Draft PFAS National Environmental Management Plan

Version 3.0 – Draft Prepared for Public Consultation

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

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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.

Front Cover
Figure by Lana Baskerville (2022). Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science.

Draft for consultation

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Introduction

The environmental management of the group of manufactured chemicals known as PFAS (per-and poly-fluoroalkyl substances) is a high priority for environmental regulators around Australia. 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 human health.

The PFAS National Environmental Management Plan (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. The NEMP is an Appendix to the Intergovernmental Agreement on a National Framework Responding to PFAS Contamination.

The first version of the NEMP, known as NEMP 1.0, was published in February 2018. It was developed by the Heads of EPAs Australia and New Zealand (HEPA) at the request of Environment Ministers around Australia. The NEMP reflects the current state of knowledge and is updated regularly to reflect new scientific evidence and guidance.

NEMP 2.0 was published in May 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 its unique properties, which have led to it being widely used for many decades. For example, PFAS are persistent and highly resistant to physical, chemical and biological degradation. Consequently, 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 materials, represents a challenge for us as environmental regulators. These are challenges best dealt with collectively.

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

1 Scope

1.1 What the NEMP does

The NEMP:

- provides guidance about the environmental management of per- and poly-fluoroalkyl substances (PFAS), with a focus on preventing and managing PFAS contamination
- recognises that different PFAS production methods and subsequent degradation processes can create complex mixtures of many different intentionally produced and unintentionally generated PFAS compounds (see Appendix A; see Buck et al. (2011); ITRC (2018b, 2017); OECD (2018, 2021); NICNAS (e.g. 2015a, 2015b, 2015c, 2017, 2019a, 2019b); and Wang et al. (2017) 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)
- 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
- recognises that the globally accepted definitions of PFOS, PFOA and PFHxS include their salts and related chemicals, including precursors, as established by the listing of PFOS and PFOA and the proposed listing of PFHxS 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 including other short-and long-chain (PFASs with six or more perfluorinated carbons and PFCAs with seven or more perfluorinated carbons (OECD 2018)) perfluoroalkyl acids (PFAAs) and PFAA precursors (other PFAAs classified as long chain include PFSAs with six or more perfluorinated carbons and PFCAs with seven or more perfluorinated carbons (OECD 2018)), where contamination stems from the historic use of products formed by processes that major manufacturers have phased out. For example, the Minnesota Mining and Manufacturing (3M) in 2000 agreed to voluntarily phase out perfluorooctanyl sulfonate (PFOS) chemistry in making its products. Examples of PFAS formed by this chemistry are found in Bazen-Hanson et al. (2017)
- recognises that PFAS other than PFOS, PFOA, and PFHxS are likely to be present in greater proportions in situations where historic contamination has not significantly degraded and where modern replacement PFAS, which are not based on PFOS, PFOA, and PFHxS and related compounds, are predominant (e.g. Weiner et al. 2013)
- 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, such as 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. 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 materials 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 n.d.)
- does not address current use and management of PFAS-containing products and articles, except in managing environmental and waste contamination, noting that environmental regulators may take action to restrict the use and management of PFAS-containing products and articles under national or their jurisdictional legislation
- 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 poly-fluoroalkyl substances. OECD (2021) defines PFAS as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), that is, with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS.

PFAS are manufactured chemicals that have been used for more than 50 years. PFAS make products non-stick, water repellent, and fire, weather and stain resistant. PFAS have been used in a range of consumer products, such as carpets, clothes and paper, and have also been used in firefighting foams, pesticides and stain repellents.

The most well-known PFAS are PFOS, PFOA and PFHxS. These three PFAS are part of a broader group of PFAS known as 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. See also www.nicnas.gov.au for information about PFAS compounds listed on the Australian Inventory of Chemical Substances.

1.2.1 Chemical structure and resulting environmental behaviour

The distinguishing characteristic of PFAS are a chain of carbon atoms bonded to fluorine 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. The Australian Industrial Chemicals Introduction Scheme (AICIS) provides information on PFASs. 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 and ground water, 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.

The 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 level. The presence of PFAS in environmental media does not necessarily constitute an unacceptable human health or environmental 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, and environmental media in which the contamination occurs. Section 9 provides further information on the assessment of PFAS contamination.

2 Australia’s international obligations

The Stockholm Convention on Persistent Organic Pollutants is a multilateral environmental agreement to protect human health and the environment from persistent organic pollutants. The Department of Climate Change, Energy, the Environment and Water is the lead agency in Australia on the Stockholm Convention on Persistent Organic Pollutants. The Convention sets globally accepted standards for the use and management of persistent organic pollutants with specific provisions tailored to each listed chemical. Parties to the Convention, including Australia, 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 is also a party to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal and the Rotterdam Convention on Certain Hazardous Chemicals and pesticides in International Trade. which address other aspects of chemicals management with a focus on international trade in chemicals, pesticides and wastes. 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 General Technical Guidelines on the Environmentally Sound Management of wastes consisting of, containing or contaminated with persistent organic pollutants. These guidelines can propose low content limits that can be taken up by the Stockholm Convention under its Article 6. See Section 14.6 for details.

2.1 International obligations in relation to PFOS, PFOA and PFHxS

To date, the PFAS compounds listed as persistent organic pollutants under the Stockholm Convention are:

- PFOS, its salts and perfluorooctane sulfonyl fluoride (PFOSF) were listed in 2009, noting the listing of PFOSF captures a wide range of PFOS-related compounds derived from PFOSF
- PFOA, its salts, and PFOA-related compounds were listed in 2019.
- PFHxS, its salts and PFHxS-related compounds

References to the listing of PFOS and PFOA, and potential listing of other PFAS, in the following discussion and throughout the NEMP include their respective salts and related compounds.

When a chemical is listed under the Stockholm Convention, a range of actions are required for Australia to ratify and implement these listings.

In general, the first step is a treaty-making process to inform an Australian Government decision on ratification of the listing. As part of this process, it is necessary to identify the management measures that would be necessary for Australia to be compliant with its international obligations. Once it is concluded that binding treaty action may be taken, government may implement measures. Australia would need to be able to fulfill the necessary obligations when it lodges an instrument of ratification.

The Australian Government is reviewing the remaining uses of PFOS, PFOA, and the PFOS- and PFOA-related compounds included in these listings, as part of the ratification process. This includes public consultation to inform the analysis. In late 2017 the Australian Government undertook public consultation on a Regulation Impact Statement on options for a national phase-out of PFOS in the context of the Stockholm Convention.

2.2 Potential future obligations in relation to other PFAS

In 2022 the parties agreed to list PFHxS, its salts and PFHxS-related compounds in the Stockholm Convention. The listing was assessed against the Annex D criteria by the Convention's subsidiary scientific body, the Persistent Organic Pollutants Review Committee, in October 2017. The Committee concluded that PFHxS meets the screening criteria for persistence, bioaccumulation, potential for long range environmental transport, and evidence for adverse impacts. Additional PFAS may be nominated in the future.

Australia will continue to participate in the Convention's processes and to address any domestic implementation requirements that result from the listing of PFHxS or other PFAS. In the meantime, the globally accepted standards outlined in the Convention for the use and management of persistent organic pollutants are a fundamental point of reference for the guidance provided in the NEMP.

