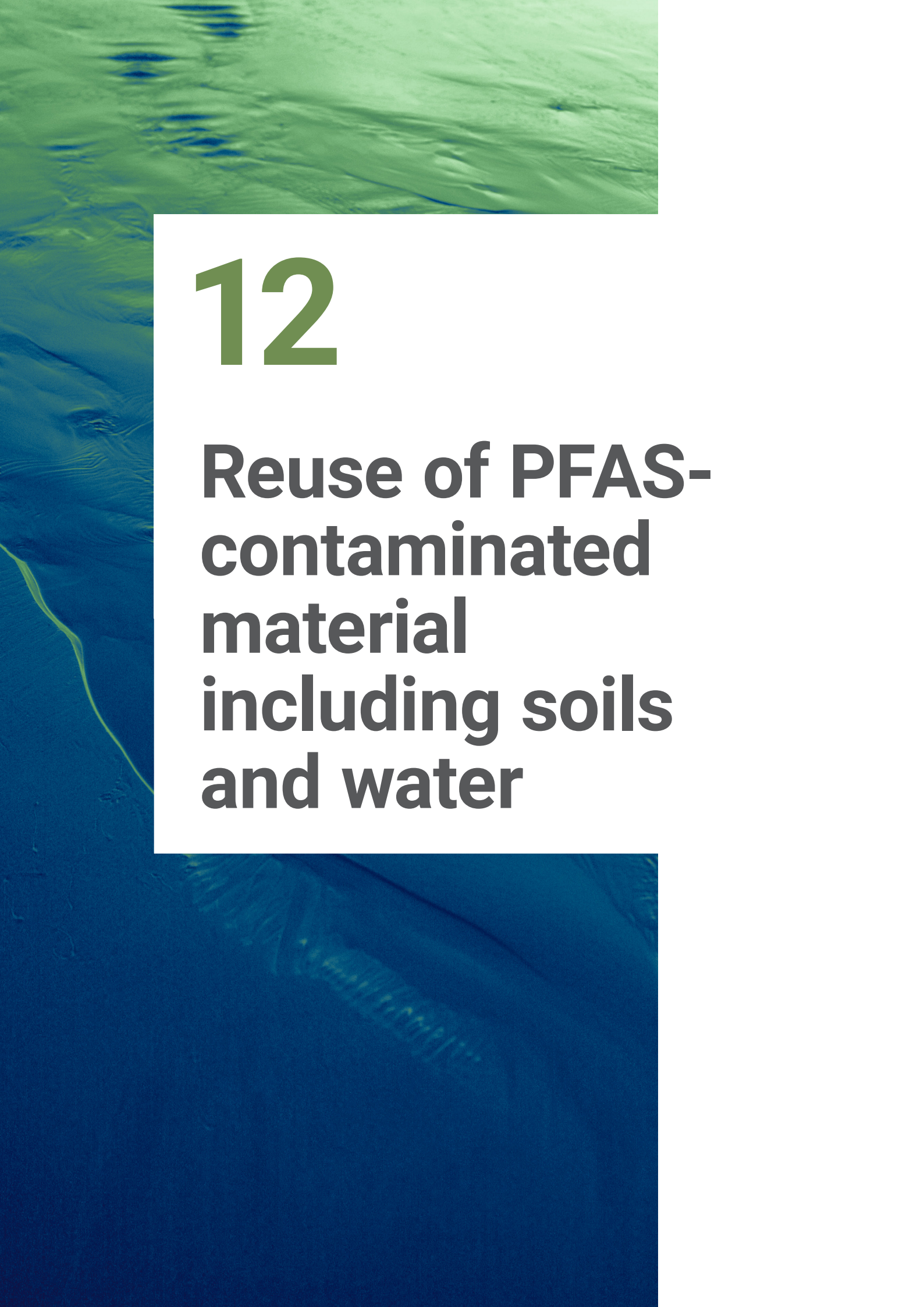


characteristics. The material must only be delivered to facilities that are licenced to receive the material, having considered all of its characteristics.

Interstate transport must only occur with approval from the required environmental regulator(s).

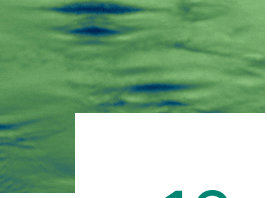
Facilities approved by the environmental regulator to receive PFAS-contaminated material should explicitly state this in the approval documentation.

As required for the movement of contaminated materials, decontamination of vehicles and transport containers to eliminate contamination of subsequent loads is important. Containers must be managed as PFAS-contaminated material until they have been appropriately cleaned.



12

**Reuse of PFAS-
contaminated
material
including soils
and water**



12 Reuse of PFAS-contaminated material including soils and water

Material containing low levels of PFAS may be considered by environmental regulators for reuse under some circumstances, particularly for the purpose of resource recovery in accordance with the waste hierarchy presented in the [National Waste Policy 2018](#) (Australian Government 2018b). However, reuse must be discussed with the environmental regulator as some may not approve this, and regulatory frameworks for 'end of waste' differ between jurisdictions. If reuse is acceptable, many environmental regulators will require that an approval be granted.

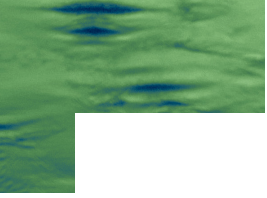
Assessment of reuse options for PFAS-contaminated material will be based on the principles that reuse must not lead to an unacceptable risk to the environment and/or human health, or an increase in the level of risk at or near the location in which it is used. It is important to consider that PFAS can travel long distances from the site, potentially affecting remote receptors. Dilution of PFAS contamination is not an acceptable waste management strategy to create material suitable for reuse (see [Section 12.4.2](#) for more information on dilution). These principles apply to all PFAS-contaminated material irrespective of source location, and can include extracted material, virgin or otherwise.

In the PFAS National Environmental Management Plan (PFAS NEMP), the term 'reuse' is intended to apply to situations involving the permanent or long-term placement of materials for a beneficial purpose in compliance with environmental legislation. This does not include short to medium-term storage or stockpiling of PFAS-contaminated material, which is covered in [Section 10](#).

Environmental regulators may require that the reuse of PFAS-contaminated material be informed by a site-specific risk assessment to ensure that the placement of PFAS-contaminated material will not increase the risk at the destination site, or lead to an unacceptable risk to the environment and/or human health. Multiple lines of evidence should be considered to support a decision on reuse.

12.1 Reuse of soil

Reuse of PFAS-contaminated soil remains subject to state, territory, regional, and local government oversight. The guidance provided here, including the decision tree in [Figure 7](#), does not override applicable



regulations or national frameworks. The application of this guidance should therefore be done in consultation with the relevant regulatory authority.

Note: The decision tree for reuse of soil may not be applicable in New Zealand – please contact local authorities for relevant advice.

The decision tree is intended to be applied only to soil and should not be used to inform the use of other material such as solid organic wastes, biosolids or other resource recovery materials. However, if the soil proposed for reuse has become PFAS-contaminated due to incorporation of these materials into the soil, the decision tree is applicable to that soil. Note that the decision tree does not address reuse of PFAS-contaminated soil in agriculture, which can entail higher risks that require specific assessment. The decision tree is focused on beneficial soil reuse and does not address operations that are essentially landfilling operations.

12.1.1 Considerations for reuse without a detailed risk assessment

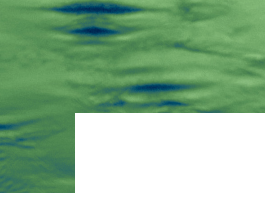
Any consideration on the reuse of soil must be informed by the principle that the levels of PFAS must be sufficiently low that they will not pose an increased or unacceptable risk to any receptor or to the environmental values of waters. Therefore, to be suitable for reuse, soil must meet the criteria for both total concentration and leachable concentration. The resulting PFAS concentrations at the reuse site should be sufficiently low to be protective of terrestrial flora and fauna and human health.

A second principle to be considered in soil reuse is the application of the waste hierarchy, as noted above. In this principle, the reuse of low-level PFAS-contaminated soil off-site only occurs after all options for on-site use, waste avoidance, waste treatment and volume reduction have been considered and implemented wherever reasonable and practicable.

Leachate criteria should be protective of groundwater and surface water quality and aquatic ecosystems both at the site of reuse and anywhere there is a reasonable possibility that transported PFAS from that site may impact sensitive receptors and environmental values. Note that PFAS can be transported many tens of kilometres from the originating site.

Adding soil with low levels of PFAS to areas that have even lower or no levels of PFAS should be considered only in consultation with the relevant environmental regulator in exceptional circumstances where there is no feasible, practicable alternative. Where soil reuse is proposed for areas with higher levels of PFAS, then the decision tree may permit reuse without a detailed assessment of risk. However, users of the decision tree should consult the relevant environmental regulator to maximise confidence in applying the decision tree under such circumstances.

For large sites where soil excavation and reuse may be a recurring issue, the decision tree may be a useful tool to support development

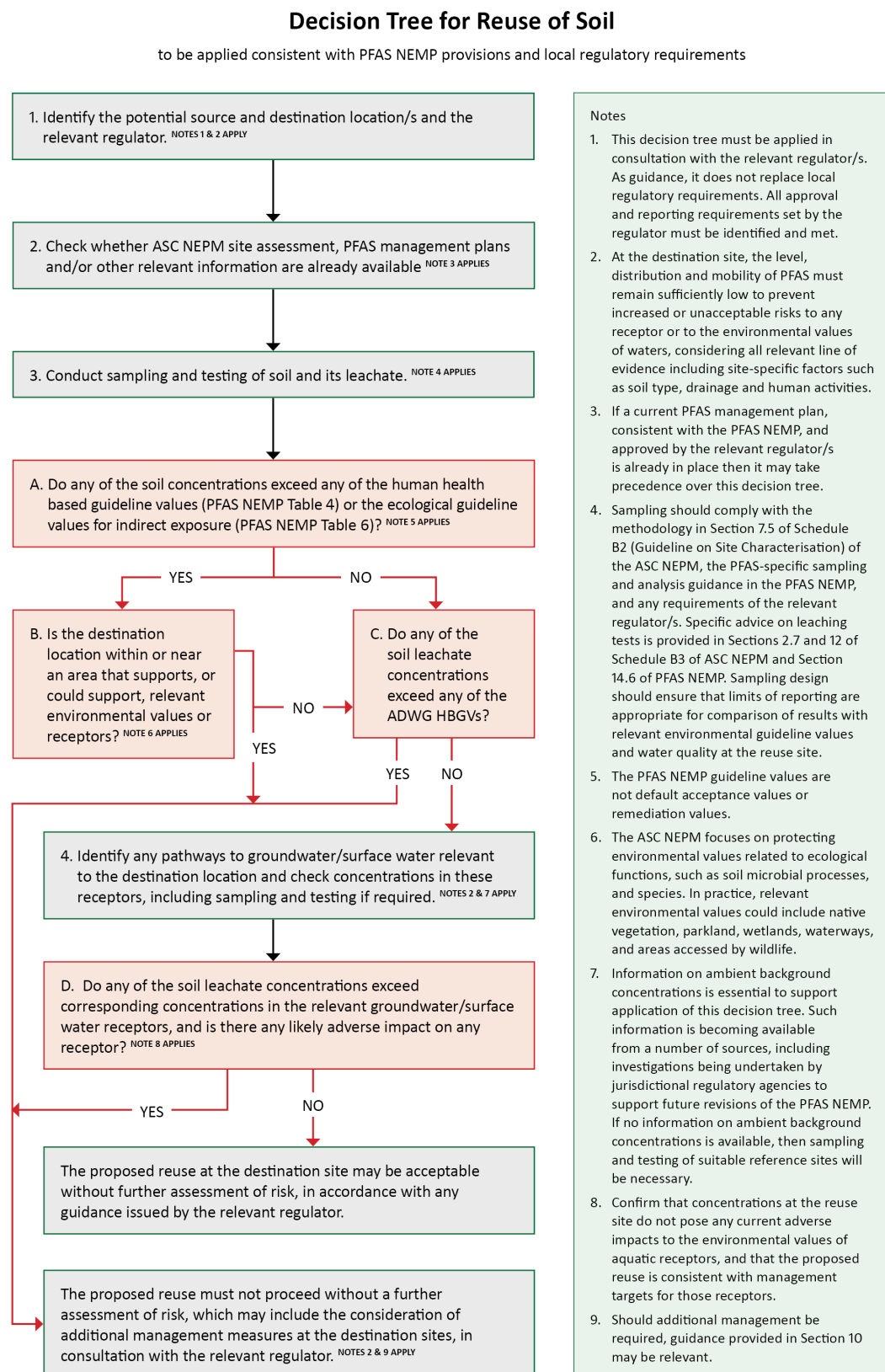


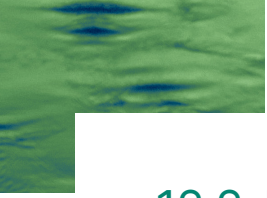
of overarching PFAS management strategies for the site, such as PFAS Management Plans (PMPs), through consultation with all relevant regulators.

12.1.2 **Decision tree for screening risk assessment for reuse of soil**

A screening risk assessment may be acceptable in instances where PFAS concentrations in the soil are at or below the relevant health and ecological assessment criteria, and where PFAS concentrations in the material can be demonstrated to be lower than concentrations of PFAS in and around the proposed reuse location. A decision tree outlining the process for a screening risk assessment is presented in [Figure 7](#) below.

Figure 7 Decision tree for soil reuse





12.2 Reuse with a detailed risk assessment

The most important pathways posing a risk to the environment and/or human health are:

- transport of PFAS to surface water and groundwater through leaching from PFAS-contaminated material
- bioaccumulation in plants and animals, in particular those consumed by humans and animals.

Therefore, any assessment of risks associated with reuse of PFAS-contaminated soil should consider the proximity and sensitivity of surface or groundwater receptors, the potential for bioaccumulation, and secondary or tertiary exposure to humans and animals.

12.2.1 Considerations for reuse with a detailed risk assessment

The following factors should be considered when assessing the potential for reuse of PFAS-contaminated material:

- potential for pre-existing 'ambient' PFAS impacts at the destination site and potential to add to the overall mass of PFAS in the receiving area
- if the receiving environment already contains PFAS, whether the addition of more PFAS to that system increases the potential for harm
- current and likely future land uses at the destination site
- hydrogeology at the destination site, including:
 - erosion
 - runoff and infiltration rates
 - nature of the aquifer systems
 - the potential for these to be impacted
 - the actual and potential beneficial uses of groundwater
- proximity of the destination site to pathways such as open drains, stormwater systems, water bodies (including groundwater), and to sensitive environmental receptors, groundwater-dependent ecosystems and sensitive animals
- potential for the receiving environmental conditions to accelerate mobilisation of PFAS in the contaminated material or in existing PFAS at that site.

Based on the legislative requirements of the environmental regulator, including whether the associated approval is lawful, the following uses may be appropriate subject to the environmental setting and findings of a risk assessment:

- use as fill material in commercial/industrial developments with minimal access to soil

- use as fill beneath sealed surfaces, including but not limited to car parks/ roads/paving/runways
- use as construction fill on road embankments (note that risks should be assessed for stormwater runoff that may mobilise PFAS)
- use as fill material in areas where ambient PFAS levels present a similar or higher contamination risk profile, providing that the volume of contaminant in the soil to be added is substantially less than the total mass of the contamination already present in that area
- reuse as construction material (for example, bricks, rammed earth and gabions), noting the need to consider PFAS leachability.

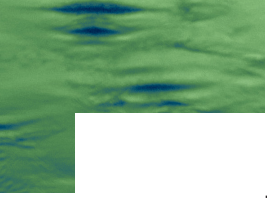
12.3 Reuse requiring consultation with the environmental regulator

The following reuse situations are likely to include exposure pathways to potentially sensitive receptors. These situations would normally be considered unacceptable uses for PFAS-contaminated material, based on risks to the environment and/or human health.

The environmental regulator may consider these uses on a case-by-case basis based on an appropriate site-specific risk assessment and applicable legislative requirements. Additional management and institutional controls, including monitoring, are likely to be required to ensure protection of the environment and/or human health, including food production.

Contact with the environmental regulator must be made before any proposal for the following uses is made:

- fill or burial less than 2m above the seasonal maximum groundwater level
- reuse within 200m of a surface water body or wetland area
- reuse in (or in the vicinity of and able to be transported to) areas which can be identified with any of the nine Matters of National Environmental Significance (MNES) protected under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act), and areas of environmental significance as identified in specific jurisdictions
- fill, burial or reuse in locations potentially affected by reasonably foreseeable future rises in groundwater or sea level, or near stormwater drains
- reuse on agricultural land
- reuse as fill in residential developments
- reuse as fill on public open space/parkland/recreational land
- inclusion in compost, fertilisers or soil conditioners.



There could be other reuse scenarios that may not be acceptable from the perspective of human health protection (for example, food production areas).

Consistent with approaches set out in the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) and the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention), the reuse of PFAS-contaminated material containing more than the low persistent organic pollutants (POPs) content limits (LPCLs) set for the POPs will not be considered. See [Section 14.6](#) for more information.

12.4 Organic waste and resource recovery materials

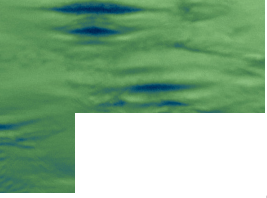
PFAS are known to occur in a range of recovered organic wastes, such as biosolids, food waste and animal wastes. General guidance provided in this section is intended to support best practice in the management of PFAS risks in organic waste recovery products, and to inform decision making by environmental regulators.

Organic waste is waste derived from material that was recently living. Organic waste recovery materials likely to be considered for beneficial reuse in the Australian and New Zealand context may include, for example, the following materials:

- biosolids
- food organics and garden organics (FOGO)
- organic fraction (mixed waste organic outputs (MWOO)) of municipal solid waste (MSW)
- waste from paper manufacturing or recycling
- digestate (products of anaerobic digestion) of organic wastes
- animal waste.

Organic waste recovery materials can be reused in a variety of applications. The most common beneficial reuse is incorporation of the material into products for application to agricultural, horticultural or forestry land as a fertiliser or soil conditioner. Other potential uses (subject to jurisdictional approval) may include:

- using the material as fuel for waste to energy facilities
- application of the material in waterbodies to control eutrophication
- use for carbon sequestration/biochar.



Note that guidance for biosolids application to land, which is also applicable for land application of resource recovery products using biosolids as a feedstock, is addressed separately in [Section 15](#). The guidance provided here should be read in conjunction with information contained in [Section 15](#).

12.4.1 PFAS occurrence in organic waste materials

The likelihood of PFAS being present in an organic waste will depend on the type of materials incorporated in the waste stream and/or the origin of those materials (for example, based on the current state of knowledge regarding the widespread use of PFAS in food packaging, paper and cooking utensils, it is expected that PFAS are likely to be present in food wastes). Due to the extensive use of PFAS in a wide range of domestic products, PFAS invariably collect in municipal wastewater and at wastewater treatment plants (WWTP), and PFAS can move through the treatment process into sewage sludge and biosolids.

Any wastes originating from activities associated with PFAS contamination (for example, those listed in [Appendix C](#)) have a high likelihood of containing PFAS. Such wastes should not be considered for reuse in resource recovery products unless analysed and their PFAS content and associated risks fully characterised.

A review of published data on the occurrence of PFAS in organic waste materials commissioned by the National Chemicals Working Group (NCWG) in 2021 indicated that, apart from biosolids, data on PFAS occurrence in organic wastes is very limited. However, based on the information provided by the literature review, and jurisdictional regulatory experience over a range of operating waste recovery industries, a qualitative risk ranking of different organic wastes has been developed.

Given the diversity of organic waste types, source and potential reuse scenarios, detailed guidance on how to appropriately assess and manage PFAS for specific waste types cannot be provided here. [Table 10](#) below presents a general ranking of organic waste materials based on the likelihood of PFAS being present in the material, and the likelihood that PFAS will be present at concentrations that may pose a potential risk for beneficial reuse of the material. [Table 10](#) is intended to guide environmental regulators and manufacturers of resource recovery products when considering the extent of PFAS assessment and management that may be required when an organic waste is proposed for reuse, including its incorporation into a resource recovery product.

12.4.2 Management of risks associated with PFAS in resource recovery products

PFAS NEMP general obligations in [Section 3.1](#) requires persons to ensure proper disposal of PFAS-contaminated waste. Obligations include properly characterising waste and sending it to a facility licensed to accept it, noting dilution is not acceptable in soil, air, compost or other wastes or products. However, with proper screening of inputs, beneficial reuse of some organic wastes through their incorporation into resource recovery products can be supported.

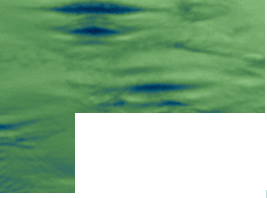
This is consistent with Target 6 of the [National Waste Policy Action Plan](#) (Australian Government 2019c), which aims to halve the amount of organic waste disposed of to landfill by 2030. Beneficial reuse involves reusing a waste material (that would otherwise be discarded) in a manner that makes it a valuable commodity. Beneficial reuse of organic wastes containing PFAS, should only occur if the reuse can be managed to avoid or minimise risks to the environment, human health and/or environmental values.

Responsible beneficial reuse of recovered organic wastes, and best-practice manufacture of organic waste recovery products should therefore include assessment of:

- the potential for PFAS to be present in various waste inputs
- appropriate controls and management of those inputs
- the development of guidelines for appropriate end uses of the product.

Managers should implement appropriate assessment, management and controls to ensure products are safe, fit-for-purpose and do not harm environmental values in use. Jurisdictional environmental regulators may choose to develop additional management frameworks for PFAS management in waste recovery products, or guidelines for appropriate end uses of specific waste types and products.

Resource recovery products (for example, compost and other soil amendment products) are often formed by blending organic waste materials that have benefits for agronomic and/or soil conditioning from different sources to produce beneficial products, often for unrestricted use. The processes used to make these products do not treat PFAS to render them non-hazardous, as is the case for some other potentially hazardous contaminants present in organic waste (for example, microbial contaminants). This necessitates a focus on testing and management of waste inputs to minimise PFAS content in resource recovery products, based on the guidance below and the hierarchy of waste types presented in [Table 10](#).



Blending versus dilution

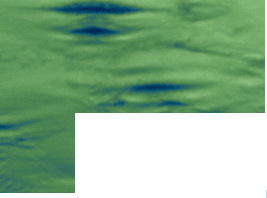
Where a resource recovery product is formed by combining different inputs (feedstocks), each of which has been screened to minimise introduction of PFAS, and which imparts a beneficial property to the final product, environmental regulators are more likely to regard this as blending. Blending of appropriate feedstocks to achieve minimal or regulated PFAS concentrations in the product is an acceptable way to safely manage beneficial reuse of organic waste materials.

However, addition of materials solely for the purpose of reducing the final concentrations of PFAS in the product to below threshold levels is considered to be dilution. Dilution is not supported in the provisions of the Stockholm Convention. Dilution is unlikely to be acceptable to environmental regulators as it would constitute widely distributing environmentally persistent contaminants throughout the environment. Some jurisdictions may have legislative mechanisms in place which allow for specific, regulated reuse of more heavily contaminated organic waste, such as end of waste (EOW) codes and recovery orders.

Table 10 provides a guide to the level of assessment that may be required for considering suitability for reuse of different organic waste types. The placement of different waste types within the 'levels of assessment' hierarchy in **Table 10** is intended as a general guide only. It is based on a broad understanding of the likelihood of PFAS being present in the material and the likelihood that PFAS will be present at concentrations that may pose a potential risk for beneficial reuse of the material. Given the variety of potential sources and inputs to waste streams in different urban, rural and regional settings, it is to be expected that similar waste types could have different risks of PFAS content in different jurisdictions. Any assessment of PFAS risks associated with a particular waste type should include a detailed consideration of where and how the waste material is sourced, and the findings of such an assessment may then be used to inform potential requirements for PFAS analysis and monitoring of the material.

Some jurisdictions restrict or prohibit the use of PFAS-containing material in resource recovery products and/or place concentration limits on the PFAS content of input materials, and the products. Practitioners should ensure that proposed reuse is compliant with jurisdiction-specific regulations.

Guidance on appropriate analytical methodologies for biosolids and other organic waste materials is provided in **Section 19.4**. Biosolids application to land will need to comply with guidance included in **Section 15**.



Feedstock management plans

In order to ensure that PFAS content in resource recovery products is kept to a minimum and complies with jurisdiction requirements, it is recommended that producers of resource recovery products should adopt a 'feedstock management plan' approach to control, monitor and record potentially PFAS-impacted waste inputs used to form a product. Where biosolids are proposed for use as a feedstock, additional guidance provided in [Section 15.4](#) is relevant.

A feedstock management plan is intended to outline procedures for the ongoing assessment and monitoring of feedstock properties. Feedstock management plans should include concentrations of PFAS and other potentially harmful contaminants as necessary, along with procedures to manage and mitigate the impacts of those contaminants on product quality. Feedstock management plans may include a range of components aimed at managing risks other than PFAS content. A feedstock management plan addressing PFAS risks should include:

- procedures for sampling and testing of inputs to fully characterise PFAS content of any feedstocks identified as posing a risk of containing PFAS
- procedures to determine whether feedstocks are suitable to meet the product requirements with respect to PFAS content
- procedures for the management of product formulation/blending/ composition to ensure PFAS content of the product meets any criteria relevant to the products proposed use
- regular monitoring of product outputs to ensure PFAS content does not exceed any relevant criteria or concentration limits.

Table 10 Hierarchy of levels of assessment and management required for some common organic waste types with respect to potential PFAS content

Waste type	Examples ^a	Level of assessment and management required
Organic-derived (industrial) liquid wastes ^b	Interceptor trap waste; textile effluent and residues; industrial wash waters; solvents	use in resource recovery products is likely to be prohibited
WWTP solid outputs	Biosolids ^{b,c} , sludge cake	PFAS assessment and management is essential to address potential risks
Septage waste	Liquid or solid components from pump-out of septic tanks	
Paper waste	Paper, cardboard, paper pulp, processing sludge from paper manufacture or recycling	
Domestic organic wastes	MWOO, FOGO	PFAS assessment and management is likely to be required
Animal wastes	Manure; abattoir wastes, animal bedding organics	PFAS assessment and management may be indicated in some instances
Treated timber waste	Waste from timber composite materials ^{c,d}	
Natural (untreated) timber wastes	Wood packaging, woodchips, sawdust, shavings	
Natural fibrous organics	Peat, seed hulls/husks, straw	PFAS analysis or management may not be necessary
Green waste/mulch derived from controlled collections	Grass, leaves, tree prunings	

This table provides a guide to potential risks associated with PFAS only. Other contaminants that may be present in organic waste materials will also require assessment.

^a Examples are provided as a general guide; however, the list is not exhaustive.

^b There may be some wastes in this category which can be demonstrated as being generally PFAS-free (for example, commercial food processing waste), which if kept segregated from other general industrial waste, constitute desirable feedstock. Consult the environmental regulator in these cases.

^c Use of resource recovery products containing biosolids must comply with concentration criteria and contaminant limited biosolids application rate (CLBAR) requirements outlined in [Section 15](#).

^d PFAS have been detected in composite wood products. The source of PFAS is likely to be adhesives used in these products (Bečanová et al. 2016).

12.5 Reuse of PFAS-contaminated water

The following guidance should be read in conjunction with [Section 15](#) and [Appendix G](#) on wastewater treatment, which also discusses the reuse of biosolids.

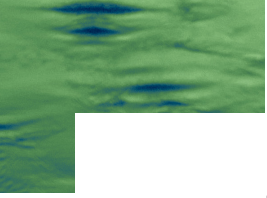
If PFAS-contaminated water is proposed for reuse, the proposed reuse must not result in an unacceptable or increased risk to the environment and/or human health. The reuse also must not breach environmental and/or health laws such as those pertaining to the contamination of drinking water, groundwater, stormwater and soil.

Human health and ecological guideline values for water provide primary guidance on the suitability of PFAS-contaminated water for reuse. These guideline values must be considered along with the potential for water to impact groundwater or aquatic ecosystems. Local catchment risk assessments in sensitive areas may require that the overall PFAS mass within the catchment should be reduced to achieve the agreed objectives for water quality.

Reuse of PFAS-contaminated water must not be undertaken until consultation with the relevant environmental regulators has taken place, as reuse activities may require specific approval. Acceptable reuse options may include:

- irrigation of crops non-edible to humans or livestock
- construction project dust suppression where likelihood of dispersal is prevented
- re-infiltration at a quality consistent with protecting environmental values
- managed aquifer recharge at a quality, rate and methodology consistent with protecting environmental values
- industrial process water, considering impacts on process emissions and product.

Where reuse involves the discharge of PFAS-contaminated water to land, the risk assessment should consider both the potential for PFAS transport to off-site sensitive receptors, and the potential for long-term build-up of the total PFAS mass in the receiving soils, groundwater, and plants. Where water is to be used for managed aquifer recharge and recovery, water quality criteria should be derived with consideration of the receiving aquifer (that is, protected environmental values; sedimentary/confined aquifer versus fractured rock; potential for future beneficial uses; long-term transport). Under some environmental legislation, waste discharge to groundwater is the least preferred management approach and may only be considered as a pump and treat scenario. Use as industrial process water must consider potential human health impacts, such as in food industries, and impacts of any reuse-derived products on the environment and/or human health.



Reuse must be for a clearly demonstrated beneficial purpose. Accepting and applying large volumes of PFAS contaminated water to land without implementing the waste minimisation hierarchy set out in the National Waste Policy 2018 (Australian Government 2018b) and absence of a clearly demonstrated beneficial purpose is considered dispersal into the environment and waste disposal rather than reuse.

12.5.1 **Management of PFAS-contaminated construction water for site dewatering**

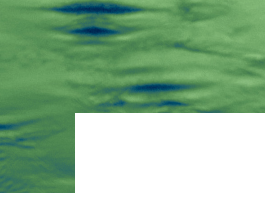
The following guidance should be read in conjunction with [Section 8](#) on PFAS guideline values and [Section 9](#) on site investigation, and the management of PFAS-contaminated water, including [Section 10](#) on containment. This guidance is intended to ensure that construction water is appropriately evaluated and managed, to minimise the risk of harm to the environment and/or human health. While this guidance focuses on PFAS, management of contaminated construction water should consider all characteristics of the water, including both toxicants and stressors.

In this context, construction water means stormwater, surface and/or ground water intercepted, collected, or extracted during construction work.

Construction work may intercept PFAS-contaminated surface water or groundwater. This can result in the collection of, or generation of PFAS-contaminated water. Construction work can also result in an alteration of PFAS migration (or chemical transport) pathways through changes to surface and groundwater flows. This can occur, for example, through:

- drainage diversions
- new drainage systems
- service trenching
- surcharging
- compaction
- earthworks
- excavation
- re-injection
- re-infiltration
- dewatering.

Reuse of PFAS-contaminated construction water for other purposes such as dust suppression, irrigation, or aquifer recharge may also introduce PFAS to areas where it was not previously present. Alternatively, additional PFAS mass may be added to an existing contamination load, further increasing the likelihood of harm. In some circumstances, changes to the groundwater hydrology, such as lowering the water table, may change conditions which can facilitate transformation of PFAA precursors. In some cases,



the construction water may also be affected by other contaminants or physico-chemical characteristics of concern.

Potential impacts from PFAS exposure through construction water may occur at some distance from PFAS sources. Therefore, if construction is going to generate PFAS-impacted water that will be released, then both off-site as well as on-site impacts should be considered (including any receptors and downgradient environmental values).

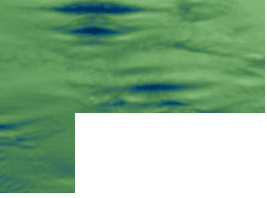
Environmental regulators should be consulted when potential PFAS contamination or actual impacts are identified. Environmental regulators should also be consulted if PFAS management measures are proposed, to ensure that any proposed measures are consistent with applicable environmental legislation and relevant jurisdictional water quality policies, and that all on- and off-site risks have been adequately mitigated. Importantly, construction work that intercepts PFAS-contaminated water should not commence until potential environmental and/or human health risks have been assessed and all necessary management measures are in place.

If PFAS contamination is likely to be encountered during construction (or its presence cannot be ruled out), management strategies should include consideration of design processes to minimise the interception and disturbance of PFAS-contaminated soil or water. During the construction process, reasonable and practical steps should be taken to minimise the production of PFAS-contaminated construction water. Management measures might include:

- staging excavation to avoid wet seasons
- limiting periods where bare soil is left uncovered
- minimising the time that excavations are left unfilled
- directing stormwater around or away from PFAS-contaminated areas
- separating PFAS-contaminated material from uncontaminated material.

Measures to minimise groundwater disturbance during construction, such as using sheet piling or casements to limit the lateral extent of groundwater drawdown during dewatering, should also be considered.

Where disturbance of existing PFAS contamination cannot be avoided, the management of construction water at a site must comply with relevant jurisdiction requirements (some jurisdictions have legislative, regulatory or policy requirements that need to be considered, such as the release/discharge of contaminants to waters or lands) and should aim to prevent new or unacceptable risks to the environment and/or human health on- or off-site. In practice, this also means managing construction water to avoid the introduction of contamination in other less contaminated or uncontaminated areas. Consistent with the National Water Quality Management Strategy (NWQMS) (Australian Government 2019b), water quality objectives for continuous improvement should be considered. As

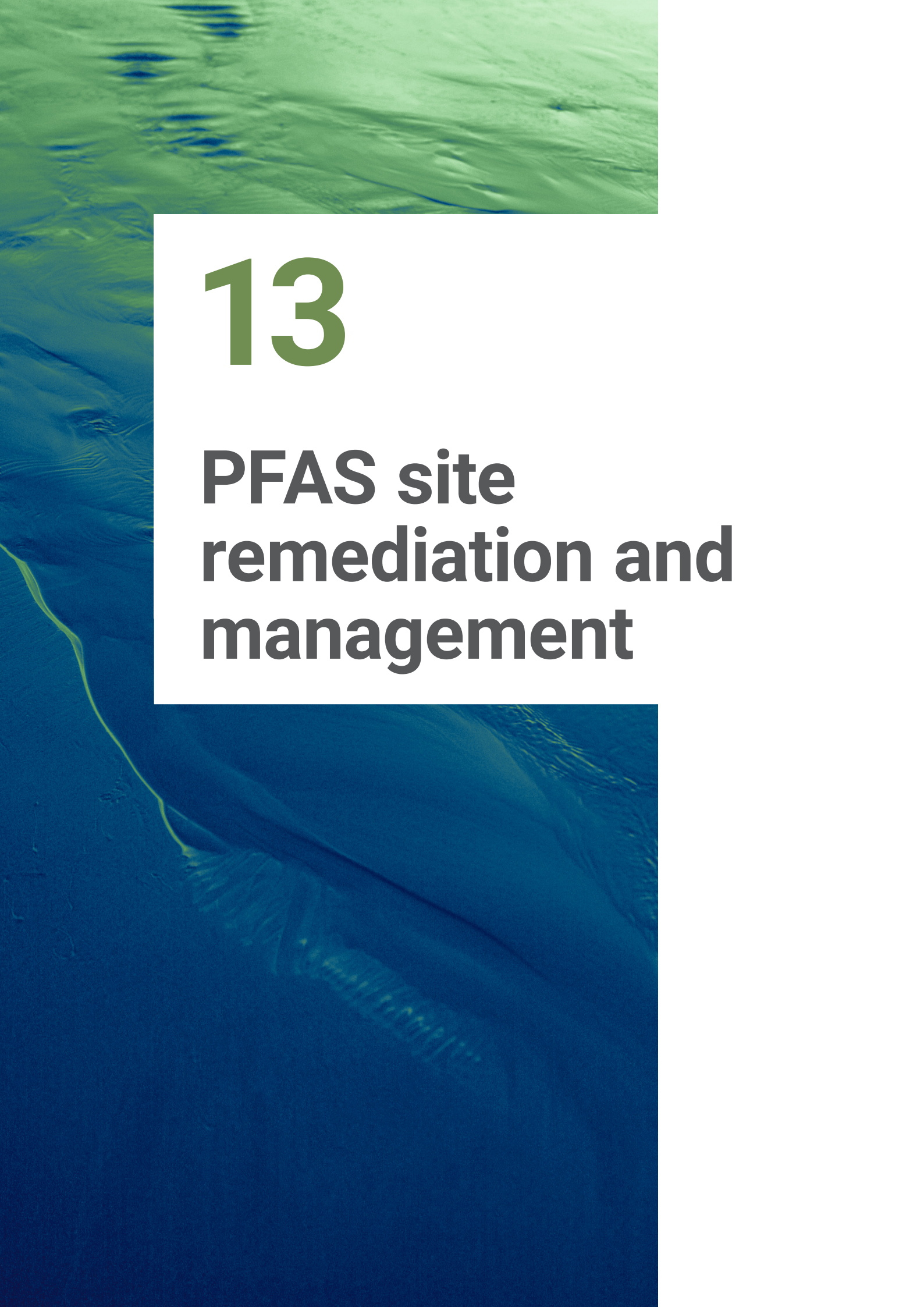


with other toxicants, where the concentration of a bioaccumulative toxicant such as PFAS is below the appropriate guideline value, then the over-riding objective should be to continue to improve, or at least maintain, water quality (that is, not to allow increases in concentration up to the guideline value (ANZG 2018)).

Construction water containing PFAS at concentrations exceeding policy or guideline criteria may need to be diverted to appropriate containment (see [Section 10](#)) and/or treated to a designated concentration prior to its release, or discharge into the receiving environment. This may be achieved through transfer to an appropriate treatment facility off-site, where practicable and available, or through modular water treatment systems deployed temporarily or permanently onto a site (see [Section 11](#)). Application of good environmental practice and reasonably available technology for PFAS water treatment can achieve levels of PFAS in treated water below current detection levels.

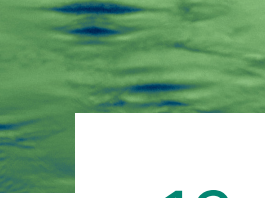
Management measures for PFAS-contaminated construction water, such as reuse, re-infiltration, re-injection, release or discharge to soil, surface water or groundwater, may require specific approval from environmental or other regulators. Similarly, a site-specific risk assessment or other environmental impact assessment may be required. There may also be jurisdiction-specific requirements for the treatment of construction water prior to its release or discharge to soil, surface water or groundwater. Information on how the project minimises generation of PFAS-contaminated water and manages the water in a way that protects environmental values, human health and beneficial use of waters is usually required to support these applications and demonstrate compliance with the general environmental obligations for managing PFAS ([Section 3](#)).

Containment and storage of PFAS-contaminated construction water should be undertaken in such a manner that ensures that PFAS cannot migrate into the surrounding environment (see [Section 10](#)). For treatment, consider the preferred hierarchy of treatment and remediation options in [Section 13](#), with more detail on treatment and remediation options in [Appendix D](#).

An aerial photograph of a river, likely the Amazon, showing a mix of green and blue water with visible sandbars and ripples. The image is used as a background for the slide.

13

PFAS site remediation and management



13 PFAS site remediation and management

Remediation is generally considered ‘any action undertaken for eliminating, reducing, controlling, or mitigating the risks resulting from contamination’ (UNEP 2024).

Remediation can encompass clean-up measures whereby contamination is removed from the site or from media on the site as well as management actions or interventions designed to eliminate or reduce risks, or to prevent harm and meet relevant environmental protection objectives. The following section sets out some of the matters to be considered when identifying and setting remediation goals and objectives, as well as deciding suitable remedial options and identifying technologies to achieve them. It also sets out some of the considerations around demonstrating remediation success, and the monitoring and management that may also be required.

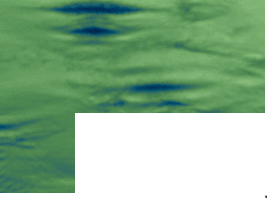
The terminology used in each jurisdiction can vary. For the purposes of this document, remediation goals are the broader protection aims and remediation objectives are the more specific subsidiary targets that support the goals.

The behaviour of these contaminants in the environment will strongly influence the setting of remediation goals, objectives and attainment approaches for PFAS-impacted sites. PFAS are not naturally occurring, are highly mobile in aquatic systems, and persist in soil and the environment for long periods. These characteristics tend to result in widespread distribution away from the source area. It is not uncommon for PFAS-impacted areas to be measured in square kilometres. Consequently, consideration of off-site transport and risks are critical. PFAS also bioaccumulate in biota, therefore consideration of effects on secondary consumers is also critical.

Because of these behaviours, the following section, as well as [Appendix E](#), also touch on some of the assessment considerations that are necessary to inform the remediation and management strategies. Finally, the information in this section is largely aimed at informing the responsible entity – that is, the entity responsible for deciding upon and effecting the remediation activity. It may be the polluter, landowner, land manager, entity disturbing the contamination, lessee or similar entity.

13.1 International obligations

Australia and New Zealand are parties to the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention), and the Basel Convention on the Control of Transboundary Movements of Hazardous



Wastes and their Disposal (Basel Convention), which set out expectations and obligations in relation to waste disposal, management and remediation, among other matters.

Among other matters, the Stockholm Convention requires that parties:

- endeavour to develop appropriate strategies for identifying sites contaminated by chemicals listed in Annex A, B or C of the Stockholm Convention
- if remediation of those sites is undertaken it shall be performed in an environmentally sound manner.

While ultimately this means that the Commonwealth and New Zealand government are responsible for establishing what activities meet the Convention's obligations for environmentally sound remediation, all Australian jurisdictions are collectively involved in setting up frameworks and requirements around environmentally sound practices.

Currently PFOS and its salts and PFOSF, PFOA and its salts and PFOA-related compounds, and PFHxS and its salts and PFHxS-related compounds are listed under the Stockholm Convention.

13.2 Australian jurisdictional requirements

In Australia, the Commonwealth and the states and territories have differing responsibilities and different legislation in relation to contamination, contaminated sites investigation, and site remediation. It is important to understand and follow the requirements in the relevant jurisdiction(s). Schedule A of the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM) provides guidance on the site investigation process and when remediation or management might be required for four generic land uses. The National Remediation Framework (CRC CARE 2019) provides technical guidance on site remediation, long-term management, and site validation and handover processes.

13.3 Why and when site remediation may be triggered

Remediation and/or management actions may be triggered for several reasons, including but not limited to:

- a change in land use or site ownership
- a reported leak, spill, or other loss of containment
- contamination being identified in a source area on-site
- contamination being identified in the environment in breach of environmental legislation
- contamination being found at or near a receptor, potentially causing harm

- as part of a catchment clean-up program
- regulatory, planning and/or development requirements (for example, PFAS phase-out), or compliance audit.

In some cases, immediate action to address off-site pollution or immediate potential risks may be required under pollution control legislation as soon as PFAS contamination is identified. In addition, there may be some exposure pathways or breaches of environmental legislation that are identified early on, and interim management or remediation strategies can be instituted before more detailed risk assessments and final remediation plans are completed.

13.4 Considerations in setting remediation goals and objectives

Remediation goals are broad targets, consistent with international obligations and jurisdictional requirements, established to protect or restore environmental values and eliminate or reduce risk presented by PFAS in environmental media.

Remedial objectives are a series of defined steps that contribute to the broader remedial goal. They are measurable, achievable and time-limited.

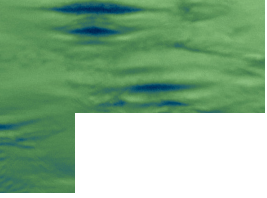
The National Remediation Framework (CRC CARE 2019) notes that considerations for remediation and/or management are protection of the environment and/or human health, expressed in terms of protection of beneficial uses or environmental values and risk reduction.

The goals of remediation are usually, but not always, defined following preliminary and detailed site investigations, and human health and environmental risk assessments. Preliminary and detailed site investigations and assessments identify:

- the nature and extent of PFAS contamination and any other contaminants of concern
- any actual or potential linkages between the contamination and receptors (that is, exposure pathways for people, animals, or the environment)
- any actual or potential adverse effects on biota and environmental values.

As part of this, receptor pathways and therefore risks into the surrounding area off-site also need to be considered. Guidance on these investigations is available in [Section 9](#).

In assessing the likelihood of risk, it is important to understand the source(s) and route of the exposure, the magnitude, frequency and duration, and possible receptors both at present and into the future. If these risks cannot be quantified over the relevant timeframes of



exposure (decades), this uncertainty should be factored into the decision and accurately reported and communicated, noting that a high-end precautionary approach may be warranted (US EPA 1992a and 2019; Department of Health and Ageing 2012; Australian Government 2017; Mallants et al. 2017). These are covered in more detail in [Appendix E](#).

Most jurisdictions allow for a risk-based approach for setting remediation objectives for on-site contamination. Where contamination has moved off-site, prescribed objectives may apply to protected environmental values. Importantly, human health-based and ecological guideline values are not designed to be used as default remediation or clean-up criteria, and should not be used for this purpose.

The goals of remediation should be focused on an overall reduction of risk both on- and off-site if PFAS are potentially or actually migrating. Examples of remediation goals include, but are not limited to:

- ensure the site is suitable/safe for all potential future uses
- make the site suitable for a more sensitive land use such as species protection, agriculture, residential, or other intended land use
- change formal classifications under a contaminated lands register
- comply with legislation, for example remediate a spill to reduce environmental harm beyond a site boundary
- protect environmental values and receptors
- prevent or reduce PFAS contamination in biota
- reduce contamination concentrations
- remove exposure pathways
- treat or remove source zones.

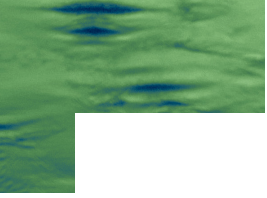
Examples of remediation objectives include, but are not limited to:

- clean up groundwater and/or surface water to a set level
- clean up of contaminated soil or sediment to a set level
- reduce mass discharges or balance by a targeted amount.

Community concerns should be sought and considered when developing remedial goals, particularly if contamination has migrated beyond the site boundary and affects off-site biota, land or water. Such goals may also be refined iteratively as understanding of the site improves and/or consultation with stakeholders is undertaken.

13.4.1 **Selecting remediation strategies and options**

Once the site and its surrounds, including any off-site chemical transport pathways and receptors, have been appropriately characterised, then strategies to eliminate or reduce risks, and meet legislative requirements



should be developed and implemented. These strategies generally fall into one or more of the following categories:

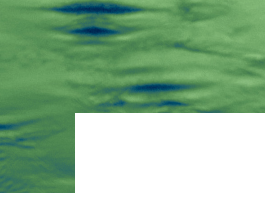
- source removal, for example:
 - removal for on- or off-site destruction
- source control, for example:
 - treatment and/or other methods to contain the contamination or limit its migration and mass flux
- exposure pathway interventions, for example:
 - barrier controls and/or diversion away from source or receptor
 - containment, stabilisation, interception, treatment and recharge schemes
- receptor management, for example:
 - receptor relocation
 - regulatory and other institutional controls
 - behaviour management
 - point-of-use treatment
 - other methods focused on the receptor.