Ratification of the PFOS, PFOA and PFHxS listing in the Stockholm Convention, would mean Australia accounting for, accepting and/or implementing international standards for the management of these chemicals. For example, this would include requirements regarding waste that contains listed chemicals, including related substances as defined by the listing, at a level above the current interim low content limit of 50 mg/kg for PFOS established under the Basel Convention. Section 14.6 provides guidance on management of waste above this limit.

3 Guiding principles

The following principles of sound environmental regulation guided the development of the 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*, 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: careful evaluation to avoid, wherever practicable, serious or irreversible damage to the environment; and 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 PFAS assessment based on appropriate analytical methods and standards, with the required quality assurance and control.
5) Consistency across jurisdictions, supported by the 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)

   b) the National Environment Protection (Assessment of Site Contamination) Measure 1999 (ASC NEPM)

   c) the National Water Quality Management Strategy, including the Australian and New Zealand Guidelines for Fresh and Marine Water Quality

   d) the Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination.

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 offsite dispersal of PFAS and onsite 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
- 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 dependant 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 materials 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, for example, by properly characterising waste and sending it to a facility licensed to accept it, noting dilution is not acceptable for example in soil, air, compost or other wastes or products
- ensuring PFAS-contaminated materials for reuse, including reused waste, are appropriately managed to prevent harm to land use, human health and the environment
- 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 materials.

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 Information Sharing, Communication and Engagement Guidelines and the PFAS Contamination Response Protocol Appendices to the *Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination*. 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 human health and the environment 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, its impacts and its management, 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 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 a 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 occupant and the environmental regulator.

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 includes data on PFAS in receptors, such as wildlife and seafood species (Section 8.7) and assessing potential for PFAS to leach from soils and construction materials (Section 18.3). This data is used by site managers and environmental regulators to inform the assessment and management of PFAS contamination for the protection of human health and the environment.

For environmental regulators, monitoring also provides the evidence base for decision-making in relation to policy development, regulatory activities and site-specific management controls, such as 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 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 in. 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 remote locations with minimal anthropogenic disturbance. The term ‘ambient’ is used for PFAS 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 assisting in identifying previously unknown PFAS sources, sinks or pathways. Where known or suspected points 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 offsite contamination caused or contributed to by contamination at the site, and the potential on- and off-site impacts on human health and the environment.

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, such as a loss of containment of PFAS-containment material, or by a need to characterise baseline site conditions prior to a change of land use or development (see Section 10 for guidance on containment of PFAS contaminated materials). 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, including identifying offsite 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 Responding to PFAS Contamination and particularly Appendix A – PFAS Contamination Response Protocol. 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 offsite or is of unknown origin. The results of this consideration should inform the scope, scale, and geographic focus of the monitoring program. For example, a monitoring plan may include data tailored to identifying and evaluating PFAS distribution patterns attributable to different sources, areas of overlapping influence and background conditions.

To be fit for purpose, data collection should be, at a minimum, 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 identifying transport, fate and exposure pathways
- enable comparison against all relevant screening criteria Section 8 provides guidance on PFAS environmental guideline values and 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 adverse impacts on the environment or 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, based on current knowledge, across a range of spatial scales.

The starting assumption should be that PFAS will travel from its sources into environmental media down-gradient 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 run-off. Air transport is relevant for volatile PFASs such as fluorotelomer alcohols and ketones, PFAS subject to thermal processes and for PFAS bound to airborne particles, and sediment transport is relevant for PFASs such as long-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 be used to assess the current status and monitor impacts from reuse of materials (e.g. 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 (e.g. tissues from fish, crustaceans and molluscs) to inform bioaccumulation trends
- air – sampling of air (including gaseous phase, condensed phase, and particulates e.g. dust), particularly where there is a high potential for airborne emissions, noting options for air sampling are not routine. Information on air sampling is provided in ITRC (2018d).

It is useful to include general environmental monitoring parameters (e.g. 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. For additional information and guidance on sampling for ambient programs refer to Appendix B.

Ambient monitoring should:

- consider where known and likely PFAS point source are located and clearly flag these data so that reporting with and without point sources is possible. A distance of 1 km from a point source should be used as a minimum distance for sites to be flagged as subject to point source impacts (see Stockholm (2015) for further information), although local movement pathways (groundwater, hydrology, soil movement) need consideration. This is discussed further in the Victorian Case Study below. Where a PFAS point source is known to extend for a large distance (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, as this will help to eliminate bias and to provide information about PFAS concentration variation (e.g. 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, thereby enabling 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 and, furthermore, the collation of comparable data across jurisdictions. The methods used to establish land-use classes are briefly outlined below and will be described in more detail by EPA Victoria (in prep.

The land use classification approach is based on the Australia Land Use and Management (ALUM) Classification (version 8) (ABARES 2016) available) scheme, and 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 scheme to ALUM exists for New Zealand (Land Cover Database (LCDB) v 5. 0).

Once the proportions of primary land use are obtained from the ALUM or LCBD schemes, a broader land use class can be assigned to the location (Table 1). The current five broad classes are: remote-ambient, agricultural-ambient, urban-ambient, mixed-ambient and marine-ambient (Table 2). 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 our understanding on PFAS distribution improves. Also, for some jurisdictions additional land use categories with finer resolution may apply, though it is recommended that they should sit under these 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, which may have high historic levels of PFAS as a result of the use of aqueous film-forming foram (AFFF) for firefighting should be clearly identified and flagged in ambient datasets. Additionally, point sources may not be limited to contaminated sites where AFFF has been used. Other potential sources such as WWTPs, landfills and land where biosolids have been applied should also be considered.

Table 1 PFAS ambient land-use classes

Land use classes	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

Land use classes	**Proportion of land uses in the upstream catchment (a)**
Urban-ambient	>50% in Victoria & >40% in Queensland, commercial or/and industrial or/and residential **(b)**
Mixed-ambient	Sites that do not fall within the remote, agricultural, or 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 or/and industrial or/and 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 (EPA Victoria, in prep) 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 >5 km away from a known point source. This is further than the 1 km recommend by Stockholm (2015), as there was evidence of transport of PFAS from known point sources beyond 1 km.

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) 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 classes 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 >1 km away from a known point source (Stockholm, 2015). The majority of ambient sites sampled in Queensland were estuarine/tidal sites, whereas in Victoria they were freshwater sites. For surface water assessment, consideration also needs be given 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 for example, 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 1 sample at a site
(b) Overall detection frequency in all samples collected over the year at all sites

5.3 Site-specific monitoring programs

Site-specific monitoring guidance is provided in the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM) as part of the nationally agreed process for characterising site contamination. This process is informed by the development of a robust conceptual site model, 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 and other biota and animal/human food sources wherever a plausible transport pathway from a contamination source exists. Note that sampling exposed aquatic biota is necessary for effective assessment even if water concentrations are below the limit of reporting (LOR) (refer NSW EPA (2016) 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 a livestock type, it may be possible to calculate potential uptake.

Some types of monitoring, such as 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 assessors to differentiate between ambient (diffuse) contamination, and point source contamination originating from the site, and the extent to which onsite source(s) are contributing to offsite impacts.

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 materials. Quantitative data includes mass, volume and PFAS concentration. Qualitative data includes 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 includes the types, locations and quantities of PFAS-containing products or PFAS contaminated materials, management practices employed and 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 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 (major commercial, industrial and government facilities, infrastructure and activities that historically or currently use or store PFAS-containing products, noting that all PFAS formulations should be considered, such as surfactants used in chrome plating or firefighting, hydraulic fluids and lubricants, and wastes and waste liquids)
- identifying other primary sources (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 (sites where diffuse PFAS inputs are or have been received such as landfills, wastewater treatment facilities, liquid waste treatment facilities, and biosolids stockpiles – 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:

1) 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.
2) 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.
3) Define the scope of the inventory, which involves identifying the following:

   a) industry and government sectors that should be considered further, based on the relevant areas of industrial use from the stakeholder identification stage
   b) existing and potential waste sources
   c) the resources available to perform the inventory
   d) spatial priorities, such as where there are areas of environmental significance or other values of specific interest.

4) Plan the inventory. This involves agreement on aims, objectives, timeframes, outputs, resources, stakeholder engagement, governance, probity and conflict of interest.
5) Data management. This involves arrangement for data acquisition, input, storage, integration, and issues such as 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.
6) 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 effected the Operational Policy – Environmental Management of Firefighting Foam 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 425,000 kg of foam was reported, mostly at bulk fuel and chemical storage facilities. PFAS-containing foams were reported at 98% of sites, and it was estimated that 5% of sites were compliant.

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, and ensure environmental regulators focus on activities that address the highest risk sites.

7.1 Site prioritisation process

This risk-based prioritisation 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, 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, as is the nature of the current and past site use and the efficacy of any measures 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 such as biodiversity, social values such as Indigenous cultural practices and economic values, such as 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 human health and/or the environment, and where there are known or probable exposure pathways. As investigations proceed, 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 and consequently the potential environmental and human health risks requiring consideration.

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 prioritisation

Once the initial scan of risks has been determined and site prioritisation has been 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 exists as a contaminant. The inventory involved a desktop study of major industries that were likely to have PFAS stocks or contamination, 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 14,000 kg of PFAS-containing materials.

The identified sites were prioritised based on the risk they posed to human health and/or the environment. 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 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 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 the priority for regulatory action.

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 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 PFASs 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 consideration of 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 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 human health and the environment.
- The selection of the appropriate guideline values at a site should consider current, 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 in consultation with the environmental regulator. Relevant guidance could include the National Environment Protection (Assessment of Site Contamination) Measure (ASC NEPM), the National Water Quality Management Strategy (NWQMS) (Australian Government 2018) (including the Water Quality Guidelines (WQGs)), the Commonwealth Environmental Management Guidance for PFOS and PFOA (Australian Government, 2016), and jurisdictional tools such as Commonwealth, state and territory environment protection, catchment, groundwater basin, vegetation and biodiversity management plans; contaminated sites registers; waste and wastewater management strategies; and PFAS-specific guidance resources. It is important to note that 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 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 NEMP

The guideline values in the NEMP are drawn from, and have been derived with reference to existing nationally-agreed and long-standing Australian frameworks including the NWQMS (Australian Government 2018) and the ASC NEPM wherever possible. However, some of the guidance in these existing frameworks may not always be protective for mobile, persistent and bioaccumulative substances such as PFAS.

For guideline values where there are nationally recognised processes for the review and adoption of new criteria, such as the Australian and New Zealand Fresh and Marine Water Quality Guidelines (WQGs), appropriate draft criteria are recommended below. The 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 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 addition of more recent literature as it becomes available.

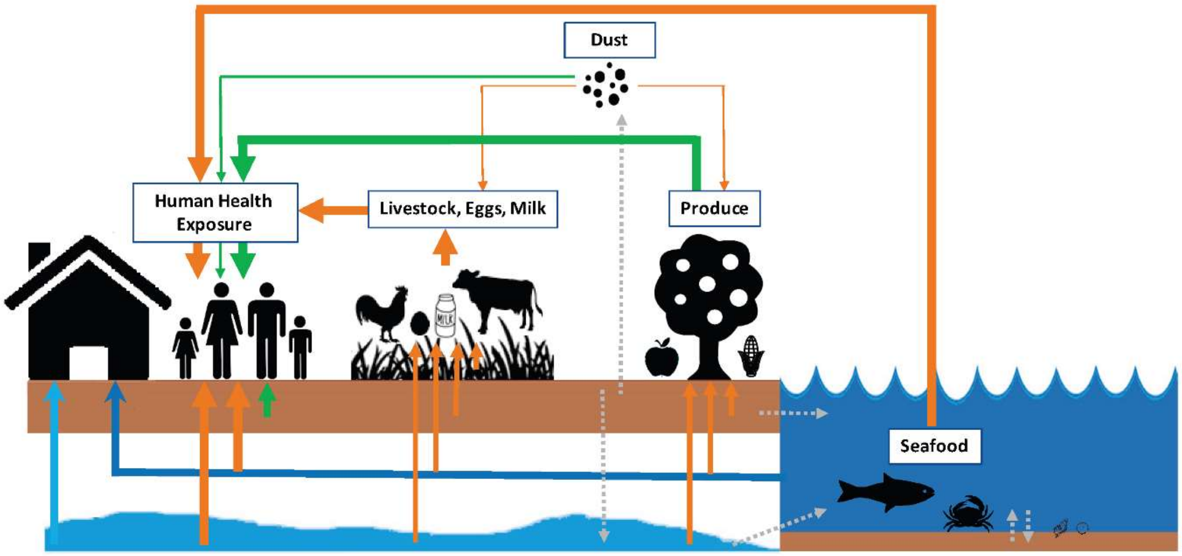
Where the above options were not possible, internationally derived guideline values are provided.

8.3 Exposure pathways for human health assessments

Section 8.6 describes PFAS guideline values for human health assessments, including health based guideline values for drinking water and recreational guidelines from the National Health and Medical Research Council (NHMRC), and health investigation levels (HILs) for soil. Note, 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 assessment.

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



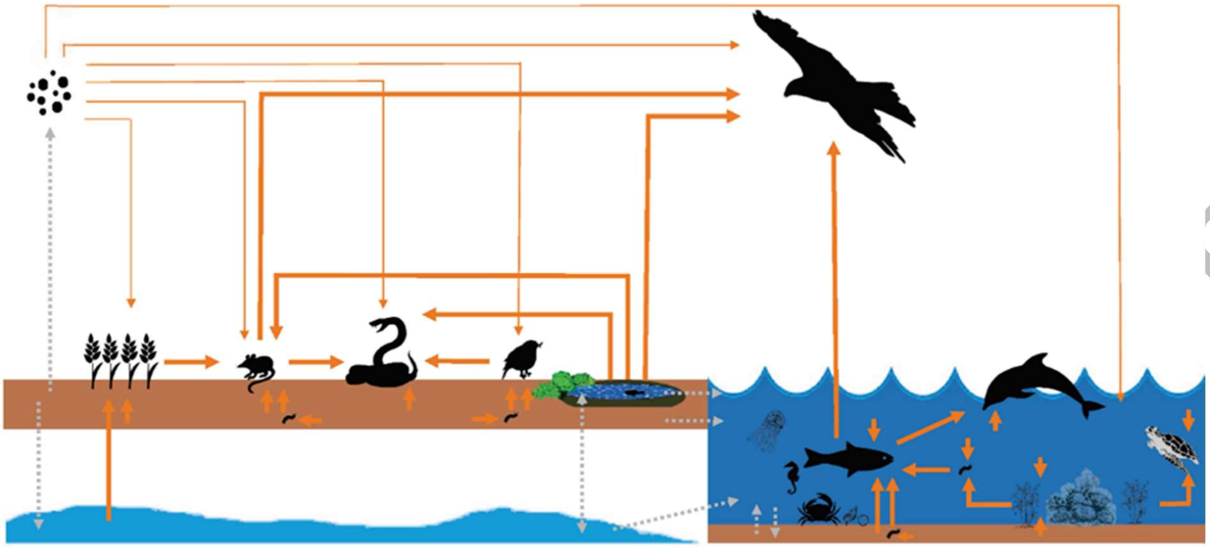
Note: Figure 1 depicts potential exposure pathways affecting human health and is a general example of potential exposure pathways to be considered in a site assessment. Note this is not intended as a comprehensive conceptual model covering all possible exposures. Dotted grey arrows indicate PFAS transport 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 health investigation levels for soil (Table 2). These include exposure via soil, dust and consumption of a small amount of home garden produce (home-grown produce provides up to 10% of fruit and vegetable intake). The arrow’s thickness infers relative magnitude of assumed exposure, showing that dust inhalation is considered typically 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 draft 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.