Identifying and agreeing remediation strategies and options can be a complex process. There are, however, two main stages in identifying remediation options and selecting the preferred strategy. Note that the choices made at each site will differ depending on the circumstances at the site and the relevant jurisdictional requirements.

The responsible entity should first consider what could potentially be done to address the risks and possible harm, and to achieve the objectives (that is, what is possible in the circumstances). Risks, possible harm and objectives are identified through the earlier work of site investigations and risk assessments for the environment and/or human health.

The responsible entity should then consider what jurisdictional requirements must be met, what achieves the remediation objectives and what is reasonable in the circumstances and whether the response is proportionate to the contamination risks. This step requires consideration of matters such as harm, the sensitivity of the receiving environment, technical capabilities, the limitations of each of the possible options, the wastes produced from any intervention, and, finally, costs and financing.

Adequate assessment of the matters and comparison of different options to determine feasibility, effectiveness, benefits, and costs is usually needed to demonstrate the best course of action. The appropriateness of any specific option will vary depending on a range of local factors. The choice of a specific option or mix of options, is therefore a matter for the site manager in consultation with, or as directed by, the environmental regulator.



Selecting appropriate remediation options for a site will require a balance that will provide the highest level of protection that is both possible and reasonable in the circumstances. In concluding an assessment of remediation options, the responsible entity will need to consider how confident they would be that there will be little or no harm, now or in the future, after their remedial actions have been completed. They will need to outline the risks, the goals and objectives, the remediation options available, explain why the preferred option was chosen and how it meets the goals and objectives, and set out how the validation criteria were developed.

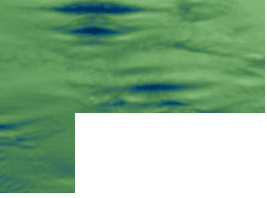
These considerations are covered in more detail in [Appendix E](#), which sets out details around the process of determining the:

- likelihood of the hazard or the risk occurring
- degree of harm that might result from the hazard or the risk, and/or the level of protection that may be required
- availability and suitability of practical mechanisms to eliminate or minimise the risk
- costs and benefits associated with available ways of eliminating or minimising the risk.

Stakeholder views will contribute to a comprehensive understanding of the context and the potential options available. There may be a requirement to report the existence of contamination as well as the remediation or management strategy to the environmental regulators. In some cases, community views on what should be protected are embedded in environmental values, and are often determined following extensive public consultation processes.

13.5 Preferred remediation hierarchy and treatment options

The Stockholm Convention's guidance on best available techniques (BAT) and best environmental practices (BEP) (UNEP 2024) notes that the best remedial option is one 'using the best available techniques, using environmentally sustainable methods, while not incurring excessive costs, adjusted to the available resources to reduce as much as possible the environmental risks'. In accordance with Article 6 of the Stockholm Convention, parties to the Stockholm Convention are required to develop appropriate strategies for identifying sites contaminated by chemicals listed in Annex A, B or C and, if remediation of those sites is undertaken, it is to be performed in an environmentally sound manner. Draft guidance on BAT and BEP for the management of sites contaminated with persistent organic pollutants (POPs) has been developed to guide the identification, assessment, management, and remediation of POPs-contaminated sites.



Source management (that is, interventions closest to the source where the concentrations of the contaminant are highest, the spatial spread of the contaminants is most contained, and the number of receptors is minimal) is an important element of remedial planning. It is noted that further interventions may also be required elsewhere, depending on risk and regulatory requirements. In particular, PFAS are often distributed unevenly throughout a site and potentially off-site. There may be one or many hotspots surrounded by lower concentration contaminated soils. Separate remediation strategies may be necessary even on a single site (and surrounding off-site areas) to account for volumes, mass flux and concentrations.

In general, due to the persistent nature of PFAS and the potential for long-term generational impacts, the preferred remediation hierarchy starts with the separation and treatment for destruction of the PFAS-contaminated material on-site, including contaminated water, so that the PFAS content is destroyed, removed, or otherwise reduced to an acceptable level. Destruction off-site at an appropriately licenced facility is also a highly preferred option, due to the permanent removal of PFAS persistent organic pollutants (POPs) from the environment. Highly preferred may not always mean that it is possible or the selected option on a site.

Less preferred options may involve management approaches to on-site interventions on source-receptor pathways, such as on-site encapsulation in constructed stockpiles or engineered storage and containment facilities, with or without chemical immobilisation (see [Section 10](#)). If the source site is hydrogeologically appropriate, on-site encapsulation may acceptably manage on- and off-site risks to direct and indirect beneficial uses and environmental values of soils, surface water, groundwater and biota.

The least preferred option in the management hierarchy is off-site removal to a specific landfill cell (see [Section 11](#)). This may or may not include immobilisation prior to landfill disposal. Note that the conditions in some landfills may affect immobilisation chemistry. Acceptance of PFAS-contaminated material is a commercial decision for the landfill operator and must be approved by the environmental regulator (see [Section 14](#)). Immobilisation prior to landfill disposal may also require environmental regulatory approval, as could the disposal to landfill itself. Leachate should be captured and treated to remove PFAS and the removed PFAS should be destroyed.

Consistent with the Basel Convention and the Stockholm Convention, specially engineered landfills or underground rock formations with zero environmental release may, in some circumstances, be acceptable repositories for certain types of high concentration wastes above low POP content limits (LPCLs) such as, for example:

- concrete, bricks, tiles and ceramics

- the inorganic fraction of soil and stones, including excavated soil from contaminated sites
- solid wastes from gas treatment, bottom ash, slag, fly ash and boiler dust.

It would not be acceptable for liquids and materials containing free liquids or biodegradable wastes. This would need to be agreed by the Australian and New Zealand Governments and the relevant jurisdiction.

In all cases, the intention of remediation will be to eliminate or reduce the risk to humans and the environment to an acceptable level, and to protect environmental values. Maintaining environmental compliance may also be a key objective.

13.5.1 Remediation technologies

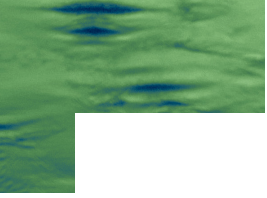
More technologies are becoming available to remove or immobilise PFAS contamination, including facilities being established in Australia for fixation, thermal desorption, thermal destruction, and others. High temperature destruction is available in a number of facilities in Australia. For processes that potentially produce air emissions, emission sampling and measurement techniques are becoming available to check that emissions are managed in accordance with best practice strategies that minimise the release of persistent organic pollutants and other contaminants.

[Appendix D](#) lists treatment technologies that are available in Australia commercially and/or are currently undergoing field trials for different media. For soil, thermal treatment, soil washing, sorption, containment and secure landfill are the most common options. While some technologies such as high temperature thermal are singular approaches, remediation strategies combining two or more treatment technologies ('treatment trains') may be needed to provide an appropriate approach to managing PFAS-impacted soils (Bolan et al. 2021). As new technologies become available over time, they will need to demonstrate proof of performance to a known standard.

The availability, practicability and feasibility of treatment options must be considered when evaluating options for PFAS treatment and remediation. An option that is an appropriate remediation treatment technique at one site may not be appropriate (or alternatively may not be sufficient) at another site. Storage and/or containment may be required where treatment options are not available. For further guidance on storage and containment see [Section 10](#), including the discussion of capping in [Section 10.3.3](#).

Special case: Remediation associated with site disturbance activities

Situations may occur when activities, such as development activities, are proposed to be undertaken on a site which may disturb, extract, or dig up contaminated soil, water or material. The area may not be subject to a remediation plan and may not be close to contamination hotspots. This soil, water or other material is usually the responsibility of the person creating



the disturbance (for example, the land developer, construction contractor, landowner, or the original polluter).

Even if not part of a current remediation action plan, any disturbed contaminated soil, water or material should be managed so as not to cause any unacceptable or increased risk to the environment and/or human health, or breach of any environment protection requirements. Once disturbed, disposal or treatment prior to any in-situ (or ex-situ) reuse of the contaminated soil, water, or other material is the preferred option.

Materials such as soil and water containing low levels of PFAS may be considered by environmental regulators for beneficial reuse, consistent with local legislative requirements and processes as outlined in [Section 12](#). Placing contaminated material without appropriate treatment back onto or into the site may not be consistent with environmental legislation. Any replacement must not cause a new or additional risk to the environment and/or human health, and may not increase the risk at or near the location at which any contaminated material is stored, transported, or reused. It should also be consistent with relevant environmental duties. Considerations on potential reuse are set out in [Section 12](#).

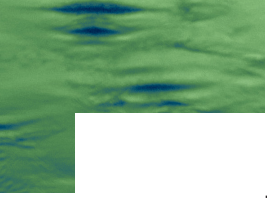
Because PFAS are highly mobile, consideration also must be given to the off-site impacts of the contaminant. In some jurisdictions, reuse of unremediated or partially remediated excavated materials may be considered pollution. It would be the responsibility of the person producing the pollution to ensure all exposure pathways, both on-site and off-site, are appropriately managed.

The National Chemicals Working Group (NCWG) notes that there may be significant co-benefits in treating contaminated materials disturbed during the development, as remediation can contribute to improved options for future land uses.

13.6 Demonstrating remediation success

Remediation is considered successful if the remediation goals, objectives and any relevant legislative requirements have been met, PFAS concentrations have been reduced, and unacceptable risks to the environment and/or human health have been mitigated or reduced to acceptable levels.

In many cases remediation success will be linked to a reduction in the measured PFAS concentration in relevant media, and sometimes to reductions in concentration, load, and/or mass flux.



Typically, success will be measured through a monitoring program, which would:

- address data gaps that were identified when setting the remediation objectives
- validate any assumptions made in the site investigations, risk assessments, conceptual site model, and/or remediation action plan
- confirm engineering controls are functioning as intended
- have trigger/intervention targets agreed
- observe other long-term trends to inform the management strategy success.

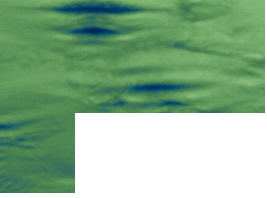
Evidence provided to environmental regulators should demonstrate that remediation goals and objectives have been met. This will often require a site audit by a suitably qualified and experienced person such as a contaminated site auditor (for example, as outlined in Schedule B9 of the ASC NEPM).

Typically, a site clearance or 'validation' report is prepared by a suitably qualified and experienced person. Guidance is often provided by state/territory governments on reporting requirements.

13.7 Long-term management strategies

In addition to, or in conjunction with, remediation, or as an alternative to remediation, some sites or parts of a site may require a long-term management strategy. This applies particularly where PFAS contamination is likely to remain present on-site for extended periods of time, remedial action is assessed as being inappropriate or ineffective, and/or remediation options are not yet available. This may result in restrictions on land use now and in the future. The implementation of a long-term management strategy (for example, long-term environmental monitoring, fencing, security and signposting) and an associated environmental plan for on-site monitoring and management may be considered where the remedial action assessment (part of remediation action planning) indicates that:

- remediation would have no immediately measurable environmental improvement at the site or within the broader catchment
- physical maintenance of the remedial solution (plant, machinery) is required in order to continue to effect the remedial outcomes
- remediation would have a net adverse environmental effect (for example, determined via a site-specific risk assessment) and long-term management can effectively eliminate or reduce the PFAS contamination risks to the environment and/or human health

- 
- management of exposure pathways rather than treating at source would be acceptable, particularly as an interim measure while other options are considered.

An on-site management strategy would be appropriate provided that:

- unacceptable risks to off-site ecosystems and/or human health exposure such as by surface water or groundwater migration is not occurring or is managed. This includes establishing triggers for unexpected risks, designed to prompt management responses
- the responsible entity agrees and has sufficient expertise and financial capacity to implement and maintain the proposed management measures and legal liabilities over extended periods of time. The responsible entity will generally be required to monitor and report to environmental regulators and affected communities on the efficacy of the measures for the duration of the activity
- the environmental regulators implement appropriate statutory tools for requiring compliance, including the ongoing provision of information (for example, publicly available fishery advice), with such strategies and ensuring community right to know
- sites may also require monitoring to ensure that the remediation has been successful over the relevant timeframe. The status of the site may need to be revisited over those timeframes, such as in circumstances where the land use changes, available clean up technology improves in performance, science changes, potential receptors in the area change, or clean up levels that were previously agreed are modified or no longer supported.

An aerial photograph of a body of water, likely a river or lake, showing a mix of green and blue hues. A white rectangular box is overlaid on the left side of the image, containing the number 14 and the text 'PFAS disposal to landfill'.

14

**PFAS
disposal to
landfill**

14 PFAS disposal to landfill

This section covers the permanent disposal of PFAS-containing waste to landfill. Additional information that may be relevant to aspects of managing PFAS in landfills is provided in [Section 10](#) on storage, stockpiles and containment.

Every jurisdiction has policy and regulatory frameworks in place for waste disposal to landfill and to manage the associated environmental and/or human health risks. The guidance in this section is supplementary to, and should be applied in conjunction with, the existing guidance issued by jurisdictions on the siting, design, management, operation and closure of landfills. All environmental regulators and landfill operators must consider the risks and management challenges associated with the widespread presence of PFAS in household, commercial and industrial waste streams. Acceptance of PFAS-contaminated materials is a commercial decision for the landfill operator and must be approved by the environmental regulator. Site-by-site assessment will be required when determining whether or not a current or new landfill is appropriate for accepting PFAS-contaminated material or whether a closed landfill may require additional monitoring or controls.

14.1 Landfill siting and design

For all new landfills, siting and design are the primary controls to minimise risk to the environment and/or human health. Landfill siting and design must give regard to topography, geology, hydrogeology, proximity to groundwater and surface water and sensitive ecological and human receptors. The widespread presence of PFAS in Australian and New Zealand waste streams means that the PFAS-specific characteristics (for example, mobility and persistence) should be taken into account.

Where siting and design are of concern for existing facilities, the environmental regulator will consider these landfills as having a higher risk to the environment, human health and/or amenity, and will require further consideration through a detailed site assessment. This may result in a refusal to accept solid PFAS-contaminated material for disposal.

Design requirements will vary by jurisdiction. However, as a minimum the following should be considered for new and existing landfills:

- new sites:
 - geotechnical aspects and site preparation
 - landfill liner system design and construction
 - leachate management system design and construction
 - stormwater management controls
 - construction quality assurance

- existing sites:
 - performance of landfill liner system
 - performance of leachate management system
 - review of existing stormwater management controls
 - review of construction quality assurance for landfill liner and leachate system.

Historic groundwater and surface water monitoring results will provide the necessary information to inform the above considerations.

14.2 Landfill operation

The following operational practices of the landfill should be reviewed and strengthened where necessary, as part of a broader site-specific assessment when considering landfill acceptance of solid PFAS-contaminated material:

- waste acceptance, handling and placement – landfill operators should consider the appropriate handling of the material once accepted onto the landfill site, including leachate collection and management systems. If possible, consideration should be given to offloading PFAS-contaminated material directly into the receiving landfill cell, where it can be moved and worked within the cells for final waste placement
- waste cover – placement of daily cover over wastes is an essential part of landfilling operations
- dust controls – handling and placement of PFAS-contaminated material may require dust suppression measures.

14.3 Leachate management practices

Leachate should be collected in a sump and pumped to a storage location (usually a suitably engineered/lined evaporation/storage pond or tank). Before treatment, disposal or reuse of the water, it should be analysed for PFAS.

When detected, options for treatment and remediation or destruction should be considered and implemented as required to prevent PFAS distribution to the environment. Further guidance is provided in [Section 10](#) on storage and containment of PFAS-contaminated liquid wastes and in [Section 15](#) on wastewater treatment that is relevant to leachate management options (such as trade waste discharge), which should be discussed with the environmental regulator and the water utility or authority.

14.4 Monitoring at landfills

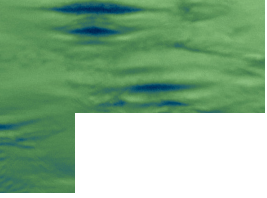
Monitoring of landfill leachate, groundwater, surface water and terrestrial receptors, should include PFAS in accordance with the regulatory requirements; specifically, conditions imposed for landfills approved to accept solid PFAS-contaminated material. If regulatory requirements do not exist, monitoring programs should include PFAS.

Information on PFAS is likely to be found in different media at landfills, and an understanding of the purpose of a monitoring program is necessary to design an effective program. The following provides information on the types of PFAS that may be associated with landfills and how they may influence monitoring.

The nature of PFAS measured in waste, leachate and environmental media related to landfill operations will be influenced broadly by the nature and age of wastes disposed, the age of the landfill and the environmental conditions prevailing within the waste mass. While a study of Australian landfill leachate has found a range of PFCA and PFSA present (Gallen et al. 2017), studies overseas using more extensive analysis suites have found a broader range of PFAS including fluorotelomer carboxylic acids (FTCA), fluorotelomer sulfonic acids (FTSA) and fluoroalkyl sulfonamido acetic acid (FASAAs) compound classes. In particular, n:3 fluorotelomer carboxylic acids have been found to be the predominant PFAS in many landfill leachates (Lang et al. 2017). This information relates to facilities receiving primarily municipal solid waste (MSW), and in some cases biosolids, rather than a large range of industrial wastes. In those cases, site-specific investigation of industrial waste or other waste PFAS composition would be desirable.

This infers that use of the standard PFAS monitoring suite used in Australia may fail to fully characterise PFAS in leachate when attempting to understand PFAS risks. FTCA are included in some extended suites offered by commercial laboratories in Australia. A total oxidisable precursor (TOP) assay in which the extraneous organic content does not exhaust the oxidant is an additional option. Effective characterisation of leachate is consistent with general environmental duty obligations and particularly relevant for leachate treatment, sewer discharge and investigations of potential leachate migration. Understanding PFAS in emissions is a necessary component of any study assessing potential impact of emissions to air from a landfill or any mass balance study of PFAS in a landfill. Monitoring of air emissions at landfills is most likely to be necessary or desirable in cases where there are large emissions and or sensitive receptors in close proximity.

It is important to recognise that only ionic, non-volatile PFAS are quantified by liquid chromatography–tandem mass spectrometry (LC-MS/MS) and therefore volatile gas phase PFAS are not detected. This is important as



degradation of fluorotelomer-based PFAS produces volatile PFAS, such as fluorotelomer alcohols, which have been measured in concentrations significantly greater than ambient levels near landfill sites (Ahrens et al. 2011; Weinberg et al. 2011). Measurement of volatile PFAS is typically carried out by gas chromatography/mass spectrometry (GC/MS) (for example, see US EPA 2023).

An indirect method of accounting for volatile PFAS which has been used in Australia is the TOP assay, where emission samples are collected and analysed using an applicable methodology (for example, see US EPA 2021a). This is based on the understanding that TOP assay oxidises FTOH to PFCA, which can be readily quantified. Methods based on analysis of volatile gases are also available overseas and may become commercially available in Australia in future (US EPA 2023). Landfill emissions have also been studied by investigating dry deposition and analysing leaves, which have been used as a form of passive air sampling for some PFAS (Tian et al. 2018). Research is underway to determine effective ways to characterise and quantify PFAS in landfill gas and emissions (US EPA 2020).

14.5 Closure considerations

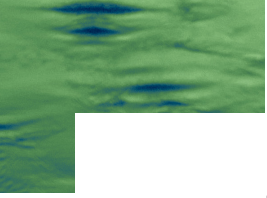
Closure of the landfill should consider ongoing containment strategies, including leachate management and maintenance of capping and groundwater management systems. Monitoring of landfill gas condensate should consider PFAS as some, such as fluorotelomer alcohols, are volatile. Decommissioning (for example, of leachate collection dams), should be assessed for the presence of PFAS and be managed accordingly.

For closed landfills with ongoing monitoring requirements, PFAS monitoring in groundwater should also be considered.

14.6 Landfill acceptance criteria

The following criteria apply to the disposal of solid PFAS-contaminated material to landfill. These have been determined based on existing jurisdiction approaches to the derivation of landfill acceptance criteria for a number of standard landfill designs, but recognise that individual jurisdiction approaches may differ, particularly in the base values and multiplication factors used.

Waste concentrations must be less than both the relevant total and leachable concentration in the Australian Standard Leaching Procedure (ASLP) conducted at both pH 5 and un-buffered reagent water – approximating the ‘worst case’ for leaching conditions.



Based on individual landfill siting, design, operation and ongoing management requirements, as well as individual environmental regulator approaches to the derivation of landfill acceptance criteria, the environmental regulator may determine that these criteria are not suitable for a specific landfill or landfills and derive and implement alternative criteria.

Landfill acceptance criteria have been capped at 50mg/kg of the sum of all PFOS-, PFOA-, and PFHxS-related compounds. This is based on a number of factors. For example, under Article 6 of the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention) the following is required:

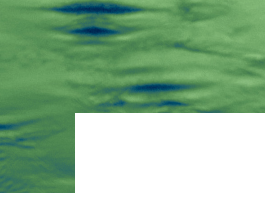
- wastes must be 'disposed of in such a way that the persistent organic pollutant content is destroyed or irreversibly transformed so that they do not exhibit the characteristics of persistent organic pollutants or otherwise disposed of in an environmentally sound manner when destruction or irreversible transformation does not represent the environmentally preferable option or the persistent organic pollutant content is low, taking into account international rules, standards and guidelines, including those that may be developed pursuant to [the Stockholm Convention], and relevant global and regional regimes governing the management of hazardous wastes' (paragraph 1(d)(ii))
- wastes are 'not permitted to be subjected to disposal operations that may lead to recovery, recycling, reclamation, direct reuse or alternative uses of persistent organic pollutants' (paragraph 1(d)(iii)).

Further, the Basel Convention on the Transboundary Movements of Hazardous Waste and Disposal (Basel Convention) provides the low persistent organic pollutants (POPs) content limits (LPCLs) for PFAS wastes for the purposes of the Stockholm Convention, as noted above. The Basel Convention's *Technical Guidelines* (UNEP 2023b) are available from the Technical Guidelines webpage.

Concentrations above these levels require treatment to destroy or irreversibly transform the chemicals so that they do not exhibit the characteristics of POPs. If destruction is not the environmentally preferable option, then it must be managed or disposed of in an environmentally sound manner.

The following criteria do not provide permission for any landfill to receive solid PFAS-contaminated material. Rather, individual landfills must seek approval from the environmental regulator to receive these wastes. In determining whether a landfill will be suitable to accept solid PFAS-contaminated material, considerations include:

- ensuring the landfill is not located on a vulnerable groundwater system (see Australian Government (2013) and Appleyard (1993))
- depending on the landfill liner design, whether the landfill is located within 1000m of a surface water body that supports an aquatic



environment (including groundwater dependent ecosystems), or within 1000m of a surface water drain that is connected to groundwater and/or discharges directly into an aquatic environment (including groundwater dependent ecosystems) or a water body that supports fish or other fauna species that may be caught and consumed

- performance of landfill liner and leachate management system (giving consideration to historical groundwater and surface monitoring results for existing sites)
- leachate management practices at the landfill, in particular whether landfill leachate is recirculated through the landfill or sent to a wastewater treatment plant, whether treatment occurs prior to release, or if leachate is likely to be reused either on- or off-site
- other factors as relevant to the specific landfill siting, design, operation and ongoing management
- whether there are significant additional PFAS compounds present in addition to PFOS, PFHxS and PFOA
- where PFAS-contaminated soils are used as day cover, more stringent requirements are likely to apply to prevent stormwater contamination.

Table 11 Landfill acceptance criteria

In New Zealand, provisions in the *Hazardous Substances (Storage and Disposal of Persistent Organic Pollutants) Notice 2024* must be followed.

Landfill type	Concentration type	Interim landfill acceptance criteria ^{a b}		Comments
		Sum of PFOS and PFHxS ^c	PFOA	
Unlined	ASLP leachable concentration (µg/L)	0.07µg/L	0.56µg/L	Drinking water × 1 (Department of Health 2017)
	Total concentration (mg/kg)	20mg/kg	50mg/kg	Soil – Human health industrial/commercial × 1 Total concentration for PFOA (including related substances) of 50mg/kg based on a proposed Basel Convention LPCL
Clay/single composite lined	ASLP leachable concentration (µg/L)	0.7µg/L	5.6µg/L	Drinking water × 10 (Department of Health 2017)
	Total concentration (mg/kg)	50mg/kg	50mg/kg	Soil – Human health industrial/commercial × 10 Total concentration for PFOS + PFHxS and PFOA (including related substances) of 50mg/kg based on the Basel Convention's LPCLs
Double composite lined	ASLP leachable concentration (µg/L)	7µg/L	56µg/L	Drinking water × 100 (Department of Health 2017)
	Total concentration (mg/kg)	50mg/kg	50mg/kg	Soil – Human health industrial/commercial ×100 Total concentration for PFOS + PFHxS and PFOA (including related substances) of 50mg/kg based on the Basel Convention's LPCLs

^a Waste concentrations must be less than both the relevant leachable concentration and the total concentration values for the type of landfill.

^b Where significant PFAS are present beyond PFOS, PFOA, and PFHxS, these solid PFAS-contaminated materials may not be acceptable for landfill disposal. This should be discussed with the environmental regulator.

^c Where the criteria refer to the sum of PFOS and PFHxS, this means concentrations of PFOS only, PFHxS only, and the sum of the two, including their respective related compounds.



15

PFAS in the wastewater treatment system

15 PFAS in the wastewater treatment system

The following guidance focuses on sewerage networks managed by water utilities and authorities. It also identifies issues relevant to organisations responsible for on-site management and treatment of wastewater and trade waste.

Sound management of PFAS contamination in the wastewater treatment system is critical. PFAS in the wastewater treatment system originate from many different sources, including domestic and industrial discharges.

In relation to preventing further release of industrial chemicals (such as PFAS) into the environment from the use of products and articles, the Australian Industrial Chemicals Environmental Management Standard (IChEMS) provides nationally consistent standards for managing chemical import, export, manufacture, use and disposal. Through IChEMS and the IChEMS Register, chemicals are listed in one of seven regulatory schedules relative to their environmental risk. PFOS and related substances, PFOA and related substances, and PFHxS and related substances are listed in Schedule 7. Chemicals listed in Schedule 7 pose the greatest risk to the environment and are typically prohibited or severely restricted. In New Zealand, restrictions on PFAS-containing substances are applied by decisions under the *Hazardous Substances and New Organisms Act 1996*. Such decisions have been taken in respect of PFAS in firefighting foams, and in cosmetics.

Criteria for existing environmental contaminants, including PFAS, are generally established by the environmental regulator, with input from the relevant wastewater utility, as part of the broader approach to managing water quality set out in each jurisdiction's environmental legislation. A common point of reference for water quality management, agreed by all jurisdictions, is the National Water Quality Management Strategy (NWQMS) (Australian Government 2019b) and the Australian and New Zealand Water Quality Guidelines (WQG) (ANZG 2018). Using a framework provides a systematic way to plan, develop and manage performance.

The NWQMS and the WQG provide detailed guidance on the development and application of guideline values to protect environmental values, also known as community values or beneficial uses. These guideline values focus on assessing potential risks to the ecosystems, and do not necessarily represent discharge criteria. It is also important to consider potential risks from toxicity in aquatic species, and bioaccumulation in both aquatic and terrestrial species, as well as potential risks to human health.

15.1 PFAS management framework

The application of a precautionary approach, guided by a PFAS management framework, makes good business sense while guidelines are being developed. This approach will minimise future risks to wastewater utilities that could otherwise arise once such criteria are established. It is also prudent in light of the rapid advances being made in the scientific understanding of PFAS and its behaviour in the environment.

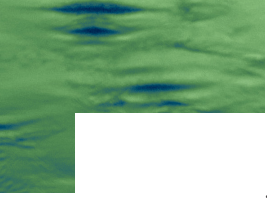
The PFAS management framework should address the specific needs and circumstances of each wastewater utility, in consultation with relevant regulators (as well as the environmental regulator, this may involve other regulators such as a utility regulator). It is recognised that adaptations may need to be made to such a framework to accommodate differences in scale and other challenges faced by smaller water utilities. An effective framework would be expected to address the following key areas:

- wastewater inputs (for example, trade waste and domestic wastewater)
- wastewater processing (for example, infrastructure and biological treatment processes)
- wastewater outputs (for example, effluent discharged to the environment, effluent used as recycled water, biosolids used for soil conditioning, and biosolids disposed to landfills or other waste disposal pathways).

The following outcomes provide a common starting point for developing a framework. Note that the first three outcomes listed address external accountabilities, while the remaining outcomes would be at the discretion of the wastewater utility:

- all relevant legal and regulatory requirements are met so that consistency with the PFAS National Environmental Management Plan (PFAS NEMP) is achieved
- the health and safety of staff, customers and the general public are protected
- the ecosystem function, biodiversity, and amenity of receiving environments are protected
- the condition of wastewater treatment infrastructure and processes are maintained across the life cycle, including:
 - production of outputs acceptable for disposal and reuse
 - affordable disposal of infrastructure at the end of its working life
- the costs for acceptance of trade waste are appropriately understood and recovered.

An example framework is provided for reference in [Appendix G](#). Addressing each element of the framework, as per the example framework provided, will enable water utilities to demonstrate compliance to regulators, stakeholders and the broader community. The example framework is



included to highlight the key aspects that wastewater utilities should consider when developing an approach to manage risk from PFAS. The specific risks from different PFAS inputs into a wastewater network will inform how much of the example framework wastewater utilities will need to consider including. Regulators may also set a requirement for a framework to be developed through wastewater utility conditions of license.

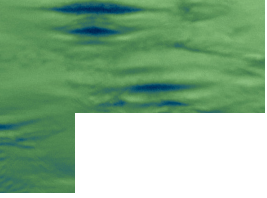
15.2 Additional management tools

Drawing on the advice provided in this plan, in the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM), and in the NWQMS, additional management tools relevant to managing PFAS in wastewater may, depending on the potential risks and the size of the water utility, include:

- PFAS inventories for specific wastewater catchments or priority areas within catchments – in addition to point sources, PFAS are present in a wide range of products, which contributes to the PFAS inputs to wastewater systems. Options to manage these diffuse sources of PFAS and reduce any associated environmental and/or human health risks are covered by other national processes outside of the PFAS NEMP
- stakeholder engagement plans for specific wastewater catchments or industries
- remedial action plans, transition plans or continual improvement plans prioritising short-, medium- and long-term actions to address identified issues
- risk assessments for specific discharges and products for beneficial reuse. Additional guidance around biosolids and recycled water is planned as part of the future work in the theme on Water outlined in [Section 20](#)
- applied research strategies to address knowledge and technology gaps
- infrastructure management and development plans
- communication strategies to publicise relevant information such as monitoring results and progress against the outcomes listed above.

15.3 Case study – PFAS contamination of a wastewater treatment system

A company accidentally discharged a large volume of aqueous film-forming foam (AFFF) containing fluorotelomer precursors and small quantities of PFOA and PFSA. The company reported that most of the spill was contained, but some of the foam entered the stormwater drainage channel and subsequently escaped into the wastewater treatment system and local waterways. The PFAS appeared at the wastewater treatment plant (WWTP)



and in local waters as frothy bubbles and contaminated the wastewater treatment system infrastructure.

To manage further contamination of the WWTP, the following activities took place:

- consultation between all stakeholders to understand impacts and options
- turning off pump stations to prevent further PFAS being released downstream
- extraction of material from the affected sewers and the pipework cleaned
- diversion and collection of sewage that would normally flow through the system
- PFAS-contaminated wastewater was contained
- ongoing monitoring of PFAS in sewage onsite and at the affected WWTP
- disposal of affected biosolids to a landfill capable of receiving PFAS-contaminated materials
- ongoing management of the site, including adaptive management to ensure no ongoing impact
- treatment of the PFAS-contaminated material to meet relevant criteria, including thermal destruction of the PFAS concentrates.

15.4 PFAS criteria in biosolids

Research in Australia and overseas (Armstrong et al. 2016; Gallen et al. 2016) has confirmed that a range of PFAS are present in the majority of biosolids that are produced by WWTPs. Currently, most biosolids meeting existing criteria for beneficial reuse are applied to land as a soil conditioner. When applied to land in this way any PFAS present are added to the environment, resulting in the potential for ecological and/or human exposure to PFAS. This could particularly be the case where biosolids are being applied to land used for agriculture, including meat, milk and fodder production (van Asselt et al. 2013; Lupton et al. 2014; Stahl et al. 2009), and some plant products.

To inform management controls aimed at protecting the environment and/or human health, the potential risks from PFAS following land application of biosolids have been investigated through a human health and ecological risk assessment (HHERA) (additional details on the text are provided in Supporting Document 1). This work has led to the derivation of criteria and guidance for all jurisdictions to incorporate within existing biosolids management frameworks where applicable. To inform this work a range of water utilities, industry associations and user groups in Australia were engaged with to better understand their knowledge of PFAS in biosolids and the frameworks in place to manage the risk.

15.4.1 Characterisation of biosolids

To understand the risks that biosolids may pose to the environment, it is recommended that biosolids are characterised for the full suite of PFAS analytes included in the standard methods as described in [Section 19](#). As biosolids are a complex matrix, it is important that robust quality assurance is included within the sampling and analysis program. Further details on the analysis of PFAS in waste materials including biosolids can be found in [Section 19.4](#). Details of biosolids sampling requirements to ensure characterisation is representative should be determined by each jurisdiction. The responsibility for sampling biosolids should be consistent with the existing guidance in each jurisdiction.

Research investigating PFAS in Australian biosolids found the dominant compounds detected were the di-substituted phosphate esters (diPAPs) which contributed 45% of the total mean sum of PFAS mass, followed by perfluoroalkyl carboxylic acids (PFCA) 17%, perfluoroalkyl sulfonates at 16%, fluorotelomer carboxylic acids (FTCA) 9% and perfluorooctane sulfonamide 5% (Moodie et al. 2021). This is consistent with overseas studies (Yeung et al. 2016) and water authority data provided to the Queensland Department of Environment and Science (DES) that reported significant increases in PFCA in biosolids analysed via total oxidisable precursor (TOP) assay.

Given that the majority of PFAS may not be detected by standard analysis which does not encompass diPAPS and FTCAs, jurisdictions may consider requesting analysis of an expanded suite including diPAPS and FTCAs or TOP assay. DiPAPS subject to TOP assay yield a range of PFCA products of $n+1$ to shorter carbon chain length (Houtz and Sedlak 2012). If TOP assay is being conducted on biosolids samples, enhanced oxidative steps compared to those employed in the Houtz and Sedlak (2012) method may be required.

15.4.2 Details on proposed land application and characterisation of in-situ soils

Information about the proposed land application approach and soil properties, including the depth of incorporation and soil bulk density is required (conservative default values can be used if these are not available, see Supporting Document 1). It is recommended that the soil at the land application site is characterised to determine the existing in-situ baseline soil concentrations of PFAS prior to application of biosolids. This will be particularly critical if biosolids re-application is considered. Some jurisdictions may also require sampling of biosolids-amended soils after land application to validate the estimated soil concentrations after land application. The sampling design to characterise the PFAS concentrations in in-situ soil should be consistent with the existing requirements in each jurisdiction. The responsibility for sampling in-situ soil should be consistent with the existing guidance in each jurisdiction.

15.4.3 Criteria

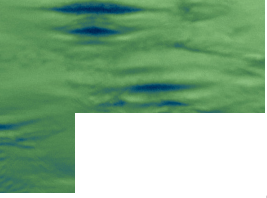
The HHERA for PFAS in biosolids was developed to identify the key exposure pathways that should be considered to derive risk-based criteria. The HHERA assessed potential risks for different classes of biosolids use with a focus on 'restricted use' and 'unrestricted use' biosolids scenarios. The 'restricted use' biosolids scenario in the HHERA assumed that biosolids are land-applied and incorporated into the soil for agricultural use (similar to Class B in some jurisdictions). The 'unrestricted use' biosolids scenarios assumed biosolids are applied to soil without any restrictions on the application rate.

For each scenario, a range of relevant human health and ecological exposure pathways were assessed. The HHERA assessed ecological risks from PFOS and PFOA, and human health risks from the sum of PFOS and PFOS + PFHxS, and PFOA. The human health risks were assessed against tolerable daily intake (TDI) values established for Australia and New Zealand. The range of exposure pathways and endpoints from PFAS in biosolids-amended soils, included:

- human health:
 - incidental ingestion of biosolids/soil/dust
 - consumption of crops
 - consumption of chicken eggs
 - consumption of beef
 - consumption of milk from cattle
 - human ingestion of drinking water
- ecological:
 - impact to aquatic organisms (direct toxicity)
 - impact to terrestrial ecosystems
 - secondary consumption in ecosystems.

Additional details on the scenarios and pathways assessed in the HHERA are provided in Supporting Document 1 and in the [NSW Biosolids Regulatory Review](#) (NSW Department of Planning and Environment (DPE) 2023).

The outcome of the HHERA was that criteria for restricted use and unrestricted use biosolids were recommended based on the most sensitive pathways, which were consumption of milk for PFOS + PFHxS and ecological secondary consumers for PFOA. These pathways were used to create the proposed biosolids criteria in [Table 12](#). The most sensitive pathways were used to derive the values in [Table 12](#), so all potential pathways are addressed allowing for changes of land use and types of agricultural production. In addition, the most sensitive exposure pathways were also used to derive maximum allowable soil contaminant concentrations (MASCC) for PFAS in relation to biosolids application for



beneficial reuse in agriculture. It is proposed that the MASCCs are used as criteria to calculate a contaminant limited biosolids application rate (CLBAR) for PFAS (for example, if the concentration in biosolids is greater than the restricted use threshold then a CLBAR can be calculated to determine an appropriate application rate to meet the MASCC). The criteria were derived at three margins of safety (MOS): 1-, 2- and 5-fold. The selection of the most suitable MOS should consider the following:

- the MOS of 1 should be the default set of criteria on the commencement of PFAS NEMP 3.0, noting that this does not offer any additional level of safety from exposure to PFAS. The following factors are relevant and may lead to some jurisdictions adopting a higher MOS as the default in their biosolids guidance
- the criteria in [Table 12](#) only relate to PFOS + PFHxS and PFOA but other PFAS, including considerable amounts of precursor chemicals (such as diPAPs) are typically found in biosolids. Risk assessment approaches to choose the preferred MOS may be informed by the total PFAS concentrations present
- the presence of additional individual PFAS or PFAS classes in biosolids may also need to be managed to mitigate risks to the environment and/or human health and may warrant a larger MOS in some jurisdictions
- the criteria were derived considering a single exposure pathway, but exposure may occur via multiple pathways
- site-specific risk assessment, which should include current and potential future land use. Due to the persistence of PFAS, it may not be suitable to only consider the current land use
- the potential for environmental regulators to implement a tiered approach where criteria can be reduced over time to encourage biosolids producers to manage and reduce PFAS inputs.

Table 12 Criteria for PFOS + PFHxS and PFOA in biosolids and maximum allowable soil contaminant concentrations based on a 1-, 2- and 5-fold margin of safety

Criteria type	Margin of safety ^a	Sum of PFOS and PFHxs µg/kg	PFOA ^b µg/kg
Biosolids threshold restricted use	5	6.2	16
	2	15	40
	1	31	81
Biosolids threshold unrestricted use ^c	5	0.22	0.6
	2	0.55	1.5
	1	1.1	3
MASCC	5	0.22	0.6
	2	0.55	1.5
	1	1.1	3

^a The default MOS is 1.

^b The PFOA criteria are based on the interim soil ecological indirect exposure guideline value for PFOA.

^c The unrestricted use threshold may not be applicable in all jurisdictions. Where it is applicable, it should be applied to the final biosolids product for land application.

Note that given the presence of a range of PFAS in biosolids, some jurisdictions may set limits on other PFAS compounds and require additional analytes to be tested and may set compliance outcomes against these (for example, short-chain PFAS and total extractable organic fluorine in Queensland).

Some jurisdictions may allow for 'site'-specific risk assessments to be undertaken to support the beneficial reuse of biosolids at concentrations greater than the criteria in Table 12. These risks assessments should be prepared consistent with guidance available in each jurisdiction, and in addition to the biosolids and site characterisation guidance given above should consider the following factors:

- local legislative requirements
- site suitability, including separation from groundwater, surface water, farm dams, steep slopes, and sensitive residential, commercial and conservation land uses
- expected land use (now and with consideration of future potential land uses)
- whether informed consent by the landowner is required and if site-specific restrictions are to be recorded on the land title
- if crops are grown, what are they? Are any more locally relevant transfer factors available to more accurately reflect the uptake of PFAS from biosolids to the specific crops?

- conversely, conservative soil to plant transfer factors as included in the NSW Biosolids Regulatory Review (DPE 2023) should be applied when plant uptake has not been assessed or precursors may be present (for example, sites with history of biosolids application)
- what is the fate of the crop material? Is it for direct human consumption, fodder or silage for animals? If for grazing animals what animals? (for example, dairy cattle, beef cattle, sheep, pigs, etc)
- if provided for animals is there any information known about other sources of PFAS in their diet (that is, stock water or other feed)?
- information about farm practices is important. Opportunities available for livestock rotation, access to clean paddocks, clean pasture and water should be considered in any risk assessment (Mikkonen et al. 2023)
- if fodder, silage or pasture is provided to cattle, are they destined for local consumption or for the national market?
- if cattle are destined for overseas markets there may be requirements to demonstrate that maximum limits (MLs) are met. If MLs are not met, then potential withholding periods may be required to allow for PFAS tissue levels to drop below the relevant MLs (potentially through access to clean water and feed to eliminate exposure to PFAS) (Mikkonen et al. 2023)
- if there are no human health pathways related to animal production, then the next most sensitive pathways should be considered and risk assessed
- the criteria do not address impacts to aquatic organisms due to bioaccumulation (indirect toxicity) so concentrations greater than these create higher risks of bioaccumulation that must be adequately managed
- monitoring, keeping records and reporting PFAS concentrations in biosolids-amended soils and, if necessary, produce and the local environment, to confirm effectiveness of the plan.

15.4.4 Additional requirements

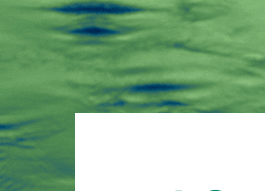
Note that biosolids application should provide a benefit to soil (for example, meet crop nutrient requirements when used in agriculture) and not constitute opportunistic disposal of waste into soil. This may restrict the beneficial reuse of biosolids in some jurisdictions. Legislation in jurisdictions may impose additional requirements (for example, in relation to stakeholder consultation, gaining approvals, reporting and land contamination). Refer to existing guidance on application of biosolids in each jurisdiction for further advice.

Where PFAS concentrations in biosolids are high enough to prohibit their beneficial reuse they must be treated or disposed of in accordance with jurisdictional requirements for PFAS-contaminated wastes.



16

**Data
sharing**



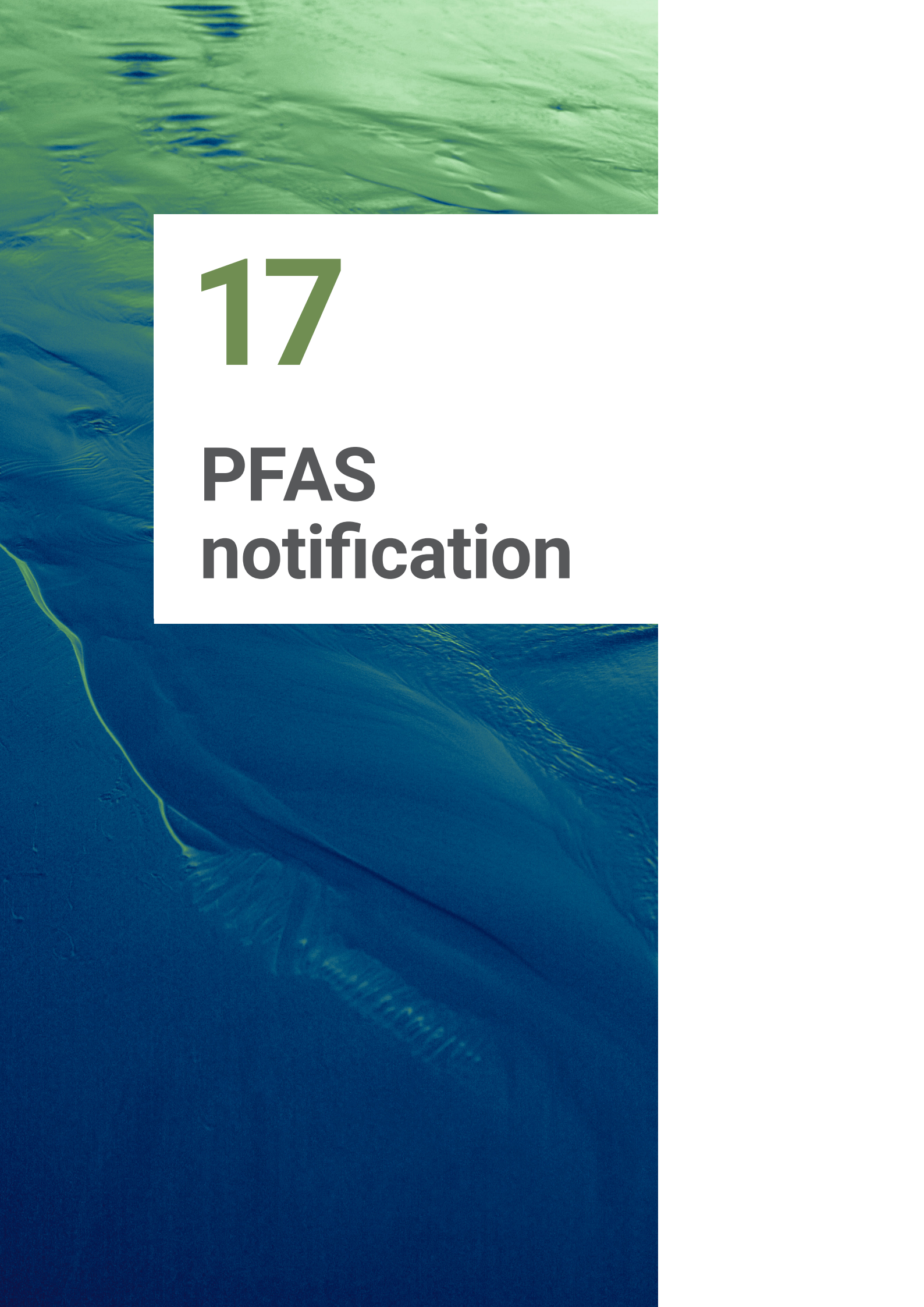
16 Data sharing

Data sharing, including the publication of data, is important for openness and transparency and to avoid duplication of effort. However, not all data can be shared or made public. Some may need to be withheld for privacy, commercial-in-confidence, or other reasons.

Environmental regulators will share data according to the following criteria:

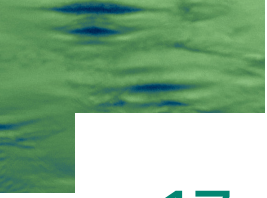
- if data is already public, it will be shared
- if there is no reason that data cannot be made public, it will be shared
- if data cannot be made public but there is a need to share, specific arrangements will be put in place.

This approach will be supported by future work (such as that outlined in [Section 20](#)) to formally establish a structured way of sharing data and information arrangements.



17

**PFAS
notification**



17 PFAS notification

Many environmental regulators require mandatory or voluntary notification of PFAS-containing products, PFAS-contaminated sites, and/or stockpiles of PFAS-contaminated material. These requirements are based on the relevant environmental legislation (for example, duty to notify, general environmental duty, requirements concerning land contamination). Generally, the environmental regulator should be notified where PFAS are found in the environment and there is a potential risk of adverse impacts to the environment and/or human health, or PFAS have caused land contamination.

Notification is not further considered in the PFAS National Environmental Management Plan (PFAS NEMP). However, it is expected that notification will require further consideration as part of the national implementation arrangements if the listings of PFOS and PFOA under the Stockholm Convention are ratified by the Australian Government.

17.1 Case study – General environmental duty

Under the *Waste Management and Pollution Control Act 1998* (NT), the Northern Territory Environment Protection Authority (NT EPA) applies the general environmental duty (section 12) and the notification requirements (section 14). Section 14 has the effect of creating a requirement for a person to notify the Authority if they are undertaking an activity that may cause, spread or enhance contamination (such as spill of a hazardous substance, or earthworks which disturb or expose contaminated soil), that could result in material environmental harm or serious environmental harm. Sections 6 and 7 of the *Northern Territory Contaminated Land Guideline* (2017) provide further detail about how this is applied in practice.

An aerial photograph of a river delta, showing a network of channels and distributaries. The water is a mix of green and blue, with the green areas likely representing shallower, vegetated regions and the blue areas representing deeper water. The land is visible as a light brown/tan color, forming a complex pattern around the water channels.

18

**PFAS
sampling**

18 PFAS sampling

The approach to PFAS sampling should be generally consistent with established methods for contaminated site investigation, as outlined in Schedule B2 (Guideline on Site Characterisation) of the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM) and references in Schedule B2. Note that the guidance in this section should be applied in conjunction with any other relevant sampling guidance issued by jurisdictions. However, the characteristics of PFAS mean that additional steps need to be undertaken to ensure that sampling adequately characterises the site and scenario and that analytical results are reliable.

This section includes key elements to consider when undertaking sampling for PFAS:

- the sampling and analysis quality plan ([Section 18.1](#))
- sampling and quality assurance and quality control ([Section 18.2](#)), including:
 - preventing sample contamination ([Section 18.2.1](#))
 - sample handling and processing ([Section 18.2.2](#))
 - considerations for sampling different environmental media ([Section 18.2.3](#))
- guidance on PFAS leachability from soils and solid materials ([Section 18.3](#))

18.1 Sampling and analysis quality plans

The purpose of a sampling and analysis quality plan (SAQP) is to ensure representative data is collected to provide a robust basis for decision-making. This minimises the likelihood of inconclusive or ambiguous results. Drawing on expert advice, including analytical testing service providers and environmental regulators where relevant, is helpful to ensure the SAQP achieves its purpose.

Consistent with the guidance in the ASC NEPM, the SAQP should be informed by a robust conceptual site model (CSM). For example, the SAQP should investigate whether precursors and their transformation products have migrated along identified pathways and to receptor sites. [Section 9](#) provides further guidance relevant to CSM development. As data is collected and analysed, understanding of the site may evolve, leading to modification of the CSM. Consequently, the SAQP should be updated as required to reflect any updates to the CSM.

The SAQP needs to consider the environmental media and material to be sampled, how a representative sample is to be collected, and how many samples are required. As a guide, refer to [Table 13](#) below for a summary of relevant PFAS National Environmental Management Plan (PFAS NEMP) sections for specific environmental media.

The guidance in this section should be read in conjunction with the information in [Section 5](#) on PFAS monitoring, [Section 8](#) on environmental guideline values, [Section 9](#) on PFAS-specific considerations in site assessment, [Section 19](#) on PFAS analysis, and [Appendix A](#) on the PFAS family.

Table 13 General guidance on sampling environmental media and materials and reference to relevant PFAS NEMP sections by media

Environmental media and materials	Relevant PFAS NEMP sections
Soils and sediments It is important representative samples are collected, considering sample locations, depths, number of samples and ensuring samples are homogenised. This is particularly important as only small volumes of samples are collected and PFAS adsorption will differ based on different soil types. Decision factors will depend on the scenario (for example, if it is a site investigation or sampling of stockpiles). Existing sampling guidelines should be applied in discussion with the relevant environmental regulator. For soils and sediments, the potential of PFAS to leach is also a critical component of the assessment.	Section 8 PFAS environmental guideline values, specifically: • 8.6.2 Human health investigation levels for soil • 8.7.2 Ecological soil guideline values • 8.7.4 Sediment quality • 8.7.5 Sediment quality guidance Section 9 PFAS-contaminated site assessment, specifically: • 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Reuse of PFAS-contaminated material including soils and water, specifically: • 12.1 Reuse of soils Section 18 PFAS sampling, specifically: • 18.1 Sampling and analysis quality plans • 18.2 Sampling and quality assurance and quality control • 18.3 Assessing PFAS leachability Section 19 PFAS analysis

continues

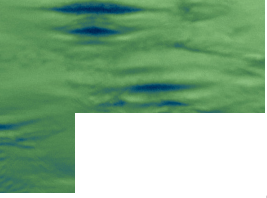
Table 13 *continued*

Environmental media and materials	Relevant PFAS NEMP sections
Surface water and groundwater It is important representative samples are collected, considering sample locations, depths, number of samples, considering potential for seasonal variability and ensuring potential for contamination is minimised during sampling. Existing sampling guidelines should be applied in discussion with the relevant environmental regulator.	Section 5 PFAS monitoring, specifically: • 5.1 Planning and design of environmental monitoring programs • 5.2 Ambient monitoring programs Section 8 PFAS environmental guideline values Section 9 PFAS-contaminated site assessment, specifically: • 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Reuse of PFAS-contaminated material including soils and water, specifically: • 12.5 Reuse of PFAS-contaminated water Section 15 PFAS in the wastewater treatment system, specifically: • 15.1 PFAS management framework Section 18 PFAS sampling, specifically: • 18.1 Sampling and analysis quality plans • 18.2 Sampling and quality assurance and quality control Section 19 PFAS analysis
Biota It is important representative samples are collected, where the sample design needs to consider if the assessment is for human health or ecological purposes. This will influence the type and number of species to be collected as well as how samples are processed (for example, fillet versus whole fish, composite, or individual samples).	Section 8 PFAS environmental guideline values, specifically: • 8.5 Consideration of bioaccumulation • 8.7.2 Biota guideline values Section 9 PFAS-contaminated site assessment, specifically: • 9.2 Risk assessment • 9.3.2 Bioaccumulation • 9.3.3 Biomagnification Section 18 PFAS sampling, specifically: • 18.2 Sampling and quality assurance and quality control Section 19 PFAS analysis

continues

Table 13 *continued*

Environmental media and materials	Relevant PFAS NEMP sections
Infrastructure material It is important representative samples are collected, where the objective and purpose of the sample need to be considered. This is particularly important for infrastructure which may be contaminated with PFAS, as there can be logistical challenges such as sampling and maintaining integrity, as well as considering how samples may need to be processed (for example, consider leaching from a slab or if sample needs to be crushed/compacted as well as how many samples and sample locations are appropriate). For contaminated infrastructure, the potential of PFAS to leach is also a critical component of the assessment. Where the material is to be recycled, sampling in the recycled state is also relevant.	Section 9 PFAS-contaminated site assessment, specifically: • 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Reuse of PFAS-contaminated material including soils and water Section 18 PFAS sampling, specifically: • Section 18.3 Assessing PFAS leachability Section 19 PFAS analysis
Organic waste, resource recovery materials and landfills It is important representative samples are collected, where the objective and purpose of the sample need to inform the SAQP. Analytical challenges need to be considered as there is a potential for the presence of other contaminants and organic materials which may interfere with analysing samples. Where reuse of material is considered, understanding the potentially affected environmental values, pathways and receptors is important, and jurisdictional requirements need to be included. For waste materials, the potential of PFAS to leach is also a critical component of the assessment.	Section 8 PFAS environmental guideline values, specifically: • 8.8 Information on alternative approaches to the risk assessment and environmental management of PFAS compounds and mixtures Section 9 PFAS-contaminated site assessment, specifically: • Section 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Reuse of PFAS-contaminated material including soils and water, specifically: • Section 12.4 Organic waste and resource recovery materials Section 14 PFAS disposal to landfill, specifically: • Section 14.4 Monitoring at landfills Section 15 PFAS in the wastewater treatment system, specifically: • Section 15.4 PFAS criteria in biosolids Section 18 PFAS sampling, specifically: • Section 18.3 Assessing PFAS leachability Section 19 PFAS analysis



For PFAS sampling, additional precautions to limit sample contamination need to be taken. This is particularly important when the data will be compared against existing low environmental guideline values. The SAQP sampling procedure should also consider the expected PFAS concentrations and thereby the order of sampling at each location based on the nature of other contaminants present and the likely level of impact. Further guidance on sampling quality assurance/quality control (QA/QC), including sample handling and preventing sample contamination, are discussed in [Section 18.2](#).

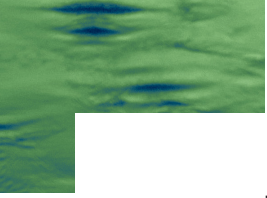
18.1.1 Responsibility for sampling

Sampling should be undertaken based on environmental regulatory requirements, including allocation of responsibility between the environmental regulator and the responsible person or organisation. For example, if the sampling is part of an investigation by environmental regulators associated with regulatory action, then sampling may be by the environmental regulator. However, if it is part of an approval application or other site activity, the responsible person or organisation must ensure that a suitably qualified person undertakes the collection of samples. For contaminated site investigations, sampling is generally undertaken by suitably qualified consultants appointed by the responsible person or organisation. More information about suitably qualified people is outlined in Schedule B9 of the ASC NEPM. The PFAS Contamination Response Protocol, (which is an Appendix to the Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination (Australian Government 2018a)) provides further guidance about roles at government-owned sites and sites where government activities have resulted in PFAS contamination.

18.2 Sampling and quality assurance and quality control

As discussed above, quality control is a particular concern for PFAS for two main reasons:

- environmental guideline values for PFAS are generally very low which requires quantification at concentrations close to the practical limits of reporting (LOR)
- PFAS samples are at high risk of contamination in the field and in the laboratory. Consequently, quality control samples should be collected at a higher frequency than would normally be applied in the investigation of other contaminants (that is, greater than the one sample in 20 recommended in the ASC NEPM).



To provide greater confidence in the reproducibility of results, blind replicates, split samples, spikes, and rinsate blanks should be collected at a rate of at least one for every 10 primary samples. Inter-laboratory replicates and re-submission of previously analysed samples should also be used to confirm reproducibility of analytical results. More details can be found in [Section 19](#).

Rinsate blanks should be collected wherever uncertainty may arise regarding the potential for contamination, or where there is doubt about whether sampling consumables and field supplies are PFAS-free. Field and trip blanks should be collected to verify the integrity of sampling and decontamination procedures. Laboratories will generally supply certified PFAS-free water on request for rinsates and blanks.

18.2.1 Considerations for sampling different environmental media

The following guidance includes general considerations for sampling of environmental media along with provisions to prevent sample contamination.

Soil, sediment and surface water

Conventional soil drilling and aquatic sampling techniques for surface water and sediment can generally be used to obtain samples for analysis of PFAS. Exceptions to this statement include the following, particularly where the PFAS concentration is expected to be low:

- sampling requirements may vary by laboratory. Prior to sampling, confirm sample size requirements with the analytical laboratory. If leach testing (for example, Australian Standard Leaching Procedure (ASLP) (AS 4439.3:2019), toxicity characteristic leaching procedure) of soils is required, a larger sample size is needed (see [Section 18.3](#))
- for drinking water, each 250mL sample bottle may be required to contain a small amount (1.25g) of Trizma®, a buffering reagent that removes free chlorine from chlorinated finished water (Shoemaker and Tettenhorst 2020), or similar sample additive as specified by the selected analytical laboratory. Prior to sampling drinking water for PFAS analysis, confirm the need for additive with the selected analytical laboratory
- use polypropylene or high-density polyethylene (HDPE) sample containers. Glass containers with lined lids are not suitable for PFAS analysis
- avoid the use of labels, stickers and inks unless confirmed to be PFAS-free
- decontamination of drilling equipment must avoid the use of detergents unless they have been confirmed to be PFAS-free. Use tap water (tested to ensure it is PFAS free) or deionised water instead

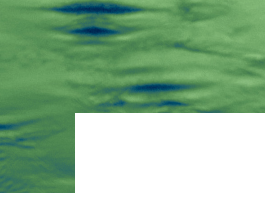
- equipment that contacts soil, sediment, or surface water must not contain or be coated with polytetrafluoroethylene (PTFE) unless the PTFE is internal to the equipment and does not contact the external environment
- prior to sample collection, any personnel handling decontaminated soil, sediment, or surface water sampling equipment that directly contacts the environmental media to be sampled must wash their hands with plain soap and rinse thoroughly in tap water before donning a clean, new pair of disposable nitrile gloves. Decontamination soaps must not be used unless confirmed to be free of fluoro-surfactants
- surface water must be collected by inserting a sampling container (polypropylene or HDPE) with the opening pointing down and the bottle opened underwater to avoid the collection of surface films
- soil and sediment core samples must be collected directly from single-use PVC liners that must not be reused
- for aquatic samples collected from shore or via wading, ensure that waders are constructed of fabric that has not been treated with waterproofing coatings
- check the cross-contamination checklist above for any other further issues. Rinsate samples can be collected if there is any doubt about whether or not sampling consumables and field supplies or personal equipment and personal protective equipment (PPE) are PFAS-free
- other quality assurance samples include transport blanks and field blanks
- larger water sample volumes and/or additional sampling bottles may be required if the required LOR are ultra-trace and/or a total oxidisable precursor (TOP) assay or total organic fluorine (TOF) assay is to be performed on the same sample.

Groundwater

Conventional groundwater drilling and well development practices are generally suitable for monitoring wells where groundwater samples will be analysed for PFAS (see also the ASC NEPM).

Exceptions include the following, particularly where low PFAS concentrations are expected:

- drilling fluids that contain PFAS must not be used
- for each sample, the required minimum volume of groundwater is 250mL as per US EPA Method 537.1 (Shoemaker and Tettenhorst 2020).
- sampling requirements may vary by laboratory and analytical method. Prior to sampling, always confirm requirements with the selected analytical laboratory
- for drinking water, each 250mL sample bottle may be required to contain a small amount (1.25g) of Trizma®, a buffering reagent that removes free

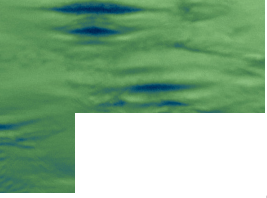


chlorine from chlorinated finished water (Shoemaker and Tettenhorst 2020), or similar sample additive specified by the analytical laboratory. Prior to sampling drinking water for PFAS analysis, the need for additive should be confirmed with the selected analytical laboratory

- use polypropylene or HDPE sample containers. Glass containers with lined lids are not suitable for PFAS analysis
- avoid the use of labels, stickers and inks unless confirmed to be PFAS-free
- decontamination of drilling equipment must avoid the use of detergents unless they have been confirmed to be PFAS-free. Use tap water (tested to ensure it is PFAS-free) or deionised water instead
- sampling must include submission of representative sample(s) of water used for drilling/decontamination purposes
- avoid using equipment (such as pumping equipment, water meters, etc) containing PTFE unless it has been confirmed not to impact water quality
- use Class 18 u-PVC casing with a lower section of slotted screen (also minimum Class 18 u-PVC). PVC casing should not be reused
- prior to well development, any personnel handling decontaminated well development equipment that directly contacts bore water must wash their hands with plain soap and rinse thoroughly in tap water before donning a clean, new pair of disposable nitrile gloves. A new pair of nitrile gloves must be worn for each well developed. Decontamination soaps must not be used unless confirmed to be free of fluoro-surfactants
- following the completion of well development, purged groundwater must be treated as PFAS-contaminated waste (that is, assumed to be contaminated until verified, and then managed accordingly)
- equipment recommended for obtaining groundwater samples includes low-flow peristaltic pumps using silicone or HDPE tubing (or similar products). Consumable sampling equipment must not be reused
- rinsate samples should be collected if there is any doubt about whether or not sampling consumables and field supplies or personal equipment and PPE are PFAS-free, including when detergents and secondary containers are being used
- larger sample volumes and/or additional sampling bottles may be necessary if the required LOR are ultra-trace and/or a TOP/TOF assay is to be performed on the same sample.

Biota

Requirements for biota sampling should be carefully considered, in consultation with the environmental regulator and relevant experts. The issues requiring consideration may include representativeness, statistical significance, sample compositing or pooling, protection of biodiversity and compliance with ethical standards. Refer to [Appendix B](#) for guidance on biota sampling for human health risk assessments (HHRA).



If analysis is intended to inform human health assessment, edible portions should be sampled (for example, for seafood skin on fillets, or de-headed and de-veined prawns). Samples of the same species should be bulked/ composited to allow larger sample numbers. However, there may be a need for additional sampling due to local consumption patterns such as consumption of the whole organism or specific parts of the organism by specific groups.

For assessment of ecological risk, sampling of the whole organisms, fillets and organs (especially liver) is recommended and samples generally should not be composited or bulked, although compositing may be useful in some instances, such as for small sediment-living organisms when assessing risks to wading birds.

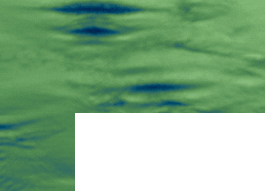
18.2.2 Preventing sample contamination

Environmental guideline values for PFAS for ecosystem protection and thresholds for the use of biosolids are generally very low (for example, maximum allowable soil contaminant concentrations (MASCC) for the use of biosolids, see also [Table 12](#)). As a result, PFAS investigations will often require quantification of analytes at concentrations close to the practical LOR for the available analytical methods. This in turn requires particular attention to avoiding sample contamination from the wide range of materials in which PFAS is used.

The following detailed guidance reflects the particular importance of preventing contamination of PFAS samples.

Attention should be given to the range of products that can cause PFAS contamination of samples (cross-contamination), including:

- new clothing, footwear, PPE and treated fabrics
- stain- and water-resistant products
- sunscreen, moisturisers, and cosmetics
- fast food wrappers
- PTFE materials (such as Teflon™)
- sampling containers with PTFE-lined lids
- foil
- glazed ceramics
- stickers and labels
- inks
- sticky notes and waterproof papers
- drilling fluids and decontamination solutions
- reusable freezer blocks.



These should not be worn or used during any stage of sampling (at site, during transport etc) where sample contamination could affect analytical results.

Information on whether field consumables, such as decontamination solutions, have been confirmed to be PFAS-free may be available from suppliers. If this information is not available, the product should be tested for the presence of PFAS, and only used where it has been demonstrated to be PFAS-free. Further details are provided below on specific considerations for sampling, and sample handling and processing.

The order of sampling in the field is particularly important to reduce the chance of sample contamination – moving from areas of likely low concentrations of PFAS contamination towards likely higher concentrations. It is good practice to inform laboratories of any samples that may be highly contaminated.

18.2.3 Sample handling and processing

Conventional sample handling and processing practices can generally be applied to groundwater, surface water, soil, and sediment samples for analysis of PFAS. Exceptions to this statement include the following, particularly where PFAS concentrations are expected to be low:

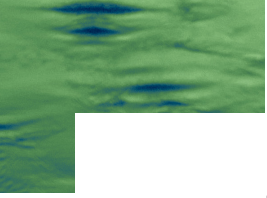
- prior to sampling, the sampling personnel must wash their hands with plain soap and rinse thoroughly in tap water before donning a clean, new pair of disposable nitrile gloves
- Teflon™-coated materials and aluminium foil may not come into contact with the sample
- all samples should be double-bagged
- following sample collection, samples should be cooled and maintained at 4°C
- it is recommended that chemical or gel-based coolant products not be used
- during sample processing and storage, minimise the exposure of the sample to light.

If in doubt, use trip blanks to determine if there is any cross-contamination.

The exceptions presented above should not result in the sample being damaged or contaminated, nor should they put sample collection or laboratory staff at risk of exposure.

18.3 Assessing PFAS leachability

Due to the nature of PFAS, it is important to assess leachability of PFAS from soils and other solids alongside analysis of PFAS in the solid.



Leaching tests are therefore included to characterise risks associated with contaminated sites, reuse of PFAS-containing materials and/or to classify PFAS impacted materials for disposal to landfill.

A variety of tests are available and leaching methods should be chosen based on the specific environmental conditions being simulated and jurisdiction specific regulatory requirements. Environmental conditions to consider include current conditions and any reasonably foreseeable longer-term changes that may influence leachability. An example is the increase in pH of leachate within municipal waste landfills following closure.

The potential for a chemical to leach (that is, how fast and how much is leached), is controlled by different chemical and mass-transfer processes that depend on the properties of the chemical and the solid material, the strength of the chemical's sorption onto the solid phase, and the environmental conditions. Given the large number of variables that can influence PFAS leaching behaviour, leaching tests often need to be adapted to suit the PFAS-containing matrix being assessed.

The partitioning behaviour of PFAS between the solid and aqueous phase is often difficult to predict compared to conventional contaminants (for example, where factors such as pH and organic content drive the behaviour of many metals). However, the behaviour of PFAS leachability cannot be explained by a single variable, and multiple variables such as organic carbon, pH and clay content only explain some of the sorption properties of PFAS such as PFOS and PFOA (Li et al. 2018). Additionally, the surfactant behaviour of PFAS can cause partitioning to the air/water interface under unsaturated conditions, further complicating predictions on their leachability (for example, see Costanza et al. 2019). This becomes even more complex considering the multitude of PFAS, where the predictors for one compound are not the same for another compound or mixtures (Nguyen et al. 2020; Silva et al. 2021).

There are several laboratory-based (Table 14) and field-based (Table 15) leachability methods available for PFAS. The National Chemicals Working Group (NCWG) commissioned a review of methods to assess PFAS leachability in soils and other solid materials. A summary of different types of methods to assess PFAS leachability, their advantages and limitations are presented in Section 18.3.1. Section 18.3.2 provides information to guide practitioners in their decision making for which test may be appropriate for their application, including discussion on how to use the information and data from the leaching assessments. Determining which test is appropriate should be based on the specific conditions being simulated and jurisdiction specific regulatory requirements. As this is a quickly evolving field, the information contained within this section should not be seen as complete.

18.3.1 Leaching methods

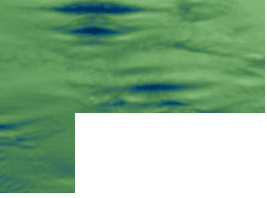
A leaching assessment is performed to gain an understanding of the extent and rate of release of a chemical through water pathways, give insights on material durability (for example, assessing the release of chemicals from stabilised materials) and/or an understanding of factors that control leaching. The following should be considered prior to adopting leaching test methods:

- whether there are specific regulatory requirements. Jurisdictions may have specific regulatory requirements for the use of leaching methods. For example, ASLP (AS 4439.3:2019) may be required to enable consistent data comparisons (as different methods are not directly comparable), though other methods are useful to include as part of multiple lines of evidence (see [Section 18.3.2](#) below for further details on ASLP)
- the suitability of the leaching method based on the leaching conditions being simulated. This should consider the aim of the assessment, the nature of the material in question and the anticipated conditions the material will be, or is currently, subject to. For example, different leaching tests, or a combination of tests, may be useful when considering reuse of soils/materials or investigating leaching of surface soils at a contaminated site. Some tests allow for variables to simulate conditions more closely to the specific application or allow for the use of field relevant materials. This could take the form of a conceptual model.

[Table 14](#) and [Table 15](#) summarise a range of available methods to assess the leaching of PFAS from soils and solid material. Note that the tables do not reflect an exhaustive list of options to assess leaching, but rather discuss common methods used for PFAS in Australia. The information presented is summarised from the literature review commissioned by the NCWG in 2021. Further details on the benefits and limitations for each leaching method listed in [Table 14](#) and [Table 15](#) are provided in [Appendix H](#).

It is not proposed that one method is to be used over another, as the choice of method depends on the circumstances and question being addressed. Further, jurisdictions may have specific regulatory requirements for the use of leaching methods.

To date, ASLP is the most common method applied for PFAS leachability analysis in Australia, and additional information on the use of ASLP for PFAS are presented in the following section. ASLP was originally designed to determine the potential leaching of industrial wastes under acidic conditions, within a putrescible landfill, although the contemporary method is now commonly used to assess the leaching of a range of chemicals and constituents under various simulated leaching conditions. Depending upon the leach solution chosen and nature of PFAS present, ASLP usually provides a conservative estimate of short duration leaching potential.



As a result, ASLP can be used as an initial screening test to assess the potential for PFAS to leach from solid materials. Where PFAS is found to be leachable, further characterisation of leaching potential can be undertaken by applying multiple leaching or other methods to enable a more complete characterisation of PFAS leaching behaviours. Details of the approach and method used, and any modifications to standard protocols should always be clearly described to ensure the implications are understood.

18.3.2 Specific guidance for ASLP

It is recognised that ASLP is commonly applied to investigate the leaching of PFAS from solid materials, therefore some specific guidance is provided that can be used when conducting this test. For investigations and comparisons of leachable PFAS, ASLP can be used as a conservative estimate of leaching potential, where the relevant worst-case pH is selected, noting that generally PFAS leachability increases with pH (Kabiri et al. 2021; Nguyen et al. 2020). In some cases, other batch leaching methods may be required for more complete understanding of PFAS leaching behaviour from a sample. Further specific guidance for the ASLP (AS 4439.3:2019) test are:

- representative sample(s) need to be collected based on soil/solid type to ensure site/scenarios are adequately represented – 100g of solid is recommended for a more representative sample at <2.4mm particle size
- thorough homogenisation and drying of samples can minimise variability in leaching results
- volume of leaching solution appropriate for the material/site/environment to be evaluated unless this is already specified by the environmental regulator or regulation
- filtration of leachate can lead to PFAS loss and sample contamination, therefore an alternative solid-liquid separation technique, such as centrifugation, can be used. The literature review that was commissioned by the NCWG suggested that leachate could be centrifuged at a g-force that will allow separation of natural colloids of <0.45µm particle size
- QA/QC processes such as duplicate samples and reagent blanks are to be included in line with soil and water sampling guidelines, as recommended by the relevant jurisdiction and laboratories.

Table 14 Examples of laboratory-based leaching methods available to assess the release of PFAS from soils and solid material

Laboratory leaching methods	Comments
Batch tests Solid material is subjected to an aliquot of leaching solution over a specified time (equilibrium test) • ASLP^a • TCLP^b • SPLP^c • LEAF 1313^d • LEAF 1316^e • Modified batch extractions (that is, variable liquid-to-solid ratio, pH or static extraction)	• Standardised and comparable • Results generally considered conservative • Quick and cost effective (allows for multiple samples and material types for comparable results) • Useful for assessing potential leachability if material will be reused/moved to another location to ensure new secondary source zones are avoided • Difficult to interpret in relation to environmental conditions. Liquid-to-solid ratios and other method aspects also may need to be considered in data interpretation • If using ASLP, the relevant worst-case pH should be selected, noting that generally PFAS leachability increases with pH
Multi-batch tests Solid material is subjected to multiple aliquots of leaching solution over a specified time (mass-transfer test) • MEP^f • Modified multi-batch extractions	• Gives some information on leaching kinetics by producing multiple temporal datapoints per sample • Useful to assess long-term leaching and behaviour of PFAS and success of fixation treatment processes • Can be modified to use leach solution relevant to simulate circumstances of concern
Column tests Solid material is packed into a column and leaching fluid (buffer, surface water, groundwater etc) is percolated through the soil at a constant flow rate, either in an up-flow or down-flow mode. The fractions are collected over a specified time and analysed • LEAF 1314^g • Columns in up-flow or down-flow mode	• Intact field-sampled cores are the most representative of in-situ conditions • More representative of environmental conditions compared to batch tests, though limitations include disturbance of soil unless soil cores are used • The experimental set up can facilitate assessments of specific conditions such as down-flow columns for unsaturated flow columns (compared with up-flow which limits preferential flow under saturated conditions) • Labour intensive and time consuming • Complex data interpretation

continues

Table 14 *continued*

Laboratory leaching methods	Comments
Semi-dynamic leaching tests Submergence of solid material or ponding of leaching fluid on solid materials with potential periodic renewal of leaching fluid. These are generally larger tank size experiments • LEAF 1315 ^h • ponding experiments ⁱ	• Can be used for compacted soils or infrastructure materials (based on environmental conditions, for example, compaction and material size more relevant to the environmental scenario) • Ability to investigate desorption rate (based on environmental conditions, for example, using volumes of water adjusted to local precipitation)

This table is not an exhaustive list of laboratory-based leaching tests.

For further details on each method see [Appendix H](#).

a ASLP: Australian Standard Leaching Procedure (Standards Australia (2019), AS4439.3:2019).

b TCLP: Toxicity Characteristic Leaching Procedure (US EPA (1992b), Method 1311).

c SPLP: Synthetic Precipitation Leaching Procedure (US EPA (1994), Method 1312).

d LEAF 1313: Leaching Environmental Assessment Framework (US EPA (2017a), Method 1313).

e LEAF 1316: Leaching Environmental Assessment Framework (US EPA (2017b), Method 1316).

f MEP: Multiple extraction procedure (US EPA (1992c), Method 1320).

g LEAF 1314: Leaching Environmental Assessment Framework (US EPA (2017c), Method 1314).

h LEAF 1315: Leaching Environmental Assessment Framework (US EPA (2017d), Method 1315).

i Example: Baduel et al. 2015.

Table 15 Examples of field-based leaching methods available to assess the release of PFAS from soils and solid material

Field-based leaching methods	Comments
Lysimeter^a - Provides a way to sample and measure the concentration of PFAS directly in pore-water - Suction/sampling lysimeter - Drainage lysimeter	- Can capture real-time events and seasonal conditions - Placement and type of lysimeter used needs to be carefully considered based on the objective, as well as data interpretation - Understanding of landscape and soil types is required to ensure preferential flow paths are captured in the sample design - Guidance on the number of lysimeters required, sampling depth and frequency to adequately characterise pore-water concentrations is lacking. Therefore, clear reporting on methods, process and data interpretation are required to consider outcomes - Can be used to assess remedial success
Pilot-scale leaching Provides a way to sample and measure the concentration of PFAS directly in surface water runoff - Large field-based leaching setups^b - Runoff collection^c	- Useful to assess leaching from infrastructure (for example, concrete pads where crushing the samples may not be representative) - Can capture real-time events and seasonal conditions - Understanding of landscape and material/soil types is required to ensure preferential flow paths are captured in the sample design - No standard protocols are available. Therefore, clear reporting on methods, justification of adopted approach with respect to what is being simulated, process, quality assurance and data interpretation are required to consider outcomes - Can provide a useful understanding of contribution of mass which is migrating from existing surfaces - Can be used to assess remedial success

This table is not an exhaustive list of field-based leaching tests.

For further details on each method see [Appendix H](#).

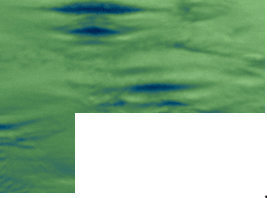
^a Davis and Rayner 2021.

^b Example: Sörendgård et al. 2021.

^c Example: Richardson et al. 2022.

18.3.3 Using information gained from leaching assessments

When performing leaching tests or reviewing data, some aspects of sample preparation may need to be considered as they may influence the leaching of PFAS. Sample preparation should be guided by the project's objectives and/or the question(s) that are being investigated, a review of appropriate literature on the test being utilised, and specific regulatory requirements.



Where the processes are not standardised within the protocol, the decision process and rationale need to be clearly documented.

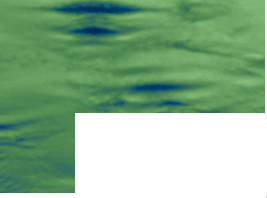
The interpretation and applicability of the leaching data also requires careful consideration. Some applications for the leaching test may require specific data processing to account for aspects of the method and/or calculation of key reporting parameters (for example, leaching rate calculations or calculation of total mass leached from a sample).

For lab-based leaching methods, such as those outlined in [Table 14](#), several sampling and sample preparation aspects may have an influence on the leaching of PFAS, and this might also be influenced by the presence of other contaminants. Aspects to consider in the design and interpretation of the data from lab-based leaching methods (and also apply to ASLP) include:

- sample collection – it is important to collect representative sample(s) based on soil type to ensure site/scenarios are adequately represented
- homogenisation of the sample matrix – variable leaching results can occur if samples are not adequately homogenised
- sample drying – leaching using dry soils may be more conservative than using field-fresh samples (Lange et al. 2020). As consistency is important, drying samples to determine a solid-to-liquid ratio would avoid variability in results due to different moisture contents in samples
- sample grinding – particle size recommendations in the standard methods fall between <2mm to <9.5mm. Choosing a particle size can also be based on the objective/question being addressed
- leachate filtering/centrifuging – filtration of leachate should be avoided due to potential sample contamination with PFAS through repetitive use of labware and sorption of PFAS to filters. The preferred approach is to collect leachate after centrifugation at a gforce that will allow separation of natural colloids <0.45µm
- the liquid-to-solid ratio used – for standardised methods, the solid to water ratio is set, and often at 1:20. Some methods allow for this to be varied, and choices can be made based on the objective/question being addressed. It is important to consider how this data is interpreted and it is important that the process is transparent and clearly outlined.

For details on the benefits and limitations by leaching method, refer to [Appendix H](#).

For field assessments of PFAS leachability that use methods described in [Table 15](#), a sampling plan should consider samples that are representative of the site and relevant to the problem being assessed. For example, careful consideration of the location and number of samples to be collected, the local topography and if there could be preferential flow paths (surface water runoff or to groundwater). The potential for different soil types should also be considered in the design. The decision processes such as the type of lysimeters, how the data is interpreted (for example, see



Davis and Rayner 2021), and the representative conditions for rain/runoff simulation need to be considered and clearly documented.

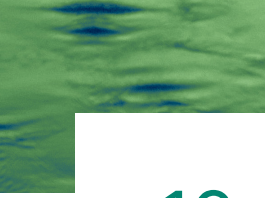
The information gained from leaching assessments can be used for a variety of purposes, which are listed below. Several different methods can be employed using a multiple lines of evidence approach. The outcomes of leaching assessments can include:

- reporting PFAS leachate concentrations for the purposes of classification and disposal to landfill (see [Section 14](#)) or reuse of PFAS-contaminated material (see [Section 12](#)) based on jurisdictional requirements
- comparison of PFAS concentrations to relevant site-specific trigger values or guideline values (see [Section 8](#))
- an estimation of the extent and rate of release of PFAS through the leaching pathway
- a mass-balance assessment to determine the PFAS mass available for leaching alongside the rate of leaching during a mass flux analysis, for example when evaluating site remediation.

An aerial photograph of a river delta, showing a network of channels and distributaries. The water is a mix of green and blue, with the green areas likely representing shallower, vegetated regions and the blue areas representing deeper water. The land is visible as a light brown/tan color, forming a complex pattern around the water channels.

19

PFAS analysis



19 PFAS analysis

The following guidance covers a range of PFAS analysis methods suitable for different site investigation, assessment and management scenarios. This guidance should be read in conjunction with [Section 8](#) on environmental guideline values, [Section 9](#) on contaminated site assessment, [Section 18](#) on PFAS sampling, [Appendix A](#) on the PFAS family, and [Appendix B](#) (Sections [B.3.4](#) and [B.3.5](#)). As PFAS analysis is a rapidly evolving field, the guidance in this section should be considered with reference to any subsequent advances in analytical systems and techniques.

19.1 Standard and non-standard analysis methods

In general, PFAS analysis methods can be categorised into standard (or validated) methods, and non-standard, emerging or supplementary methods. The available standard methods test for and quantify specific target analytes, known as standard analytical suites. The non-standard methods include a range of approaches to characterise the presence of the PFAS chemical family more broadly, including non-specific, or non-target, PFAS, which may not be individually quantifiable. A selection of standard methods of analysis and selected non-standard methods are listed in [Table 16](#). Specifically, [Table 16](#) includes the method, the analytes typically included in the analysis, the sample type, minimum internal standards required, how the method can be used, its limitations and a reference. Considerations for soil leachate analysis are discussed in [Section 14.6](#), including a method to approximate the worst case for leaching conditions.

Table 16 Methods of PFAS analysis: standard and selected non-standard methods*

Method	Use	Sample matrices	Limitations	Analytes	Internal standards ^a	References
US EPA Method 537.1-1 ^b Determination of selected per- and polyfluorinated alkyl acids in drinking water by solid phase extraction (SPE) and LC-MS/MS	To analyse for specific analytes in drinking water	Drinking water, including drinking water sourced from ground and surface water	Only analyses for specific PFAS Does not require results to be corrected for internal standard recovery Limited internal standards Further details in the reference	HFPO-DA, NEtFOSAA, NMeFOSAA, PFBS, PFDA, PFDoA, PFHpA, PFHxS, PFHxA, PFNA, PFOS, PFOA, PFTA, PFTTrDA, PFUnA, 11Cl-PF3OUdS, 9CL-PF3ONS, ADONA	¹³ C ₂ -PFOA, ¹³ C ₄ -PFOS and d ₃ -NMeFOSAA	Shoemaker and Tettenhorst (2020)
US EPA Method 1633 Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS	To analyse for specific analytes in aqueous, solid, biosolids and tissue samples	Aqueous, solid, biosolids and tissue samples		11 PFCAs 8 PFSA 3 FTSS 3 FOSAs 2 FOSAA 2 FOSE 5 PFECAs 3 PFESAs 3 FTCAs	24 extracted internal standards 7 non-extracted internal standards	US EPA 821-R-24-001 Method 1633

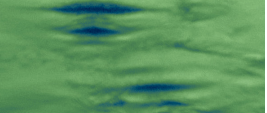
continues

Table 16 *continued*

Method	Use	Sample matrices	Limitations	Analytes	Internal standards ^a	References
Total Oxidisable Precursor (TOP) assay	Can be used in conjunction with a US EPA method to estimate the total PFAS, and sometimes the approximate end point PFAS Can help inform risk assessment	Water samples and extracts including soil, biota, firefighting foam products and wastes	Cannot be used to target exact PFAS precursors, as it is a semi-quantitative ^c method Allows for some inferences as to precursor chain length	Total PFAS chains (C4-C14)	Linear and branched isomers should be included	Houtz and Sedlak 2012

* This table does not present an exhaustive list of methods.

- a An internal standard is a pure isotopically labelled version of each compound used as a reference for quantitation of native compounds. A known amount of this compound is spiked into the sample prior to extraction to measure the relative response of other method analytes and surrogates. Use of a commercially available, isotopically labelled internal standard for each PFAS analysed is recommended where available. If not available, a suitably scientifically justified alternative that meets the method quality control requirements should be used.
- b The 2018 US EPA Method 537.1-1 is for identifying and measuring selected per- and polyfluorinated alkyl acids in drinking water by SPE and LC-MS/MS. It includes additional analytes compared to the original 2009 version. Some laboratories may use a modified US EPA Method 537 or 537.1 to obtain additional analytes, such as 6:2 and 8:2 fluorotelomers.
- c The method is semi-quantitative as it has not yet been extensively developed and validated. As it is further developed, it should become more quantitative. This method cannot be used to identify exact PFAS precursor because the oxidation transforms them so that they can be measured.



19.1.1 Standard methods

The methods published by the US EPA are most commonly used in Australia and New Zealand. These methods test for a standard analytical suite of PFAS in each case, using liquid chromatography–tandem mass spectrometry (LC-MS/MS) with additional methodological adaptations for specific environmental media. The US EPA is developing further validated methods for determining PFAS in various media.

The cost of standard methods is influenced by a range of factors, such as a request for analytical reporting at lower levels (generally referred to as ultra-trace analysis). Ultra-trace analysis is often used to compare PFAS with environmental guideline values. Ultra-trace limits of reporting are also typically utilised to delineate the extent of spread of low-level PFAS contamination in soils, surface water, groundwater or biota.

Analytical laboratories may also offer different versions of the standard methods, such as US EPA Method 537 and 537.1 and US EPA Method 821-R-11, or modified methods, including proprietary methods (such as ASTM International (ASTM) Method D7968-23 and ASTM Method D7979-20). These methods include additional sample media or additional PFAS. Any modifications to the US EPA methods that result in poorer method performance are not supported (for example, see Shoemaker and Tettenhorst 2020).

19.1.2 Non-standard methods

Several techniques exist and are available in Australia to determine the presence of PFAS not included in standard methods, including precursors.

The total organic fluorine (TOF) assay considers the total mass of organic fluorine. The fluorine extracted by TOF represents extractable organic fluorine. The results reported by TOF analysis do not include inorganic fluorine, such as that contained in fluoride added to drinking water, as inorganic fluorine is subtracted from the total.

The TOP assay considers PFAS with perfluorinated carbon chain lengths from C4 to C14. The use of advanced spectroscopy techniques allows screening for unknown or non-targeted substances. These techniques include liquid chromatography quadrupole time-of-flight mass spectrometry (LC-QToF-MS) and particle induced gamma emission (PIGE) spectroscopy.

High resolution, accurate mass LC-QToF-MS is available in Australia to identify which PFAS are present in media, including precursors. This technique is helpful in circumstances such as:

- when the composition of PFAS is unknown
- when TOF assay shows the presence of a significant proportion of unknown organic fluorine

- when carrying out PFAS fingerprinting to identify different PFAS sources and differentiate their respective contributions to contamination.

Considerations for the use and interpretation of the TOP assay and TOF assay are discussed in detail below.

19.2 Considerations for selecting an analysis method

The following guidance should be read in conjunction with the information on standard and non-standard methods above. The selection of an analysis method should consider the type of sample, the information being sought and therefore what needs to be analysed for (that is, what the method can help you understand), and the quality assurance and control required. Each method has specific advantages and limitations.

For all methods, care needs to be taken in analysing the results, with an understanding of the advantages and limitations. This is particularly important where non-standard methods are used.

The following environmental indicators may potentially affect the mobility of PFAS and the degradation of precursors:

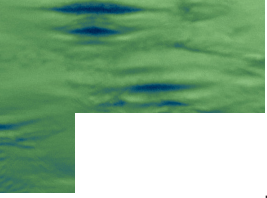
- pH
- electrical conductivity
- redox potential
- metals (iron, etc)
- soil particle size
- biological activity.

19.2.1 Limit of reporting

The sensitivity of PFAS analysis should be matched to the decision-making requirements. Consequently, it may not always be appropriate to select the lowest cost analysis available from analytical service providers. This is particularly important when results will be compared to environmental guideline values.

The limit of reporting (LOR) for PFAS trace or ultra-trace analyses available at commercial analytical laboratories is shown in [Table B2](#). Trace and ultra-trace analyses are more sensitive, although the cost is usually higher, and may be necessary depending on the purpose of the assessment. The LOR obtainable is dependent on the matrix and method.

The LOR may be affected by the presence of other contaminants or components in individual samples that cause analytical interferences that raise the achievable LOR. This problem is more likely to occur in complex matrices such as soil, waste, biosolids and biota samples.



The requirement for ultra-low LOR depends on the sample type. For example, a sample with very low levels of PFAS will need to be submitted for trace analysis (that is, with a lower LOR) compared to a firefighting foam that has a high concentration of PFAS.

Not all Australian or New Zealand laboratories have low LOR capabilities so it is important to check that the laboratory engaged to do the analysis has an LOR capability aligned with the monitoring program objectives, risks and pathways being assessed.

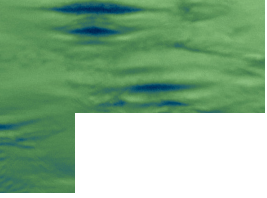
19.2.2 Managing uncertainty

Commercially available analytical techniques generally measure between 30-50 of the more than 4,700 PFAS compounds known to exist (OECD 2018), with analytical suites increasing over time with the improved availability of standards and growing interest in specific chemicals. Some of the remaining compounds can be identified through advanced analytical techniques. However, there are still thousands of PFAS that cannot be measured.

Measuring individual chemicals (for example, PFOS, PFHxS, and PFOA) is important for assessment against guidelines and criteria. Further, toxicological and ecotoxicological data are usually generated for individual chemicals.

Of the specific PFAS that have been identified (see [Appendix A](#)), comprehensive toxicological data is available for only a few. Moreover, in products, articles, and in the environment, PFAS are always found as complex mixtures. For any mixture of PFAS, there is a lack of data to determine whether the toxicity of the compounds will act in an additive, synergistic or antagonistic manner. Moreover, the amount and variety of PFAS may be influenced by the nature of the PFAS source, the time the PFAS have been present in the environment, movement and dispersion from the source and the characteristics of the environment. Despite these uncertainties, the community, industry and other stakeholders expect environmental regulators to act decisively in areas of identification, assessment, monitoring, remediation and the overall management of PFAS-contaminated material and sites.

The TOP assay and TOF assay can provide a more complete indication of the amount of PFAS present in a sample. When such an estimate is compared to the mass of the PFAS in the standard suite of analytes, the difference will indicate the amount of other fluorinated organic compounds present, including PFAS. If the percentage of other PFAS compounds is low, this provides more certainty that the specific PFAS present are the main PFAS. Conversely, if the percentage of other PFAS is high, there is more uncertainty and a greater potential risk to manage. These analyses can also provide useful information to differentiate sources of contamination.