833 **Figure 2 An example of potential ecological pathways for PFAS exposure**



834

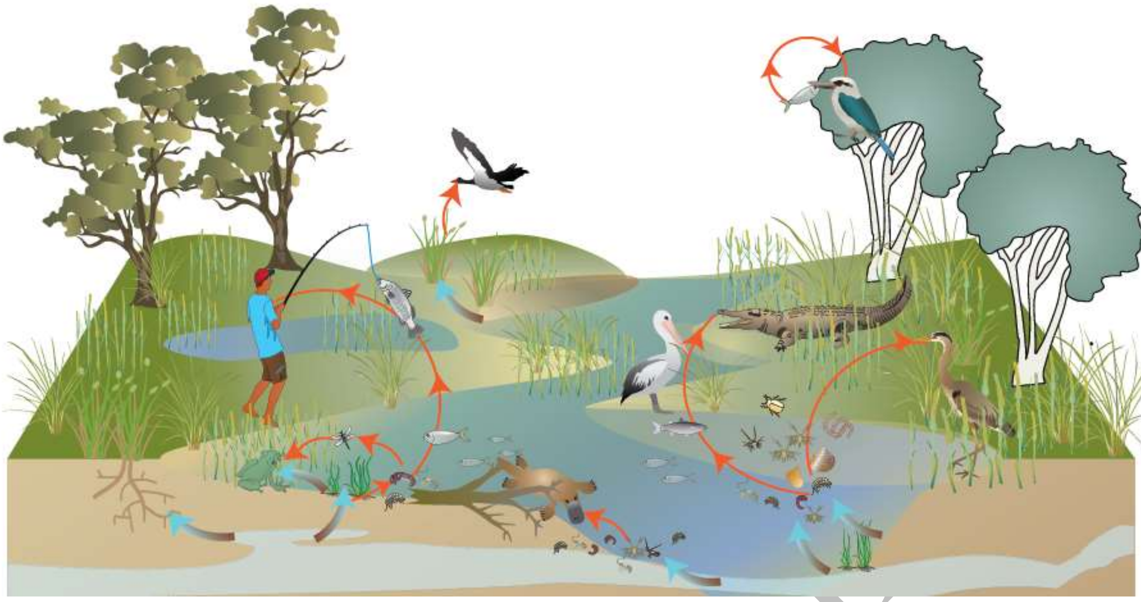
835 Note: The conceptual model shown in Figure 2 is a general example of potential exposure pathways to be considered in a
836 site assessment, and is not intended as a comprehensive conceptual model covering all possible exposures. Dotted grey
837 arrows indicate PFAS transport mechanisms in the environment. Solid orange lines indicate potential PFAS uptake and
838 exposure pathways to ecological receptors. The arrow thickness is relative to the significance of the PFAS exposure
839 pathway.

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

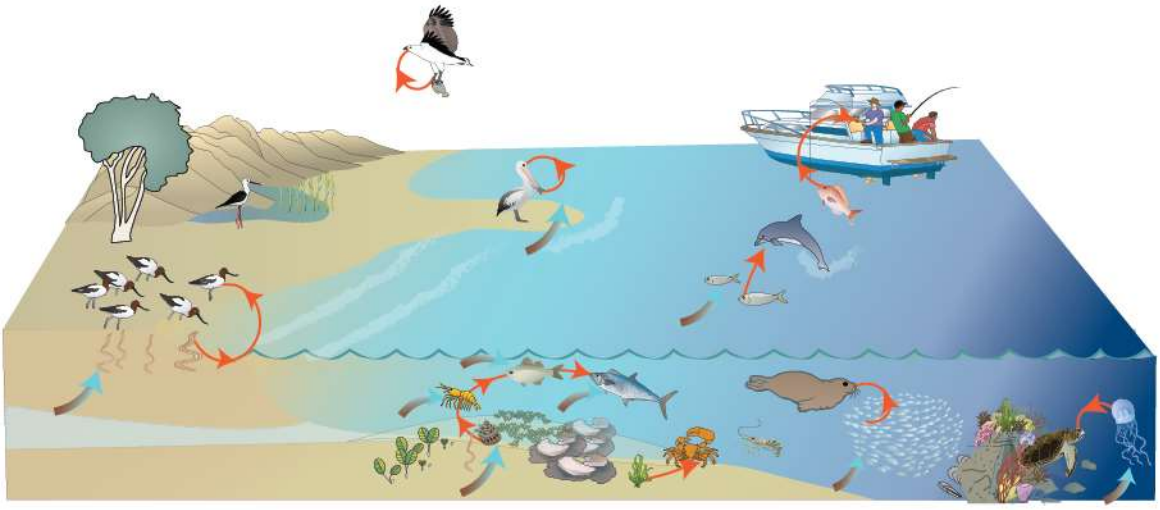
842 **(a)**

843

(b)



(c)



Source: Lana Baskerville (2022). Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Note:

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.

8.5 Consideration of bioaccumulation

For PFAS, bioaccumulation in aquatic species cannot currently be 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 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 such as fish may have faster elimination rates compared with aquatic air breathing (e.g. fish) and relatively slow for air-breathing animals, (e.g. marine mammals; SA EPA 2017, Taylor et al. 2017). Elimination rates may also differ in terrestrial animals (Lupton et al., 2015, Numata et al., 2014) which need to be considered for potential implication for assessing risk for home consumption of livestock. 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 will reduce 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 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 Human health guideline values

The human health guideline values 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 environment regulators, along with guidance from Sections 5 – PFAS monitoring, 9 – PFAS contaminated site assessment, 18 – PFAS sampling and 19 – PFAS analysis in the NEMP and ASC NEPM for monitoring, site assessment, sampling and analysis.

8.6.1 Human health guideline values developed by health authorities

For humans, the main sources of PFAS are via ingestion of food and drinking water in a contaminated site setting. Health authorities have set health-based guidance values 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 health-based guidance values for PFOS and PFOA were recommended by Food Standards Australia and New Zealand in the form of a tolerable daily intake (TDI) (FSANZ, 2017). The TDI was then used to calculate the human health-based guidance values listed here.

As a precaution, the Australian Government Department of Health 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 national methodologies used by health agencies in deriving the values in Table 4 include a level of conservatism in the drinking water and recreational water health-based guideline values. The methods assume only a minor portion (10%) of the TDI is allocated to this source.

The recreational water quality values have been updated from the values published in the NEMP 1.0 and are based on revised numbers derived by NHMRC (2019). The revised numbers are based on changes in the assumption for the frequency and likelihood of exposure during recreational activities.