A recent development available commercially in Australia, as discussed in [Section 19.1.2](#), is high resolution accurate mass LC-QToF-MS. This non-targeted analytical technique can further reduce uncertainty by providing information on the structures of unidentified PFAS compounds. In turn, knowledge of structure allows some inferences to be drawn regarding potential degradation pathways, including whether the unidentified compounds may ultimately transform into PFAA end-products of concern such as PFOS, PFOA or PFHxS.

19.2.3 Laboratory requirements

When choosing a method, practitioners should ensure that the proposed analytical laboratories (primary and secondary) can provide the following:

- details on the method being used and the target PFAS analytes
- details on whether the requested quality criteria were met or not, including flagging within the lab's analytical and quality assurance/quality control (QA/QC) reporting
 - for example, as specified in [QSM 5.4](#) (USDoD and USDoE 2021). Importantly, QSM 5.4 is not an analytical method; it provides quality control criteria to manage uncertainty and provide assurance of confidence and consistency in laboratory reporting. For example, QSM 5.4 indicates the entire water sample bottle provided should be extracted using SPE; this is an important quality requirement when choosing a laboratory
- details on accreditation or validation of the method
 - Schedule B3 of the [National Environment Protection \(Assessment of Site Contamination\) Measure](#) (ASC NEPM) states that comparable established methods from recognised sources such as Standards Australia, the US EPA, the American Public Health Association (APHA), ASTM, and the International Organization for Standardization (ISO) should be used when analysis is required for contaminants not included in the ASC NEPM, as where such methods adequately address the requirements of the situation (for example, scope of the matrix type or analytes). While nationally agreed methods and standards are preferred, in-house analytical methods may be used so long as they are properly validated against performance criteria (for example, limit of detection (LOD)/limit of quantification (LOQ)) and measured uncertainty
- sufficiently sensitive limits of reporting that are relevant to the environmental criteria and, if known, the expected concentration levels in the samples
- whether the method reporting limits can be achieved for the specific guidelines and criteria being applied (for example, for US EPA Method 537.1)

- whether the minimum requirements are met for control, internal and surrogate standards for the method
- whether or not the method has been, or is, affected by other contaminants present in the sample
- details as to whether a linear only or a mixed linear/branched standard is used for calibration purposes, including which PFAS standard was used
- analytical results representing the concentration of summed linear and branched isomers
- whether they use an isotopically labelled internal standard for each compound analysed
- a statement on whether internal standards are used for each target compound where several different PFAS and derivative compounds are being analysed
- correction of report results for internal standard recoveries, including when in the analysis process the internal standards are added
 - this information should be included with a statement of the recovery, noting typical recoveries are between 50–150% ($\pm$ 50%) depending on media and the specific analyte
- if undertaking TOP assay, that assessment of the efficacy of oxidation using detectable oxidisable precursors (for example, labelled internal standards) is undertaken and reported, and that dilutions are also recorded and reported.

Additional quality assurance measures for TOP assay include:

- the total PFAS concentration post-TOP assay should be greater or equal to the total PFAS concentration pre-TOP assay, which signifies no material losses observed in preparation steps, noting a decrease consistent with the measurement uncertainty of the method may occur
- the sum of PFCA post-TOP assay should be equal to or greater than the sum of PFCA pre-TOP assay, which signifies any precursors being converted to PFCA products
- the sum of PFSA post-TOP assay should approximate the sum of PFSA pre-TOP assay, signifying that precursors did not convert to PFSA products
- for a full oxidation, no PFAA precursors (for example, 6:2 FtS, FOSA) are detectable post-oxidation, signifying complete oxidation
- material losses occurring during preparation during steps should be assessed using appropriate PFCA- and PFSA-labelled internal standards
- for situations where a near complete oxidation is acceptable, minimal PFAA precursors are detectable post-oxidation
- for aqueous samples, sum of [PFAA precursors] divided by sum of [Total PFAS] <5%
- for soil samples, sum of [PFAA precursors] divided by sum of [Total PFAS] <10%

- greater leniency may be applied for samples where PFAS were detected ≤ 10 times LOR.

See Ventia (2019) for detailed consideration of technical challenges associated with the TOP assay, including consideration of the significance of pre- and post-TOP assay levels of PFCA, PFSA, and PFAA precursors.

Laboratories will determine maximum sample dilution that can be performed to achieve the adopted reporting limits. An understanding of the sample dilution undertaken for sample analysis is important when comparing results from the primary and secondary laboratories.

19.3 Consideration of non-standard methods including relevance to site assessment and broader environmental assessment

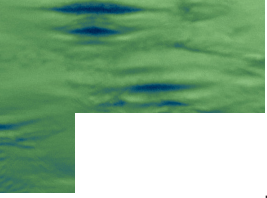
This section discusses the application of the TOP assay and TOF assay to site assessment and to broader environmental assessment.

19.3.1 TOP assay

The TOP assay is a method for indirectly measuring the total precursor concentration in environmental samples. This includes circumstances where the presence of precursors is suspected, for example from information in the literature, and also when the monitoring objective is to effectively characterise the PFAS content of a sample. As the TOP assay is designed to characterise the extent of overall PFAS contamination in a sample, it can be used where the US EPA methods may not adequately measure all the PFAS likely to be present.

The TOP assay is particularly useful to identify source areas and characterise the potential presence of precursors that may convert to end-point PFAS compounds of interest. Examples include contamination where the PFAS product composition is unknown, where the known PFAS composition extends beyond the US EPA suite or where PFAS may have been subject to transformation, such as in wastewater treatment, contaminated site remediation, and in the wider environment. For example, in an immediate spill, TOP assay provides information on whether precursors are present and informs risk management (for example, considerations such as whether the environment is oxidative, and whether remediation might transform the precursors).

The TOP assay involves standardised pre-treatment of samples or sample extracts designed to reveal PFAS not identifiable by standard analysis. It has been used for water samples and extracts including soil, biota, firefighting foam products and wastes. The pre-treatment step consists of oxidant digestion under strong alkaline conditions at 85°C for 6 hours.



The digestion converts previously undetectable PFAS to PFCA and PFSA. Treated samples are then neutralised and analysed via LC-MS/MS. The process enables detection of the component previously not available for analysis.

As for TOF assay, similar results would indicate absence of substantial precursors whereas a large divergence in results would suggest that there are large quantities of precursors present that the standard analysis does not detect.

Unless there are adverse matrix effects or the need to dilute samples, as in the case of firefighting foam samples, the LOR achieved by TOP assay is generally similar to standard analysis.

As transformation processes in the environment may differ from laboratory-simulated oxidation, the laboratory results may not necessarily align with the environmental end point. For example, it is possible that in the laboratory, some PFSA precursors oxidise to PFCA, whereas in the environment, they would transform to PFSA.

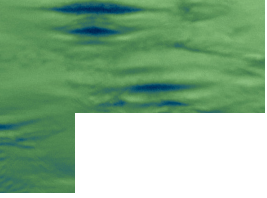
The TOP assay relies on sufficient oxidation, so an oxidation validation should be included. Absence of fluorotelomers in TOP assay results is an indicator of full oxidation. Laboratories find it helpful if the nature of the sample can be advised, for example product concentrate, groundwater, mixed with organic waste.

Inter-laboratory studies have found that applying the original method developed by Houtz and Sedlak (2012) without modification may lead to insufficient oxidation for samples with high organic content or high concentrations of PFAA precursors (for an in-depth discussion see Ventia (2019)). Consequently, some laboratories have developed modified methods.

19.3.2 TOF assay

TOF assay analysis is useful when there is uncertainty as to whether the US EPA methods adequately measure all the PFAS likely to be present. Examples include contamination where the PFAS product composition is unknown and where known PFAS composition extends beyond the US EPA suite; and where there is likely to be some transformation of PFAS or where the precursors are unknown.

The TOF assay is not specific to chain length or PFAS precursors or end point compounds; it is an estimate of the total organic fluorine content in a sample and is derived from the isolation of organofluorine compounds with activated carbon and the subsequent measurement of fluorine by combustion ion chromatography. The technique cannot be used to determine the approximate carbon chain length of precursors as it relies on comparing the mass of fluorine present in a standard analysis for PFAS



with the mass found in the TOF assay analysis. Similar results indicate the absence of substantial precursors, whereas a large divergence in results suggests that large quantities of precursors are present that the standard analysis does not detect.

The TOF assay has a significantly higher LOR when compared to that usually available with the TOP assay and so may not be suitable with low screening levels. As a non-standard method, reporting needs to be clear if the amount of fluorine in a sample measured includes either total fluorine, which includes both organic and inorganic fluorine, or extractable/adsorbable organic fluorine (EOF/AOF), which more closely approximates total organofluorine and PFAS. Understanding and reporting which method the laboratory has employed and understanding the limits of these data is key.

Overall, this approach is useful in screening potential presence of PFAS at comparatively high concentrations in circumstances when there is little information about available compounds potentially present in matter under investigation. They have been used as a screening tool estimating PFAS mass in samples including products, articles and waste. In samples where there is a likely precursor presence identified by a TOP assay, knowledge of extractable or adsorbable organic fluorine content by comparison for fluorine equivalent measured in the assay helps identify the extent to which the assay has accounted for precursor presence.

19.3.3 Interpreting results

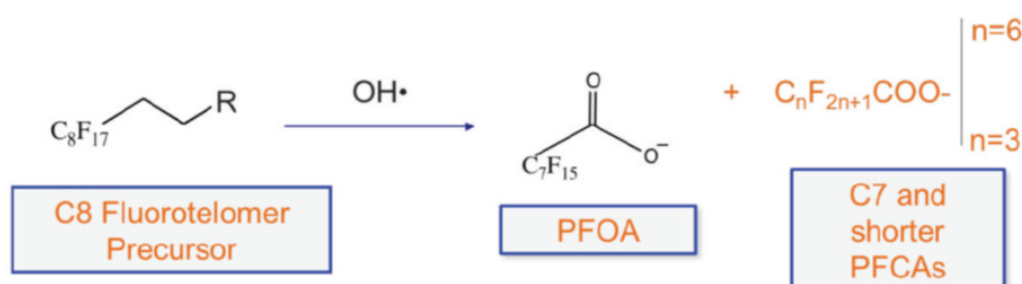
The TOP assay and TOF assay analyses are useful for making comparisons with the standard LC-MS/MS analysis results to ascertain the relative degree to which precursors may be present. They help answer the question: are precursors present in the sample? The TOP assay provides further additional insights about the nature of the precursors not available with TOF assay. Below are some important points concerning the use of total PFAS measurement methods like TOP assay and TOF assay:

- oxidation via TOP assay is not equivalent to the process or the rate of oxidation in the environment
- for an old contaminated site, if all possible oxidation has already occurred, the TOP assay and standard analysis should yield similar PFAS levels. If there is a difference, this would suggest that the environmental oxidation process is slow and the rate of transformation is likely to remain slow provided the environmental conditions remain the same
- legacy contamination and new spills are not equivalent. A new spill may benefit from TOP assay as no oxidation in the environment has yet occurred

- risk assessment of precursors requires consideration of where they are found, with different risks related to presence in sources zones, pathways and at receptors. Precursors have been found to oxidise into PFAA in receptors, including when taken up into plants (Zhao et al. 2018) and when fish are exposed to them (Chen et al. 2015).

For PFCA precursors such as fluorotelomers, the TOP assay oxidation generally follows what happens in the environment. It converts precursors to a range of PFCA with some partial de-fluorination, which creates a result that includes some slightly shorter chain PFAS products, as shown in [Figure 8](#) below.

Figure 8 Example of PFCA precursor oxidation in the TOP assay



In contrast, PFSA precursors oxidise to an equivalent carbon chain length PFCA in the digestion, as shown in [Figure 9](#) below. This differs from oxidation in the environment where they would transform to the equivalent PFSA. For example, a PFHxS precursor in the TOP assay digestion would oxidise into PFHxA rather than PFHxS, as would occur in the environment.

Figure 9 Example of PFSA precursor oxidation in the TOP assay



As can be seen, the TOP assay transforms both sulfonamide and fluorotelomer precursors to carboxylate, while sulfonamide precursors are more likely to form perfluoroalkyl sulfonates when transformed by biological processes in the environment, or *in vivo* if ingested.

A technique used to infer prediction of eventual transformation end products relies on the finding (Martin et al. 2010) that PFAS produced by an electrochemical fluorination (ECF) process contains both linear and branched isomers, whereas those produced by telomerisation contain no branched perfluoroalkyl chains.

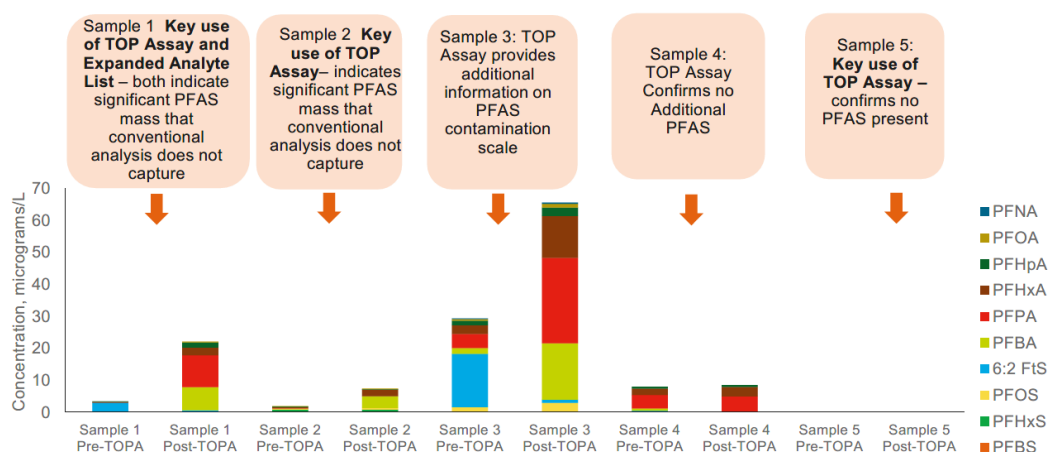
These differences can be detected if the quantification of PFAS uses both branched and linear isomeric analytical standards of perfluoroalkyl carboxylates in the analysis.

If an increase in branched perfluoroalkyl carboxylates is found in the TOP assay results, an inference can be drawn that the precursors are likely to form perfluoroalkyl sulfonates. Conversely, if only linear perfluoroalkyl carboxylates are found, perfluoroalkyl carboxylate precursors can be inferred.

Finally, the digestion occurs over a number of hours in the laboratory, compared to a wide range of rates environmentally, depending upon conditions, which will also increase the difference between laboratory and environmental samples.

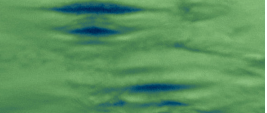
Figure 10 illustrates possible different outcomes of TOP assay analysis for contrasting cases, including where significant precursors are present, where there is no additional PFAS resulting from precursor oxidation and where there is no PFAS (including precursors) present.

Figure 10 TOP assay applied to groundwater



Source: Courtesy Erika Houtz (2017).

Another broad-brush assessment approach would be to look at the approximate carbon chain length and use this information to infer which aspects of the environment that PFAS tend to accumulate in. For example, longer carbon chain precursors (>C7) would present more of a bioaccumulation risk to animals, and shorter chain to plants (refer Martin et al. 2003 and Blaine et al. 2014).



19.4 Guidance on analysis of PFAS in solid organic waste and resource recovery materials

Considerable quantities of organic waste materials are generated from various municipal and industrial sources. In certain cases, PFAS concentrations in such waste may need to be determined to support management decisions to minimise human and ecological health impacts associated with disposal or reuse of the waste. The analysis of PFAS in organic waste and resource recovery materials can present considerable challenges due to their diverse nature and potential heterogeneity.

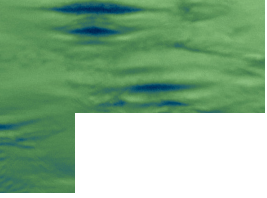
Organic wastes are characterised by their high level of organic matter and highly variable homogeneity, depending on the source inputs and final composition. Representative samples must be taken in order to gain a good understanding of the PFAS content. In addition, the moisture content of solid organic wastes can vary significantly, to the extent that the distinction between solid and liquid waste types may be unclear. Different jurisdictions may apply different approaches to defining what constitutes a 'solid' or 'liquid' waste.

A review of published literature on the analysis of PFAS in solid organic waste materials commissioned by the National Chemicals Working Group (NCWG) in 2021 indicated that there are currently very few standard methodologies available for the extraction and analysis of PFAS specifically from solid organic waste materials. Most research has relied on optimising and applying methods that have previously been validated for the extraction and analysis of PFAS in soils, sediments or other matrices.

Standard methods are available for the extraction and analysis of PFCAs and PFSAAs in sewage sludge and biosolids from the US EPA (US EPA 821-R-11-007, now replaced by CWA Method 1633 and ASTM (D7979-20)), which can give some guidance. These methods, however, may not be applicable to all waste types. Some types of wastes may require a more flexible approach to release PFAS from the surrounding matrix. Some guidance on the analysis of PFAS in complex matrices is discussed below, for use both in interpretation of data, and to support the establishment of analytical procedures for such samples.

Most published studies do not apply standard methodologies, but rather utilise methods that have been adapted to the specific samples on hand. It is important to recognise that there may be several acceptable sample preparation methodologies that could be applied to a particular waste type, but any methodology should be adequately validated and supported by initial as well as ongoing QA/QC. Notable common features of the published methodologies have been used to inform the following general guidance:

- methanol is the most common solvent used to release PFAS from an organic waste matrix, often in combination with other solvents such as



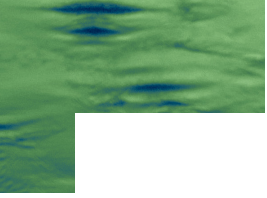
acetonitrile, and sometimes pH-adjusted. Selection of the extraction solvent should be guided by the:

- sample type
 - suite of PFAS to be analysed
 - method of extraction used
 - extent of sample clean-up conducted
- ultrasonication and/or shaking are appropriate methods to assist in releasing PFAS from organic waste materials. Longer/harsher extractions may also release more interfering compounds from the matrix
 - thorough sample clean-up is recommended to reduce matrix interferences (see below for more information on matrix interferences). Sample clean-up can be done by solid phase extraction, where PFAS are reversibly adsorbed to a material, or by carbon clean-up, where interfering compounds are bound to the carbon and thus removed from the sample extract (this can be done using dispersive carbon or using carbon cartridges). In some cases, a combination of these two methods may be necessary to produce sample extracts of sufficient purity
 - the use of isotope dilution standards is encouraged. Where mass-labelled PFAS are not available, spiked matrices matching the waste material should be included to demonstrate recovery.

19.4.1 Quality control and quality assurance

The inclusion of robust QA/QC measures are essential for the analysis of solid organic waste and resource recovery materials. Some of the performance metrics that can be monitored and assist in the interpretation of data are:

- *Procedural blank samples* – the inclusion of procedural blanks is a must, to monitor for contamination during the extraction and clean-up process. For organic waste matrices, finding a material suitable as a blank can be a challenge, as they are often inherently contaminated with PFAS. In such cases, a material as close to the one being assessed, but free of PFAS contamination, should be chosen
- *Defining the limit of reporting based on the matrix being analysed* – providing a lower quantification boundary for reporting is important, especially in a regulatory context. Organic-rich matrices with many inherent interferences tend to have higher limits of reporting compared to water, and a realistic measure of the reporting limit can help in the interpretation of data
- *Analyte recoveries* – minimum and maximum recoveries should be set as performance criteria and samples falling outside of those ranges should be flagged; QSM 5.3 recommends recoveries between 50% to 150% as acceptable, while EPA-821-R-11-007 recommends variable compound recoveries for the lower boundary, depending on the PFAS analysed (from 30% for PFUnDA to 70% for PFHxA), all with an upper bound



of 130%. CWA Method 1633 includes a list of acceptable recoveries specific to each target analyte and matrix investigated

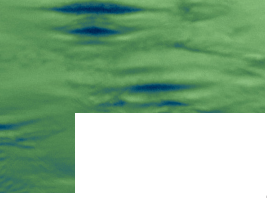
- recoveries can be affected by a number of different factors including, but not limited to, the extraction method and clean-up steps as well as the instrument performance and the matrix under investigation. Matrices with high amounts of co-eluting interferences can lead to low recoveries. Mass-labelled standards can be used for the quantification and recovery correction of PFAS
- it is recommended that a clear statement is included in sample reports, detailing if results are recovery corrected and recoveries should be reported for each sample (as well as for native and mass-labelled standards)
- *Reference materials* – where available, the inclusion of a certified reference material (CRM) can help to monitor method performance. For example, the National Measurement Institute Australia (NMI) provides a soil reference material with concentrations of PFAS (MX019) (NMI 2024a)
- *Matrix-matched spikes* – matrix-matched native spiked samples can be used to investigate accuracy of the extraction and analytical method
- *Duplicates* – the inclusion of duplicate samples in each analysis batch is advised as a measure of repeatability
- *Laboratory controls* – laboratory control samples can be included in each batch of samples and serve as a measure of reproducibility.

19.4.2 Matrix interferences

Matrix effects (or interferences) are prone to occur during LC-MS/MS analysis using an electrospray ionisation source. These interferences are caused by compounds that co-elute with targeted compounds and can lead to either ion suppression or enhancement of the signal of targeted analytes by affecting their ionisation. This can result in erroneous quantification, either an underestimation or an overestimation, of the analyte concentrations and can adversely impact data reliability.

Matrix effects are commonly observed in organic-rich matrices such as wastes and often need to be assessed and understood prior to reporting of accurate results. An assessment of matrix interferences should be part of the initial method validation process and should be undertaken for each waste material assessed.

There are several methods to assess matrix effects. Two common ones are the standard addition, where a native standard spike is added to the final extract just before analysis and is compared to pure standards in solvent. A second approach is through the use of matrix-matched calibrations, where matrix effects can be calculated as the ratio of the slope of the matrix-matched standards to the slope of standards in neat solvent.



Recoveries higher than 100% indicate an enhancement of the signal, whereas recoveries lower than 100% indicate ion suppression.

Common ways to overcome matrix effects in solid waste materials are:

- reducing initial sample size for extraction
- sample clean-up
- using isotope dilution standards for quantification of PFAS
- sample dilution
- reducing the instrument injection volume
- using alternative ion transitions, where available.

Matrix effects are often more pronounced for longer chain PFCAs (>C10) and for short-chain PFCAs, PFBA and PFPeA. The effects can vary significantly by matrix as well as between samples of the same matrix and are dependent upon the extraction procedures chosen. Reducing the matrix through extract clean up, as well as choosing appropriate mass-labelled standards that are either isotope dilution standards or have similar chemical and physical properties to the target analyte, are effective measures to overcome matrix effects.

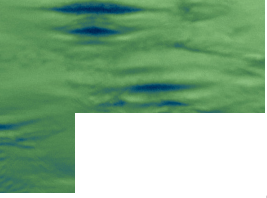
19.4.3 Measurement of 'total PFAS' in solid organic wastes

Organic wastes inherently include a wide suite of PFAS, many of which are not included in the standard analysis suites for PFAS.

If a better understanding of the 'total PFAS' load of a sample is needed, several methods are available to investigate broader suites of PFAS, or methods to gain an understanding of the total fluorinated content of wastes.

High resolution mass spectrometry (HR-MS) workflows are a useful tool for suspect screening and identification of PFAS outside of the targeted PFAS list. However, the required instrumentation is costly, requires expert knowledge and data evaluation can be tedious and time-consuming. Nonetheless, some analytical labs offer these services commercially in Australia and thus can present an avenue for a more complete assessment of organic waste matrices. In some cases, it may be better to establish a list of priority chemicals that are suspected in the waste materials. With a growing number of PFAS standards that are commercially available these can often be easily incorporated into targeted analysis suites. If analysis of an extended suite of PFAS is the goal, then the extraction and clean-up methodology should be considered carefully. The recovery of zwitterionic and cationic PFAS or other precursors can be difficult using conventional extraction methods. If measurement of such chemicals is attempted in organic waste, then extended or adapted extraction protocols may be necessary to achieve good/high recoveries.

Other avenues to gain a more complete picture of the PFAS present in an organic waste is the use of TOP assay and TOF assay, both of which have



been described in more detail above. Most of the analysis methods for measuring total PFAS in environmental samples have inherent capabilities and limitations, that should be considered when data is interpreted. In all cases, analysis for total PFAS should be applied in conjunction with data derived using targeted PFAS analysis and/or together with HR-MS analysis. A mass-balance approach can then be used to deduce the amount of unknown PFAS in a sample.

Due to differences in matrices and the amount of organic carbon, the unmodified use of the original Houtz and Sedlak (2012) protocol for the TOP assay cannot be recommended for organic-rich waste matrices. The methods will in each case need to be adapted to the samples at hand, perhaps using multiple rounds of oxidation, a higher dose of the oxidant or prolonged oxidation time. These parameters have been discussed in the TOP inter-laboratory study performed by Ventia and will also broadly apply to organic wastes (Ventia 2019). Further experimental details on the adaption of the TOP assay to biosolids and waste samples can be found in publications such as Hutchinson et al. (2020), Choi et al. (2019), and Lazcano et al. (2020). A key message is that a prolonged and stronger oxidation is necessary to oxidise PFAS in high organic content samples. A further option may be to perform the oxidation of the sample after a clean-up of the extract to remove solubilised organic carbon that otherwise consumes radicals and leads to incomplete conversion of PFAA precursors.

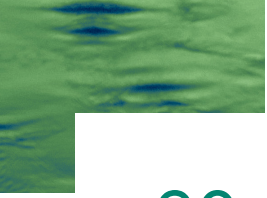
It should be noted that the TOP assay is selective to those PFAS that oxidise to PFAAs included in targeted methods and therefore does not capture chemicals with degradation products that are not monitored or chemicals that do not degrade in the TOP assay (for example, F-53B). Chemicals that are produced in the TOP assay but are not routinely monitored in targeted analysis include ultra-short-chain chemicals such as TFA and PFPrA.

Analysis of TOF can indirectly measure total PFAS in samples through calculating the measured fluorine as PFAS equivalents. Samples such as sludges and biosolids and other wastes may have a high content of inorganic fluorine due to the high concentrations of fluoride in tap water. Therefore, direct combustion of the sample through TOF is often not advisable and a sample preparation to remove inorganic fluorine from the sample is necessary. The extractable organic fluorine assay followed by TOF analysis offers this option but has the disadvantage of relatively high detection limits and is operationally defined, as it can either overestimate or underestimate the amount of fluorine in a sample depending on the degree of removal of inorganic fluorine.



20

**Future
work**



20 Future work

The PFAS National Environmental Management Plan (PFAS NEMP) work program is organised into six themes to focus resources and expertise and drive progress on the main priorities for environmental regulation and management of PFAS contamination. The National Chemicals Working Group (NCWG) works in partnership with researchers, industry, and other external partners to address common priorities within these themes.

20.1 Theme 1 – The PFAS chemical family

This theme includes, for example, activities to progress validation of analytical methods including total oxidisable precursor (TOP) assay, additional guidance on sampling and the analysis of PFAS other than PFOS, PFOA and PFHxS, and consideration of the need for additional advice on PFAA precursors.

20.2 Theme 2 – Environmental data and monitoring

This theme includes, for example, activities to progress ambient monitoring and data sharing, such as:

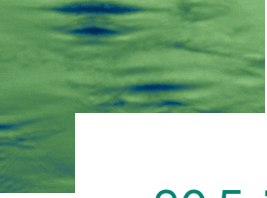
- develop a data sharing agreement between jurisdictions and come to an agreement on what data will be provided externally
- collate monitoring data already undertaken across the country and develop a digital sharing platform (partially complete but no progress on digital sharing platform).

20.3 Theme 3 – Water

This theme includes, for example, activities to progress the development of ecological guideline values and underpinning research, additional guidance on managing PFAS in wastewater including biosolids, wastewater treatment effluent and groundwater, and further guidance on the importance of considering bioaccumulation in risk assessment.

20.4 Theme 4 – Soil

This theme includes, for example, activities to progress the further development of indirect and direct ecological guideline values for soil, PFAA behaviour and the influence of soil chemistry, and guidance on managing PFAS in soil, such as potential criteria for reuse of soil.

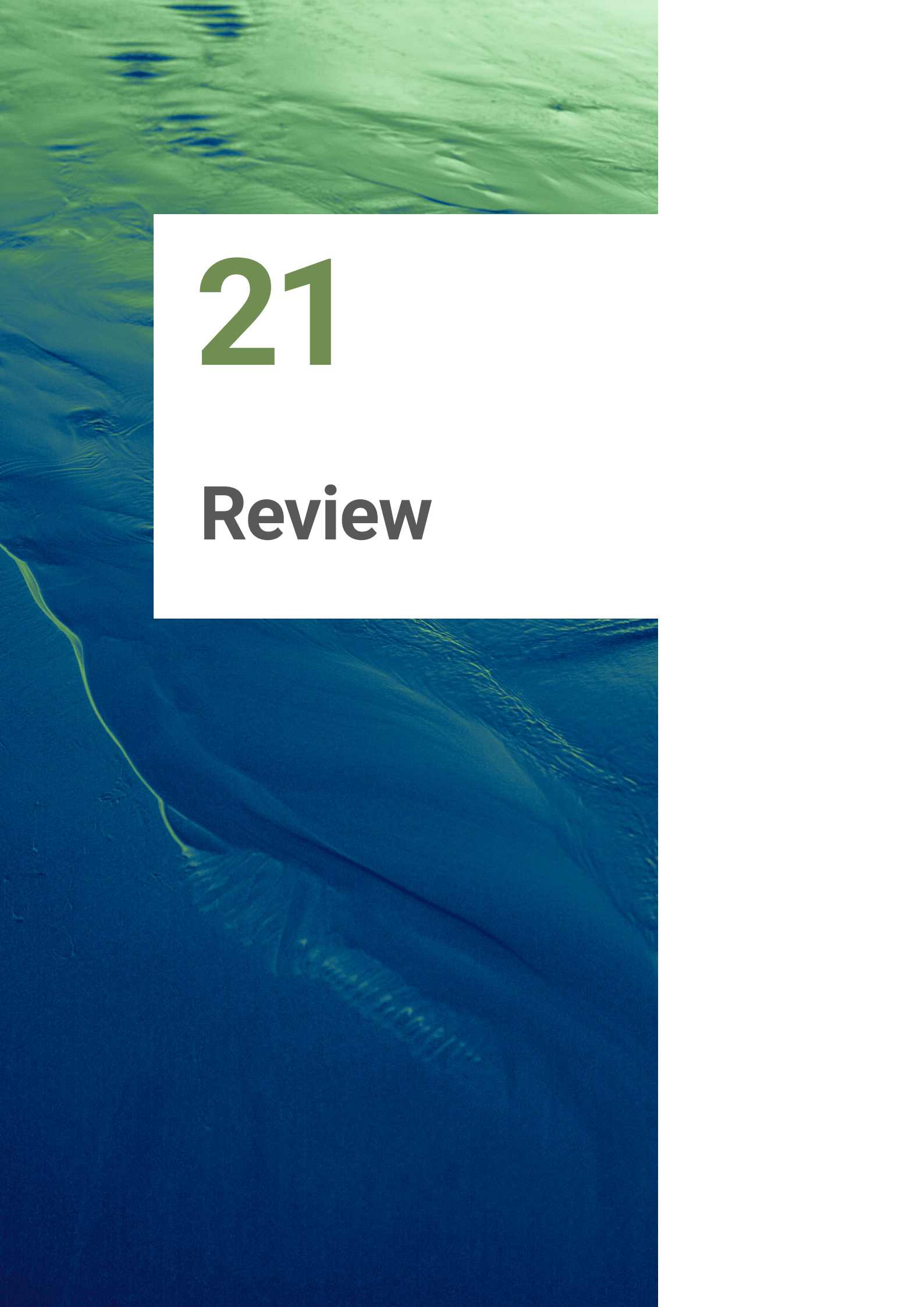


20.5 Theme 5 – Resource recovery and waste management

This theme includes, for example, activities to progress the development of additional guidance on managing PFAS in resource recovery for non-organic and organic waste, and sampling of unusual matrices including those found in construction waste.

20.6 Theme 6 – Site-specific application of the PFAS NEMP guidance

This theme includes, for example, activities to progress guidance on site assessment, sediment quality, remediation and treatment trials, site prioritisation, sampling, and on-site containment. This theme will include developing interim estuarine and marine sediment quality guideline values, which represents the first steps in an iterative process for developing a more comprehensive set of PFAS sediment guideline values. Further work on freshwater sediment guidance is also required.



21

Review

21 Review

The PFAS National Environmental Management Plan (PFAS NEMP) is a living document designed to reflect the current state of knowledge. It will be updated periodically to reflect new scientific evidence and guidance.

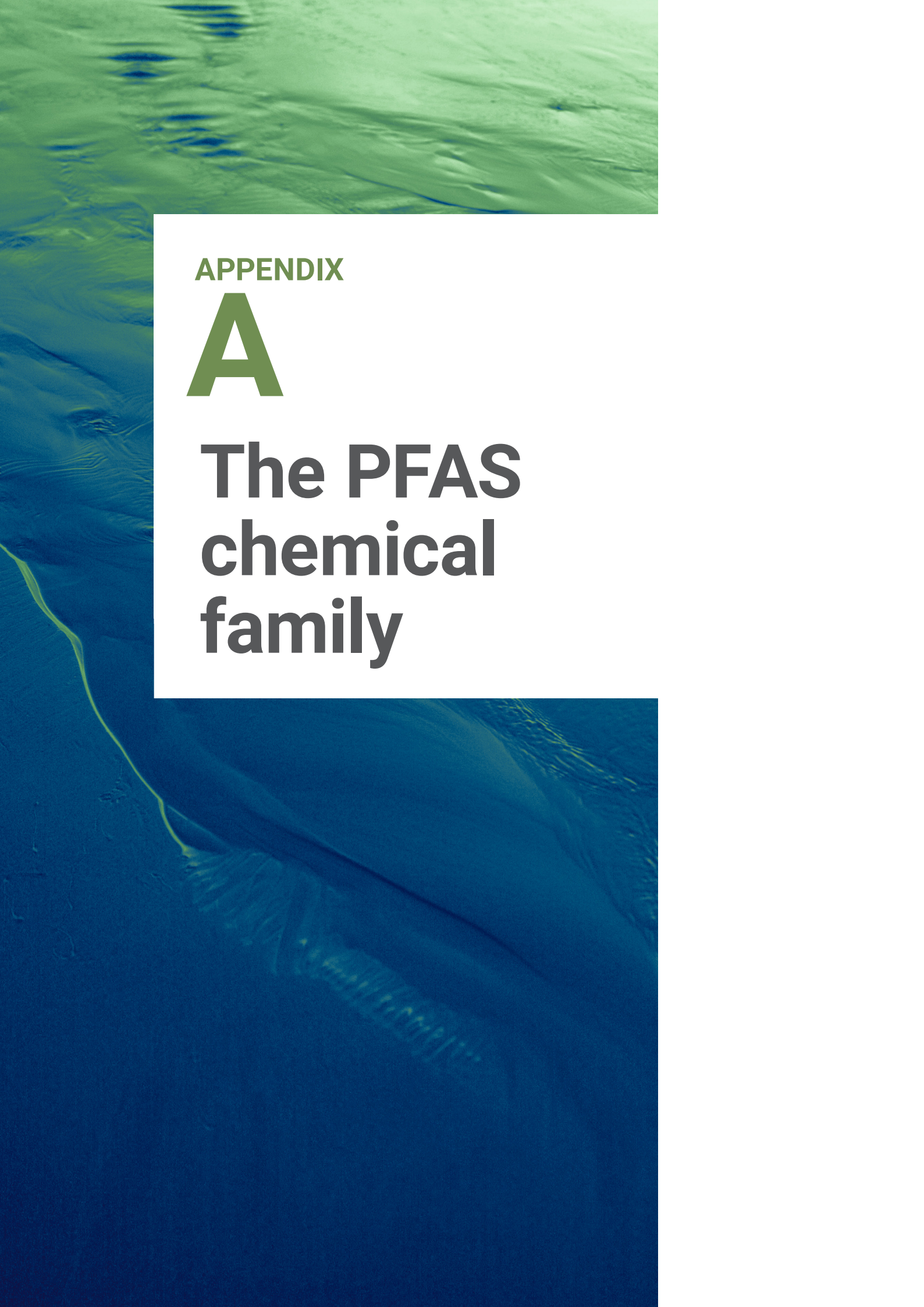
21.1 Informal review

The National Chemical Working Group (NCWG), in consultation with other working groups appointed by the Heads of EPA Australia and New Zealand (HEPA), will:

- monitor PFAS research and information
- monitor relevant developments in other national frameworks and policy processes
- consider lessons learned from PFAS NEMP implementation
- consider the outcomes of the future work listed in [Section 20](#)
- engage and consult with stakeholders
- provide recommendations to HEPA on proposed updates.

21.2 Formal review

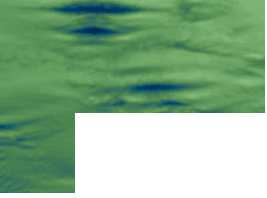
The PFAS NEMP will be subject to a formal review every five years, with the first formal review due to commence in 2025.



APPENDIX

A

The PFAS chemical family

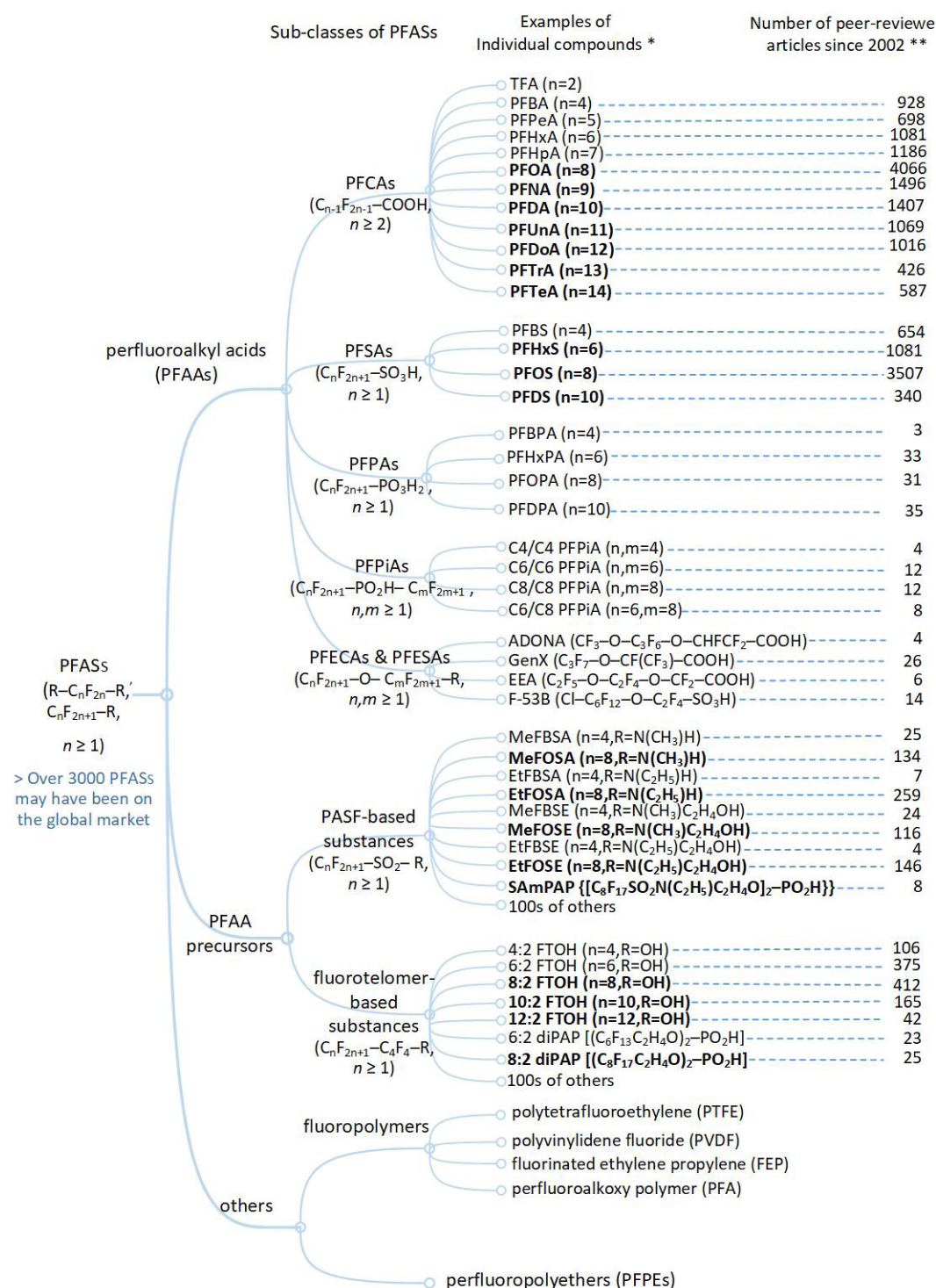


Appendix A

The PFAS chemical family

For detailed information about the PFAS compounds listed on the Australian Inventory of Industrial Chemicals, see the [Australian Industrial Chemicals Introduction Scheme \(AICIS\)](#).

Figure A1 The PFAS chemical family with examples of individual compounds



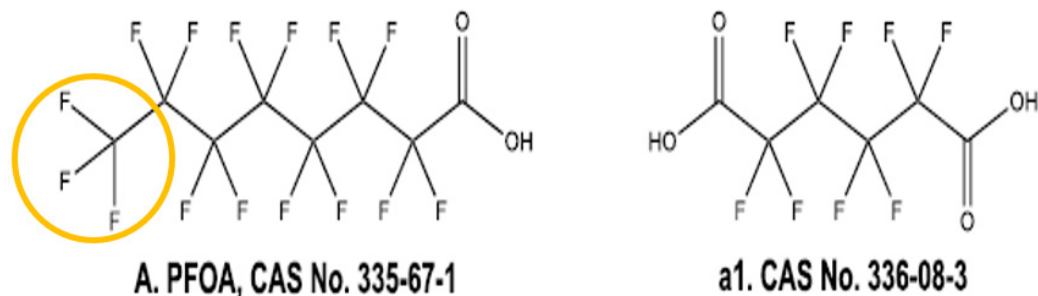
* PFASs in **BOLD** are those that have been restricted under national/regional/global regulatory or voluntary frameworks, with or without specific exemptions (for details, see OECD (2015), Risk reduction approaches for PFASs. <http://oe.cd/1AN>).

** The numbers of articles (related to all aspects of research) were retrieved from SciFinder® on Nov 1, 2016.

Adapted from Wang et al. (2018). See also Buck et al. (2011); ITRC (2018a); OECD (2018 and 2021).

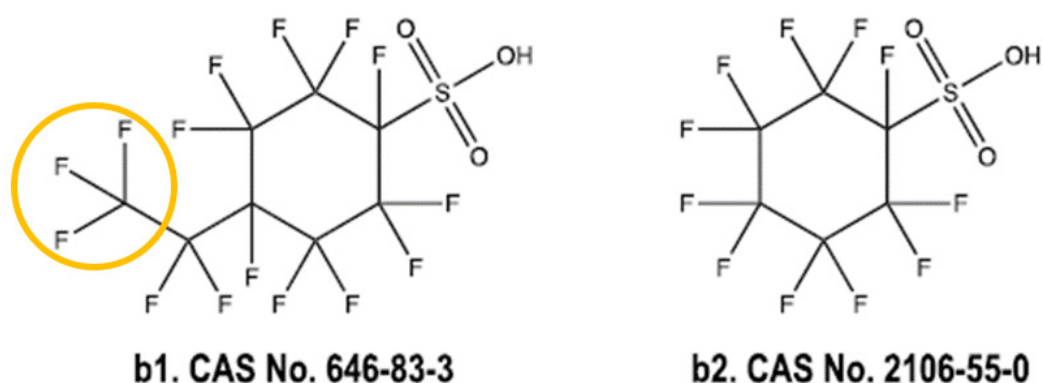
Numerous classes of fluorinated substances outside the scope of the Buck et al. (2011) primary structure (that is, C_nF_{2n+1}) are now recognised as PFAS (OECD 2021). Examples are given below.

Figure A2 Alkyl chain with a functional group at both ends



In this example, a fully fluorinated saturated carbon chain is connected with a functional group on both ends instead of just one. This can be seen below with the compound a1 on the right compared to PFOA on the left. Unlike PFOA, the compound a1 does not contain a terminal ($-CF_3$) group (circled in PFOA).

Figure A3 Cyclic compounds with and without a fully fluorinated alkyl side chain



In this example, two fully fluorinated aliphatic cyclic compounds are contrasted. The compound b2 on the right does not contain a fully fluorinated alkyl side ($-CF_3$) chain whereas compound b1 on the left contains a side ($-CF_3$) group (circled).