NHMRC (2019) notes that there may be cases where recreational water may be used more frequently than the assumptions underpinning the guidelines. For example, surfing activities may be longer in duration and higher in ingestion risk, compared to NHRMC assumptions. For such activities, more locally-appropriate recreational guidance based on actual event frequency should be considered in consultation with the state or territory health regulator.

Table 4 Human health guideline values developed by health authorities[a]

Description	Sum of PFOS and PFHxS	PFOA	Comments and source
Tolerable daily intake (TDI)	0.02 µg/kg_{bw}/day	0.16 µg/kgbw/day	FSANZ 2017
Drinking water quality guideline value	0.07 µg/L	0.56 µg/L	Australian Government Department of Health 2019
Recreational water quality guideline value[b]	2 µg/L	10 µg/L	NHMRC 2019

Notes: bw = body weight, µg = micrograms. Where the guideline values refer to the sum of PFOS and PFHxS, this includes PFOS only, PFHxS only, and the sum of the two.

[a] 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. In such cases more locally-appropriate event frequency based recreational guidelines can be considered in consultation with the state and regulatory health regulator.

[b] 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 human health-based investigation levels for soil were derived using a methodology consistent with assumptions set out in the ASC NEPM for the health investigation levels (HILs). Note these values have not been derived under the ASC NEPM. The PFAS HILs (Table 5) should only 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 potential leaching, off-site transport, bioaccumulation and secondary exposure.

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 these criteria do not account for potential home consumption of eggs from home-raised poultry, nor of milk or meat from stock on the premises. 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 (e.g. consumption of other home grown produce and recreational activities) as well as background exposure. This means that exceeding these values does not 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 NEMP 3.0. The 'residential with garden/accessible soil' investigation levels listed in the previous version of the NEMP (NEMP 2.0) have been retained, and the values are considered reliable and protective based on the existing and additional transfer factors reviewed for PFAS from soil to plants. Details on the methods and transfer factors considered as part of the work for this version of the NEMP are detailed in the NCWG supporting document (2021). Specifically:

- Relevant studies additional to those included in the derivation described in OEH (2019) were considered, where a full review for PFOA was undertaken.
- The soil to plant transfer factors were based on PFAS concentrations per wet weight plant (where only data for dry weight 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 are detailed in the National Chemicals Working Group (NCWG) supporting document Soil health investigation levels (NCWG, 2021).

Table 5 Human health investigation levels for soil

Land use	Sum of PFOS and PFHxS	PFOA	Comments and source
Residential with garden/accessible soil (HIL A)	0.01 mg/kg	0.1 mg/kg	Assumes home-grown produce make up to 10% of fruit and vegetable consumed (does not account for consumption of any eggs from home poultry, nor of milk or meat from stock on the premises). Also includes children's day care centres, preschools and primary schools. Note: If home-grown produce provides make up more than the 10% of fruit and vegetable intake 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 intake consumption, the screening value would be 0.002 mg/kg for the sum of PFOS and PFHxS, and 0.02 mg/kg for PFOA.
Residential with minimal opportunities for soil access (HIL B)	2 mg/kg	20 mg/kg	Assumes soil is not used to grow and consume home-grown produce. Includes dwellings with fully and permanently paved yard space such as high rise-buildings and flats. These were derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL B.
Public open space (HIL C)	1 mg/kg	10 mg/kg	Relevant for public open space such as parks, playgrounds, playing fields (e.g. 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 were derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL C.
Industrial/commercial (HIL D)	20 mg/kg	50 mg/kg	Assumes eight hours is spent indoors and one hour spent outdoors at a site such as a shop, office, factory or industrial site. If the typical exposure for a site is predominantly outdoors

Land use	Sum of PFOS and PFHxS	PFOA	Comments and source
			with significant earthen areas, recalculation of a site-specific value is recommended. These were derived using the methodology consistent with assumptions set out in the ASC NEPM for HIL D. Note: the industrial/commercial direct exposure criterion for PFOA (including its salts and related compounds) has been set as 50 mg/kg in anticipation of the Stockholm Convention low content limit of 50 mg/kg.

Note: Where the guideline values refer to the sum of PFOS and PFHxS, this includes PFOS only, PFHxS only, and the sum of the two.

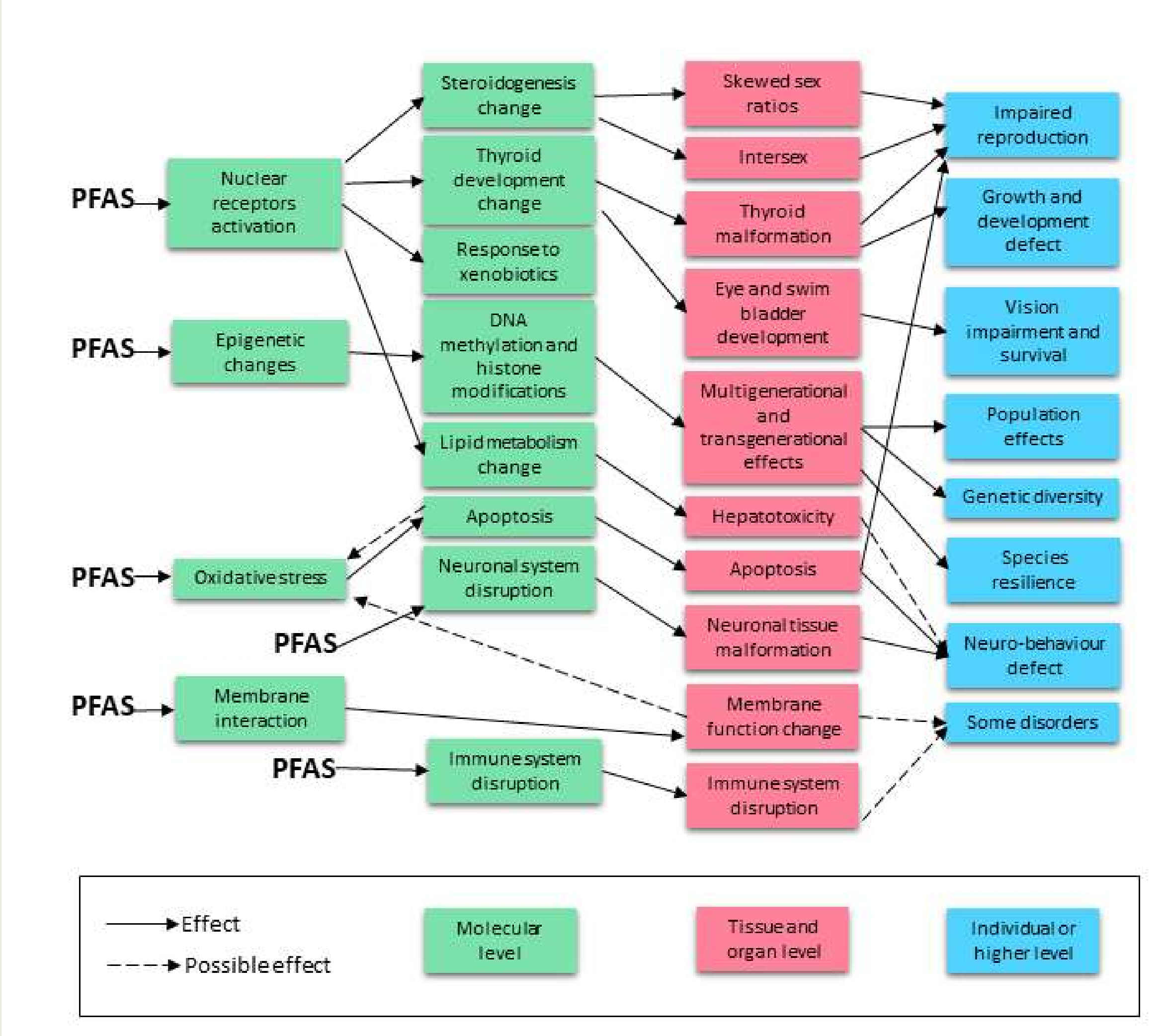
8.7 Ecological guideline values

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 NEMP and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality framework on considerations for monitoring, site assessment, sampling and analysis (see Sections 5 – Monitoring; 9 – Contaminated site assessment; 18 – PFAS sampling; and 19 – PFAS analysis). The general environmental duty to prevent offsite 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. However, we acknowledge that understanding based on 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 (see e.g. Figure 5). 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 Plausible mechanistic pathways for PFAS toxicity



Adapted from Kumar et al. (2020a: 23) adapted from Lee et al. (2021).

The ecological guideline values are intended to indicate threshold concentrations that provide a defined degree of confidence that there are unlikely to be unacceptable risks, except where indicated. The ecological guideline values are not intended to be generic contaminated site remediation criteria. Importantly, the National Water Quality Management Strategy'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 (i.e. not to allow increases in concentration up to the guideline value) (ANZG 2018b) . Furthermore, disturbed or impacted systems should not be regarded as 'pollution havens' (ANZG 2018b).

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.

The direct exposure ecological soil guideline applies specifically to 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 (see

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 are detailed in the National Chemicals Working Group (NCWG) supporting document Soil health investigation levels (NCWG, 2021).

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, a protective direct soil guideline value for PFOA for reptiles, has also been included in Table 6, and intended to be used where reptiles are present. This value is based on limited reptilian research (Zhang et al. 2020) and details on the methods considered as part of the work for this version of the NEMP are detailed in the NCWG supporting document PFOA Direct Soil Guideline Value (2021).

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 (i.e. exposure through the food chain). 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) were considered. The values calculated for exposure of a secondary consumer are based on the most sensitive exposure pathway and were adopted as the PFOS indirect exposure value in the NEMP.

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 thus recognises that traditional land use categories are not relevant to ecological risks, and therefore a single guideline value is now applicable to all land use scenarios. This better 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 0.14 mg/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 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	PFOA	Comments and source
Ecological direct exposure – All land uses	1 mg/kg	10 mg/kg	Future work may be undertaken to review available soil guideline values proposed by Australian research and industry organisations. Where reptiles may be exposed directly to soil an interim screening value of 5 µg/kg for PFOA is recommended (a).
Ecological indirect exposure –All land uses	0.01 mg/kg	0.005 mg/kg	The guideline value is based on dietary exposure of a secondary consumer as the most sensitive exposure pathway assessed. This value may not be protective of specific animals relevant to Australia, including predatory animals such as quolls and antechinus. For intensively developed sites with no secondary consumers and minimal potential for indirect ecological exposure, a higher criterion of up to 0.14 mg/kg PFOS may be appropriate as outlined in the accompanying text in Section 8.7.1.

(a) Based on a LOAEL of 50 µg/kg for reduced growth (Zhang et al. 2020), divided by an uncertainty factor of 10 for inter species differences (NEPC 2013). As this is based on a LOAEL, it may not be sufficiently protective of endangered, threatened or vulnerable reptiles and high ecological value sites.

8.7.2 Biota guideline values

The wildlife diet values for PFOS + PFHxS provided in the second version of the NEMP (NEMP 2.0) are considered to have been derived in a manner consistent with the Australian context. For details on the rationale for adopting the ECCC (2018) guidelines in NEMP 2.0, refer to the NCWG supporting document Review of applicability of the Canadian federal environmental ecological guidelines in Australia (2021). In this current NEMP, the wildlife diet value for PFOA has been derived following the same approach and using wildlife consumption data for a representative mammalian Australian species. This consumption data has been used to also update the PFOS + PFHxS mammalian guideline. Details on the methods and data used as part of the work for this version of the NEMP are provided in the NCWG supporting document PFOA direct ecological values (2021).

The bird tissue egg value adopted from the Environment and Climate Change Canada (ECCC; 2018) which was listed in NEMP 1.0 was updated in NEMP 2.0, and retained in NEMP 3.0. The change was due to an additional uncertainty factor for intra- and interspecies variability that reflects the paucity of toxicological data for birds.

The tissue guideline for acceptable contaminant levels in bird egg is to assess potential risks to avian populations where these receptors may be relevant. 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 **(b)**	Description
Ecological direct exposure for wildlife diet **(d)**	3.1 µg/kg	2.8 µg/kg	Mammalian diet – consumption of biota as wet weight food
	8.2 µg/kg	N/A	Avian diet – consumption of biota as wet weight food **(c)**
Ecological exposure protective of birds **(e)**	0.2 µg/g	N/A	Whole bird egg as wet weight

(a) Where the guideline values refer to the sum of PFOS and PFHxS, this includes PFOS only, PFHxS only, and the sum of the two**.** The Canadian ECCC (2018) guidelines refer to the criterion for PFOS only; in the 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. For the sum of PFOS and PFHxS the tolerable daily intakes adopted are 1.1 µg/kg BW/day for mammals and 7.7 µg/kg BW/day for avian. Details on the methods are provided in the NCWG (2021) supporting documents.

(b) For PFOA, a tolerable daily intake of 1 µg/kg BW/day based on ECCC (2018) approach using representative local species was used. 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 are preferred. The food intake rate of 0.36 kg/kg bw/day is based on consumption data for the platypus *Ornithorhynchus anatinus* supporting lactation (Thomas et al. 2018). This guideline value is to be used on sampled biota tissue for assessing risk to mammal receptors based on their diet. Details on the methods are provided in the NCWG (2021) supporting documents.

(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) The wildlife diet values may also not be protective of reptiles and amphibian, and the PFOS + PFHxS values may not be protective for PFOA exposure.

(e) Adapted from Canadian Federal Environment Quality Guidelines (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.

8.7.3 Ecological water quality guideline values developed by water authorities

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 NEMP. Further information about the WQG Framework, including the development and application of DGVs and site specific values, is available on the WQG 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 in this NEMP. The species protection DGV may be below the ambient background concentration. Actions to determine reliable background concentrations for organic chemicals with widespread (e.g. global) contamination are discussed in the WQGs and in Section 5.2 in this NEMP.

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 (ANZECC and ARMCANZ 2000, 8.3–45). 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 µg/L
	95% species protection – slightly to moderately disturbed systems **(c)**	0.13	220 µg/L
	90% species protection – highly disturbed systems	2	632 µg/L
	80% species protection – highly disturbed systems	31	1824 µg/L
Interim marine **(d)**	99% species protection – high conservation value systems	0.00023	19 µg/L
	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

(a) The draft 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 level of detection. Agencies may wish to apply a 'detect' threshold in such circumstances rather than a quantified measurement.
(c) The WQGs 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. 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 Australian and New Zealand Guidelines for Fresh and Marine Water Quality. 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.
Data source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality – technical draft default guideline values for PFOS and PFOA.