Table A1 Common PFAS compounds

Sub-class	Analyte	Abbreviation	CAS RN ^a	Carbon chain length
Perfluoroalkyl carboxylic acids (PFCAs)	perfluorobutanoic acid	PFBA	375-22-4	C4
	perfluoropentanoic acid	PFPeA	2706-90-3	C5
	perfluorohexanoic acid	PFHxA	307-24-4	C6
	perfluoroheptanoic acid	PFHpA	375-85-9	C7
	perfluorooctanoic acid, or perfluorooctanoate	PFOA	335-67-1	C8
	perfluorononanoic acid	PFNA	375-95-1	C9
	perfluorodecanoic acid	PFDA	335-76-2	C10
	perfluoroundecanoic acid	PFUdA	2058-94-8	C11
	perfluorododecanoic acid	PFDoA	307-55-1	C12
	perfluorotridecanoic acid	PFTTrDA	72629-94-8	C13
	perfluorotetradecanoic acid	PFTeDA	376-06-7	C14
	perfluorohexadecanoic acid	PFHxDA	67905-19-5	C16
	perfluorooctadecanoic acid	PFODA	16517-11-6	C18
Unsaturated telomer acids	2H-perfluoro-2-decenoic acid	FOUEA	70887-84-2	-

continues

Table A1 *continued*

Sub-class	Analyte	Abbreviation	CAS RN ^a	Carbon chain length
Perfluoroalkyl sulfonic acids (PFSAs)	perfluorobutane sulfonic acid	PFBS	375-73-5	C4
	perfluoropentane sulfonic acid	PFPeS	2706-91-4	C5
	perfluorohexane sulfonic acid, or perfluorohexane sulfonate	PFHxS	355-46-4	C6
	perfluoroheptane sulfonate	PFHpS	375-92-8	C7
	perfluorooctane sulfonic acid, or perfluorooctane sulfonate	PFOS	1763-23-1	C8
	perfluorononane sulfonic acid	PFNS	68259-12-1	C9
	perfluorodecane sulfonic acid	PFDS	335-77-3	C10
Perfluoroalkyl sulfonamides	perfluorooctane sulfonamide	PFOSA	754-91-6	C8
	N-methyl perfluorooctane sulfonamide	N-MeFOSA	31506-32-8	C8
	N-ethyl perfluorooctane sulfonamide	N-EtFOSA	4151-50-2	C8
	N-methyl perfluorooctane sulfonamidoacetic acid	N-MeFOSAA	2355-31-9	C8
	N-ethyl perfluorooctane sulfonamidoacetic acid	N-EtFOSAA	2991-50-6	C8
	N-methyl perfluorooctane sulfonamidoethanol	N-MeFOSE	24448-09-7	C8
	N-ethyl perfluorooctane sulfonamidoethanol	N-EtFOSE	1691-99-2	C8

continues

Table A1 *continued*

Sub-class	Analyte	Abbreviation	CAS RN ^a	Carbon chain length
(n:2) fluorotelomer sulfonic acids, or fluorotelomer sulfonate (FTSs)	4:2 fluorotelomer sulfonic acid	4:2 FTS	757124-72-4	6
	6:2 fluorotelomer sulfonic acid	6:2 FTS	27619-97-2	8
	8:2 fluorotelomer sulfonic acid	8:2 FTS	39108-34-4	10
	10:2 fluorotelomer sulfonic acid	10:2 FTS	120226-60-0	12
Phosphate esters	8:2 fluorotelomer phosphate diester	8:2 diPAP	678-41-1	20
Others	sodium perfluoro-1-propanesulfonate	PFPrS	359868-82-9	C3
	sodium perfluoro-1-dodecanesulfonate	PFDoS	79780-39-5	C12
	3:3 fluorotelomer carboxylic acid	3:3 FCTA/ FPrPA	356-02-5	6
	5:3 fluorotelomer carboxylic acid	5:3 FCTA/ FPePA	914637-49-3	8
	7:3 fluorotelomer carboxylic acid	7:3 FCTA/ FHpPA	812-70-4	10
	hexafluoropropylene oxide dimer acid (GenX)	HFPO-DA	13252-13-6	6
	perfluoro-3-methoxypropanoic acid	PfMPA/ PF4OPeA	377-73-1	4
	perfluoro-5-methoxybutanoic acid	PfMOA/ PF5OHxA	863090-89-5	5
	nonafluoro-3,6-dioxahexanoic acid	NFDHA/ 3,6-OPFHpA	151772-58-6	5
	bis(1H,1H,2H,2H-perfluorooctyl) phosphate	6:2 diPAP	407582-79-0	16

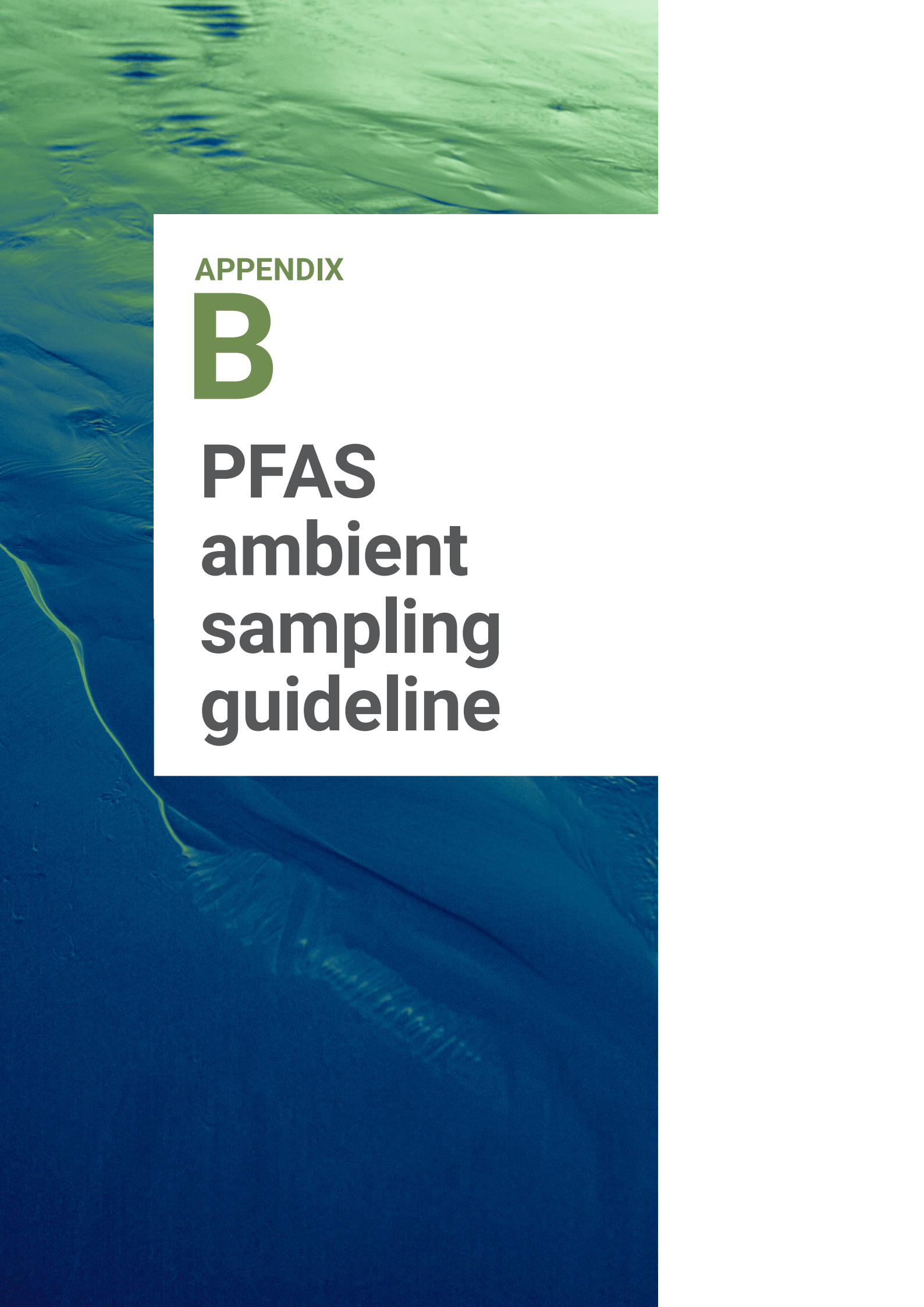
continues

Table A1 *continued*

Sub-class	Analyte	Abbreviation	CAS RN ^a	Carbon chain length
Others	(1H,1H,2H,2H-perfluorooctyl-1H,1H,2H,2H-perfluorodecyl) phosphate	6:2/8:2 diPAP	943913-15-3	16/20
	potassium perfluoro-4-ethylcyclohexanesulfonate	PFECHS	335-24-0	8
	perfluoro(2-ethoxyethane)sulfonate	PFEESA	117205-07-9	4
	9-chlorohexadecafluoro-3-oxanonane-1-sulfonate	6:2 Cl-PFESA/ 9Cl-PF3ONS	73606-19-6	8
	11-chloroeicosafluoro-3-oxaundecane-1-sulfonate	8:2 Cl-PFESA/ 11Cl-PF3OUdS	83329-89-9	10
	6:2 fluorotelomer sulfonamide alkylbetaine	6:2 FTAB/ N-CMAmp-6:2FOSA	34455-29-3	8
	4,8-dioxa-3H-perfluorononanoic acid	ADONA	919005-14-4	7
	perfluorobutylsulphonamide	FBSA	30334-69-1	4

Source: adapted from National Measurement Institute (2024b)

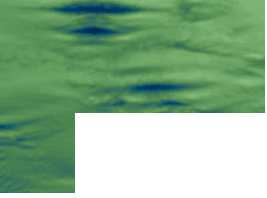
a CAS RN applies to acid form of the compound.



APPENDIX

B

PFAS ambient sampling guideline



Appendix B

PFAS ambient sampling guideline

B.1 Objectives

This Appendix presents a guideline to undertake sampling for per- and polyfluoroalkyl substances (PFAS) in locations that are defined as ‘ambient’ or not directly impacted by point sources (see [Section 5.1](#)). It provides guidance which can form part of jurisdictional programs or one-time sampling projects that aim to determine ambient or baseline concentrations of PFAS in surface waters, groundwater, sediments or biota. Current ambient programs have not considered soil or air comprehensively, and this will be included as future work progresses. It also provides information on quality control measures and advice on how to assess data. It should be used in conjunction with the PFAS National Environmental Management Plan (PFAS NEMP) to ensure a consistent approach is taken for the sampling and analysis of PFAS. This Appendix is not intended for use in sampling known contaminated sites or investigation areas. It may, however, provide useful context for the design of monitoring programs for off-site monitoring of contaminated sites.

B.2 Background

The implementation of ambient PFAS monitoring programs within jurisdictions can support the assessment of ambient PFAS concentrations in different media across Australia and New Zealand and allow for a greater understanding of the distribution or patterns in concentrations of these compounds. In order to achieve this, a consistent approach to the design of ambient PFAS sampling is necessary.

[Section 5.2](#) (ambient monitoring programs) recommends the use of land use classes for ambient monitoring programs and sampling programs, including samples from a range of land uses across a catchment (such as industrial, agricultural, etc). Sample sites should be classified by land use areas using the [Australian Land Use and Management \(ALUM\)](#) classification scheme or New Zealand [Land Cover Database \(LCDB\)](#) to allow comparison between similar land use areas. This information will enable better characterisation and management of PFAS in Australia and New Zealand.



B.3 Sampling design

PFAS sampling and analysis are discussed in [Section 18](#) and [Section 19](#). However, some considerations relevant to ambient sampling are considered here.

B.3.1 Sampling locations

Sampling locations should include a variety of adjacent land use areas as defined in [Section 5.2.1](#).

Sampling sites can be further defined using other variables (for example, catchment layers, slope/terrain, land cover, stream type, etc) with profiles determined for each sampling location.

Sampling locations can be selected based on existing monitoring programs to minimise cost, benefit from existing staff technical expertise, and access to historical data. Locations should be chosen at least 1km from the known extent of plumes from point sources of PFAS (see [Appendix C](#)), including:

- airports and aviation facilities
- fire stations
- wastewater treatment plants (WWTP)
- landfills
- specific industries (for example, chrome plating)
- land where recycled water is used for irrigation (for example, golf courses, farms, etc)
- land where biosolids are applied (for example, farms)
- known contaminated sites and areas under investigation.

B.3.2 Sampling information

Sampling information collection will need to align to the intent of the sampling program. The evaluation of land use classes according to [Section 5.2.1](#) prior to sample collection is advised, to ensure balanced representation of land-use classes. Table B1 is an example of how to record this information.

Table B1 Example sample location data

Sampling location	Sampling ID	Latitude	Longitude	Water type ^a	Land use ^b	Samples
e.g. Gregory River	e.g. GR-0220-W	-20.1804	148.48233	e.g. Middle estuary	Agricultural-ambient	Water, biota, sediment

a Water type in example as described in the Queensland Environmental Protection (Water and Wetland Biodiversity) Policy 2019 but will vary for each jurisdiction.

b Land use class as per [Section 5.2.1](#).

There are many relevant parameters that can influence and be useful when interpreting variability in PFAS concentrations, including pH, total organic carbon (TOC), salinity, turbidity, suspended solids (SS), sediment/soil characteristics like grain size, as well as other field parameters such as previous rainfall and flow. These should be collected and evaluated where possible to support the objectives of the monitoring program.

B.3.3 Temporal design

The temporal design will be dependent on the aim and scale of the program, as well as climatic conditions of the area/location (for example, seasonality of rainfall, temporal versus perennial rivers/streams, etc). Other considerations include wet/dry seasons, number of samples per season, or event-related sampling (rainfall) in locations where seasonality is less pronounced.

B.3.4 Choosing a laboratory and analysis type

The choice of a particular laboratory should be based on the objectives of the sampling program, including guideline levels, risk to the environment and/or human health from consumption of water, exposure to soil, and uptake in plants or animals through bioaccumulation.

The limit of reporting (LOR) for an analytical method should be lower than the benchmark (such as water quality objective, water quality guidelines or trigger values) to which the results will be compared. The LOR is the lowest concentration of an analytical parameter that can be detected by a particular method that has acceptable precision and accuracy. If the LOR is higher than the benchmark, alternative methods of sampling and/or analysis should be investigated (for example, passive sampling). For ambient sampling, the generally available and recommended LORs are provided in [Table B2](#).

As PFAS analytical methods are evolving, the method used by the analytical laboratory should be obtained for each sampling round and retained for records. If a method is substantially changed, the laboratory should inform its clients of the changes and any implications for the sampling program.

Currently a typical suite of PFAS for all matrices is around 40 PFAS (see [Table B2](#)). The standard suites of PFAS by laboratories are constantly evolving, and further PFAS should be added as they become available for testing. Some laboratories provide as an option analysis of extended suites containing additional compounds relevant to additional PFAS risks, products and waste.

Table B2 Typical suite of PFAS compounds and LOR currently analysed by commercial laboratories (grouped by PFAS analyte)

Analyte (abbreviation)	CAS RN	Water (µg/L)	Soil (mg/ kg)	Biosolids (mg/kg)	Biota (mg/ kg)
Perfluoroalkyl carboxylic acids (PFCAs)					
Perfluorobutanoic acid (PFBA)	375-22-4	0.002	0.0005	0.001	0.005
Perfluoropentanoic acid (PFPeA)	2706-90-3	0.001	0.0002	0.0002	0.0005
Perfluorohexanoic acid (PFHxA)	307-24-4	0.0002	0.0001	0.0001	0.0005
Perfluoroheptanoic acid (PFHpA)	375-85-9	0.0002	0.0001	0.0001	0.0005
Perfluorooctanoic acid (PFOA)	335-67-1	0.0001	0.0001	0.0001	0.0003
Perfluorononanoic acid (PFNA)	375-95-1	0.0005	0.0001	0.0001	0.0005
Perfluorodecanoic acid (PFDA)	335-76-2	0.0005	0.0001	0.0001	0.0005
Perfluoroundecanoic acid (PFUdA)	2058-94-8	0.0005	0.0002	0.0005	0.0005
Perfluorododecanoic acid (PFDoA)	307-55-1	0.0005	0.0002	0.0005	0.0005
Perfluorotridecanoic acid (PFTrDA)	72629-94-8	0.001	0.0002	0.0005	
Perfluorotetradecanoic acid (PFTeDA)	376-06-7	0.001	0.0002	0.0005	
Perfluorohexadecanoic acid (PFHxDA)	67905-19-5	0.001	0.0002	0.0005	
Perfluorooctadecanoic acid (PFODA)	16517-11-6	0.001	0.0005	0.0005	

continues

Table B2 *continued*

Analyte (abbreviation)	CAS RN	Water (µg/L)	Soil (mg/ kg)	Biosolids (mg/kg)	Biota (mg/ kg)
Unsaturated telomer acids					
2H-perfluoro-2-decenoic acid (FOUEA)	70887-84-2	0.001	0.0001	0.0002	
Perfluoroalkyl sulfonic acids (PFSA's)					
Perfluorobutane sulfonic acid (PFBS)	375-73-5	0.0005	0.0001	0.0001	0.0005
Perfluoropentane sulfonic acid (PFPeS)	2706-91-4	0.0005	0.0001	0.0001	0.0005
Perfluorohexane sulfonic acid (PFHxS)	355-46-4	0.0001	0.0001	0.0001	0.0005
Perfluoroheptane sulfonic acid (PFHpS)	375-92-8	0.0005	0.0001	0.0001	0.0005
Perfluorooctane sulfonic acid (PFOS)	1763-23-1	0.0001	0.0002	0.0002	0.0003
Perfluorononane sulfonic acid (PFNS)	68259-12-1	0.0005	0.0001	0.0005	
Perfluorodecane sulfonic acid (PFDS)	335-77-3	0.0005	0.0001	0.0005	0.0005
Perfluoroalkyl sulfonamides					
Perfluorooctane sulfonamide (PFOSA)	754-91-6	0.0005	0.0001	0.0001	0.0005
N-methyl perfluorooctane sulfonamide (N-MeFOSA)	31506-32-8	0.002	0.0002	0.0005	
N-ethyl perfluorooctane sulfonamide (N-EtFOSA)	4151-50-2	0.002	0.0002	0.0005	
N-methyl perfluorooctane sulfonamidoacetic acid (N-MeFOSAA)	2355-31-9	0.002	0.0002	0.0005	0.0005
N-ethyl perfluorooctane sulfonamidoacetic acid (N-EtFOSAA)	2991-50-6	0.002	0.0002	0.0005	0.0005
N-methyl perfluorooctane sulfonamidoethanol (N-MeFOSE)	24448-09-7	0.002	0.0002	0.0005	
N-ethyl perfluorooctane sulfonamidoethanol (N-EtFOSE)	1691-99-2	0.002	0.0002	0.0005	

continues

Table B2 *continued*

Analyte (abbreviation)	CAS RN	Water (µg/L)	Soil (mg/ kg)	Biosolids (mg/kg)	Biota (mg/ kg)
(n:2) fluorotelomer sulfonic acids (FTSs)					
4:2 fluorotelomer sulfonic acid (4:2 FTS)	757124-72-4	0.001	0.0001	0.0005	0.001
6:2 fluorotelomer sulfonic acid (6:2 FTS)	27619-97-2	0.0005	0.0001	0.0005	0.0005
8:2 fluorotelomer sulfonic acid (8:2 FTS)	39108-34-4	0.0005	0.0001	0.0005	0.0005
10:2 fluorotelomer sulfonic acid (10:2 FTS)	120226-60-0	0.001	0.0002	0.001	0.001
Phosphate esters					
8:2 fluorotelomer phosphate diester (8:2 diPAP)	678-41-1	0.001	0.0005	0.001	
Others					
Sodium perfluoro-1-propanesulfonate (PFPrS)	359868-82-9	0.001	0.001	0.01	
Sodium perfluoro-1-dodecanesulfonate (PFDoS)	79780-39-5	0.001	0.001	0.01	
3:3 fluorotelomer carboxylic acid (3:3 FCTA/FPrPA)	356-02-5	0.001	0.001	0.01	
5:3 fluorotelomer carboxylic acid (5:3 FCTA/FPePA)	914637-49-3	0.001	0.001	0.01	
7:3 fluorotelomer carboxylic acid (7:3 FCTA/FHpPA)	812-70-4	0.001	0.001	0.01	
Hexafluoropropylene oxide dimer acid (GenX) (HFPO-DA)	13252-13-6	0.001	0.001	0.01	
Perfluoro-3-methoxypropanoic acid (pFMPPA/PF4OPeA)	377-73-1	0.001	0.001	0.01	
Perfluoro-5-methoxybutanoic acid (pFMOA/PF5OHxA)	863090-89-5	0.001	0.001	0.01	
Nonafluoro-3,6-dioxaheptanoic acid (NFDHA/3,6-OPFHpA)	151772-58-6	0.001	0.001	0.01	

continues

Table B2 *continued*

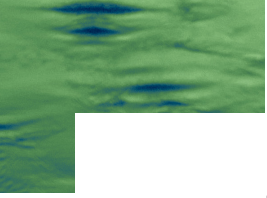
Analyte (abbreviation)	CAS RN	Water (µg/L)	Soil (mg/ kg)	Biosolids (mg/kg)	Biota (mg/ kg)
Bis(1H,1H,2H,2H-perfluorooctyl) phosphate (6:2 diPAP)	57677-95-9	0.001	0.001	0.01	
(1H,1H,2H,2H-perfluorooctyl-1H,1H,2H,2H-perfluorodecyl) phosphate (6:2/8:2 diPAP)	943913-15-3	0.001	0.001	0.01	
Potassium perfluoro-4-ethylcyclohexanesulfonate (PFECHS)	335-24-0	0.001	0.001	0.01	
Perfluoro(2-ethoxyethane) sulfonate (PFEESA)	113507-82-7	0.001	0.001	0.01	
9-chlorohexadecafluoro-3-oxanonane-1-sulfonate (6:2 Cl-PFESA/9Cl-PF3ONS)	756426-58-1	0.001	0.001	0.01	
11-chloroeicosafluoro-3-oxaundecane-1-sulfonate (8:2 Cl-PFESA/11Cl-PF3OUdS)	763051-92-9	0.001	0.001	0.01	
6:2 fluorotelomer sulfonamide alkylbetaine (6:2 FTAB/N-CMAmp-6:2FOSA)	34455-29-3	0.001	0.001	0.01	
4,8-dioxa-3H-perfluorononanoic acid (ADONA)	919005-14-4	0.001	0.001	0.01	
Perfluorobutylsulphonamide (FBSA)	30334-69-1	0.001	0.001	0.01	

Source: adapted from National Measurement Institute (2024b)

B.3.5 Quality control samples

Blanks

Blanks are used to trace sources of contamination that may be introduced into a sample from the sampling process, sample transportation, or from laboratory sources of contamination. This is particularly important for ultra-trace analysis, where even slight contamination could result in false positive results. The number of blanks collected for each sampling program will depend upon the program's objectives and size, and the types and concentrations of analytes being measured. Blanks should be analysed for the same analytes as all other samples. Blank water should be ultra-pure



PFAS-free water provided by the analytical laboratory, or if from another source, routinely tested to show no contamination is present. Distilled water purchased from retailers is not adequate for use as a blank. Guidance on the number of blank samples is provided in [Table B3](#). Some types of blanks are outlined below:

- *Container blank* – used to quantify and trace contamination problems associated with the sample containers. A bottle is filled with ultra-pure PFAS-free water supplied by the analytical laboratory, and the sample is stored for the same time period as the samples for analysis
- *Trip or transport blanks* – used to estimate contamination of a sample from shipping and laboratory sources of contamination. A bottle is filled with ultra-pure PFAS-free water and the sample is transported using the same procedures as the samples. These blanks are generally used for assessing volatile contamination. However, it may also be appropriate to include field blanks for all analytes if using ice for shipping, and there is a chance of melted water coming into contact with sample bottles and very low levels of contaminants are being measured
- *Field blanks* – used to estimate contamination of a sample during the collection procedure. Field blanks are prepared in the field in the same manner as the sample. A bottle is filled in the field with ultra-pure PFAS-free water. It is recommended that water supplied by the testing laboratory, or if produced in-house, undergoes testing to ensure it is PFAS-free
- *Rinsate/equipment blank* – used where PFAS-free water is poured over or through decontaminated field sampling equipment (for example, a trowel to collect soil or sediment) to assess potential contamination from the equipment.

Other field quality control samples

- *Blind samples/blind replicates* – duplicate (or triplicate) results provide an estimate of the error associated with the sub-sampling/splitting process and laboratory analysis and are a measure of precision. Duplicate or triplicate samples should be sent as blind samples to the laboratory. Blind samples are collected by sampling at exactly the same time and place as the primary sample. Depending on the circumstances of the sampling program, it is recommended that a subset of duplicate or triplicate samples be sent to a second laboratory to confirm the primary laboratory results

- *Certified reference material (CRM) or reference material (RM)* – CRMs/RMs are available for some PFAS analytes in some matrixes. CRMs/RMs can be used to assess laboratory accuracy and precision. Samples should be sent in as a blind sample, with consideration that re-bottling a CRM/RM may lead to a change in concentration (for example, ultra-trace PFAS in water). Where possible, the concentration of analytes in the CRM/RM should be in the range of the analytes expected in the environmental samples.

Note: A *blind sample* is a sample named so that it is indistinguishable from the other samples. This means the source and chemical composition of the sample/s are not known to the analyst. Blanks, duplicates and CRMs are often used as blind samples. Blind samples can determine variability within a laboratory or bias and variability between batches within the same laboratory or between two or more laboratories.

Table B3 Guidance on the frequency of collection and purpose of quality control samples

Quality control sample	Number of quality control samples to be collected	Notes
Container blank	One per trip	N/A
Field blank	One per field team per trip or one per 20 samples	If sampling in a particularly dirty environment and for trace or ultra-trace concentrations of analytes, it may be useful to collect more field blanks (for example, one per team per day)
Trip/transport blank	One per trip minimum and in some cases one per cooler box	N/A
Rinsate/equipment blank	One for any equipment item per field team per trip	N/A
Duplicates (or triplicates)	For waters: one per 10 samples for primary laboratory, one per 20 samples to the secondary laboratory (or one per program when there are less than 20 samples) For soils: one per 20 samples	Assesses precision of the results within a laboratory and between laboratories. Send as a blind sample
Certified reference material	Ad hoc. One per large sampling project	Evaluates laboratory accuracy and precision. Should be sent in as a blind sample

continues

Table B3 *continued*

Quality control sample	Number of quality control samples to be collected	Notes
Blind replicates	Depends upon the program objectives	Informs variability for statistical testing; consider a statistical power analysis prior to sampling

B.3.6 Collecting samples

Preventing contamination when collecting PFAS samples is critical as PFAS are found in many types of materials. Appropriately prepared bottles should be supplied by the analytical laboratory. Laboratories should be consulted on the minimum sample size required for each sample type being analysed.

Prior to sample collection, wash hands with soap and rinse thoroughly in tap water before donning a clean, new pair of disposable non-powdered nitrile gloves. To mitigate the risk of sample contamination it is mandatory that staff wear nitrile gloves during all stages of sample collection, and avoid touching the mouths of bottles, undersides of lids, or insides of bags. Visually inspect all items ensuring the lids of all sample bottles/jars are firmly secured. Discard all items if the integrity is compromised or potential for contamination has occurred. A new pair of nitrile gloves must be worn for each different sampling location.

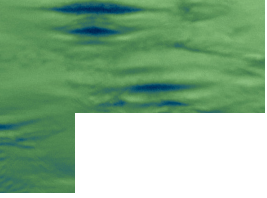
Surface water

Samples should be collected directly from the stream into the bottles where possible (or using a clean sampling pole if unsafe to do so). Bottles should be immersed into an area of representative flow where the water is well mixed. It is important that samples are collected upstream of significant in-stream structures and known point sources of pollutants.

Samples should be collected submerging the bottle opening at a consistent depth of at least 10cm below the water surface and 10cm above the bed to avoid elevated concentrations of PFAS in sediments and surface films. If the water depth is less than 30cm, samples should be collected in a way which avoids disturbance of the sediments and collection of surface films. Samples should be collected by removing the lid underneath the water, tilting the bottle upright and allowing the bottle to fill. The lid is then replaced underneath the water.

Note: PFAS samples must not be filtered in the field.

Record sample location, date and time on sample bottle labels. Check all information on the sample bottle and mandatory documentation has been



completed and is correct, then place in double resealable bags and place on ice in a cooler box or fridge to rapidly chill the sample to below 4°C.

Sediment

Composites of a minimum of five sub-samples should be taken from the top 10cm of sediment in estuarine or marine sites or 2–5cm in freshwater sites. Samples can be collected using the sample container directly (using the jar or lid to scoop sediment) or using a Van Veen sampler, stainless-steel trowels or mud grab devices. If equipment is used it should be thoroughly rinsed (three times) using PFAS-free water before and after sampling. Rinsate blank samples should be collected for one in every 10 samples to check this process.

Record sample location, date and time on sample jar labels. Check all information on the sample jar and mandatory documentation has been completed and is correct, then place in double resealable bags and placed on ice in a cooler box or fridge to rapidly chill the sample to below 4°C.

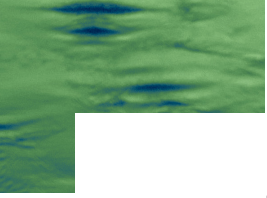
Groundwater

There are multiple methods available for groundwater monitoring such as:

- low-flow purging (for example, using micro-purge pump)
- passive sampling (for example, microporous polyethylene samplers)
- bailing.

We recommend that low-flow purging is used in ambient monitoring to ensure that a sample representative of groundwater conditions is obtained consistently. A consistent pumping technique is recommended during ambient campaigns. Where possible, low-flow purging using a peristaltic pump is the preferred method, otherwise micro-purge pumping should be used. Peristaltic pumping is preferred due to the ability to use dedicated consumables (high-density polyethylene (HDPE) tubing and silicon) for a single well, reducing cross-contamination potential and minimising decontamination steps.

When using a micro-purge or bladder pump, the bladder, tubing and o-rings should be replaced at each bore sampling location. O-rings may be reused after rinsing, but a fresh bladder and tubing should be used for each sampling location. All instrumentation and equipment (that is, pumping equipment, flow cells, and standing water level recorders) are to be rinsed with PFAS-free water prior to, and after sampling at each location. Decontamination of the pump is conducted by disassembling the pump, then thoroughly rinsing (three times) all pump components with copious quantities of PFAS-free water. A final rinse of the pump components is conducted using laboratory-supplied PFAS-free water. Any equipment that is not in the direct flow path from the bore to the sample bottle (that is, the flow cell and multiprobe meter) need not be rinsed with PFAS-free water.



For every 10 samples collected, one rinsate blank sample is to be collected by collecting rinsate water that has been used to complete an additional rinse of the equipment after completion of the rinsing process described above.

Groundwater wells should be purged before sampling commences. The groundwater sample for lab analysis is to be collected once purging has removed all stagnant water from the bore so that water within the bore is representative of formation water **and** water quality parameters show stable readings. If the bore is very poor yielding the sample may be collected after less than three volumes are purged, provided stable water quality parameters are being measured.

In-situ groundwater quality parameters should be recorded at regular intervals to provide a record of the time taken for parameters to stabilise and the stable parameters measured at the time of sample collection.

Groundwater levels (from top of casing) are to be recorded for each bore location. The pump is to be lowered to approximately 1m below the standing water level. Pumping rate is to be measured as a standard procedure each time a bore is sampled. Target pumping rate is approximately 3-4L per minute.

Record sample location, date and time on sample bottle labels. Record any other field observations such as the time taken to complete sampling at each bore, presence of large quantities of particulate matter and smells.

Check all information on the sample bottle and mandatory documentation has been completed and is correct, then place in double resealable bags and place on ice in a cooler box or fridge to rapidly chill the sample to below 4°C.

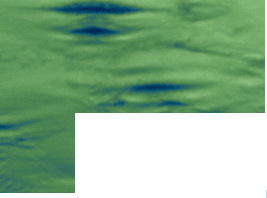
Biota

Depending on the circumstances, permits and ethics approvals may be required for the collection of biota.

Sample data should be recorded, for example:

- sample identification number
- date
- species/sample description
- specimen size when caught
- location taken.

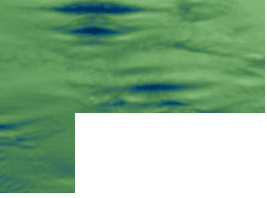
Record sample location, date and time on sample jar/bag labels. Check all information on the sample jar/bag and mandatory documentation has been completed and is correct, then place in double resealable bags and place on ice in a cooler box or fridge to rapidly chill the sample to below 4°C. Samples should be frozen if not sending to laboratory immediately.



Biota sampling for human health risk assessment

The requirements below should be considered when collecting samples to inform a human health risk assessment (HHRA):

- biota samples should be legally caught only in recognised fishing or hunting areas (excluding green zones, drains, and so on) and should be of a legal and commercial or recreational size (see below for more information on sample requirements)
- only edible species that are consumed from the area of interest must be used, also taking into consideration any consumption by First Nations people, traditional custodians, or other cultural groups
- consideration should be given to whether any species need to be harvested for testing that are likely to form a significant proportion of the diet of any sub-populations at risk of higher exposure than the general population
- ideally a range of species should be sampled including fish, crustaceans and molluscs, or other wild caught foods where appropriate. Preference should be given to targeting species that may have higher exposure to PFAS from the contamination source under investigation, such as their position in the food chain. Migratory movements of some species may reduce their exposure. Predatory fish and benthic dwelling species should be included where possible
- only edible portions should be analysed. The following portions are recommended as they are likely to represent the most typical parts consumed by the general population:
 - fish – fillet, skin on with scales removed
 - prawns, yabbies, crabs, lobsters and molluscs – extracted meat
 - wildfowl – breast tissue and liver
- a sufficient number of specimens should be obtained to account for variability between specimens. Composite samples of a single species from a set area are preferred as an initial screening tool to help overcome and average differences between individual specimens. Tracking and archiving of individual specimens that make up a composite sample is important, as it allows for re-testing individual specimens if the composite samples show high results. Compositing of samples across broad areas and along pollution gradients must be avoided. Ideally, the same weight of sample should be collected and composited from each specimen (for example, 100g)
- if the concentration of PFAS is required in the whole organism to assist with any ecological risk assessment, which is generally conducted alongside the HHRA, the portions of seafood which are not consumed by humans (for example, fish carcass excluding edible portion), can be weighed and analysed separately. This enables the total PFAS concentration in the whole organism to be calculated by adding a



weight-averaged concentration of the edible and inedible portions once testing is completed

- contamination of samples with PFAS during harvesting and the handling of samples should be avoided. PFAS may be found in some water- and oil-repellent clothing, footwear and fabrics, such as Gore-Tex™ products. Teflon™-containing or -coated fishing equipment such as knives should not be used. Potential contamination from bait should also be excluded
- where possible, samples should be prepared (for example, scaled, gutted, filleted, shelled) in a laboratory or suitable facility to minimise the potential for environmental contamination and cross-contamination
- samples should be placed into sample containers provided or recommended by the laboratory. If not known, new, clean snap-lock sample bags should be used
- samples should be appropriately labelled for the laboratory. Consideration may need to be given to photographing whole specimens to later aid correct identification of the species
- samples should be chilled or frozen and packaged to minimise degradation and contamination until received by the laboratory
- it is advisable when preparing a sampling and analysis plan to separate requirements for wild-caught food sampling for HHRA from ecological risk assessment to help ensure a sufficient number of specimens appropriate for HHRA are sampled.

Ecological risk

Assessment of more than one tissue may be important for assessing bioaccumulation or risks to biota and ecosystem health. Comparison against PFAS NEMP guidelines for avian and aquatic mammals entails whole organisms. Whole small fish or invertebrates can be made into a composite sample to obtain the required amount for analysis (approximately 20g), although the number of individuals and their weights should be recorded.



APPENDIX

C

Activities associated with sources of PFAS contamination

Appendix C

Activities associated with sources of PFAS contamination

Table C1 and Table C2 identify activities associated with PFAS contamination, focusing on primary and secondary sources.

Table C1 Activities associated with PFAS contamination due to fire risk

Activity	Description
Airports and aviation infrastructure	On-site firefighting – see also further information below
Aluminium production	On-site firefighting
Battery production	On-site firefighting – see also further information below
Bitumen production	Kerosene use and storage
Brewing, distilling and refining	Ethanol production
Coal works	On-site firefighting
Dangerous goods production	On-site firefighting – likely to use specialised firefighting products and systems due to the presence of a range of hydrocarbons, polar solvents etc
Explosives production	On-site firefighting – explosions
Food production	On-site firefighting associated with use of bulk oils and solvents – see also further information below
Fuel exploration, assessment, production, transport and storage including petrochemicals, other fossil fuels and renewable liquid fuels	On-site firefighting, also used as a surfactant for gas well stimulation
General chemical storage	On-site firefighting – likely to use a range of hydrocarbons, polar solvents etc
Generation of electrical power	On-site firefighting – see also further information below
Hardware retailers	Firefighting foam deluge systems – see also further information below on the construction industry

continues

Table C1 *continued*

Activity	Description
Mining	On-site firefighting
Paints, polishes, adhesives production	On-site firefighting – see also further information below
Petroleum products other than fuels	On-site firefighting, potential use in processing
Underground infrastructure including car parks and tunnels	Firefighting foam deluge systems

Table C2 Activities associated with PFAS contamination more broadly

Activity	Description
Agriculture	Potentially used as an adjuvant or active ingredient in fertilisers and pesticides, firefighting foam used in the poultry industry to destroy infected flocks
Automotive industry including retailing, detailing and car wash facilities	Surface treatments including polishing, cleaning, stain and water protection products, lubricants, hydraulic fluids, tubing, oil pan, head gaskets, sealant, wire and cabling, fire retardant and metal plating applications
Aviation, aerospace and defence	As for automotive industry plus aviation-specific products, articles and activities, such as aviation hydraulic fluid
Battery use and disposal	Used in batteries, particularly for high-end use such as lithium-style batteries
Boating and marine supply industry	As for automotive industry plus marine-specific products, articles and activities, such as awnings, painting, waterproofing and sealant applications, and shipboard firefighting
Chrome/metal plating industry	High concentration PFAS mist suppressants used to reduce chromium exposure to workers
Commercial laundries and dry cleaners	Effluent from cleaning of fabrics containing or treated with PFAS
Construction industry	Tile coatings, stone coatings, paints, varnishes, sealants, other architectural coatings for films, facades and infrastructure, rigid foams, silicone rubber, thread sealant tapes and pastes and personal protective equipment (PPE)

continues

Table C2 *continued*

Activity	Description
Electricity, telecommunication and information technologies	Wireless devices, hard drives, fibre optic cables, dirt-repellent coatings on glass surfaces such as smartphone screens, flame-resistant devices, fittings, coatings and wrappings, semiconductor etching, firefighting at electricity generation sites and in electricity distribution networks with oil-containing equipment such as transformers, reactors, large regulators, circuit breakers, pipe-type cable systems and bulk storage tanks, reported to be in high-end lithium batteries
Firefighting and fire protection sales and services	Storage and disposal of large quantities of firefighting foam associated with formulation, transport, sale and servicing of firefighting and fire protection products and services including refurbishment of deluge systems and fire extinguishers at fire protection retailers, rural supply stores, council depots and outstation service centres
Manufacturing of building products	As for construction industry
Manufacturing of chemicals, fertilisers and pesticides	Equipment and fittings including pipes, tanks and valves, use as an intermediate in the production of other substances, potentially used as an adjuvant in fertilisers and pesticides
Manufacturing of food, food packaging and food preparation products	Baking paper, aluminium foil, fast food wrappers, non-stick equipment including food processing facility surfaces, pipes, tanks and valves, and firefighting especially at facilities where bulk oil is used
Manufacturing of healthcare products	Surface protection for medical garments, small quantities in X-ray film, charged-coupled devices (CCDs), artificial blood, flexible tubing, needle coatings, denture cleaners, potentially in contact lenses
Manufacturing of household appliances	Heaters, heat lamps, irons, stoves, refrigerators, other flammable components, and high-end (lithium) batteries
Manufacturing of personal care products	Cosmetics, shampoo, shaving cream, dental floss, sunscreen, nail polish, talc, lotions
Manufacturing of textiles, leather, upholstery, carpets, clothing, shoes, outdoor gear	Widespread use of fluorinated compounds to provide stain, water and fire protection

continues

Table C2 *continued*

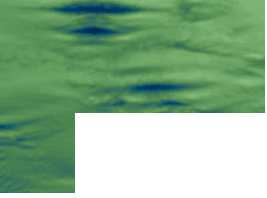
Activity	Description
Manufacturing of safety gear	Widespread use of fluorinated compounds to provide stain, water and fire protection for PPE and bulletproof clothing
Manufacturing of paints, polishes, coatings and adhesives	Historically used in sealants, adhesive products, coatings, paint and varnishes
Manufacturing of paper or pulp	Used in internal and surface sizing agents for paper manufacturing
Printing, packaging and merchandising	Used to apply grease, oil and water resistance to packaging product, also used in inks particularly for inkjet and photo printing
Recovery of waste oil	Collection and processing of PFAS-containing waste oil
Soap and detergents production	Household goods such as shampoos and cosmetics, commercial and industrial cleaning products such as floor polishes and vehicle cleaning agents
Solar energy	Used in photovoltaic solar cells to repel dirt and in lithium batteries
Sporting goods manufacturers and suppliers and sports facilities	Ski wax, high performance textiles including outdoor clothing, water-resistant treatments
Waste processing and disposal	PFAS-containing solid and liquid waste and leachate in landfill, high temperature incineration, chemical and other treatment regimes
Waste storage – hazardous, restricted solid, liquid, clinical, asbestos waste	On- and off-site storage and/or collection of waste PFAS-containing products
Wastewater treatment	Inputs from domestic sewage and commercial and industrial wastewater and outputs applied to land or discharged to the environment



APPENDIX

D

Treatment technologies potentially available in Australia



Appendix D

Treatment technologies potentially available in Australia

Table D1 provides a summary of PFAS treatment technologies which are currently available in Australia.

The PFAS treatment technologies listed in Table D2 include technologies that may be in the experimental, proof of concept and field trial stages. As such, these lists have not considered commercial availability or feasibility, and do not imply regulatory endorsement of the technology or process. The available treatment technologies, disposal options, and associated regulatory requirements may vary in each jurisdiction. Many studies are trialling a combination of technologies to determine which technologies may be complimentary in the removal, immobilisation or destruction of PFAS compounds.

These are by no means exhaustive lists as technologies are continuing to be developed at a rapid rate.

Table D1 PFAS treatment technologies currently available in Australia

Process		Definition	Application	Media	Status
Destruction or transformation	Pyrolysis and oxidative thermal destruction (Ross et al. 2018)	Alteration of chemical composition to convert to inorganic fluoride using high temperature in the absence or presence of limited oxygen	High temperature plasma arc, cement kilns	Soil, aqueous film-forming foam concentrates, solid concentrates from adsorption, liquid concentrates from reverse osmosis, nanofiltration and ion exchange	Facilities available in Australia and trials to improve this technology, to make it more portable, are underway
	Electrochemical oxidation/reduction (AsA n.d.; Ross et al. 2018)	Defluorination of PFAS using electrodes	In-situ	Water and wastewater	Currently available and effective for wastewater treatment. Under further trial/development to increase effectiveness in other media
Separation and concentration (requires concentrated PFAS to be managed appropriately)	Adsorption (Tan et al. 2022; Ross et al. 2018; Appleman et al. 2013)	Adhesion of PFAS to the surface of an adsorbent	In-situ or ex-situ using powdered or granular activated carbon (PAC or GAC), resins, ion exchange polymers, proprietary absorbents	Water and wastewater	Currently available and current trial to improve technique
	Foam fractionalisation/separation (ozofractionation) (Australian Government 2016)	Separation of PFAS from groundwater and wastewater into a foam using air or ozone bubbles	Ex-situ –removed PFAS must be managed appropriately	Surface, groundwater and wastewater	Currently in use for water and in trial for wastewater

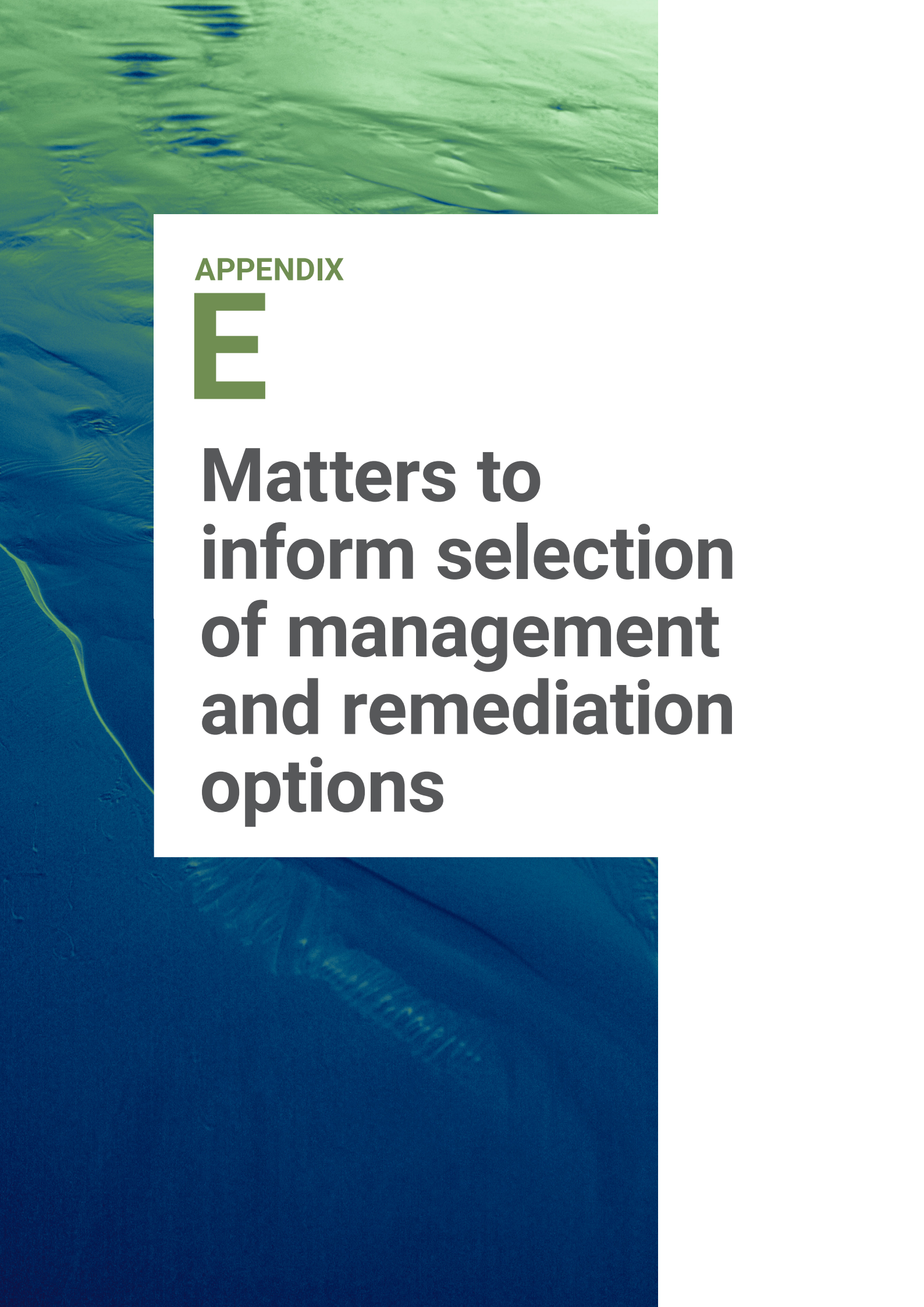
continues

Table D1 *continued*

Process		Definition	Application	Media	Status
	Reverse osmosis and nanofiltration (Liu et al. 2021; Ross et al. 2018; Appleman et al. 2013; Thompson et al. 2011)	Removal of PFAS from water using semi-permeable membranes	Ex-situ –removed PFAS must be managed appropriately	Water and wastewater	Various systems available. Currently in use (wastewater)
	Thermal desorption (often first stage of thermal destruction)	Separation of PFAS from solid materials using high temperatures to increase the volatility of the PFAS	Ex-situ. Indirect and direct-fired thermal desorption. Once PFAS is removed it must be managed appropriately	Soil and waste	Not being used in Australia as a stand-alone option at this stage
	Soil washing (Høisæter et al. 2021)	Removal of PFAS through washing with water, followed by treatment of the water to remove PFAS	Ex-situ – soil must be removed and often cannot be returned to original site	Soil	Currently available
Stabilisation and immobilisation	Immobilisation (Bräunig et al. 2019 and 2021; Ross et al. 2018)	Addition of a binding agent to soil to reduce PFAS mobility	Ex-situ using GAC or PAC, proprietary adsorbents followed by return of material. In-situ using modified clays	Soil and waste	Available and under further development including in-situ application
	Stabilisation (Australian Government 2016)	Minimising the movement of PFAS-contaminated material by adding a physical barrier	In-situ using cement or polymers	Soil and waste	Available

Table D2 PFAS treatment technologies in Australia currently on trial or require further development

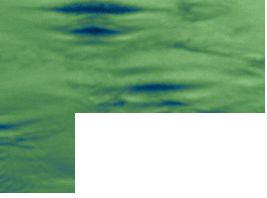
Process		Definition	Application	Media	Status
Destruction or transformation	In-situ chemical oxidation or reduction (ISCO) (Australian Government 2016)	Application of chemicals and often heat to convert the PFAS to inorganic fluoride	In-situ – though there is potential for increased mobility of short-chain PFAS	Soils and groundwater	Not being used in Australia at this stage
	Ultrasonication/ sonochemistry (Ross et al. 2018; Australian Government 2016)	Treatment using intense ultrasonic-wave energy to defluorinate PFAS to convert the compounds into more environmentally friendly forms	Laboratory based studies have been difficult to scale up to field applications	Water and wastewater	Current trial
	Soil smouldering (Major 2019)	Converts PFAS compounds to inorganic fluoride using a front of smouldering soil	This approach can be used for ex-situ treatment of excavated soils and sludges, and in-situ above and below the water table	Soil	Current trial
	Ball milling (mechanochemical) (US EPA 2021b; Ross et al. 2018)	Mineralisation of PFAS to inorganic fluoride using mechanical energy	Ex-situ	Soil	Current trial
	Microwave (Merino et al. 2016)	Mineralisation of PFAS to inorganic fluoride using microwave energy	Ex-situ	Soil	Current trial
	Photocatalysis (Merino et al. 2016)	Uses catalysts to mineralise PFAS to inorganic fluoride with visible or ultraviolet (UV) radiation	Laboratory	Water and wastewater	Current laboratory development



APPENDIX

E

Matters to inform selection of management and remediation options



Appendix E

Matters to inform selection of management and remediation options

There are different remedial technologies and treatments available (see [Appendix D](#)). In selecting an appropriate remediation or management strategy for the site in question, all relevant matters must be considered and a balance achieved that will provide the highest level of protection that is both possible and reasonable in the circumstances. No single matter determines what is practicable at a given point in time.

Some of the matters that can be used to inform the identification of remediation options are:

- likelihood of the hazard or risk occurring
- degree of harm that might result from the hazard or the risk
- level of protection that may be required
- availability and suitability of practical mechanisms to eliminate or minimise the risk
- costs and benefits associated with available options.

These matters are expanded on below.

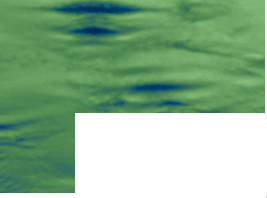
E.1 Likelihood of hazard or risk occurring

The site investigations and risk assessments (see [Section 9.2](#)) will help determine:

- environmental values to be protected
- receptors
- exposure pathways
- likelihood of risks.

If PFAS concentrations are above the screening or guideline concentrations, then harm is considered increasingly likely.

In assessing the likelihood of risk, it is important to understand the source(s) of the exposure, the magnitude, frequency and duration of the exposure, and possible receptors (both at present and into the future). If these risks cannot be quantified over the relevant timeframes, then this uncertainty should be factored into the decision and accurately reported and communicated, noting that a high-end precautionary approach may



be warranted (US EPA 1992a and 2019; Department of Health and Ageing 2012; Australian Government 2017; Mallants et al. 2017).

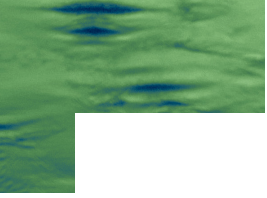
Below is a non-exclusive list of questions that can help determine the likelihood of hazards or risks.

E.1.1 Types of questions the responsible entity may need to answer or demonstrate they have considered regarding likelihood of hazard or risk

- Has the sampling, site characterisation and conceptual site model (CSM) set out what contamination is where on the site? Is that well understood or are the results variable? If variable, is additional sampling needed?
- Are all the sources of PFAS contamination identified? Has the site history been properly described and quantified? If it is poorly understood, how has the investigation addressed this?
- What are the soil characteristics, including porosity, mineralogy and percentage of organic matter, that may affect how PFAS are transported? For example, will they travel along the vadose zone and into other surface bodies?; Are PFAS likely to go through karstic or fractured rock systems, or into surrounding aquifers?
- Are there other contaminants or potential issues (for example, asbestos, hydrocarbons, acid sulfate soils, sodic soils, etc)?
- Is the hydrogeology properly understood? Is the site linked via groundwater to anywhere else and if so, how and where?
- Is the contamination moving and if so, where? Can a site mass flux model be generated?
- What are the local environmental values and beneficial uses of water?
- What humans, plants and animals are on the site, around the site, or in the path of the plume or stormwater runoff from the site which may be affected by contaminated soil or water? For example, since PFAS particularly impact secondary consumers and air-breathing aquatic animals, are there frogs, platypus, water rats, echidnas, birds, turtles, lizards, snakes or antechinus present?

E.2 Degree of harm that might result from hazard or risk, and/or level of protection that may be required

The CSM will help to identify receptor pathways and the human health and ecological risk assessment (HHERA) should elaborate potential risks. Reliable, reputable sources, such as this document, and engaging with suitably qualified persons with experience in PFAS assessment and management will assist in articulating the risk. In addition to the



site investigation, knowledge may come from First Nations people and traditional custodians, business and industry organisations, and regulatory and government agencies.

In quantifying or assessing risks, it is important to understand impacts relevant to the periods of exposure and whether there are more than one PFAS present, or other contaminants are present.

Given that a number of PFAS are persistent, bioaccumulative, toxic, and mobile in the environment, ecological risks need to be assessed for chronic or multigenerational exposure across different trophic levels. If such risks cannot be quantified, then this uncertainty should be factored into the decision, noting that a high-end precautionary approach may be warranted (US EPA 1992a and 2019; Department of Health and Ageing 2012; Australian Government 2017; Mallants et al. 2017).

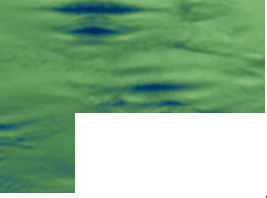
Risk communication with stakeholders and engagement about risk perception may help to determine the severity of social and economic risks.

E.2.1 Types of questions the responsible entity may need to answer or demonstrate they have considered regarding degree of harm

- What are the current and future land uses – existing vegetation, wildlife and/or livestock?
- Is anywhere off site potentially affected?
- Are there sensitive areas or environmental values, such as waterways, affected?
- What PFAS concentrations are animals, plants and people being exposed to? Are any above the guideline values in the PFAS NEMP? If below, there may be little to no risk. If above, has a detailed risk assessment been done?
- What precursor load is present? Is that included in the risk assessment? How have other contaminants been considered?
- How long is exposure likely to be? Will animals and plants be exposed for weeks, months or years? Is this uncertain? If so, is that uncertainty described in the options?
- If contamination is reaching other people's properties, will this affect their amenity?

E.3 Availability and suitability of practical mechanisms to eliminate/minimise risk

This requires consideration of not only what is available, but also what is suitable for the elimination or minimisation of risk for that particular site or situation. A remedial option (or other risk control) that may be effective



in some circumstances or environments may not be effective or suitable in others.

Failing to obtain the necessary data and information about PFAS contamination and about mechanisms to eliminate and minimise risk is not considered an acceptable constraint on acting, or on adequately assessing options.

Treatment technology to eliminate or minimise a hazard or risk is regarded as being available if it is provided in the market, has a demonstrated effectiveness, or if it is possible to manufacture the technology and it is feasible to implement. Modelling, lab research, bench tests, pilot studies and field trials can be important components of developing treatment technologies, although may not in themselves constitute demonstrated long term effectiveness for the site.

A way of eliminating or minimising a hazard or risk (for example, a treatment technology) is generally regarded as suitable if it:

- is effective in either eliminating or, failing that, minimising the likelihood or degree of harm from a hazard or risk to a level considered acceptable by stakeholders and regulators
- does not introduce new and additional risks, having regards to all the circumstances, and is practical to implement at the specific site. For example, the chosen treatment for PFAS does not increase the potential for adverse impacts of other contaminants, and that the chosen treatment for other contaminants does not increase the risks of PFAS. Note that some treatments will result in the transformation of PFAS, thus potentially changing the PFAS present in the treated materials needing subsequent removal. Treatment outputs also need to comply with the applicable waste, air and water emission standards (state and national).

E.3.1 Types of questions the responsible entity may need to answer or demonstrate they have considered regarding suitability and practicality of remedial options

- Which option will achieve the remediation objectives?
- Have all applicable and established remedial methods and technologies been considered?
- Have some of those considered technologies and methods been successfully implemented?
- Will each option ensure that PFAS-contaminated waste materials generated (or intended to be generated) during remedial works are appropriately disposed of?
- Are ongoing PFAS waste streams subject to management controls and defined destinations?

- Has the site location and the availability of services and resources been considered?
- Have the reductions in concentration, load, and/or mass flux after each type of intervention been described and weighed up?
- Will any options have other undesirable effects such as destroying habitat or creating other types of contaminants? Have these effects been quantified?
- For groundwater, has the possibility of contaminant rebound been considered?
- Are the risks presented by the residual PFAS mass understood?
- Are there other technologies available that may contribute to the desired risk reduction or substantially accelerate achieving the long-term remedial goals?

E.4 Costs and benefits associated with available ways of eliminating/minimising risk

All reasonably foreseeable hazards and risks must be considered when identifying what is the sufficient level of clean up, including consideration of the risks and degree of harm associated with each of the 'do nothing', preferred, and alternative remediation options.

When deciding which option to choose in meeting the required outcomes, the sustainability (environmental, economic and social) of each option should be considered in terms of achieving an appropriate balance between the benefits and effects.

E.4.1 Considerations for economic costs

Economic costs of remediation can be high, so tools have been developed to maximise the benefits of remediation using limited resources. Such tools include:

- risk assessments of multiple areas within a single site to direct resources to those areas that present the highest risk to the environment and/or human health
- combining the risk assessment with cost-benefit analysis for a range of remedial options. In addition to benefits from stopping or reducing harm to ecosystem services, the environment and/or human health, or enhancing the beneficial use, amenity or ecological value of an area, benefits may include reductions in external costs or damages that may otherwise be caused to parties off-site such as:
 - loss of land value
 - loss of use of a resource
 - loss of recreational resource or amenity impacts

- any combination of the above.

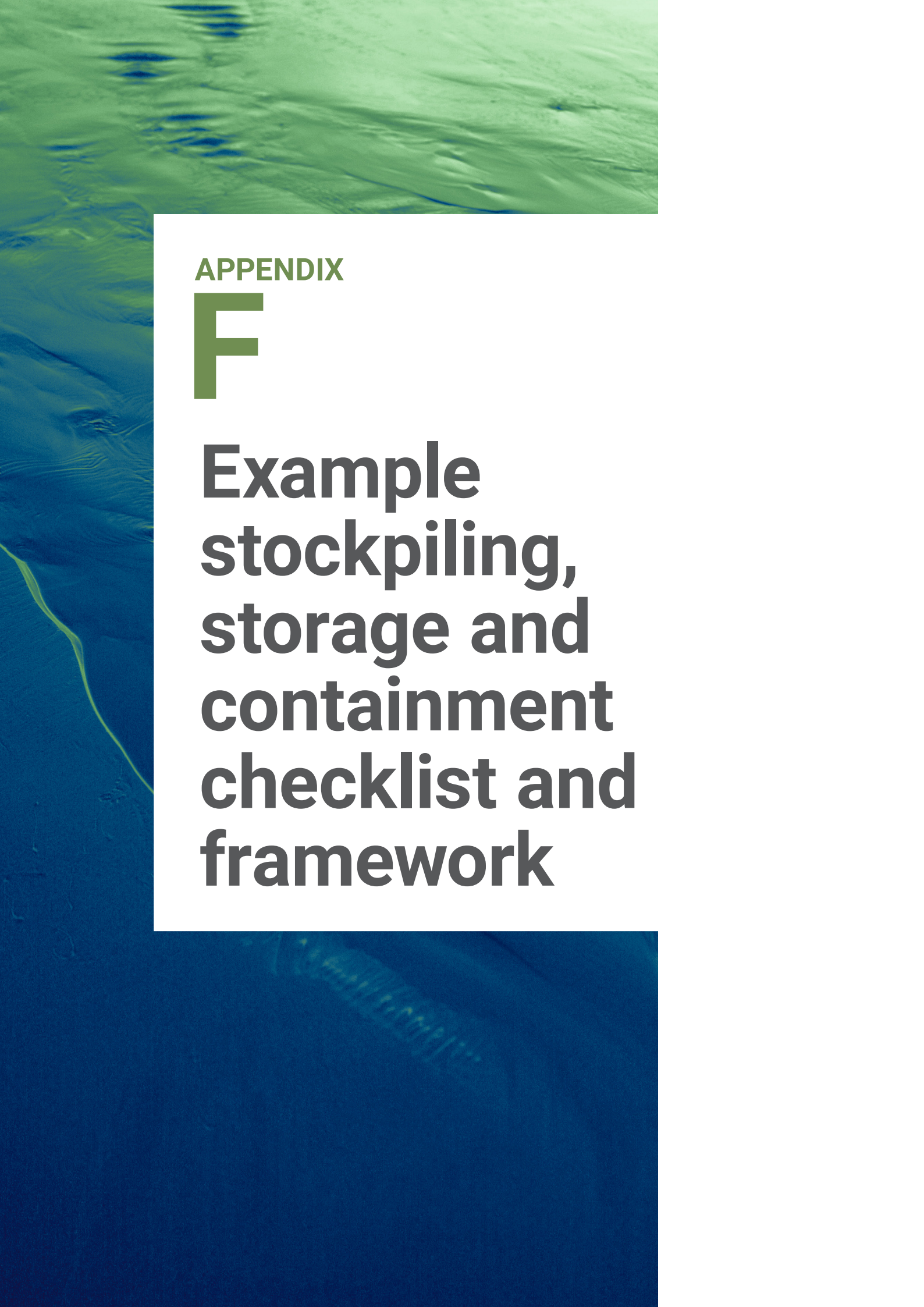
These benefits would need to be weighed against costs associated with treatment or intervention.

These tools should be adjusted to minimise uncertainties and used as an input into decision-making rather than the sole method of assessment.

E.4.2 Considerations for costs of unintended impacts

Potential ways of eliminating or minimising the risk should also consider unintended adverse impacts, such as:

- potential for precursor transformation
- potential for cross-contamination (new contamination resulting from the action), and/or remobilisation (actions that may trigger movement of PFAS, usually from a previously stable condition)
- evaluation of proposed reuse sites that may create new potential pathways to human health or sensitive environmental receptors (additional management options that prevent or mitigate new pathways may be required)
- community impacts (for example, truck movements associated with off-site management)
- external costs or damages that may be caused to parties off-site such as:
 - loss of land value
 - loss of use of a resource
 - loss of recreational resource
 - amenity impacts
 - any combination of the above.



APPENDIX

F

Example stockpiling, storage and containment checklist and framework

Appendix F

Example stockpiling, storage and containment checklist and framework

Table F1 Example checklist for storage of unused chemicals containing PFAS

Storage of unused chemicals containing PFAS	
Control	Achieved?
Install appropriate signage.	☐
Store chemicals/unused stocks in accordance with legal requirements.	☐
Wherever possible, store chemicals under a roof or within a building.	☐
Where this is not possible outline the alternative control measures:	
Store in approved containers.	☐
Provide appropriate secondary containment.	☐
Prevent rain from entering the bunded area.	☐
Label containers appropriately as to the contents, relevant inspection dates and relevant instructions on storage and handling, including prohibitions on disposal.	☐
Ensure emergency response documentation is prepared and in place.	☐
Test Emergency Response Plan.	☐
Ensure verification of controls by authorities or experts.	☐
Insert relevant section of PFAS NEMP or reference to other legislation for more information and assistance.	☐

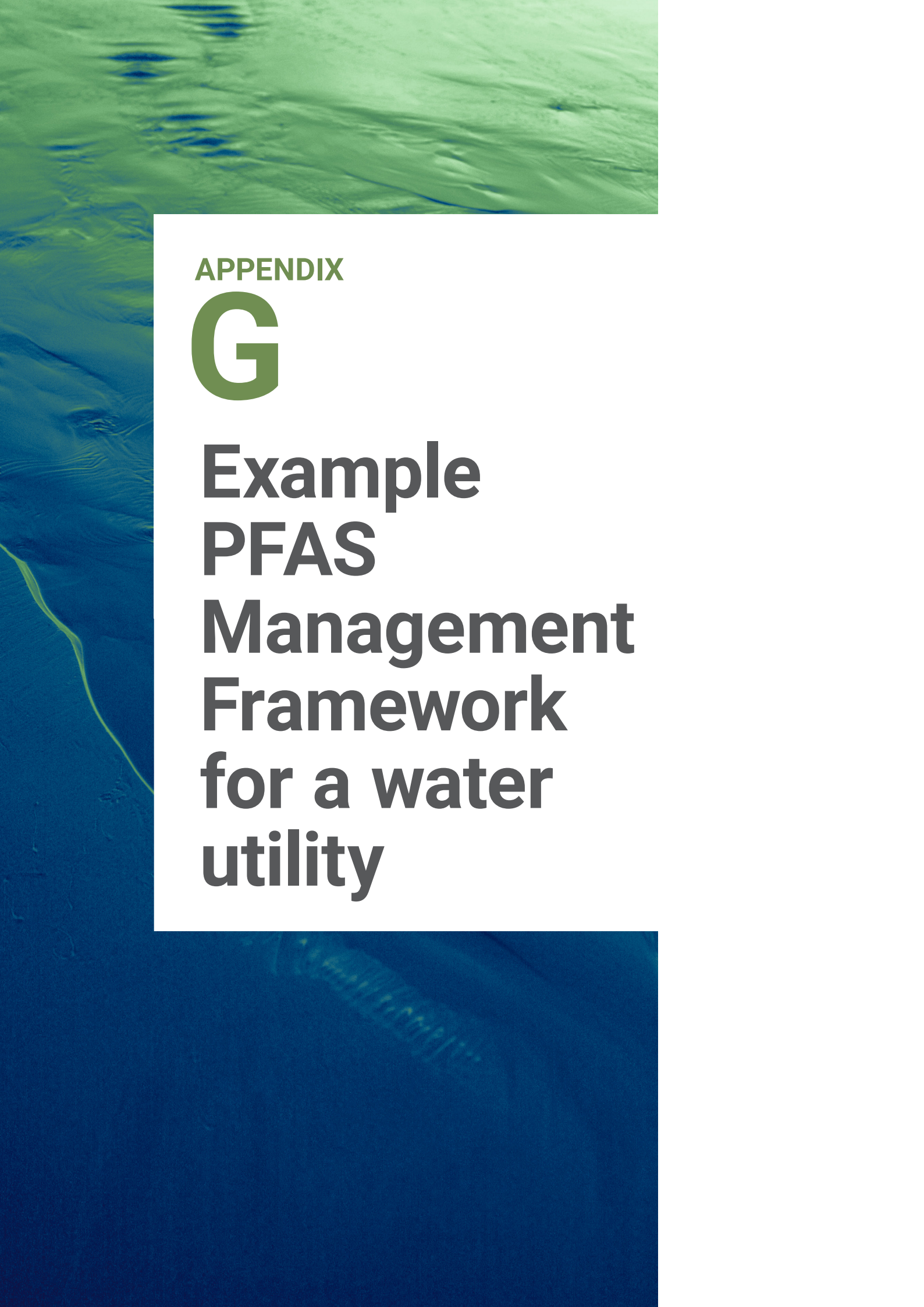
Table F2 Example framework for short-term stockpile management

Short-term stockpile management framework – for temporary storage only – up to six months	
Risks	Design considerations and management requirements
Permitting and authorisation	Ascertain regulatory status of the proposed activity. Ensure all licences/authorisations have been obtained prior to commencement, including the landowner's permission.
Health and safety	Determine all exposure pathways for site users and adjacent land users. Ensure adequate space for safe access, loading/unloading and inspection. Ensure compliance with stockpile height and maximum slope angle requirements. Implement demarcation/fencing of excavations, confined spaces, etc Management measures for specific risks present at site, such as excavations, confined spaces, hazardous atmospheres, working at height, machinery guarding, etc As relevant, ensure site induction includes instructions on the rules regarding the stockpile for workers and contractors assessing the site.
Contaminant-specific risks	Consider specific properties of PFAS compounds, including: • transport in soil, water, groundwater • volatility • ability to infiltrate liners or clay • consider other contaminants present.
Contamination levels	Ensure that the waste material contains less than the low persistent organic pollutants (POPs) content limits (LPCLs) set for the POPs – relevant in terms of managing wastes in accordance with the Stockholm and Basel Conventions.
Sensitive receptors	Determine whether any sensitive receptors are located on the site, adjacent to the site, or in close proximity. Implement measures to block pathways to sensitive receptors.
Climate – rainfall	Determine whether proposed location is on land prone to flooding, landslips, etc In high rainfall areas, stockpiles should be protected from rainfall at all times. Avoid temporary stockpiling during rainfall, or when rainfall is likely. Ensure stockpiles are not in stormwater flow paths.
Climate – wind	Characterise the wind direction, speed and frequency at the site. Prevent wind transport of stockpile material.

continues

Table F2 *continued*

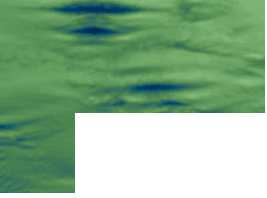
Short-term stockpile management framework – for temporary storage only – up to six months	
Risks	Design considerations and management requirements
Discharge to stormwater drains or waterways	Check as-built plans for infrastructure and verify accuracy of the plans. Locate all stormwater drains and waterways prior to planning the location of stockpiles. Protect stormwater drains and waterways from receiving contaminated runoff.
Risk to groundwater	Prevent contamination of permeable substrate. Locate stockpiles away from sensitive groundwater areas.
Any additional requirements	As necessary for each activity and site characteristic.



APPENDIX

G

**Example
PFAS
Management
Framework
for a water
utility**



Appendix G

Example PFAS Management Framework for a water utility

This deliberative document provides initial sample text to illustrate the key elements of a potential PFAS Management Framework that could be applied by a wastewater utility. It includes references to a model wastewater utility, Example Water, and a model environmental regulator, Example Environment Protection Authority, which are not intended to represent or resemble any specific organisation. As it is not possible to reflect the situation of every wastewater utility in one example framework, it will need to be adapted to address differences such as scale. The text in square brackets ([...]) is example text provided for readability purposes.

The example framework is not intended to be used as an enforcement tool but to provide an overview of potential considerations in the development of such a PFAS Management Framework. Any legal implications of development and implementation would need to be scoped on a case-by-case basis and are not considered further here.

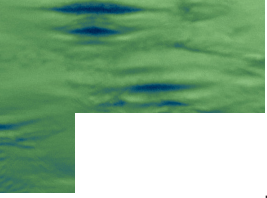
It is acknowledged that some water utilities may have already undertaken extensive PFAS risk assessment and/or sampling. Water utilities should consider the need for a PFAS Management Framework on a case-by-case basis accordingly.

The environmental regulator, along with other regulators where relevant, should be consulted for details of the specific requirements, guidelines and criteria applying in each jurisdiction. Where the example requirements, guidelines and criteria referenced here differ from those set by jurisdictions, the latter will take precedence.

G.1 Introduction

Example Water (EW) acknowledges that the sound environmental management of per- and polyfluoroalkyl substances (PFAS) in wastewater is an important responsibility.

This responsibility arises from the risks and uncertainties that science has identified regarding the mobility, persistence and effects that PFAS have on environmental values, also known as beneficial uses (this term is separate from beneficial reuse) or community values. Protection of environmental values, including freshwater and marine animals (such as air-breathing mammals) as well as other wildlife, is important to EW and to the whole community.



This framework sets out the key elements of effective management of PFAS in wastewater. It focuses on EW's core business of delivering wastewater services to the Example Region in order to maintain and improve quality of life for the community while protecting the local environment and beyond.

G.2 Governance

The [EW Board and senior leadership] have endorsed this framework as the authoritative reference for managing PFAS across EW's operations.

The PFAS National Environmental Management Plan (PFAS NEMP), agreed by Australian environment ministers, provides the expert guidance that underpins this framework. The framework is consistent with the [Month Year] version of the PFAS NEMP and will be reviewed within three months of any subsequent version being published.

The Example Environment Protection Authority (EPA) is the authority providing ongoing advice and direction on the PFAS NEMP, its application and any other PFAS management requirements within Example Jurisdiction (this term covers the relevant Commonwealth, state, territory and environment agency/authority as appropriate).

G.3 Purpose

The purpose of this framework is to support the sustainable management of PFAS across EW's operations and to ensure that EW is well positioned to anticipate and respond to PFAS-related issues.

The outcomes sought from implementing this framework include:

- all relevant legal and regulatory requirements are met
- consistency with the PFAS NEMP is achieved
- the health and safety of staff, customers and the general public are protected
- the ecosystem function, biodiversity, and amenity of receiving environments are protected
- the condition of wastewater treatment infrastructure and processes are maintained across the life cycle, including:
 - the ability to produce outputs acceptable for disposal and reuse
 - affordable disposal of infrastructure at the end of its working life
- the costs for acceptance of trade waste are appropriately understood and recovered.

G.4 Scope

This framework applies to all of EW's operations and services where PFAS inputs are to be managed. It addresses PFAS management at all stages of the wastewater treatment life cycle including:

- input stage – including trade waste and domestic waste
- processing stage – including infrastructure and biological treatment systems
- output stage – including products for beneficial reuse.

G.5 Risks

The following identification of the risks for EW that may be linked to PFAS in wastewater is consistent with guidance provided in the PFAS NEMP and additional advice from EW's industry partners and regulators, including the Example Jurisdiction EPA and the Example Jurisdiction Department of Health.

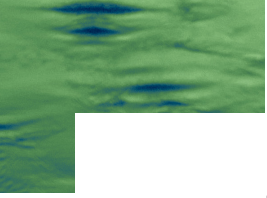
Recognising that scientific knowledge on PFAS is rapidly evolving, this is a point in time assessment as at [Month Year]. It will be regularly reviewed and updated in accordance with EW's corporate risk management processes.

G.5.1 Risk sources

The key source of risk addressed by this framework is the release of PFAS into the EW sewage network.

PFAS are known to be released constantly into Australian sewage networks at a relatively low background level due to a wide range of domestic and non-domestic activities (PFAS are present in a wide range of products. Other national processes outside of the PFAS NEMP are looking into options to reduce any environmental and/or human health risks associated with this. One such process is the National PFAS Position Statement). Consequently, the identification and prioritisation of risk sources is an important step in focusing control efforts on significant and readily actionable controls at the sources. At present there is limited evidence on the sources of PFAS in wastewater. Some Australian data indicates that trade waste from certain high-risk activities is likely to be a significant source of PFAS in wastewater, particularly for substances such as PFOS that are thought to be no longer in general use. Relevant management actions to address PFAS risks in relation to trade waste are discussed in [Section G.7.1](#) below.

The flow of PFAS through the wastewater system results in chronic contamination of wastewater infrastructure and the release of a mass load of PFAS, contributing to chronic exposure in the receiving environment.



Day-to-day flows are the key sources of PFAS risk. In addition, temporal and spatial fluctuations in PFAS concentrations above this level, including peak events, can occur due to specific businesses using or handling PFAS-containing products such as foam suppressants or aqueous film forming foam (AFFF). The resulting additional quantities may impact the effectiveness of biological treatment processes and other aspects of wastewater treatment plant (WWTP) operations, and environmental risks associated with the release of an increased mass load of PFAS (and potentially an increased PFAS concentration, depending on the management measures applied).

Over the past two decades, a widespread transition away from the use of PFAS-containing firefighting foam has taken place. However, some organisations have advised EW that PFAS-containing firefighting foam is still in use. Firefighting foam also contains a range of other substances that may pose a risk to WWTP biological treatment systems and to the environment.

An important consideration in relation to all of these PFAS risks is the significant uncertainties regarding the behaviour of PFAS, including the scientific evidence that PFAS precursors in WWTP influent may transform into persistent PFAS end products in effluent and biosolids.

The geographical distribution of PFAS use is an important consideration. Businesses using firefighting foam, like most other types of businesses linked to high-volume PFAS releases, are likely to be located in industrial areas. However, it is important to take into account that some businesses that use or handle high volumes of PFAS-containing products, possibly including car washes and laundries, are likely to be located in residential or commercial areas.

G.5.2 Risk assessment

The following model assessment of risks (Table G1) is a high-level summary to inform detailed risk assessments for each WWTP with its catchment area. It will be updated with additional information as these detailed risk assessments are developed.

Table G1 Example wastewater treatment plant risk assessment

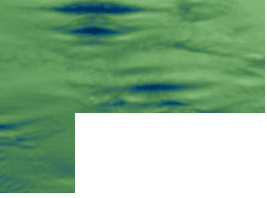
Example wastewater treatment plant risk assessment		
Hazardous event	Risk type	Consequence
Staff health and safety at risk due to elevated PFAS within sewage network including WWTP	WHS/OHS	Psychological distress Potential harm to health
Environment at risk from elevated PFAS in discharged effluent or any other emissions from WWTP	Environmental	Environmental harm
Beneficial reuse of effluent/recycled water affected due to elevated PFAS	Health	Potential harm to health
	Environmental	Environmental harm
	Financial	Financial costs
Beneficial reuse of biosolids/sludge affected due to elevated PFAS	Health	Potential harm to health
	Environmental	Environmental harm
	Financial	Financial costs
Biosolids/sludge disposal to landfill or other disposal method affected due to elevated PFAS	Health	Potential harm to health
	Environmental	Environmental harm
	Financial	Financial costs
Cost and/or feasibility of infrastructure disposal at end of life affected due to elevated PFAS	Financial	Financial costs
		Logistical burdens
Reputation and/or regulatory compliance affected due to elevated PFAS	Reputational	Financial costs
	Legal	Reputational harm

G.5.3 Risk prevention

The preventative measures identified to address these hazards are described in subsequent sections of this framework. The primary focus of risk prevention activity will be on minimising the key source of risk identified above (that is, the release of PFAS into the EW sewage network).

G.6 Monitoring and analysis

Monitoring of PFAS levels through systematic, catchment-based sampling and analysis is a critical element of responsive management to address PFAS in wastewater. The levels and types of PFAS in wastewater provide a



starting point to identify sources, risks and potential management actions for each wastewater catchment.

The monitoring program has been designed in consultation with the Example Jurisdiction EPA to align with the guidance in the PFAS NEMP. The aim is to generate a representative picture of PFAS and their potential impacts across EW's operations to inform preventative action.

G.6.1 Sampling

The sampling strategy targets relevant media. The following locations will be considered:

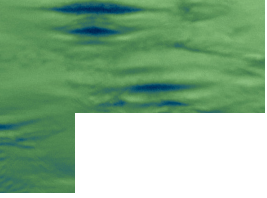
- influent from high-risk trade waste (and potentially other commercial) premises
- influent in the sewage network, stratified to separately identify sewage from domestic, general non-domestic and industrial catchments
- effluent at critical control points within WWTPs
- treated effluent and any other emissions discharged to the environment
- WWTP products for beneficial reuse prior to sale
- sites where beneficial reuse products have been used in the environment.

The sampling strategy, including the laboratory analytical methodology, for PFAS data is consistent with the PFAS NEMP and additional guidance issued by Example Jurisdiction EPA. The Example Jurisdiction EPA guidance requires testing for a standard set of 28 analytes comprising perfluoroalkyl acids (PFAAs) and selected PFAA precursors at a level of resolution relevant to the environmental values being protected. In addition, summative measures and holistic analytical methods, such as total oxidisable precursor (TOP) assay and non-target analysis, are used as required by regulators and to build a weight of evidence understanding of total PFAS loads and associated transformation within the sewage network.

Whenever possible, data held by EW on PFAS in wastewater is shared with the Example Jurisdiction EPA and the research community as a contribution to the scientific understanding of PFAS in the environment across Example Jurisdiction. Quality control and customer privacy protection procedures are applied before any PFAS-related data is released.

G.6.2 Catchment-based monitoring and analysis

For each WWTP managed by EW, the background levels of PFAS and patterns of variation over time are characterised. This may include using 24-hour composite influent samples collected as part of routine monitoring for higher risk WWTPs. Consideration is also given to the influence of seasonal and day-to-day weather patterns, with supplementary



data collected as needed if there are concerns about the quality and representativeness of the data originally collected.

WWTP monitoring data is supplemented with PFAS monitoring data from the upstream sewerage network. This consists of targeted sampling at junction points proceeding upstream along major sewerage lines to discharge points from specific areas of interest, such as residential suburbs, industrial estates, landfills, etc. As well as providing a general catchment-wide understanding of PFAS contamination, the analysis of upstream sampling will also assist EW to identify and work with industries and specific customers to address higher-risk PFAS contamination in trade waste discharges.

The WWTP and sewerage network data are then combined and analysed to improve the understanding of PFAS inputs and behaviour for each catchment and for prototypical urban, peri-urban and rural catchments within EW's service area. Further work will look at specific areas of interest such as [the major industrial estate at Example Meadows]. Data from ongoing monitoring is fed into the analysis to better understand PFAS trends over time including identification of improvements delivered by EW's targeted PFAS management activities.

G.7 Input stage

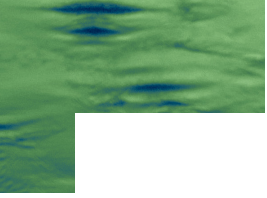
For the input stage of the wastewater system, the main PFAS intervention is source control. As well as standard measures to control known sources of contamination, such as trade waste agreements, EW recognises that customers often may not know that their premises are discharging PFAS to the wastewater system. EW will cooperatively work with customers to identify and address sources of unintentional and legacy PFAS pollution.

G.7.1 Trade waste controls

The initial focus of work for the input stage will be working with trade waste customers (that is, trades, businesses, and manufacturing sites), to identify and manage PFAS in trade waste.

Trade waste customers are responsible for managing PFAS in trade waste in accordance with the requirements set by EW and by relevant legislation or policies. The specific authority for EW to require its customers to take action on environmental contaminants, including PFAS, is established by the *Wastewater Act 2020* (Example Jurisdiction).

Customers are encouraged to raise any queries with EW about the availability of, and the conditions for, acceptance of PFAS-containing trade waste, and any concerns associated with the effect of this framework on their individual trade waste agreement. EW will also draw on guidance in



the PFAS NEMP to proactively identify and engage with industries and specific customers identified as being at risk of discharging PFAS to trade waste.

Key industries with the potential to be significant sources of PFAS in trade waste include:

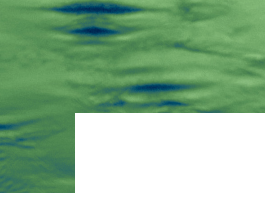
- airport operations
- landfill operations
- liquid waste collection and treatment operations (including tanker operations)
- aerospace, aviation and defence manufacturers and processors
- metal manufacturers and processors
- textile manufacturers and processors
- paper manufacturers and processors
- chemical manufacturers and processors
- vehicle manufacturers
- car retailers, car detailers and car washes
- commercial laundries and dry cleaners.

As outlined in the EW Trade Waste Management Plan, EW may use any or all of the following tools to support the appropriate management of PFAS by trade waste customers:

- trade waste agreements for customers with routine needs
- trade waste audits to identify issues
- trade waste improvement plans for customers with identified issues
- compliance orders for customers with recurring breaches
- potential withdrawal of trade waste services as a last resort.

Where potentially significant sources of PFAS are identified, EW will aim to work with affected customers to ensure trade waste discharge is consistent with the customer's trade waste agreement and EW's trade waste management policy. For significant or complex issues, it is likely that customers will need to seek professional advice from a consultant with specific expertise in PFAS management.

The risk of accidental PFAS contamination events, discharging significantly elevated levels of PFAS in the wastewater system, is not covered by the routine control measures described above. Consequently, EW also requires all trade waste customers who use or generate substances high in PFAS, such as fume suppressants, firefighting foam concentrate, foam and associated firewaters, to have measures in place to prevent these substances entering the wastewater system. A range of enforcement measures are employed to ensure compliance with these conditions, such as unannounced site visits and effluent sampling. EW recognises that not all emitters of PFAS contamination hold trade waste licenses. EW will work



with its customers, experts and regulators to identify risks associated with accidental PFAS contamination events and ensure measures are implemented to anticipate and manage any issues in this regard.

G.7.2 Domestic controls

The role of domestic wastewater as a vector for PFAS, mainly from consumer products, is also recognised. For legacy PFAS of high concern, such as perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS), domestic wastewater may not be a major source, although this is yet to be confirmed by field data. For PFAS still on the market in consumer products, however, domestic wastewater is highly likely to be a major source. In the short term, there is limited opportunity for EW or its domestic customers to identify or control PFAS in consumer products. The manufacturers and suppliers of consumer products, and the manufacturers and suppliers of the chemicals included in these products, bear the primary responsibility for taking action to reduce the levels of PFAS reaching domestic wastewater.

In the meantime, EW will draw on data from its monitoring program to build a better understanding of the contribution of domestic wastewater to the burden of PFAS, including temporal and spatial variation, types of PFAS and total PFAS load. This data will contribute to assessment of the risks arising from this source and the identification of possible management responses.

In consultation with the Example Jurisdiction EPA, EW will actively consider the suitability of new technologies and any other opportunities that may arise to assist with controlling PFAS in domestic wastewater.

G.8 Processing stage

For the processing stage of wastewater treatment, a range of strategies are being employed to better understand and manage PFAS impacts. [Further details of the measures planned and in place at each WWTP are provided in the WWTP Environmental Management Plans which are available on the EW website].

Routine monitoring, as described above, is a critical element of managing PFAS risks in the processing stage. It provides the baseline data enabling EW to understand PFAS flows through its systems under business-as-usual conditions and to identify significant deviations from these patterns. This in turn informs follow-up actions, such as cost recovery from polluters to cover the costs of measures including:

- additional environmental sampling
- diversion of effluent

- environmentally sound disposal of PFAS-contaminated material that would otherwise go to beneficial reuse.

Over the longer term, EW will draw on routine monitoring to identify any emerging trends in PFAS levels within the processing stage of its operations.

As limited information is currently available to inform action at the processing stage to address the chronic risks associated with the day-to-day flow of PFAS, a key focus for the first phase of this work is addressing the acute risks to wastewater processing that may arise from short-term pulses of elevated PFAS, such as major contamination events. This is discussed in more detail below.

EW will continue to work with regulators and experts to review options to better manage PFAS contamination across the board at the processing stage. A key focus for this work will be identifying affordable, efficient and scalable infrastructure or other technologies to control PFAS before they reach the environment. This consideration will take place in the context of EW's broader capital investment strategy informed by a cost benefit analysis and confirmation of appropriate cost recovery arrangements.

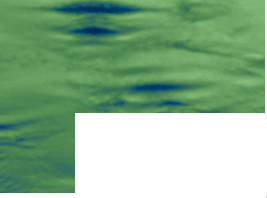
The mix of strategies selected will be consistent with local Example Jurisdiction regulations or policies and may reflect considerations such as:

- protection of the environment
- protection of biological treatment systems. EW has identified a knowledge gap in relation to the impacts of PFAS, including firefighting foam effluent, on biological treatment systems and is contributing to research on this issue
- prevention of contamination that could impact on the cost and logistical burden of appropriate disposal of sewage infrastructure at the end of its working life.

G.8.1 Managing processing impacts from major contamination events

A key immediate focus for PFAS management in the processing stage is ensuring that EW has robust strategies in place to effectively identify and respond to the impacts of major PFAS contamination events.

The foundation of effective preparation for major PFAS contamination events is maintaining strong working relationships with trade waste customers, particularly those with significant fire protection requirements. This ensures that EW will be immediately alerted to a potential contamination event as soon as it is discovered by the responsible customer, allowing EW to immediately implement management actions to minimise impacts on processing, treatment, effluent discharge and beneficial reuse due to elevated PFAS levels.



If a major contamination event does occur, EW will consider the full range of response strategies in consultation with the Example Jurisdiction EPA. Possible strategies, depending on the severity of contamination, could include diversion of PFAS-contaminated wastewater from specific sites or sewer lines, altered processing arrangements within the affected WWTP to prevent or minimise PFAS impacts such as reduced treatment effectiveness, and diversion to environmentally sound disposal or destruction of PFAS-contaminated materials.

G.9 Outputs stage

The outputs stage of PFAS management is a significant focus for EW, as this is the stage where any PFAS contamination that is not successfully controlled within the wastewater system reaches receiving environments. It is therefore the final opportunity for EW to take action to protect environmental values from any PFAS-related risks.

The management actions to be implemented in this stage are designed to address the risks of PFAS across all WWTP outputs including:

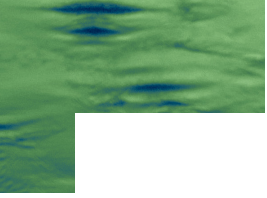
- effluent discharged to fresh, estuarine and marine ecosystems
- recycled water used in the built environment or in products, discharged to stormwater systems, applied to terrestrial ecosystems, or injected into groundwater
- biosolids applied to terrestrial ecosystems or in products
- biosolids disposed to landfill or other forms of treatment such as incineration.

The detailed requirements set by Example Jurisdiction EPA for management of PFAS in effluent, recycled water and biosolids are provided on the EW website and may be updated from time to time.

G.9.1 Standards and principles

The PFAS NEMP provides extensive guidance on managing PFAS in the environment, including standards and criteria for a wide range of PFAS-containing substances to protect environmental values. It also refers to and is consistent with the detailed guidance provided in the National Water Quality Management Strategy (NWQMS) (Australian Government 2019b) and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (WQG) (ANZG 2018) on achievement of catchment water quality objectives as they relate to toxicants such as PFAS that may reach aquatic environments.

Although common principles apply across the board to responsible management of PFAS risks at the outputs stage, it is also critical to consider the specific characteristics and values of the receiving environment. EW



works closely with the Example Jurisdiction EPA and Parks and Wildlife Services to tailor management actions to ensure these actions are protective of environmental values. EW also works with the Commonwealth Department of Climate Change, Energy, the Environment and Water (DCCEEW) in relation to Matters of National Environmental Significance (MNES).

G.9.2 Effluent discharged to aquatic ecosystems

The monitoring program described above is the foundation of effective identification and management of PFAS risks in effluent discharged to aquatic ecosystems.

Consistent with the PFAS NEMP, EW aims to reduce the concentration and load of PFAS in effluent as low as possible and, in the long term, towards the limit of detection for PFOS, PFOA and PFHxS, and any other PFAS identified as being of high concern (note, however, that due to technical advances the limit of detection may be reduced so low that this is impractical). This reflects the fact that PFAS are anthropogenic contaminants that biological systems, including plants, animals and humans may accumulate and are not adapted to deal with. Consequently, the potential long-term risks of PFAS to the environment and/or human health are not known.

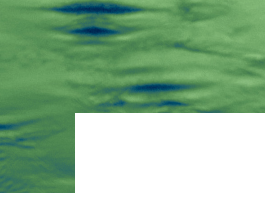
In practice, EW aims to work towards the reduction of PFAS in effluent over the long term, in partnership with the Example Jurisdiction EPA, other stakeholders and the community, to work towards achieving water quality and environmental management objectives. This level of protection recognises the persistent, mobile and bioaccumulative nature of PFAS consistent with the NWQMS.

The exception is the Example Bay catchment, where the Example Jurisdiction EPA has set a site-specific guideline value adapted to the environmental values in that catchment.

As discussed above, one option for minimising the level of PFAS in effluent is investing in trialling and implementing effective WWTP-scale treatment technologies as they are introduced to the marketplace. EW will continue to work with the Example Jurisdiction EPA and industry organisations to consider and evaluate treatment technology options.

G.9.3 Recycled water used in the built environment or in products, discharged to stormwater systems, applied to terrestrial ecosystems or injected into groundwater

The use of recycled water requires careful management to avoid contamination of sensitive environments or food webs with repeated applications of persistent substances, including PFAS. The standards and



criteria provided in the PFAS NEMP and the NWQMS for environmental water and water recycling provide the basis for sound management actions.

At present, EW does not direct significant quantities of treated effluent to beneficial use as recycled water. Where recycled water is already being used, EW is working with the Example Jurisdiction EPA to understand PFAS management and impacts on environmental values from recycled water. Options are also being explored for water recycling in several additional locations.

In consultation with the Example Jurisdiction EPA, EW will consider what trials will be conducted before water recycling is rolled out at scale. This may include testing of receiving soils, groundwater and downstream environments for PFAS contamination before the application of recycled water, testing of recycled water, and testing of receiving soils, groundwater and downstream environments after the application of recycled water across several years.

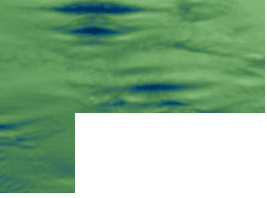
If water recycling is approved as a broadscale use of effluent, ongoing monitoring will be conducted to ensure that its use in this way remains safe. The locations, volumes and monitoring results for recycled water use will be precisely recorded. This will enable the swift identification of and response to any emerging issues.

The use of recycled water in the built environment (that is, residential, commercial and industrial settings) and the discharge of recycled water to stormwater and groundwater (that is, aquifer recharge) are not known to occur in EW's management area. Should these measures be proposed, EW will work with the proponent and the environmental regulator to ensure that the environmental and/or human health risks of the proposal are carefully assessed, including risks associated with PFAS accumulation at the point of use and in downstream receptors, and that any financial impacts are fully cost-recovered.

The beneficial reuse of recycled water in products, such as soil conditioners, is a matter for the Example Jurisdiction EPA. However, EW recommends against this use.