8.7.4 Sediment quality

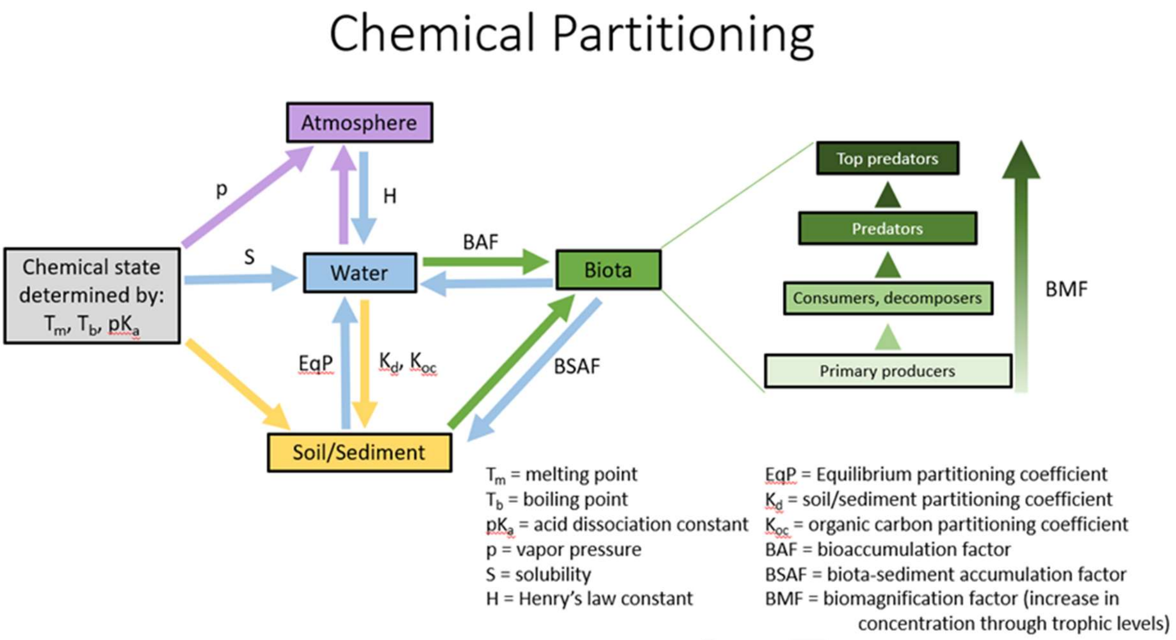
The sediments of many of the urban river systems, estuaries and near-shore coastal waters worldwide have higher contaminant loads, derived largely from past and present industrial discharges and urban drainage (Simpson and Batley 2016; Yang et al. 2011). This guidance on sediment quality is intended 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. 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 (for example, in terrestrial, freshwater, estuarine or marine ecosystems). Marine sediments are, for example, often less varied in their physical characteristics and properties. Examples include the effects of 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, which 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 (i.e., 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 PFASs (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, whilst having significant technical limitations. Thus, 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(a)(b)(c) (See Sections 8.3 and 8.4). Chemical partitioning relationships between environmental compartments between 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 guideline or investigation values should not be used as screening values for aquatic sediment contamination.

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 sediment quality guideline values for PFASs 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; EU 2011; OECD 2002). The reported methods have been reviewed and limitations found in almost all studies (Kumar et al. 2020b).

Where criteria for PFASs 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 PFASs 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 2018c). 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 PFASs 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, Kd, 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 persistent organic pollutants (EU [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 species sensitivity distribution (SSD) based on PFOS toxicity data for benthic marine species and measured Kd values, to derive a screening value for estuarine benthic sediments. The Simpson et al. (2021) study used a Kd value of 10 to derive a 99% species protection (PC99) concentration of 60 µg/kg for PFOS (normalised to 1% OC) in benthic marine sediment. It provides a line of evidence in considering direct toxicity. It is noted 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 (Table 8). For these reasons, and because the PC99 screen value proposed in the study is not currently endorsed by regulators, the advice of environmental regulators should be sought if considering its use.

8.7.6 Organic carbon and sediment adsorption coefficients

In estuarine and marine sediments organic carbon (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; Aherns 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 sediment to water partitioning coefficient (Kd) ranges from 16 to 150 L/kg. This relationship has been reported in some sedimentary systems (Simpson et al. 2021; Oliver 2020); whilst other studies did not show these strong relationships (Celis-Hernandez et al. 2021; Oliver 2020). How OC Kd relationship 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 data should be collected when sampling sediments for site assessments.

8.7.7 Considerations for bioaccumulation

Multiple lines of evidence are an important consideration when assessing and monitoring sediment quality (ANZG 2018c; Commonwealth of Australia 2009; Simpson and Batley 2016). More detailed guidance is available in range of publications including: *National Assessment Guidelines for Dredging 2009* (Commonwealth of Australia 2009), *Monitoring and Sampling Manual: Environmental Protection (Water) Policy* (DES 2018), *Water quality – Sampling – Part 12: Guidance on the sampling* *of bottom sediments* (AS/NZS 5667.12:1999), *Field Manuals for Marine Sampling to Monitor Australian Waters* (Przeslawski and Foster 2020) and 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 thus 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 (LOR 0.9 – 1 µg/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 conceptual site model (CSM) and Sampling, Assessment and 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 9.0 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 sampling and analysis quality plans).

8.8 Information on alternative approaches to the 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 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 PFASs. It is provided to assist in understanding that approaches to deal with multiple PFASs 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 to assessing risks associated with complex PFAS mixtures, practitioners may need to consult with jurisdictional 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 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 health-based guidelines. It is assumes that a guidance 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 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 Section 8 of this management plan. 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.

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 refers to 'PFOA, its salts and PFOA-related compounds.

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 bioaccummulative’. Germany has proposed a new regulatory grouping under 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 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.

8.8.4 Grouping perfluoroalkyl acids together with their precursors

Under this approach, a PFAS of concern is managed together with all its salts and precursors. This approach is used in international regulation and involves managing a PFAS of concern together with its salts and precursors, with the most well-known example being the Stockholm Convention, which lists or proposes listing of PFOS, PFOA and PFHxS this way by including ‘related substances’ in the purview.

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 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. Organic fluorine, measured by TOF or EOF, is used in some countries regulating PFAS content in food contact material (Ministry of Environment and Food of Denmark 2020). TOF analysis is further described in Section 19.3.2.

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 (i.e. –CnF2n–, n ≥ 3) or a perfluoroalkylether moiety with two or more carbons

(i.e. –CnF2nOCmF2m–, n and m ≥ 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.

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 polycyclic aromatic hydrocarbons. 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 7 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 (ASTDR 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).

8.8.8 Development of specific toxicity reference values

Some international jurisdictions have developed toxicity values for a range of individual PFAS (e.g. Danish Ministry of Environment 2015; US EPA 2021). 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.

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.

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 (i.e. potential risks to human health, to the environment and to environmental values).

The established national guidance document for the assessment of site contamination in Australia is the ASC NEPM.

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
- 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 of a food chain, in a way that differs from other contaminants, such as the lipophilic 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 and, although sorbing to some extent to soils and sediment, most of the mass will be transported over time in the aqueous phase via surface drainage to surface water bodies and via leaching to groundwater. 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 via ingestion of 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 including drains and groundwater. The possibility of long-distance movement of contamination should be considered, noting 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 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 conceptual site model/sampling and analysis quality plan.