G.9.4 Biosolids applied to terrestrial ecosystems or in products

The considerations described above for recycled water regarding transport and dispersal of PFAS contamination also apply to biosolids. Consequently, the standards and criteria provided in the PFAS NEMP for direct and indirect soil exposure, and the additional guidance on reuse of soil with low PFAS levels (including PFAS in leachate), should be taken into account for biosolids. Further information and specific criteria are provided [on the EW website] and will be supplemented with additional information under development. This is expected to include a biosolids lifecycle risk



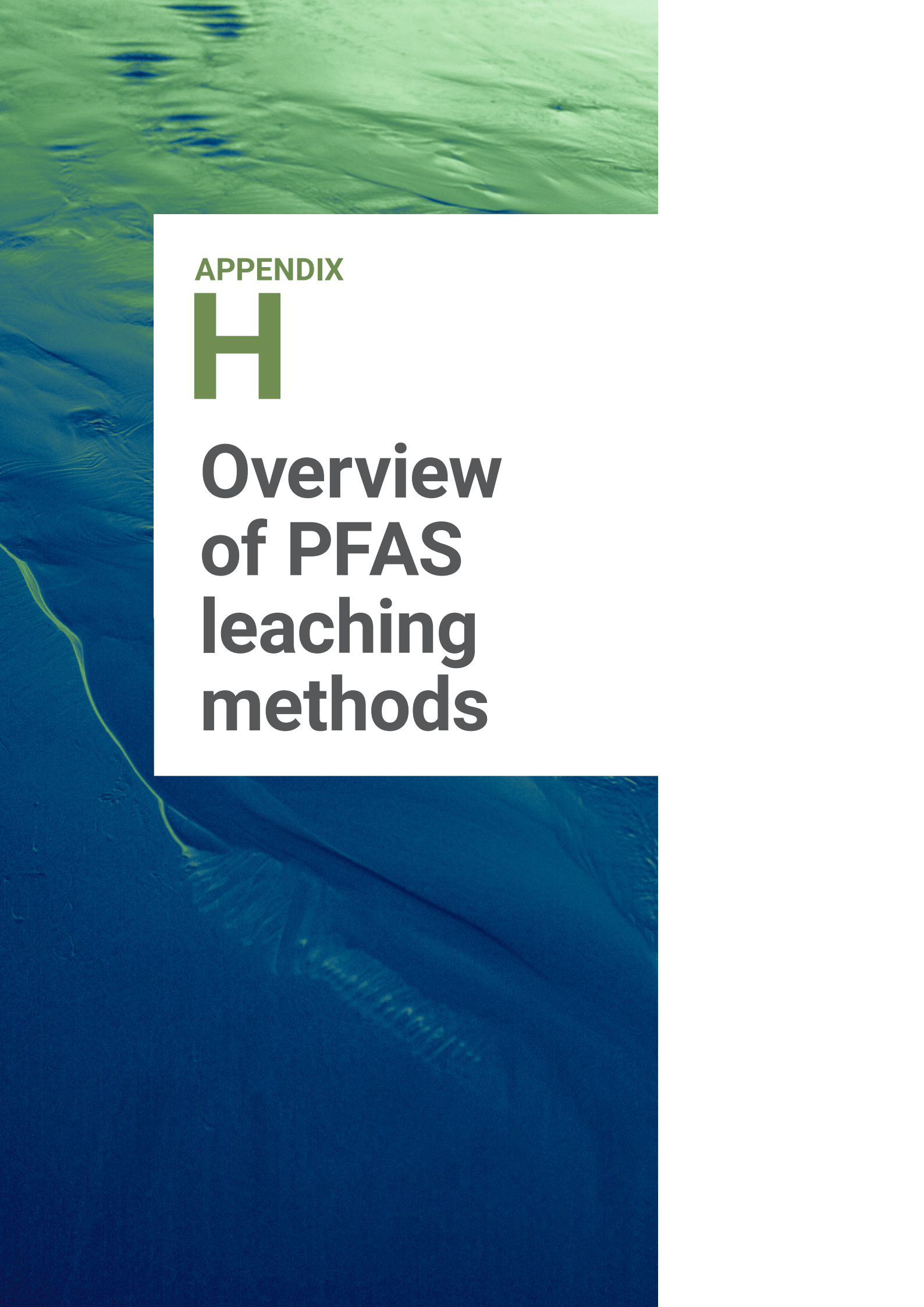
assessment and an inventory of PFAS in biosolids produced across the EW WWTP network.

The rationale for requiring management actions for biosolids consistent with the PFAS NEMP is the behaviour of PFAS in solid materials such as soil. Although biosolids are intended to remain in the location where they are applied as a soil conditioner, it is well recognised that PFAS leach out of soil and other solid materials to reach groundwater and aquatic ecosystems off-site. As PFAS behave differently than other contaminants, existing management controls are unlikely to be sufficient. There is the potential for a proportion of sedimentary particles from the biosolids to be transported off site in most receiving environments and these are likely to carry adsorbed PFAS and other contaminants.

G.9.5 Biosolids disposed to landfill or other disposal

The disposal of biosolids to landfill or other forms of waste disposal is at the discretion of the operator of the waste facility. The PFAS NEMP provides further guidance, including national criteria for landfill acceptance of PFAS-contaminated material. Authoritative guidance, oversight and licensing on this issue is provided by the Example Jurisdiction EPA.

In some locations, EW operates on-site landfills or incineration facilities. These are managed in accordance with the PFAS NEMP and all available guidance. For incineration facilities, the combustion temperature and duration required to destroy PFAS is a critical consideration. The incineration facilities operated by EW are licensed to destroy PFAS as they achieve combustion temperatures and durations that are consistent with the current advice provided by the Example Jurisdiction EPA. The beneficial reuse of the outputs from the incineration process is managed in accordance with the guidance on biosolids above.



APPENDIX

H

Overview of PFAS leaching methods

Appendix H

Overview of PFAS leaching methods

Table H1 Overview of laboratory-based leaching methods commonly applied and commercially available in Australia

Standard methods are marked with #. Refer also to [Section 18.3](#).

Leaching method and description	Potential application*	Advantages and limitations
Batch test – standard method ASLP# Australian standard leaching procedure Method: AS4439.3:2019 Equilibrium based batch leaching method: 18h shaking with reagent water (pH 2.9, 5 9.2 or unbuffered reagent water) at 20:1 liquid-to-solid ratio The test is primarily designed for waste characterisation in Australia (refer to Section 14.6 Landfill acceptance criteria)	For PFAS this test has also been used in: Classification of waste for landfill disposal Site assessments Soil reuse evaluation Evaluation of remediation effectiveness	Advantages • Conservative assessment and standardised procedure which allows comparisons between investigations • Can adjust pH (2.9, 5, 9.2 or unbuffered) depending on scenario being assessed • Leaching using dry soil samples may be more conservative than using field-fresh samples (Lange et al. 2020). As consistency is important, drying samples to determine liquid-to-solid ratio would avoid variability in results due to different moisture contents in samples • Useful when assessing leachability of soil if soil is being re-located/moved to a different location (compared with field-based methods used to monitor potential leaching in-situ) • Low cost and available as a standard laboratory test

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Batch test – standard method ASLP# Australian standard leaching procedure Method: AS4439.3:2019 Equilibrium based batch leaching method: 18h shaking with reagent water (pH 2.9, 5 9.2 or unbuffered reagent water) at 20:1 liquid-to-solid ratio The test is primarily designed for waste characterisation in Australia (refer to Section 14.6 Landfill acceptance criteria)	For PFAS this test has also been used in: Classification of waste for landfill disposal Site assessments Soil reuse evaluation Evaluation of remediation effectiveness	Limitations • For PFAS investigations, centrifugation is recommended for separation of particulates; however specific guidance on the appropriate centrifugation conditions is lacking, which may lead to inconsistencies between laboratories • Not reflective of most in-situ undisturbed environmental conditions due to the use of dilution and shaking, resulting in aggressive extraction conditions – destroys the soil/solid structure • Not applicable to encapsulated waste that cannot be reduced to the specified maximum particle size, without breaking integrity of encapsulation • Limited in consideration of leaching kinetic due to aggressive leaching procedure and absence of temporal sampling • Typically undertaken under saturated conditions and does not account for partitioning to the air/water interface under unsaturated conditions • Careful consideration of the specific application is needed for comparison of the leachate concentration to specific trigger levels or water quality guidelines • Due to the conservatism, dilution factors are often proposed to account for mixing with groundwater/surface water, and these are uncertain and unvalidated • The high liquid-to-solids ratio, typically 20:1, is much greater than typical rainfall volumes and hence results are likely to underestimate stormwater concentrations in highly leachable material

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Batch test – standard method TCLP# Toxicity characteristic leaching procedure (US EPA) Method: US EPA 1311 Equilibrium based batch leaching method: 18h shaking with acetic acid buffer (pH 2.9 or 4.9) and reagent water at 20:1 liquid-to-solid ratio This method is typically used in the classification of waste for disposal in a landfill containing putrescible material. The test is designed to simulate leaching from a landfill		See advantages and limitations for ASLP Additional limitations include: • Assesses leaching in acidic conditions only, where sorption of PFAAs is greatest • Not suitable for alkaline wastes • Can be modified to use leach solution relevant to simulate circumstances of concern
Batch test – standard method SPLP# Synthetic precipitation leaching procedure (US EPA) Method: US EPA 1312 Equilibrium based batch leaching method: 18h shaking with unbuffered acid mixture (pH 4.2 or 5.0) and reagent water at 20:1 liquid-to-solid ratio This method is typically used in the classification of waste for disposal in a landfill containing putrescible material. The test is designed to simulate acidic conditions and leaching from waste after exposure to rainfall		See advantages and limitations for ASLP Additional limitations include: • Assesses leaching in acidic conditions, where sorption of PFAAs is greatest • Not suitable for alkaline wastes

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Batch test – standard method MEP# Multiple extraction procedure (US EPA) Method: US EPA 1320 Mass transfer-based batch leaching method in acidic conditions, repetitive batch extraction with agitation at 20:1 liquid-to-solid ratio (24h × 10 times) The test is designed to simulate 1000 years containment in a landfill, simulating repetitive rain events	For PFAS this test has also been used in: Soil reuse evaluation Evaluation of remediation effectiveness Long-term remediation performance testing	Advantages • Simple method (that is, batch extraction at one leaching condition) • Provides some information on the rate of desorption • Useful in assessment of long-term fate • More representative of field leaching than single batch tests due to the replacement of the extractant solution Limitations • Need to have well-homogenised sample, especially if small sample size is used • Limited in conditions it simulates; aggressive leaching - destroys the soil/solid structure • Higher cost and more labour intensive than other standards batch tests • Can overestimate total leaching due to high liquid-to-solid ratios and harsh extraction conditions • Not suitable for alkaline wastes • Not applicable to encapsulated waste that cannot be reduced to the specified maximum particle size, without breaking integrity of encapsulation • Typically undertaken under saturated conditions and does not account for partitioning to the air/water interface under unsaturated conditions • Careful consideration of the specific application is needed for comparison of the leachate concentration to specific trigger levels or water quality guidelines • Due to the conservatism, dilution factors are often proposed by industry/consultants to account for mixing with groundwater/surface water, and these are uncertain and unvalidated and therefore not accepted by many environmental regulators

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Batch and column tests – standard method LEAF# Leaching Environmental Assessment Framework (US EPA) Integrated set of testing methods which comprise of both static (batch) and column leaching tests under various pH conditions and liquid-to-solid ratio scenarios (see details below). The test is designed to work individually or to be integrated as a set LEAF 1313 (US EPA 1313) Liquid-solid partitioning as a function of extract pH using a parallel batch extraction procedure LEAF 1314 (US EPA 1314) Liquid-solid partitioning as a function of liquid-to-solid ratio for constituents in solid materials using an up-flow percolation column procedure LEAF 1315 (US EPA 1315) Mass transfer rates of constituents in monolithic or compacted granular materials using a semi-dynamic tank leaching procedure LEAF 1316 (US EPA 1316) Liquid-solid partitioning as a function of liquid-to-solid ratio in solid materials using a parallel batch procedure	Specifically designed for inorganic chemicals, but has been used for PFAS in: Assessing worst-case leaching Soil reuse evaluation Evaluation of remediation effectiveness Assessment of leaching closer to field conditions (site investigations) (LEAF 1314) Suitable for monolithic and compacted materials (LEAF 1315)	Advantages • Flexible approach to evaluating release of chemicals under different conditions where each method simulates a variety of conditions • LEAF 1313: leaching tested at a range of pH values (for example, pH relevant to site can be chosen) • LEAF 1314: gives an insight to leaching kinetics through use of a column • LEAF 1315: only standard method for monolithic/compacted solids and can be used for encapsulated waste • LEAF 1316: provides eluate solutions over a range of liquid-to-solid ratios (for example, changes in precipitation, wet-dry cycles, size of contaminated area vs underlying groundwater aquifer) Limitations • Generally, LEAF assessments are more costly and time-consuming (hindering quick turnaround times) • LEAF 1313: assumes that pH is a key factor controlling leaching of the contaminant from the solid media. While pH has influence on PFAS leaching, more work is needed to determine if it is the single most important factor that will influence leaching of PFAS • LEAF 1313: cost and labour intensive (pH 2-12) and generates a lot of waste but can be limited to three analysis (pH) points (acidic, natural and alkaline). May not be ideal if sample size is limited. • LEAF 1315: time consuming method (69 days) • LEAF 1316: liquid-to-solid ratio can be too low for some samples presenting analytical challenges

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Column leaching assessments Soil is packed into a column and leaching fluid (buffer, surface water, groundwater etc) is percolated through the soil at a constant flow rate, either in an up-flow or down-flow mode. The fractions are collected over a specified time and analysed The test is designed to evaluate release of chemicals under either local equilibrium or advection conditions as a function of time	For PFAS this test has been used to investigate leaching and transport from contaminated soils	Advantages • Can simulate leaching closer to in-situ conditions • Provides information on the rate of desorption • Provides a more accurate representation of the concentration of the target analyte in the leachate • Test environment can be adapted to some field conditions (pH, temperature, salinity, etc) • Can be run in saturated or unsaturated conditions to assess the impact of air/water interface • Less aggressive leaching method than batch leaching assessments • Intact soil cores can be used for an assessment of leaching closer to field conditions Limitations • Time consuming, labour intensive and produces many samples for analysis • Methods can be technically challenging • Not practical for routine assessments • Requires more complex interpretation of the data than batch experiments • Relationship between batch and column studies is unclear

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Non-standardised batch tests Non-standardised or modified methods with varying liquid-to-solid ratios, pH, variable extraction times, with or without tumbling Modified methods have not been listed but have varying sample preparation (homogenisation, tumbling sample or saturating sample)	For PFAS this test has also been used in: Site investigations Assessment of remediation performance Assessing worst case leaching Assessing leaching closer to field conditions	Advantages • Simple method, quick and easy to perform • Test environment can be adapted to some field conditions (pH, temperature, salinity, etc) • Liquid-to-solid ratios can be chosen • Can be run in static mode (such as ponding or one-time saturation simulations) Limitations • A non-standardised approach cannot easily be compared to other leaching test results • Can be adjusted to consider dilution and shaking depending on objectives • Any processing of the data to account for aspects of the protocol should be undertaken with care and in accordance with appropriate guidance • Need to have well-homogenised sample, especially if small sample size is used • Limited in consideration of leaching kinetic • Typically undertaken under saturated conditions and does not account for partitioning to the air/water interface under unsaturated conditions • Not applicable to encapsulated waste that cannot be reduced in particle size without breaking integrity of encapsulation • Careful consideration of the specific application is needed for comparison of the leachate concentration to specific trigger levels or water quality guidelines • Due to the conservatism, dilution factors are often proposed by industry/consultants to account for mixing with groundwater/surface water, and these are uncertain and unvalidated and therefore not accepted by many environmental regulators

continues

Table H1 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Static leaching tests Assessment of leaching from a surface such as through ponding experiments, where leaching fluid can be renewed to simulate multiple wet-dry cycles (Baduel et al. 2015) Assessment of leaching from a solid through one-time saturation followed by separation (Rayner et al. 2022)	For PFAS these tests have been used to investigate leaching that is more representative of field conditions	Advantages • Can be adapted to situations encountered in the field • Can be used to test leaching from contaminated infrastructure without modifying the integrity of the sample • Can provide information on the rate of desorption • May provide a more realistic measure of leachable PFAS Limitations • No standardised protocols are available • Not practical for routine assessments (ponding experiment)

* Jurisdictions may have specific requirements for the use of listed methods

Table H2 Overview of field-based leaching methods commonly applied and commercially available in Australia

Refer also to [Section 18.3](#)

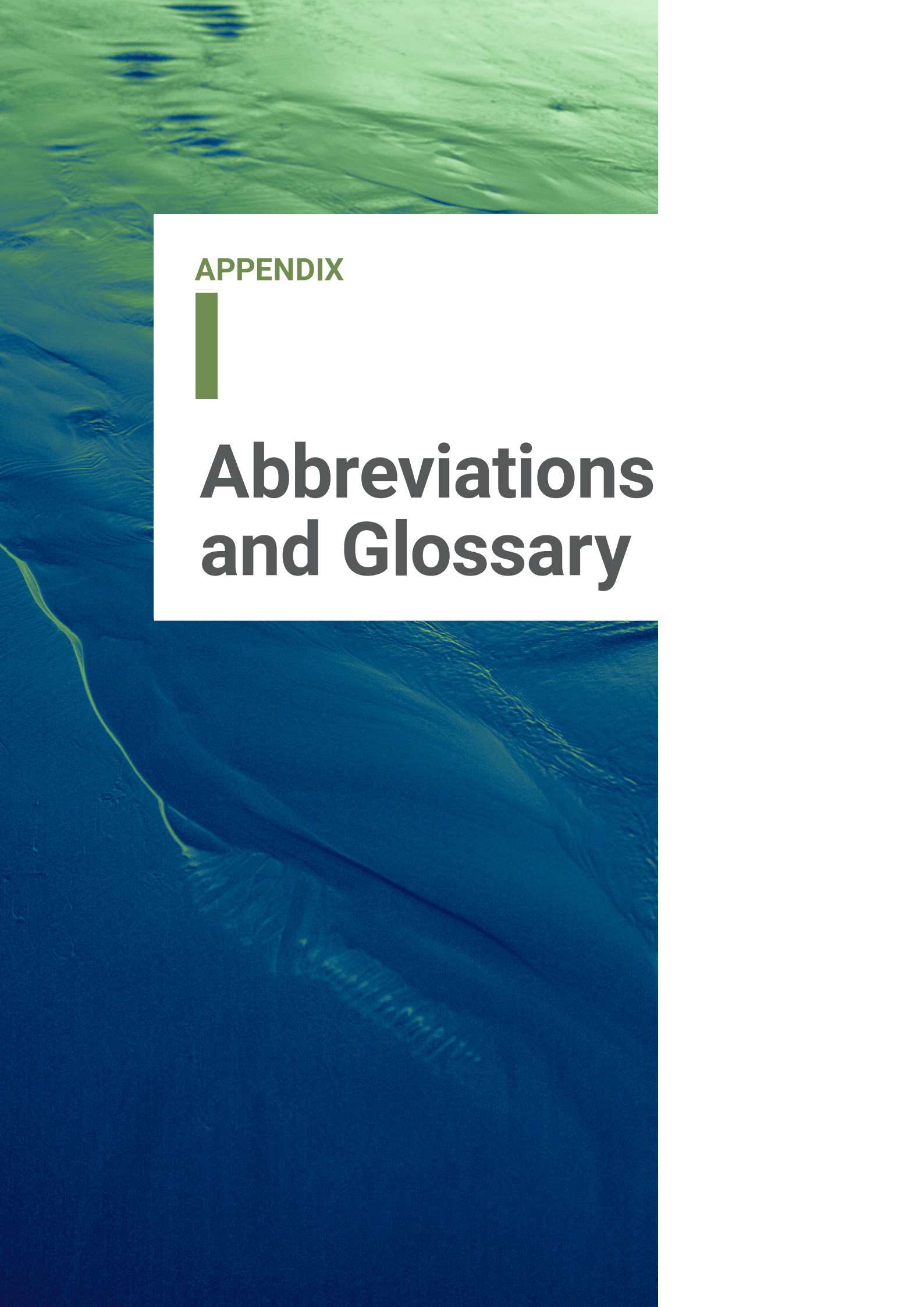
Leaching method and description	Potential application*	Advantages and limitations
Lysimeter A lysimeter measures water movement in a soil and can be used to collect soil porewater	Can be used to investigate long-term leaching of PFAS or on-site assessments Can be used to gain an understanding of soil pore water concentrations	Advantages • Able to provide information on leaching under field-relevant conditions, such as water infiltration rates and local climate, as well as soil/landscape situation • Allows investigation of vertical transport of PFAS directly in the field • The solid structure can be maintained and more accurately reflect actual conditions and concentration of the target analyte in the leachate • Can provide rate of leaching • Can capture real-time events and seasonal conditions • Useful in the investigation of contaminated infrastructure/soils, as lysimeters can be installed in flow path from source zone • An understanding of total mass flux can allow for targeted remediation on-site Limitations • There are different types of lysimeters (for example, suction and drainage), and these are not directly comparable. Lysimeter choice will have different implication/outcomes • Requires more considerations to interpret the data than batch experiments • Guidance on the number of lysimeters required, sampling depth and frequency to adequately characterise porewater concentrations is lacking. Therefore, clear reporting on methods, process and data interpretation are required to consider outcomes • Placement and type of lysimeter used needs to be carefully considered based on the objective, as well as data interpretation • Understanding of landscape and soil types is required to ensure preferential flow paths are captured in the sample design • Relationship between lysimeter, batch and column studies are unclear

continues

Table H2 *continued*

Leaching method and description	Potential application*	Advantages and limitations
Pilot-scale leaching Leaching assessments at a larger scale, for example using trays of soil that can be irrigated to simulate rainfall, or sampling water runoff directly in the field or from a simulation experiment	Can be used to investigate leaching from soil simulating field conditions Can be used to determine runoff concentrations	Advantages • Collection of runoff water in the field is relatively easy • Allows for gaining an understanding of the horizontal flow pathways and site dynamic • Can help to identify surface soils that contribute to surface water contamination through rainfall runoff • Can capture real-time events and seasonal conditions • An understanding of the contribution of surface runoff to total mass flux can allow for targeted remediation on-site • Useful in the investigation of contaminated infrastructure, as samples do not need to be crushed Limitations • Requires more interpretation of the data than batch experiments • Understanding of landscape and material/soil types is required to ensure preferential flow paths are captured in the sample design • No standard protocols are available. Therefore, clear reporting on methods, justification of approach, quality assurance, process and data interpretation are required to consider outcomes

* Jurisdictions may have specific requirements for the use of listed methods



APPENDIX



Abbreviations and Glossary

Appendix I

Abbreviations and Glossary

See also the list of PFAS abbreviations in [Appendix A](#).

Table I1 Abbreviations

Abbreviation	Meaning
µg	micrograms (10 ⁻⁶ g)
µm	microns
AEP	annual exceedance probability
AFFF	aqueous film-forming foam
AICIS	Australian Industrial Chemicals Introduction Scheme
ALUM	Australian Land Use and Management Classification
AOF	adsorbable organic fluorine
APHA	American Public Health Association
ASC NEPM	National Environment Protection (Assessment of Site Contamination) Measure
ASLP	Australian Standard Leaching Procedure
ASTM	Former American Society for Testing and Materials, now ATSM International
BAF	bioaccumulation factor
BAT	best available techniques
BEP	best environmental practices
BMF	biomagnification factor
Br	bromine
BSAF	biota-sediment accumulation factor
bw	body weight
C	carbon
CAS RN	Chemical Abstracts Service Registry Number
CCD	charge-coupled device
Cl	chlorine
CLBAR	contaminant limited biosolids application rate
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment

continues

Table I1 *continued*

Abbreviation	Meaning
CRM	certified reference material
CSM	conceptual site model
Cth	Commonwealth
DCCEEW	Australian Government Department of Climate Change, Energy, the Environment and Water
DER	Former Western Australian Department of Environment Regulation
DES	Queensland Department of the Environment and Science
DGV	default guideline value
DoEE	Former Australian Government Department of the Environment and Energy
DPE	New South Wales Department of Planning and Environment
dw	dry weight
ECCC	Environment and Climate Change Canada
ECF	electrochemical fluorination
EMP	environmental management plan
enHealth	Environmental Health Standing Committee of the Australian Health Protection Principal Committee
EOF	extractable organic fluorine
EOW	end of waste
EPA	Environmental Protection Agency/Environment Protection Authority
EPBC Act	<i>Environment Protection and Biodiversity Conservation Act 1999</i> (Commonwealth)
EqP	equilibrium partitioning coefficient
F	fluorine
FOGO	food organics and garden organics
FSANZ	Food Standards Australia New Zealand
g	gram
GAC	granular activated carbon
GC/MS	gas chromatography/mass spectrometry
GIS	geographic information system
H	hydrogen

continues

Table I1 *continued*

Abbreviation	Meaning
HAIL	Hazardous Activities and Industries List
HBGV	health-based guideline value
HDPE	high-density polyethylene
HEPA	Heads of EPA Australia and New Zealand
HHRA	human health risk assessment
HHERA	human health and ecological risk assessment
HIL	health investigation level
HR-MS	high resolution mass spectrometry
I	iodine
IBC	intermediate bulk container
IChEMS	Industrial Chemicals Environmental Management Standard
ISCO	in-situ chemical oxidation
ISO	International Standards Organisation
ITRC	Interstate Technology Regulatory Council
kg	kilogram
km	kilometre
K_d	soil/sediment partitioning coefficient
K_{oc}	organic carbon partitioning coefficient
K_{ow}	octanol-water partition coefficient
L	litre
LC-MS/MS	liquid chromatography - tandem mass spectrometry
LC-QToF-MS	liquid chromatography quadrupole time-of-flight mass spectrometry
LCDB	Land Cover Database
LEAF	Leaching Environmental Assessment Framework
LEAF 1313	Leaching Environmental Assessment Framework Method 1313
LEAF 1314	Leaching Environmental Assessment Framework Method 1314
LEAF 1315	Leaching Environmental Assessment Framework Method 1315

continues

Table I1 *continued*

Abbreviation	Meaning
LEAF 1316	Leaching Environmental Assessment Framework Method 1316
LOAEL	lowest observed adverse effect level
LOC	loss of containment
LOD	limit of detection
LOQ	limit of quantification
LOR	limit of reporting
LPCL	low POP content limits
MASCC	maximum allowable soil contaminant concentration
MCW NEPM	National Environment Protection (Movement of Controlled Waste between States and Territories) Measure
MEP	multiple extraction procedure
mg	milligrams (10^{-3}g)
mL	millilitre
ML	maximum limit
mm	millimetre
MNES	Matters of National Environmental Significance
MOS	margin of safety
MSW	municipal solid waste
MWOO	mixed waste organic outputs
NCWG	National Chemicals Working Group
NEMP	National Environmental Management Plan
NEPC Act	<i>National Environment Protection Council Act 1994</i> (Commonwealth)
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
ng	nanograms (10^{-9}g)
NHMRC	National Health and Medical Research Council
NIST	National Institute of Standards and Technology
NMI	National Measurement Institute
NSW	New South Wales
NT	Northern Territory

continues

Table I1 *continued*

Abbreviation	Meaning
NWQMS	National Water Quality Management Strategy
NZ	New Zealand
NZIoC	New Zealand Inventory of Chemicals
OC	organic carbon
OECD	Organisation for Economic Co-operation and Development
OHS	occupational health and safety
p	vapour pressure
PAC	powdered activated carbon
PAH	polycyclic aromatic hydrocarbon
PC99	99% species protection concentration
PFAS	per- and polyfluoroalkyl substances – refer to Appendix A for information and abbreviations on compounds within the PFAS chemical family
PIGE	particle induced gamma emission
pK _a	acid dissociation constant
PMP	PFAS Management Plan
PNEC	predicted no effect concentration
POP	persistent organic pollutant
POPRC	Persistent Organic Pollutants Review Committee
PPE	personal protective equipment
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RM	reference material
S	solubility
SA	South Australia
SAQP	sampling and analysis quality plan
SDS	safety data sheet
SPE	solid phase extraction
SPLP	synthetic precipitation leaching procedure

continues

Table I1 *continued*

Abbreviation	Meaning
SS	suspended solids
SSD	species sensitivity distribution
T _b	boiling point
T _m	melting point
TCLP	toxicity characteristic leaching procedure
TDI	tolerable daily intake
TOC	total organic carbon
TOF	total organic fluorine
TOP	total oxidisable precursor
tPOD	transcriptomics points-of-departure
UNEP	United Nations Environment Programme
UV	ultraviolet
WHS	work health and safety
WQG	Water Quality Guidelines (Australian and New Zealand Guidelines for Fresh and Marine Water Quality)
ww	wet weight
WWTP	wastewater treatment plant

Table I2 Glossary

Unless a contrary intention appears elsewhere in the PFAS NEMP, the following definitions apply. Note that the meaning of each term will take its meaning from the context in which it is used in the PFAS NEMP.

Term	Definition
adsorption	adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to a surface
ambient (concentrations)	The distribution, concentrations, and types of PFASs present in a defined area or region The term 'ambient' is used for PFAS rather than 'background', as PFAS are not naturally occurring and so there are no naturally occurring 'background' concentrations of PFAS in the environment (for example, see Schedule B1 and B5b of the ASC NEPM)
ambient monitoring	monitoring program producing chemical, physical and/or biological condition data

continues

Table I2 *continued*

Term	Definition
analyte	the chemical being measured in a sample
aqueous film-forming foam	a type of PFAS-containing firefighting foam product, commonly known by its acronym AFFF – see also the definition for firefighting foam
aquifer	underground layer of permeable rock, sand or gravel that is saturated and sufficiently permeable to store and transmit quantities of water
attenuation	reduction in contaminant concentration through natural processes such as ion exchange, chemical precipitation, adsorption, filtration, biodegradation and hydrodynamic dispersion
background, natural background (concentrations)	The naturally occurring concentrations of substances present in the local area of a site (see Section 3 of the ASC NEPM) The term ‘ambient’ is used for PFAS rather than ‘background’, as PFAS are not naturally occurring and so there are no naturally occurring ‘background’ concentrations of PFAS in the environment (for example, see Schedule B1 and B5b of the ASC NEPM)
beneficial uses	environmental values and human activities that need protection from the effect of pollution and waste
beneficial reuse	Beneficial reuse is ‘reusing a material – that would otherwise be discarded – in a manner that uses its inherently beneficial properties’ Note: Merely diluting a waste into products to dispose of the waste or contaminate the product up to a PFAS quality limit is not beneficial reuse
bioaccumulation	accumulation of a substance in organisms from all routes of exposure so that the concentration of the substance in or on the organism is increased relative to the concentration in the surrounding medium
bioavailability	proportion of a chemical substance that is available to an organism for uptake through, or adsorption onto, its cellular membrane
biomagnification	increase in concentration of a substance in organisms with each trophic level of a food chain
biosolid	organic residuals remaining after domestic sewage treatment
biota	living organisms in a given area
bund	structural barrier built to retain water or to hold waste
compost	a product used for fertilizing and/or conditioning land, comprising a mixture of organic materials which may include organic waste-derived materials

continues

Table I2 *continued*

Term	Definition
conceptual site model	description of a site including the environmental setting, geological, hydrogeological and soil characteristics, the nature and distribution of contaminants and potentially exposed populations and exposure pathways
consequence	the result or effect of an action
construction water	Construction water means surface and/or ground water intercepted, collected, or extracted during construction work or generated such as by stormwater contacting disturbed contaminated soils, defined in the <i>Australian Work Health and Safety Regulations 2011</i> , as implemented in each jurisdiction
contaminant	substance which causes contamination
contamination	condition of land or water where any chemical substance or waste has been added as a direct or indirect result of human activity at above natural background level and represents, or potentially represents, an adverse health or environmental impact
criteria	concentrations that indicate a potential risk to the environment and/or human health
diffuse source	widespread, usually small-scale sources of contamination without a single identifiable point source
ecological	referring to ecology
ecology	the study of the relationships among organisms as well as the relationships between them and their physical environment
ecosystem	a community of organisms and their environment with all the interactions that transfer energy and recycle resources
environmental attenuation	reduction in contaminant concentration through natural processes such as ion exchange, chemical precipitation, adsorption, filtration, biodegradation and hydrodynamic dispersion
environmental regulator	a HEPA member agency, or another agency with regulatory responsibility for the environment, at the Commonwealth, state or territory level
environmental risk assessment	assessment, including human health risk assessment and ecological risk assessment estimating the potential impact of a chemical, physical, microbiological or psychosocial hazard on a specified human population or ecological system, under a specific set of conditions and for a certain timeframe
exposure	amount of a chemical released to the environment, the route by which it is released and the consequent contact of organisms with the chemical

continues

Table I2 *continued*

Term	Definition
firefighting foam	a foam used to suppress fire, that is made by mixing air with foam solution, that is made by mixing air with firefighting foam concentrate – note that firefighting foam products may or may not contain PFAS
FOGO	food waste and garden organic waste separated from other waste types at the source (that is, prior to kerbside collection)
groundwater system	groundwater and associated processes, including recharge, flow, discharge and interaction with other aquifers and surface water, at a specific location
harm	any adverse impact on the environment or human health of any degree or duration. This includes impacts that add up over time or are caused by a number of sources (often referred to as ‘cumulative impacts’) or factors
hazard	for a chemical, the inherent characteristics of the substance that have the potential to cause harm to an organism or any other aspect of the environment
high-end	above the 90 th percentile of population distribution, but not higher than the individual in the population who has the highest exposure. For example, a high-end exposure estimate is a plausible estimate of the individual exposure for those organisms at the upper end of an exposure distribution. High-end estimates are often used to describe reasonable maximum, reasonable worst-case, or maximum exposures, and are generally more realistic than bounding estimates. They generally involve a combination of high and central tendency data (US EPA 1992a and 2019)
homologue	a structurally similar molecule within a series with the same functional group but different numbers of some repeated groups, such as CF ₂
hydrogeology	the study of groundwater and the geological factors influencing its presence, flow, availability and chemistry
indicator	physical, chemical or biological characteristic used as a measure of environmental quality
infiltration	the passing of water into the soil or into a drainage system
intermediate bulk container	a pallet-mounted industrial grade reusable container for storing and transporting bulk liquids, pastes, granules and powders
internal standard	an isotopically labelled version of each compound used as a reference for quantitation of native compounds spiked into the sample prior to extraction

continues

Table I2 *continued*

Term	Definition
isotainer	a tank container, built to an International Organisation for Standardisation standard; that is, designed to carry both hazardous and non-hazardous liquids in bulk and is made of stainless steel surrounded by various types of protective layers
landfill	a facility for the disposal of waste by burial
leaching	the release of contaminants from solid materials, such as soil or waste, into liquids
lead agency	government agency responsible for coordinating interagency work on a specific issue
level of protection	degree of protection based on current or desired ecosystem condition
likelihood	probability that something might happen
long-term	greater than five years – also used for a very long timescale such as greater than 20 years
mass flux	the rate that a mass of chemicals (for example, contaminants, amendments, tracers, NORMs, and other chemical additives) pass through a defined cross-sectional area over a measured period of time (ITRC 2010) The symbol for mass flux is J and the SI units are $\text{kg m}^{-2} \text{s}^{-1}$
mass balance	a quantitative estimation of the mass loading into the dissolved plume from various sources, as well as the mass transport, phase transfer, degradation, and attenuation capacity of the dissolved plume (ITRC 2010) Mass balance as a quantitative estimation of the source 'strength' (that is, source zone mass discharge) into a dissolved phase plume, which is then compared to the plume's attenuation rate. If the mass discharge from the source is greater than the plume attenuation rate, then the dissolved plume will expand in length. If the mass discharge and plume attenuation rates are similar in magnitude then, all other factors being equal, the plume will be stable. And if the mass discharge is less than the plume attenuation rate, then the mass delivered by the plume will decrease (ITRC 2010)
medium-term	2–5 years
mesocosm	artificial systems containing complex and self-sustaining populations or communities set in natural environmental conditions (ANZG 2018)
MWOO	the product of a practice aiming to separate the organic waste fraction of household domestic waste from other waste types

continues

Table I2 *continued*

Term	Definition
octanol-water partition coefficient	used as a measure of the hydrophobicity or lipophilicity of an organic compound
organic waste	waste derived from material that was once living, excluding petroleum-based materials
pathway	the route by which a contaminant can reach a receptor
per- and polyfluoroalkyl substances	group of manufactured chemicals, containing a component with multiple fluorine atoms, with many specialty applications – examples are perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA)
persistent	a chemical substance that has a half-life in water greater than two months, or a half-life in soil greater than six months, or a half-life in sediment greater than six months, or a half-life in air greater than two days, taking into account environmentally relevant considerations
PFAS-contaminated material	PFAS-contaminated soil, sediment, timber, asphalt, concrete, containers etc
point source	specific location where a contaminating substance is present that is then emitted from that location into the environment – see also primary source and secondary source
precursor	a substance from which another substance is transformed
primary source	specific location where a contaminating substance has been used that is then emitted from that location into the environment – see also point source and secondary source
receptor	living organisms (including humans), the habitat which supports such organisms, or natural resources that could be adversely affected by environmental contamination resulting from a release at, or migration from, a site
rehabilitation	restoration of original or alternative environmental values or beneficial uses at a site
remediation	‘any action undertaken for eliminating, reducing, controlling, or mitigating the risks resulting from contamination’ (UNEP 2024). This includes removal or other treatment of contamination from soil, groundwater, sediment, surface water, or biota to mitigate or minimise environmental and/or human health risks
resource recovery product	a product that is created using (entirely or in part) wastes as an input material
risk	the probability of adverse effects caused under specified circumstances by an agent, in an organism, a population, or an ecological system, based on the hazard of a chemical and its level of exposure for a specific use and location

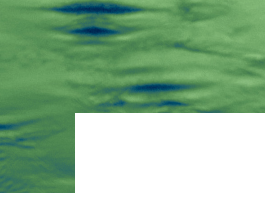
continues

Table I2 *continued*

Term	Definition
risk management	the process by which policy and regulatory actions are chosen and implemented to control risks identified in the risk assessment, involving consideration of the scientific evidence and risk assessment and, if needed, any social and economic factors
screening	process of comparison of site data to screening criteria to obtain a rapid assessment of contaminants
secondary source	specific location where contamination originating from other point sources and/or diffuse sources is collected and then emitted from that location into the environment – see also point source and primary source
short-term	6 months to 2 years
soil/sediment partitioning coefficient	the ratio of a contaminant concentration in a sediment (or soil) to that in water at equilibrium
temporary	up to 6 months – see also transient
toxicity	the degree to which a substance is toxic (that is, has an adverse biochemical effect)
trade waste	wastewater from commercial and/or industrial sites
transient	less than 48 hours – see also temporary
vulnerable aquifer	aquifer potentially exposed to contamination For the purposes of PFAS management a very highly vulnerable aquifer has one or more of the following: limestone with known karst features or sand, peat and clay deposits (wetland areas) with a shallow water table $\leq 3\text{m}$ while a highly vulnerable aquifer has sand and limestone with a shallow to intermediate water table $\leq 30\text{m}$, or fractured rocks with a high hydraulic conductivity $\geq 40\text{m/d}$ or a shallow to intermediate water table $\leq 30\text{m}$ (adapted from Appleyard 1993)
wastewater	water that has been used and is not suitable for reuse for the same purpose without treatment, including sewage and trade wastewater
wastewater treatment facility, or wastewater treatment plant	facility for treatment of wastewater, including domestic sewage and commercial and/or industrial wastewater
weight of evidence approach	approach based on collecting, analysing and evaluating a combination of different qualitative, semi-quantitative and/or quantitative lines of evidence to form an overall assessment, including judgements about data quality, quantity, relevance and congruence

References

- Agency for Toxic Substances and Disease Registry (2021) Toxicological Profile for Perfluoroalkyls, Agency for Toxic Substances and Disease Registry (ATSDR), US Department of Health and Human Services, Georgia, doi: 10.15620/cdc:59198, accessed 24 May 2024.
- Ahrens L, Shoeib M, Harner T, Lee CS, Guo R and Reiner EJ (2011) Wastewater treatment plant and landfills as sources of polyfluoroalkyl compounds to the atmosphere, *Environmental Science & Technology* 45(19):8098–8105, doi: 10.1021.es1036173.
- Ahrens L, Yeung LWY, Taniyasu S, Lam PKS and Yamashita N (2011) Partitioning of perfluorooctanoate (PFOA), perfluorooctane sulfonate (PFOS) and perfluorooctane sulfonamide (PFOSA) between water and sediment, *Chemosphere*, 85(5):731–737, doi: 10.1016/j.chemosphere.2011.06.046.
- Airservices Australia (n.d.) National PFAS Management Program, Airservices Australia (AsA), Australian Government, accessed 30 May 2024.
- Alcaraz AJG, Baraniuk S, Mikulášek K, Park B, Lane T, Burbridge C, Ewald J, Potěšil D, Xia J, Zdráhal Z, Schneider D, Crump D, Basu N, Hogan N, Brinkmann M and Hecker M (2022) Comparative analysis of transcriptomics points-of-departure (tPODs) and apical responses in embryo-larval fathead minnows exposed to fluoxetine, *Environmental Pollution*, 295:118667, doi: 10.1016/j.envpol.2021.118667.
- Appleman TD, Dickenson ERV, Bellona C and Higgins CP (2013) Nanofiltration and granular activated carbon treatment of perfluoroalkyl acids, *Journal of Hazardous Materials*, 260:740–746, doi: 10.1016/j.hazmat.2013.06.033.
- Appleyard SJ (1993) Explanatory notes for the groundwater vulnerability to contamination maps of the Perth Basin, Record 1993/6, Geological Survey of Western Australia, Department of Minerals and Energy, Western Australian Government.
- Armstrong DL, Lozano N, Rice CP, Ramirez M and Torrents A (2016) Temporal trends of perfluoroalkyl substances in limed biosolids from a large municipal water resource recovery facility, *Journal of Environmental Management*, 165:88–95, doi: 10.1016/j.jenvman.2015.09.023.
- ASTM International (2020) ASTM D7979-20 Standard Test Method for Determination of Per- and Polyfluoroalkyl Substances in Water, Sludge, Influent, Effluent, and Wastewater by Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS), ASTM International, accessed 30 May 2024.



—(2023) ASTM D7968-23 Standard Test Method for Determination of Polyfluorinated Compounds in Soil by Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS), ASTM International, accessed 30 May 2024.

Australian Bureau of Agricultural and Resource Economics and Sciences (2016) Australian Land Use and Management Classification Version 8 (October 2016), Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Department of Agriculture, Fisheries and Forestry, Australian Government, accessed 1 May 2024.

Australian Government (1994) *National Environment Protection Council Act 1994*, Department of the Environment, Sport and Territories, Australian Government, accessed 1 May 2024.

—(1998) National Environment Protection (Movement of Controlled Waste between States and Territories) Measure, National Environment Protection Council (NEPC), Department of the Environment and Heritage, Australian Government, accessed 24 April 2024.

—(1999a) National Environment Protection (Assessment of Site Contamination) Measure (amended 2013), NEPC, Department of the Environment and Heritage, Australian Government, accessed 24 April 2024.

—(1999b) *Environment Protection and Biodiversity Conservation Act 1999*, Department of the Environment and Heritage, Australian Government, accessed 1 May 2024.

—(2009) National Assessment Guidelines for Dredging 2009, Department of the Environment, Water, Heritage and the Arts, Commonwealth of Australia, accessed 23 May 2024.

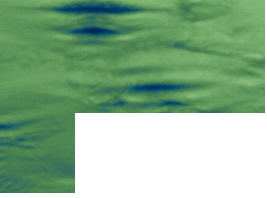
—(2013) Guidelines for Groundwater Quality Protection in Australia, Water Quality Australia, Australian Government, accessed 29 May 2024.

—(2016) Draft Commonwealth Environmental Management Guidance on Perfluorooctane Sulfonic Acid (PFOS) and Perfluorooctanoic Acid (PFOA) [PDF], Department of the Environment and Energy, Australian Government, accessed 30 May 2024.

—(2017) Chemical Risk Assessment Guidance Manual: for chemicals associated with coal seam gas extraction (exposure draft) [PDF], Department of the Environment and Energy, Australian Government, accessed 28 June 2024.

—(2018a) Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination (updated 2020), National Cabinet website, Federation Homepage | Federation, accessed 30 April 2024.

—(2018b) 2018 National Waste Policy: Less waste, more resources – DCCEEW, Department of the Environment and Energy, Australian Government, accessed 10 April 2024.

- 
- (2019a) National per- and polyfluoroalkyl substances (PFAS) Position Statement (federation.gov.au) [PDF], Australian Government, accessed 18 April 2024.
- (2019b) National Water Quality Management Strategy, Water Quality Australia website, About (waterquality.gov.au), Australian Government, accessed 18 April 2024.
- (2019c) National Waste Policy Action Plan, Department of the Environment and Energy, Australian Government, accessed 28 May 2024.
- Australian and New Zealand Governments (1999) Guidelines for the assessment of on-site containment of contaminated soil [PDF], Australian and New Zealand Environment and Conservation Council (ANZECC), accessed 28 May 2024.
- (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality: Aquatic Ecosystems — Rationale and Background Information (Paper No. 4) [PDF], ANZECC and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), accessed 23 May 2024.
- (2018) Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Water Quality Australia, Australian Government, accessed 30 April 2024.
- (2023) Perfluorooctane sulfonate (PFOS) in freshwater, toxicant default guideline values for protecting aquatic ecosystems (draft), Water Quality Australia, Australian Government, accessed 28 June 2024.
- Australian Industrial Chemicals Introduction Scheme (n.d.) Per- and Polyfluoroalkyl Substances (PFAS), Australian Industrial Chemicals Introduction Scheme (AICIS), Department of Health and Aged Care, Australian Government, accessed 15 April 2024.
- Backe WJ, Day TC and Field JA (2013) Zwitterionic, cationic, and anionic fluorinated chemicals in aqueous film forming foam formulations and groundwater from U.S. military bases by nonaqueous large-volume injection HPLC-MS/MS, *Environmental Science & Technology*, 47(10):5226–5234, doi: 10.1021/es3034999.
- Baddiley BL, Munns T, Braun C and Vardy S (2020) Queensland Ambient PFAS Monitoring Program 2019-2020 [PDF], Department of Environment and Science, Queensland Government, accessed 1 May 2024.
- Baduel C, Paxman CJ and Mueller JF (2015) Perfluoroalkyl substances in a firefighting training ground (FTG), distribution and potential future release, *Journal of Hazardous Materials*, 296:46–53, doi: 10.1016/j.hazmat.2015.03.007.

- Barzen-Hanson KA, Roberts SC, Choyke S, Oetjen K, McAlees A, Riddell N, McCrindle R, Ferguson PL, Higgins CP and Field JA (2017) Discovery of 40 Classes of Per- and Polyfluoroalkyl Substances in Historical Aqueous Film-Forming Foams (AFFFs) and AFFF-Impacted Groundwater, *Environmental Science & Technology*, 51(4):2047–2057, doi: 10.1021/acs.est.6b05843.
- Batley GE, Kumar A, Adams MS and Simpson SL (2020) *Review of national and international literature on PFAS in estuarine and marine benthic environments: 2. Compilation and analysis of adopted investigation/screening levels for PFAS in estuarine and/or marine sediments in Australia and other countries*, Report EP205317, CSIRO Land and Water, Adelaide.
- Beale DJ, Hillyer K, Nilsson S, Limpus D, Bose U, Broadbent JA and Vardy S (2022) Bioaccumulation and metabolic response of PFAS mixtures in wild-caught freshwater turtles (*Emydura macquarii macquarii*) using omics-based ecosurveillance techniques, *Science of The Total Environment*, 806(3):151264, doi: 10.1016/j.scitotenv.2021.151264.
- Bečanová J, Melymuk L, Vojta Š, Komprdová K and Klánová J (2016) Screening for perfluoroalkyl acids in consumer products, building materials and wastes, *Chemosphere* 164:322–329, doi: 10.1016/j.chemosphere.2016.08.112.
- Bil W, Zeilmaker MJ, Fragki S, Lijzen JPA, Verbruggen EM and Bokkers B (2021) Risk Assessment of Per- and Polyfluoroalkyl Substance Mixtures: A Relative Potency Factor Approach, *Environmental Toxicology and Chemistry*, 40(3):859–870, doi: 10.1002/etc.4835.
- Blaine AC, Rich CD, Sedlacko EM, Hundal LS, Kumar K, Lau C, Mills MA, Harris KM and Higgins CP (2014) Perfluoroalkyl acid distribution in various plant compartments of edible crops grown in biosolids-amended soils, *Environmental Science & Technology*, 48(14):7858–7865, doi: 10.1021/es500016s.
- Bolan N, Sarkar B, Yan Y, Li Q, Wijesekara H, Kannan K, Tsang DCW, Schauerte M, Bosch J, Noll H, Ok YS, Scheckel K, Kumpiene J, Gobindlal K, Kah M, Sperry J, Kirkham MB, Wang H, Tsang YF, Hou D and Rinklebe J (2021) Remediation of poly- and perfluoroalkyl substances (PFAS) contaminated soils – To mobilize or to immobilize or to degrade?, *Journal of Hazardous Materials*, 401:123892, doi: 10.1016/j.hazmat.2020.123892.
- Bräunig J, Baduel C, Barnes CM and Mueller JF (2019) Leaching and bioavailability of selected perfluoroalkyl acids (PFAAs) from soil contaminated by firefighting activities, *Science of the Total Environment*, 646:471–479, doi: 10.1016/j.scitotenv.2018.07.231.
- (2021) Sorbent assisted immobilisation of perfluoroalkyl acids in soils - effect on leaching and bioavailability, *Journal of Hazardous Materials*, 412:125171, doi: 10.1016/j.hazmat.2021.125171.

- Buck RC, Franklin J, Berger U, Conder JM, Cousins IT, de Voogt P, Jensen AA, Kannan K, Mabury SA, and van Leeuwen SPJ (2011) Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins, *Integrated Environmental Assessment and Management*, 7(4):513–541, doi: 10.1002/ieam.258.
- Celis-Hernandez O, Cundy AB, Croudace IW, Ward RD, Busquets R and Wilkinson JL (2021) Assessing the role of the “estuarine filter” for emerging contaminants: pharmaceuticals, perfluoroalkyl compounds and plasticisers in sediment cores from two contrasting systems in the southern U.K., *Water Research*, 189:116610, doi: 10.1016/j.watres.2020.116610.
- Cement Australia (2018) Post Trial Report for Fire Fighting Foam Co-processing at Cement Australia’s Fisherman’s Landing Kiln, Department of the Environment and Energy, Australian Government, accessed 17 April 2024.
- Chapman AD (2009) *Numbers of Living Species in Australia and the World*, 2nd edn, Australian Biodiversity Information Services, Report for the Australian Biological Resources Study, Australian Government, accessed 26 June 2024.
- Chen H, Zhang C, Yu Y and Han J (2012) Sorption of perfluorooctane sulfonate (PFOS) on marine sediments, *Marine Pollution Bulletin*, 64(5):902–906, doi: 10.1016/j.marpolbul.2012.03.012.
- Chen M, Qiang L, Pan X, Fang S, Han Y and Zhu L (2015) In Vivo and in Vitro Isomer Specific Biotransformation of Perfluorooctane Sulfonamide in Common Carp (*Cyprinus carpio*), *Environmental Science & Technology*, 49(23):13817–13824, doi: 10.1021/acs.est.5b00488.
- Choi YJ, Lazcano RK, Yousefi P, Trim H and Lee LS (2019) Perfluoroalkyl Acid Characterization in US Municipal Organic Solid Waste Composts, *Environmental Science & Technology Letters*, 6(6):372–377, doi: 10.1021/acs.estlett.9b00280.
- Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (2019) National Remediation Framework, Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE), Newcastle, accessed 28 May 2024.
- Costanza J, Arshadi M, Abriola LM and Pennell KD (2019) Accumulation of PFOA and PFOS at the Air–Water Interface, *Environmental Science & Technology Letters*, 6(8):487–491, doi: 10.1021/acs.estlett.9b00355.
- Cousins IT, DeWitt JC, Glüge J, Goldenman G, Herzke D, Lohmann R, Miller M, Ng CA, Scheringer M, Vierke L and Wang Z (2020) The high persistence of PFAS is sufficient for their management as a chemical class, *Environmental Science: Processes & Impacts*, 22(12):2307–2312, doi: 10.1039/d0em00355g.

D'Agostino LA and Mabury SA (2014) Identification of novel fluorinated surfactants in aqueous film forming foams and commercial surfactant concentrates, *Environmental Science & Technology*, 48(1):121–129, doi: 10.1021/es403729e.

Danish Ministry of the Environment (2015) *Perfluoralkylated substances: PFOA, PFOS and PFOSA – Evaluation of health hazards and proposal of a health based quality criterion for drinking water, soil and groundwater* [PDF], Environmental Project No. 1665, Danish Environmental Protection Agency, Denmark, accessed 24 May 2024.

Danish Veterinary and Food Administration (2020) *Ban on fluorinated substances in paper and board food contact materials (FCM) – Fact sheet, June 2020*, Ministry of Food, Agriculture and Fisheries, Denmark, accessed 24 May 2024.

Davis GB and Rayner JL (2021) Advancing the Direct Vadose Zone Measurement of Soil-to-Groundwater PFAS Concentrations in Soil Pore Water using Lysimeters, CSIRO Land and Water Technical Report.

Dennis NM, Hossain F, Subbiah S, Karnjanapiboonwong A, Dennis ML, McCarthy C, Heron CG, Jackson WA, Crago JP, Field JA, Salic CJ, and Anderson TA (2021) Chronic reproductive toxicity thresholds for Northern bobwhite quail (*Colinus virginianus*) exposed to perfluorohexanoic acid (PFHxA) and a mixture of perfluorooctane sulfonic acid (PFOS) and PFHxA, *Environmental Toxicology and Chemistry*, 40(9):2601–2614, doi:10.1002/etc.5135.

Department of Environment and Science (2018) *Monitoring and Sampling Manual: Environmental Protection (Water) Policy 2009*, Department of Environment and Science (DES), Queensland Government, accessed 24 May 2024.

—(2019a) *Environmental Management of Firefighting Foam—Operational Policy* (updated 2021), DES, Queensland Government, accessed 1 May 2024.

—(2019b) *Environmental Protection (Water and Wetland Biodiversity) Policy 2019*, DES, Queensland Government, accessed 30 May 2024.

Department of Health (2017) *Health-based guidance values for PFAS for use in site investigations in Australia* | Australian Government Department of Health and Aged Care, Department of Health, Australian Government, accessed 22 May 2024.

Department of Health and Aged Care (2024) *enHealth guidance statement – Per- and polyfluoroalkyl Substances (PFAS)* | Australian Government Department of Health and Aged Care, enHealth, Department of Health and Aged Care, Australian Government, accessed 15 April 2024.

- Department of Health and Ageing (2012) Environmental Health Risk Assessment: Guidelines for assessing human health risks from environmental hazards, enHealth, Department of Health and Ageing, Australian Government, accessed 1 July 2024.
- Department of Planning and Environment (2023), Biosolids Regulatory Review, Department of Planning and Environment (DPE), New South Wales Government, accessed 29 May 2024.
- Ding G, Zhang J, Chen Y, Wang L, Wang M, Xiong D and Sun Y (2013) Combined effects of PFOS and PFOA on zebrafish (*Danio rerio*) embryos, *Archives of Environmental Contamination and Toxicology*, 64(4):668–675, doi: 10.1007/s00244-012-9864-2.
- Environment and Climate Change Canada (2018) Canadian Environmental Protection Act, 1999 Federal Environmental Quality Guidelines Perfluorooctane Sulfonate (PFOS), Environment and Climate Change Canada (ECCC), Canadian Government, accessed 22 May 2024.
- Environment Protection Authority Victoria (2022) EPA science report: Summary of PFAS concentrations detected in the environment | Environment Protection Authority Victoria (publication 2049), Victorian Government, accessed 18 April 2024.
- European Commission (2011) PFOS EQS dossier 2011: Perfluorooctane sulphonate (PFOS) [PDF], Working Group E of the Common Implementation Strategy for the Water Framework Directive, European Commission (EC), Communication and Information Resource Centre for Administrations, Businesses and Citizens, Brussels, accessed 23 May 2024.
- European Union (2020) Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption, *Official Journal of the European Union*, 63:1–62, accessed 24 May 2024.
- Food Standards Australia New Zealand (2017) Perfluorinated chemicals in food, Food Standards Australia New Zealand (FSANZ), Australian Government, accessed 2 May 2024.
- Gallen C, Drage D, Kaserzon S, Baduel C, Gallen M, Banks A, Broomhall S and Mueller JF (2016) Occurrence and distribution of brominated flame retardants and perfluoroalkyl substances in Australian landfill leachate and biosolids, *Journal of Hazardous Materials*, 312:55–64, doi: 10.1016/j.hazmat.2016.03.031.
- Gallen C, Drage D, Eaglesham G, Grant S, Bowman M and Mueller JF (2017) Australia-wide assessment of perfluoroalkyl substances (PFASs) in landfill leachates, *Journal of Hazardous Materials*, 331:132–141, doi: 10.1016/j.jhazmat.2017.02.006.

- Golkar-Narenji A, Dziegiel P, Kempisty B, Petite J, Mozdziak PE and Bryja A (2023) In vitro culture of reptile PGCS to preserve endangered species, *Cell Biology International*, 47(8):1314–1326, doi: 10.1002/cbin.12033.
- Gomis MI, Vestergren R, Borg D and Cousins IT (2018) Comparing the toxic potency in vivo of long-chain perfluoroalkyl acids and fluorinated alternatives, *Environment International*, 113:1–9, doi: 10.1016/j.envint.2018.01.011.
- Goodrum PE, Anderson JK, Luz AL and Ansell GK (2020) Application of a Framework for Grouping and Mixtures Toxicity Assessment of PFAS: A Closer Examination of Dose-Additivity Approaches, *Toxicological Sciences*, 179(2):262–278, doi: 10.1093/toxsci/kfaa123.
- Guruge KS, Hikono H, Shimada N, Murakami K, Hasegawa J, Yeung LW, Yamanaka, N and Yamashita N (2009) Effect of perfluorooctane sulfonate (PFOS) on influenza A virus-induced mortality in female B6C3F1 mice, *Journal of Toxicological Sciences*, 34(6):687–691.
- Haenel GJ and Moore V Del Gaizo (2018) Functional divergence of mitochondria and coevolution of genomes: cool mitochondria in hot lizards, *Physiological and Biochemical Zoology*, 91(5):1068–1081, doi: 10.1086/699918.
- Harrill JA, Everett LJ, Haggard DE, Bundy JL, Willis CM, Shah I, Friedman KP, Basili D, Middleton A and Judson RS (2024) Exploring the effects of experimental parameters and data modeling approaches in in vitro transcriptomics point-of-departure estimates, *Toxicology*, 501:153694, doi: 10.1016/j.tox.2023.153694.
- Heads of EPA Australia and New Zealand (2018) PFAS National Environmental Management Plan, Heads of EPA Australia and New Zealand (HEPA), Department of the Environment and Energy, Australian Government, accessed 1 May 2024.
- (2020), PFAS National Environmental Management Plan 2.0 HEPA, Department of the Environment and Energy, Australian Government, accessed 1 May 2024.
- Health Canada (2022) Objective for Canadian Drinking Water Quality: Per- and Polyfluoroalkyl Substances (Objective for Public Consultation), Water and Air Quality Bureau, Health Canada, Canadian Government, accessed 28 June 2024.
- Høisæter Å, Arp HPH, Slinde G, Knutsen H, Hale SE, Breedveld GD and Hansen MC (2021) Excavated vs novel in situ soil washing as a remediation strategy for sandy soils impacted with per- and polyfluoroalkyl substances from aqueous film forming foams, *Science of the Total Environment*, 794:148763, doi: 10.1016/j.scitotenv.2021.148763.

- Houtz EF and Sedlak DL (2012) Oxidative conversion as a means of detecting precursors to perfluoroalkyl acids in urban runoff, *Environmental Science & Technology*, 46(17):9342–9349, doi: 10.1021/es302274g.
- Houtz EF, Higgins CP, Field JA and Sedlak DL (2013) Persistence of perfluoroalkyl acid precursors in AFFF-impacted groundwater and soil, *Environmental Science & Technology*, 47(15):8187–8195, doi: 10.1021/es4018877.
- Hutchinson S, Rieck T and Wu XL (2020) Advanced PFAS precursor digestion methods for biosolids, *Environmental Chemistry*, 17:558–567, doi: 10.1071/EN20008.
- Industrial Chemicals Environmental Management Standard (n.d.) Industrial Chemicals Environmental Management Standard - IChEMS - DCCEEW, Industrial Chemicals Environmental Management Standard (IChEMS), Department of Climate Change, Energy, the Environment and Water, Australian Government, accessed 21 May 2024.
- Interstate Technology Regulatory Council (2010) Use and Measurement of Mass Flux and Mass Discharge, Interstate Technology Regulatory Council (ITRC), Environmental Council of the States, Washington DC, accessed 31 May 2024.
- (2017) History and Use of Per- and Polyfluoroalkyl Substances (PFAS) found in the Environment [PDF] (updated 2023), ITRC, Environmental Council of the States, Washington DC, accessed 30 April 2024.
- (2018a) Naming Conventions for Per- and Polyfluoroalkyl Substances (PFAS) [PDF] (updated 2023), ITRC, Environmental Council of the States, Washington DC, accessed 30 April 2024.
- (2018b) Site Characterization Considerations and Media-Specific Occurrence for Per- and Polyfluoroalkyl Substances [PDF] (updated 2023), ITRC, Environmental Council of the States, Washington DC, accessed 1 May 2024.
- (2020) Fate and Transport of Per- and Polyfluoroalkyl Substances (PFAS) [PDF] (updated 2023), ITRC, Environmental Council of the States, Washington DC, accessed 23 May 2024.
- (2023) PFAS – Per-and Polyfluoroalkyl Substances: 12 Treatment Technologies, ITRC, Environmental Council of the States, Washington DC, accessed 17 April 2024.
- International Organization for Standardization (2017) Water quality – Sampling – Part 12: Guidance on sampling of bottom sediments from rivers, lakes and estuarine areas, ISO 5667-12:2017, International Organization for Standardization (ISO), Geneva, accessed 24 May 2024.

- Kabiri S, Centner M and McLaughlin MJ (2021) Durability of sorption of per- and polyfluorinated alkyl substances in soils immobilised using common adsorbents: 1. Effects of perturbations in pH, *Science of the Total Environment*, 766:144857, doi: 10.1016/j.scitotenv.2020.144857.
- Kumar A, Adams MS, Simpson SL, and Batley GE (2020a) *Review of national and international literature on PFAS in estuarine and marine benthic environments: 1. Ecotoxicological studies and bioaccumulation*, Report EP205318, CSIRO Land and Water, Adelaide.
- Kumar A, Batley GE, Adams MS and Simpson SL (2020b) *Review of national and international literature on PFAS in estuarine and marine benthic environments: 3. A critical evaluation of the methodologies used to determine adopted investigation/screening levels for marine sediments in other countries around the world*, Report EP205319, CSIRO Land and Water, Adelaide.
- Landcare Research Manaaki Whenua (2020) Land Cover Database (LCDB version 5), Landcare Research Manaaki Whenua, New Zealand Government, accessed 1 May 2024.
- Lang JR, Allred BM, Field JA, Levis JW and Barlaz MA (2017) National Estimate of Per- and Polyfluoroalkyl Substance (PFAS) Release to U.S. Municipal Landfill Leachate, *Environmental Science & Technology*, 51(4):2197–2205, doi: 10.1021/acs.est.6b05005.
- Lange FT, Scheurer M, Bierreth C, Borho W, Seeger AK, Dreher P and Nöltner T (2020) Air-drying of soil samples - A crucial step in the determination of leachable concentrations of per- and polyfluoroalkyl substances, *Chemosphere*, 269:128745, doi: 10.1016/j.chemosphere.2020.128745.
- Lazcano KR, Choi YJ, Mashtare ML and Lee LS (2020) Characterizing and Comparing Per- and Polyfluoroalkyl Substances in Commercially Available Biosolid and Organic Non-Biosolid-Based Products, *Environmental Science & Technology*, 54(14):8640–8648, doi: 10.1021/acs.est.9b07281.
- Lee A (8 December 2021) 'Defence PFAS Remediation Overview' [unpublished forum presentation], *Australian Research Council: PFAS Remediation and Destruction Forum*, Canberra.
- Lettoof DC, Nguyen TV, Richmond WR, Nice HE, Gagnon MM and Beale DJ (2023) Bioaccumulation and metabolic impact of environmental PFAS residue on wild-caught urban wetland tiger snakes (*Notechis scutatus*), *Science of the Total Environment*, 897:165260, doi: 10.1016/j.scitotenv.2023.165260
- Li Y, Oliver DP and Kookana RS (2018) A critical analysis of published data to discern the role of soil and sediment properties in determining sorption of per and polyfluoroalkyl substances (PFASs), *Science of the Total Environment*, 628:110–120, doi: 10/1016/j.scitotenv.2018.01.167.

- Liu CJ, Strathmann TJ and Bellona C (2021) Rejection of per- and polyfluoroalkyl substances (PFASs) in aqueous film-forming foam by high-pressure membranes, *Water Research*, 188:116546, doi: 10.1016/j.watres.2020.116546.
- Lupton SJ, Huwe JK, Smith DJ, Dearfield KL and Johnston JJ (2014) Distribution and excretion of perfluorooctane sulfonate (PFOS) in beef cattle (*Bos taurus*), *Journal of Agricultural and Food Chemistry*, 62(5):1167–1173, doi: 10.1021/jf404355b.
- Major D (2019) Demonstration of Smouldering Combustion Treatment of PFAS-impacted Investigation-Derived Waste, SERDP Project ER18-1593, Strategic Environmental Research and Development Program, Virginia, accessed 30 May 2024.
- Mallants D, Bekele E, Schmid W, Miotlinski K and Bristow K (2017) Literature review: Identification of potential pathways to shallow groundwater of fluids associated with hydraulic fracturing [PDF], National assessment of chemicals associated with coal seam gas extraction in Australia, CSIRO, Australian Government, accessed 28 June 2024.
- Martin JW, Mabury SA, Solomon KR and Muir DC (2003) Bioconcentration and tissue distribution of perfluorinated acids in rainbow trout (*Oncorhynchus mykiss*), *Environmental Toxicology and Chemistry*, 22(1):196–204.
- Martin JW, Asher BJ, Beesoon S, Benskin JP and Ross MS (2010) PFOS or PreFOS? Are perfluorooctane sulfonate precursors (PreFOS) important determinants of human and environmental perfluorooctane sulfonate (PFOS) exposure?, *Journal of Environmental Monitoring*, 12(11):1979–2004, doi: 10/1039/c)em00295j.
- McGuire ME, Schaefer C, Richards T, Backe WJ, Field JA, Houtz E, Sedlak DL, Guelfo JL, Wunsch A and Higgins CP (2014) Evidence of Remediation-Induced Alteration of Subsurface Poly- and Perfluoroalkyl Substance Distribution at a Former Firefighter Training Area, *Environmental Science & Technology*, 48(12):6644–6652, doi: 10.1021/es5006187.
- Merino N, Qu Y, Deeb RA, Hawley EL, Hoffmann MR and Mahendra S (2016) Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl Substances in Water, *Environmental Engineering Science*, 33(9):615–649, doi: 10.1089/ees.2016.0233.
- Mikkonen AT, Martin J, Upton RN, Moenning J-L, Numata J, Taylor MP, Roberts MS and Mackenzie L (2023) Dynamic exposure and body burden models for per- and polyfluoroalkyl substances (PFAS) enable management of food safety risks in cattle, *Environment International*, 180:108218, doi: 10.1016/j.envint.2003.108218.

Ministry of the Environment of Japan (2013) Summary of the Guideline on the Treatment of Wastes Containing Perfluorooctane Sulfonic Acid (PFOS), and Its Salts in Japan [PDF], Ministry of the Environment, Japan, Tokyo, accessed 28 May 2024.

Moodie D, Coggan T, Berry K, Kolobaric A, Fernandes M, Lee E, Reichman S, Nugegoda D and Clarke BO (2021) Legacy and emerging per- and polyfluoroalkyl substances (PFASs) in Australian biosolids, *Chemosphere*, 270:129143, doi: 10.1016/j.chemosphere.2020.129143.

National Health and Medical Research Council (2008) Guidelines for Managing Risks in Recreational Water, National Health and Medical Research Council (NHMRC), Department of Health and Ageing, accessed 1 May 2024.

—(2011) Australian Drinking Water Guidelines 6 (Version 3.8, updated 2022), NHMRC, Department of Health and Ageing, accessed 1 May 2024.

—(2019) Guidance on Per and Polyfluoroalkyl substances (PFAS) in Recreational Water, NHMRC, Department of Health, accessed 1 May 2024. URL: <https://www.nhmrc.gov.au/about-us/publications/guidelines-managing-risks-recreational-water#block-views-block-file-attachments-content-block-1> (Guidelines for managing risks in recreational water | NHMRC).

National Industrial Chemicals Notification and Assessment Scheme (2015a) Perfluorooctanoic acid (PFOA) and its direct precursors: Environment tier II assessment [PDF], National Industrial Chemicals Notification and Assessment Scheme (NICNAS), Department of Health, Australian Government, accessed 30 April 2024.

—(2015b) Direct precursors to perfluoroheptanesulfonate (PFHpS), perfluorohexanesulfonate (PFHxS) and perfluoropentanesulfonate (PFPeS): Environment tier II assessment [PDF], NICNAS, Department of Health, Australian Government, accessed 30 April 2024.

—(2015c) Indirect precursors to perfluoroalkyl sulfonates: Environment tier II assessment [PDF], NICNAS, Department of Health, Australian Government, accessed 30 April 2024.

—(2017) Direct precursors to perfluorooctanesulfonate (PFOS): Environment tier II assessment [PDF], NICNAS, Department of Health, Australian Government, accessed 30 April 2024.

—(2019a) Indirect precursors to perfluorooctanoic acid (PFOA): Environment tier II assessment [PDF], NICNAS, Department of Health, Australian Government, accessed 30 April 2024.

—(2019b) Indirect precursors to perfluorooctanesulfonate (PFOS): Environment tier II assessment [PDF], NICNAS, Department of Health, Australian Government, accessed 30 April 2024.

- National Measurement Institute (2024a) Reference Material Product Information Sheet: NMIA MX019: PFAS in Soil [PDF], Department of Industry, Science and Resources, Australian Government, accessed 24 September 2024.
- (2024b) Per- and poly-fluoroalkyl substances, Department of Industry, Science and Resources, Australian Government, accessed 11 April 2024.
- Neumann M and Schliebner I (2017) Protecting the sources of our drinking water: A revised proposal for implementing criteria and an assessment procedure to identify Persistent, Mobile and Toxic (PMT) and very Persistent, very Mobile (vPvM) substances Registered Under REACH, Umweltbundesamt (German Environment Agency), Dessau-Roßlau, accessed 31 May 2024.
- New South Wales Environment Protection Authority (2022) Sampling design part 1 – application [PDF], New South Wales Environment Protection Authority (NSW EPA), NSW Government, accessed 21 May 2024.
- New Zealand Environmental Protection Authority Te Mana Rauhi Taiao (n.d.) New Zealand Inventory of Chemicals, New Zealand Government, accessed 19 June 2024.
- New Zealand Government (1996) *Hazardous Substances and New Organisms Act 1996*, New Zealand Government, accessed 17 April 2024.
- (2003) Contaminated land management guidelines No. 2: Hierarchy and application in New Zealand of environmental guideline values (revised 2011), Ministry for the Environment Manatū Mō Te Taiao, New Zealand Government, accessed 19 June 2024.
- (2011a) *Resource Management (National Environmental Standard for Assessing and Managing Contaminants in Soil to Protect Human Health) Regulations 2011*, Ministry for the Environment Manatū Mō Te Taiao, New Zealand Government, accessed 1 May 2024.
- (2011b) Hazardous Activities and Industries List (HAIL), Ministry for the Environment Manatū Mō Te Taiao, New Zealand Government, accessed 1 May 2024.
- (2021a) Contaminated land management guidelines No.1: Reporting on contaminated sites in New Zealand (revised 2021), Ministry for the Environment Manatū Mō Te Taiao, New Zealand Government, accessed 19 June 2024.
- (2021b) Contaminated land management guidelines No. 5: Site investigation and analysis of soils (revised 2021), Ministry for the Environment Manatū Mō Te Taiao, New Zealand Government, accessed 19 June 2024.
- (2022) Water Services (Drinking Water Standards for New Zealand) Regulations 2022, Department of Internal Affairs Te Tari Taiwhenua, New Zealand Government, accessed 19 June 2024.

- Ng C and Hungerbühler K (2014) Bioaccumulation of perfluorinated alkyl acids: observations and models, *Environmental Science & Technology*, 48(9):4637–4648, doi: 10.1021/es404008g.
- Nguyen TMH, Bräunig J, Thompson K, Thompson J, Kabiri S, Navarro DA, Kookana RS, Grimison C, Barnes CM, Higgins CP, McLaughlin MJ and Mueller JF (2020) Influences of Chemical Properties, Soil Properties, and Solution pH on Soil–Water Partitioning Coefficients of Per- and Polyfluoroalkyl substances (PFASs), *Environmental Science & Technology*, 54(24):15883–15892, doi: 10.1021/acs.est.0c05705.
- Northern Territory Environment Protection Authority (2017) Northern Territory Contaminated Land Guideline [PDF], Northern Territory Environment Protection Authority (NT EPA), Northern Territory Government, accessed 29 May 2024.
- Northern Territory Government (1998) *Waste Management and Pollution Control Act 1998*, Department of Environment, Parks and Water Security, Northern Territory Government, accessed 29 May 2024.
- Numata J, Kowalczyk J, Adolphs J, Ehlers S, Schafft H, Fuerst P, Müller-Graf C, Lahrssen-Wiederholt M and Greiner M (2014) Toxicokinetics of seven perfluoroalkyl sulfonic and carboxylic acids in pigs fed a contaminated diet, *Journal of Agricultural and Food Chemistry*, 62(28):6861–6870, doi: 10.1021/jf405827u.
- Office of Environment and Heritage (2019) Human health soil screening criteria for PFOS, PFHxS and PFOA [PDF], Office of Environment and Heritage (OEH), NSW Government, accessed 22 May 2024.
- Ojo AF, Peng C and Ng JC (2020) Combined effects and toxicological interactions of perfluoroalkyl and polyfluoroalkyl substances mixtures in human liver cells (HepG2), *Environmental Pollution*, 263(Pt B):114182, doi: 10.1016/j.envpol.2020.114182.
- Oliver DP, Navarro DA, Baldock J, Simpson SL and Kookana RS (2020) Sorption behaviour of per- and polyfluoroalkyl substances (PFASs) as affected by the properties of coastal estuarine sediments, *Science of the Total Environment*, 720:137263, doi: 10.1016/j.scitotenv.2020.137263.
- Organisation for Economic Cooperation and Development (n.d.) Portal on Per and Poly Fluorinated Chemicals, Chemical Safety, Organisation for Economic Cooperation and Development (OECD), accessed 30 April 2024.
- (2002) Co-operation on Existing Chemicals: Hazard assessment of perfluorooctane (PFOS) and its salts [PDF], Environment Directorate, OECD, accessed 23 May 2024.
- (2015) Risk Reduction Approaches for PFASs – A Cross-Country Analysis [PDF], OECD Series on Risk Management (No. 29), OECD Publishing, Paris, accessed 30 May 2024.

- (2018) Toward a New Comprehensive Global Database of Per- and Polyfluoroalkyl Substances (PFASs): Summary Report on Updating the OECD 2007 List of Per- and Polyfluoroalkyl Substances (PFASs) [PDF], OECD Series on Risk Management (No. 39), OECD Publishing, Paris, accessed 30 April 2024.
- (2021) Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance, OECD Series on Risk Management (No. 61), OECD Publishing, Paris, accessed 30 April 2024.
- Place BJ and Field JA (2012) Identification of novel fluorochemicals in aqueous film-forming foams used by the US military, *Environmental Science & Technology*, 46(13):7120–7127, doi: 10.1021/es301465n.
- Przeslawski R and Foster S (eds) (2020) Field Manuals for Marine Sampling in Australian Waters, Version 2, Report to the National Environmental Science Program, Marine Biodiversity Hub, Geoscience Australia and CSIRO, Canberra, doi: 10.11636/9781925848755, accessed 24 May 2024.
- Rayner JL, Slee D, Falvey S, Kookana R, Bekele E, Stevenson G, Lee A and Davis GB (2022) Laboratory batch representation of PFAS leaching from aged field soils: Intercomparison across new and standard approaches, *Science of the Total Environment*, 838:156562, doi: 10.1016/j.scitotenv.2022.156562.
- Richardson MJ, Kabiri S, Grimison C, Bowles K, Corish S, Chapman M and McLaughlin MJ (2022) Per-and poly-fluoroalkyl substances in runoff and leaching from AFFF-contaminated soils: a rainfall simulation study, *Environmental Science & Technology*, 56(23):16857–16865, doi: 10.1021/acs.est.2c05377.
- Ross I, McDonough J, Miles J, Storch P, Thelakkat Kochunarayanan P, Kalve E, Hurst J, Dasgupta SS and Burdick J (2018) A review of emerging technologies for remediation of PFASs, *Remediation*, 28(2):101–126, doi: 10.1002/rem.21553.
- Sardiña P, Leahy P, Metzeling L, Stevenson G and Hinwood A (2019) Emerging and legacy contaminants across land-use gradients and the risk to aquatic ecosystems, *Science of the Total Environment*, 695:133842, doi: 10.1016/j.scitotenv.2019.133842.
- Sardiña P, Sharp S, Saaristo M, Coggan T, Hoak M and Leahy P (2024) A quantitative method of land uses and assessment of per-and poly-fluoroalkyl substances (PFAS) occurrence in freshwater environments, *Environmental Pollution*, 363:125272, doi: 10.1016/j.envpol.2024.125272.

- Shoemaker J and Tetttenhorst D (2020) Method 537.1 Determination of Selected Per- and Polyfluorinated Alkyl Substances in Drinking Water by Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry (LC/MS/MS), US Environmental Protection Agency (US EPA), Washington DC, accessed 23 April 2024.
- Silva JAK, Martin WA and McCray JE (2021) Air-water interfacial adsorption coefficients for PFAS when present as a multi-component mixture, *Journal of Contaminant Hydrology*, 236:103731, doi: 10.1016/j.conhyd.2020.103731.
- Simpson SL and Batley GE (eds) (2016) *Sediment Quality Assessment: A Practical Handbook*, 2nd edn, CSIRO Publishing, Melbourne.
- Simpson SL, Liu Y, Spadaro DA, Wang X, Kookana RS and Batley GE (2021) Chronic effects and thresholds for estuarine and marine benthic organism exposure to perfluorooctane sulfonic acid (PFOS)-contaminated sediments: Influence of organic carbon and exposure routes, *Science of the Total Environment*, 776:146008, doi: 10.1016/j.scitotenv.2021.146008.
- Söregård M, Gago-Ferrero PB, Kleja D and Ahrens L (2021) Laboratory-scale and pilot-scale stabilization and solidification (S/S) remediation of soil contaminated with per- and polyfluoroalkyl substances (PFASs), *Journal of Hazardous Materials*, 402:123453, doi: 10.1061/j.hazmat.2020.123453.
- South Australian Environment Protection Authority (2017) Per and polyfluorinated alkyl substances (PFAS) in the marine environment – Preliminary ecological findings [PDF], South Australian Environment Protection Authority (SA EPA), South Australian Government, accessed 22 May 2024.
- Stahl T, Heyn J, Thiele H, Hüther J, Failing K, Georgii S and Brunn H (2009) Carryover of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from soil to plants, *Archives of Environmental Contamination and Toxicology*, 57(2):289–298, doi: 10.1007/s00244-008-9272-9.
- Standards Australia (2019) AS4439.3:2019 – Wastes, sediments and contaminated soils, Part 3: Preparation of leachates – Bottle leaching procedures, Standards Australia, accessed 29 May 2024.
- Tan X, Dewapriya P, Prasad P, Chang Y, Huang Y, Wang Y, Gong X, Hopkins TE, Fu C, Thomas KV, Peng H, Whittaker AK and Zhang C (2022) Efficient Removal of Perfluorinated Chemicals from Contaminated Water Sources Using Magnetic Fluorinated Polymer Sorbents, *Angewandte Chemie*, 61(49):e202213071, doi: 10.1002/anie.202213071.

- Taylor MD, Bowles KC, Johnson DD and Moltschaniwski NA (2017) Depuration of perfluoroalkyl substances from the edible tissues of wild-caught invertebrate species, *Science of the Total Environment*, 581–582:258–267, doi: 10.1016/j.scitotenv.2016.12.116.
- Thompson J, Eaglesham G, Reungoat J, Poussade Y, Bartkow M, Lawrence M and Mueller JF (2011) Removal of PFOS, PFOA and other perfluoroalkyl acids at water reclamation plants in South East Queensland Australia, *Chemosphere*, 82(1):9–17, doi: 10.1016/j.chemosphere.2010.10.040.
- Tian Y, Yao Y, Chang S, Zhao Z, Zhao Y, Yuan X, Wu F and Sun H (2018) Occurrence and Phase Distribution of Neutral and Ionizable Per- and Polyfluoroalkyl Substances (PFASs) in the Atmosphere and Plant Leaves around Landfills: A Case Study in Tianjin, China, *Environmental Science & Technology*, 52(3):1301–1310, doi: 10.1021/acs.est.7b05385.
- Tingley R, Macdonald SL, Mitchell NJ, Woinarski JC, Meiri S, Bowles P, Cox NA, Shea GM, Böhm M, Chanson J and Tognelli MF (2019) Geographic and taxonomic patterns of extinction risk in Australian squamates, *Biological Conservation*, 238:108023, doi: 10.1016/j.biocon.2019.108203.
- United Nations Environment Programme (2019a) Stockholm Convention on Persistent Organic Pollutants (POPs), Secretariat of the Stockholm Convention, United Nations Environment Programme (UNEP), accessed 30 April 2024.
- (2019b) Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, Secretariat of the Basel Convention, UNEP, accessed 30 April 2024.
- (2019c) Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, Secretariat of the Rotterdam Convention, UNEP, accessed 30 April 2024.
- (2021a) Guidance on the global monitoring plan for persistent organic pollutants, Parties to the Stockholm Convention, UNEP, accessed 21 May 2024, URL: <https://chm.pops.int/implementation/globalmonitoringplan/monitoringreports/tabid/525/default.aspx>
- (2021b) Guidance on best available techniques and best environmental practices for the use of perfluorooctane sulfonic acid, perfluorooctanoic acid, and their related compounds listed under the Stockholm Convention, Parties to the Stockholm Convention, UNEP, accessed 17 April 2024. URL: <https://www.brsmeas.org/Decisionmaking/COPsandExCOPs/20212022COPs/MeetingDocuments/tabid/8810/language/en-US/Default.aspx> (Meeting Documents (brsmeas.org)).

- (2023a) General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants, Parties to the Basel Convention, UNEP, accessed 17 April 2024. URL: <https://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx>; (Technical Guidelines (basel.int)).
 - (2023b) Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride (PFOSF), perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds, and perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS related compounds, Parties to the Basel Convention, UNEP, accessed 17 April 2024. URL: <https://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx>; (Technical Guidelines (basel.int)).
 - (2024) Draft guidance on best available techniques and best environmental practices for the management of sites contaminated with persistent organic pollutants, Parties to the Stockholm Convention, UNEP, accessed 27 June 2024. URL: [https://chm.pops.int/Implementation/BATandBEP\(new\)/POPscontaminatedsites\(new\)/Guidance\(new\)/tabid/9649/Default.aspx](https://chm.pops.int/Implementation/BATandBEP(new)/POPscontaminatedsites(new)/Guidance(new)/tabid/9649/Default.aspx); (POPs contaminated sites Guidance)
- United States Department of Defense and Department of Energy (2021) [Consolidated Quality Systems Manual \(QSM\) for Environmental Laboratories \[PDF\]](#), Version 5.4, Department of Defense (DoD) and Department of Energy (DoE), accessed 24 September 2024.
- United States Environmental Protection Agency (n.d.) [PFAS Thermal Treatment Database \(PFASTT\) | US EPA](#), US Environmental Protection Agency (US EPA), Washington DC, accessed 17 April 2024.
- (1992a) [Guidelines for Exposure Assessment](#), EPA/600/Z-92/001, US EPA, Washington DC, accessed 28 June 2024.
 - (1992b) [SW-846 Test Method 1311: Toxicity Characteristic Leaching Procedure](#), US EPA, Washington DC, accessed 29 May 2024.
 - (1992c) [SW-846 Test Method 1320: Multiple Extraction Procedure](#), US EPA, Washington DC, accessed 29 May 2024.
 - (1994) [SW-846 Test Method 1312: Synthetic Precipitation Leaching Procedure](#), US EPA, Washington DC, accessed 29 May 2024.
 - (2003a) [PROCEDURES FOR THE DERIVATION OF EQUILIBRIUM PARTITIONING SEDIMENT BENCHMARKS \(ESBS\) FOR THE PROTECTION OF BENTHIC ORGANISMS: ENDRIN | Science Inventory | US EPA](#), Report EPA/600/R-02/009, US EPA, Washington DC, accessed 23 May 2024.

- (2003b) PROCEDURES FOR DERIVING EQUILIBRIUM PARTITIONING SEDIMENT BENCHMARKS (ESBS) FOR THE PROTECTION OF BENTHIC ORGANISMS: DIELDRIN | Science Inventory | US EPA, Report EPA/600/R-02/010, US EPA, Washington DC, accessed 23 May 2024.
- (2003c) PROCEDURES FOR THE DERIVATION OF EQUILIBRIUM PARTITIONING SEDIMENT BENCHMARKS (ESBS) FOR THE PROTECTION OF BENTHIC ORGANISMS: PAH MIXTURES | Science Inventory | US EPA, Report EPA/600/R-02/013, US EPA, Washington DC, accessed 23 May 2024.
- (2003d) Technical Basis for the Derivation of Equilibrium Partitioning Sediment Benchmarks (ESBs) for the Protection of Benthic Organisms: Nonionic Organics [PDF], US EPA, Washington DC, accessed 5 June 2024.
- (2011) Draft Procedure for Analysis of Perfluorinated Carboxylic Acids and Sulfonic Acids in Sewage Sludge and Biosolids by HPLC/MS/MS [PDF], EPA-821-R-11-007, US EPA, Washington DC, accessed 30 May 2024.
- (2012) A Citizen's Guide to Capping [PDF], Citizen's Guide Series, EPA 542-F-01-022, US EPA, Washington DC, accessed 28 May 2024.
- (2017a) SW-846 Test Method 1313: Liquid-Solid Partitioning as a Function of Extract pH Using a Parallel Batch Extraction Procedure, US EPA, Washington DC, accessed 29 May 2024.
- (2017b) SW-846 Test Method 1316: Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio in Solid Materials Using a Parallel Batch Procedure, US EPA, Washington DC, accessed 29 May 2024.
- (2017c) SW-846 Test Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using An Up-Flow Percolation Column Procedure, US EPA, Washington DC, accessed 29 May 2024.
- (2017d) SW-846 Test Method 1315: Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure, US EPA, Washington DC, accessed 29 May 2024.
- (2019) Guidelines for Human Exposure Assessment, EPA/100/B-19/001, US EPA, Washington DC, accessed 2 July 2024.
- (2020) 2020 Progress Report: Characterization and Quantification of per- and polyfluoroalkyl substances in landfill gas and estimate of emissions from U.S. Landfills, EPA Grant Number: RD839600, US EPA, Washington DC, accessed 28 May 2024.
- (2021a) Other Test Method 45 (OTM-45) Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources [PDF], US EPA, Washington DC, accessed 30 April 2024.

- (2021b) Potential PFAS Destruction Technology: Mechanochemical Degradation [PDF], US EPA, Washington DC, accessed 30 May 2024.
- (2023) Other Test Method 50 (OTM-50) Sampling and Analysis of Volatile Fluorinated Compounds from Stationary Sources Using Passivated Stainless-Steel Canisters [PDF], US EPA, Washington DC, accessed 30 April 2024.
- (2024) Method 1633 Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS, US EPA, Washington DC, accessed 24 June 2024.
- van Asselt ED, Kowalczyk J, van Eijkeren JCH, Zeilmaker MJ, Ehlers S, Fürst P, Lahrssen-Wiederholt M, van der Fels-Klerx HJ (2013) Transfer of perfluorooctane sulfonic acid (PFOS) from contaminated feed to dairy milk, *Food Chemistry*, 141(2):1489–1495, doi: 10.1016/j.foodchem.2013.04.035.
- Ventia (2019) Improving Measurement Reliability of the PFAS TOP Assay, Ventia Utility Services Pty Ltd, accessed 30 May 2024, URL: [Ventia | Ventia plays key role producing PFAS report](#)
- Wang Z, DeWitt JC, Higgins CP, Cousins IT (2018) Correction to “A Never-Ending Story of Per- and Polyfluoroalkyl Substances (PFASs)?”, *Environmental Science & Technology*, 52(5):3325, doi: 10.1021/acs.est.8b00599.
- Warne MStJ, Batley GE, van Dam RA, Chapman JC, Fox DR, Hickey CW and Stauber JL (2018) Revised method for deriving Australian and New Zealand water quality guideline values for toxicants, Australian and New Zealand Governments, accessed 28 May 2024.
- Washington JW, Jenkins TM and Weber EJ (2015) Identification of Unsaturated and 2H Polyfluorocarboxylate Homologous Series and Their Detection in Environmental Samples and as Polymer Degradation Products, *Environmental Science & Technology*, 49(22):13256–13263, doi: 10.1021/acs.est.5b03379.
- Weinberg I, Dreyer A and Ebinghaus R (2011) Landfills as sources of polyfluorinated compounds, polybrominated diphenyl ethers and musk fragrances to ambient air, *Atmospheric Environment* 45(4):935–941, doi: 10.1016/j.atmosenv.2010.11.011.
- Weiner B, Yeung LW, Marchington EB, D’Agostino LA, and Mabury SA (2013) Organic fluorine content in aqueous film forming foams (AFFFs) and biodegradation of the foam component 6: 2 fluorotelomermercaptoalkylamido sulfonate (6: 2 FTSAS), *Environmental Chemistry*, 10(6):486–493, doi: 10.1071/EN13128.
- Yang LP, Zhu LY and Liu ZT (2011) Occurrence and partition of perfluorinated compounds in water and sediment from Liao River and Taihu Lake, China, *Chemosphere*, 83(6):806–814, doi: 10.1016/j.chemosphere.2011.02.075.

- Yeung L, Eriksson U and Kärrman A (2016) A pilot study on unidentified poly- and perfluoroalkyl substances (PFASs) in sewage in Sweden, Report for Swedish Environmental Protection Agency, Örebro University, Sweden, accessed 29 May 2024.
- You C, Jia C and Pan G (2010), Effect of salinity and sediment characteristics on the sorption and desorption of perfluorooctane sulfonate at sediment-water interface, *Environmental Pollution*, 158(5):1343–1347, doi: 10.1016/j.envpol.2010.01.009.
- Zareitalabad P, Siemens J, Hamer M and Amelung W (2013) Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in surface waters, sediments, soils and wastewater - A review on concentrations and distribution coefficients, *Chemosphere*, 91(6):725–732, doi: 10.1016/j.chemosphere.2013.02.024.
- Zeilmaker MJ, Fragki S, Verbruggen EMJ, Bokkers BGH and Lijzen JPA (2018) *Mixture exposure to PFAS: A Relative Potency Factor approach*, RIVM Report 2018-0070, Rijksinstituut voor Volksgezondheid en Milieu (RIVM), doi: 10.21945/RIVM-2018-0070, accessed 24 May 2024.
- Zhang L, Meng Z, Chen L, Zhang G, Zhang W, Tian Z, Wang Z, Yu S, Zhou Z and Diao J (2020) Perfluorooctanoic acid exposure impact a trade-off between self-maintenance and reproduction in lizards (*Eremias argus*) in a gender-dependent manner, *Environmental Pollution*, 262(July 2020):114341, doi: 10.1016/j.envpol.2020.114341.
- Zhao S, Zhou T, Zhu L, Wang B, Li Z, Yang L and Liu L (2018) Uptake, translocation and biotransformation of N-ethyl perfluorooctanesulfonamide (N-EtFOSA) by hydroponically grown plants, *Environmental Pollution*, 235:404–410, doi: 10.1016/j.envpol.2017.12.053.
- Zhu Z, Wang T, Wang P, Lu Y and Giesy JP (2014) Perfluoroalkyl and polyfluoroalkyl substances in sediments from South Bohai coastal watersheds, China, *Marine Pollution Bulletin*, 85(2):619–627, doi: 10.1016/j.marpolbul.2013.12.042.