Consideration should be given to the presence of both primary sources (such as firefighting training areas, landfills or wastewater treatment plants) 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 (for example, change in firefighting foam usage from an electrochemical fluorination-based AFFF to a fluorotelomer- or fluoropolymer-based AFFF), should be considered.

9.1.1 Identification of off-site receptors

The ASC NEPM guidance allows for both the classic site assessment approach, starting 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 screening values as discussed in Section 8. In many cases the conceptual site model 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 by livestock of contaminated stockwater (surface water and/or groundwater) and of contaminated grazing material and soil
- human intake of contaminated water through drinking or cooking
- human exposure to contaminated water through activities such as cleaning, showering and swimming
- consumption by humans 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) and telomerisation.

For example, firefighting foam products produced by ECF were based on PFOS and sulfonamide-based surfactants, which are understood to be precursors to perfluorosulfonic acids (PFSA) such as PFOS.

Conversely, products based on fluorotelomers are considered perfluorocarboxylic acid (PFCA) precursors (D'Agostino and Maybury 2014). Thus, sites where only one type of product was used are likely to have one type of dominant precursor, whereas sites were 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 (e.g. 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 Australian Industrial Chemicals Introduction Scheme (AICIS) aicis.gov.au for information about PFAS compounds listed on the Australian Inventory of Chemical Substances. For example, the sampling and analysis quality plan should investigate whether precursors and their transformation products, if present, have migrated along identified pathways and to receptor sites. If so, the conceptual site model should also incorporate potential transformation products. For example, pathways and receptors affected by a fluorotelomer-based source zone should consider PFCA 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.

Commercially available analytical techniques based on LC-MS/MS will, depending on the analysis requested, typically identify and measure up to 33 PFAS compounds including the three PFAS of highest concern (PFOS, PFOA and PFHxS). However, this may only contribute a small proportion of the PFAS present, since compounds such as fluorotelomers and fluoropolymers present in some formulations, and intermediate transformation products, are not within the typical analytical suite (Weiner et al. 2013). Tools for screening for the presence of a broader range of PFAS include non-selective analytical techniques (such as TOP Assay and TOF Assay). If precursors are present and further information is required on the specific PFAS (e.g. discriminating between potential sources of PFAS emissions), more advanced analytical options are available such as untargeted high resolution mass spectrometry (e.g. Liquid Chromatography Quadrupole Time-of-Flight Mass Spectrometry (LC-QToF)). 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 (i.e. equivalent length or one to two carbons shorter) perfluorinated group. Due to their potential to form more persistent perfluoroalkyl acids (PFAA), these polyfluorinated compounds are often referred to as PFAA precursors or simply precursors. An example is the transformation of 8:2 and 10:2 fluorotelomer compounds to form the persistent endpoint products PFOA and PFDA. Various PFAS transformation processes that occur in the environment are described in Washington et al. (2015).

The biotransformation of precursors can thus 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, such as when PFAS co-occurs 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 are likely to markedly facilitate transformation of precursors. This is also the case if PFAS precursors are discharged to aerobic wastewater treatment plants.

9.3.2 Bioaccumulation

Bioaccumulation is the uptake of a contaminant from food and/or water by an organism resulting in an increase in concentration of the contaminant in that organism. 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 PFAS contrast with the behaviour of many other persistent organic pollutants that accumulate in fatty tissues (See for example Ng and Hungerbühler (2014). Hence, using predictive models based on octanol-water partition coefficients (Kow) 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 whole prey organisms used in ecological assessments. Sampling of specific organs (e.g. 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 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 NWQMS and WQGs (ANZG 2018a) when assessing bioaccumulative contaminants is to use a higher degree of species protection than would normally be used (ANZECC and ARMCANZ 2000; Australian Government 2018; Warne et al. 2018).

In most situations, this means the 99% species protection level would be used 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 and that the use of a value providing a lower level of protection may not be permitted.

In the case of PFOS, the draft ANZECC freshwater guideline value for 99% species protection is 0.23 ng/L (0.00023 µg/L), which is around 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 and 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. For the purpose of informing conceptual site models for contaminated sites, consideration should be given to humans and predatory species (birds, terrestrial and semi-terrestrial mammals, reptiles, etc) that may be exposed to PFAS via their food chain. Humans, for example, may be exposed via drinking water, meat, fruit, vegetables, and eggs following exposure via PFAS-contaminated feed, soils, or groundwater. Fruit and vegetables may also represent pathways for exposure.

In relation to human exposure to PFAS, direct measurement of PFAS in foodstuffs/produce is advisable for informing the conceptual site model. Timely sampling should be prioritised to obtain produce that is representative of human exposure, as precautionary advice (for example, ceasing 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 exacerbate exposure.

For the development of the conceptual site model, modelling food uptake of contaminants may in some instances provide an alternative to field measurements in biota, direct measurement in foodstuffs/produce or mesocosm data. However, food web modelling can introduce significant uncertainties due to the multiple assumptions required and variation in the information available (e.g. transfer factors to estimate PFAS uptake from water, soil, or vegetation into animals or food products such as meat, eggs and plants; ANZECC and ARMCANZ 2000; ASC NEPM Sched B5B). 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. For guidance on transfer factors from soil to plants for terrestrial environments also refer to the NEMP supporting documents, noting 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 persistent organic pollutants (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 (e.g. 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 (e.g. 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 (e.g. 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, such as the liver or eyes, necessitating a broader suite of sampled organs
- recognition that birdlife, such as wetland waders, may be particularly affected and require appropriate assessment.

10 On-site stockpiling, storage and containment

This section covers the on-site stockpiling, storage, and containment of PFAS contaminated material, at locations that are not intended to be for permanent re-use, storage or disposal. The description in this Section of materials as contaminated is premised on a range of on-site processes such as site investigation, construction, demolition, remediation, care and maintenance, and site management, and assumes that a decision has previously been made to manage these materials due in whole or in part to their 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, regulators, developers, industry, and the community when considering on-site containment options for PFAS-contaminated materials. It is not intended to apply to more permanent off-site solutions such as the reuse of PFAS contaminated material, remediation approaches such as capping, the off-site disposal of PFAS–contaminated wastes in licenced landfill facilities, the destruction of concentrated PFAS wastes, or management of PFAS associated with wastewater treatment plants. It includes detailed guidance on stockpiling, storage and containment during investigation, remediation and construction projects. Additional information is provided in Section 12 on the reuse of PFAS-contaminated materials, in Section 13 on the treatment and destruction of PFAS-containing wastes, and in Section 14 on the disposal of PFAS-contaminated wastes to landfill.

The preferred hierarchy for PFAS treatment and remediation options is discussed in more detail in Section 13. As set out in Section 13, consideration should be given to the following hierarchy of PFAS waste management options:

1) Separation, treatment and destruction – This involves on-site 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.

2) 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.

3) 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.

Section 13 also provides information about treatment, remediation and destruction. The advice set out here in Section 10 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 (ANZECC 1999).

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

- PFAS-containing firefighting foam stocks
- PFAS-contaminated solid material, such as soil, sludge, sediment, biosolids, timber, asphalt, tarmac, rock, concrete and rubble
- PFAS-contaminated equipment such as 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 is often required during the investigation, remediation and/or construction 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 PFOS, PFOA, PFHxS and/or related substances content below 50 mg/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.

See Section 14.6 for further information about the management of waste material with more than 50 mg/kg of PFOS, PFOA, PFHxS, and/or related substances. Consistent with agreed international approaches, if waste material contains more than 50 mg/kg of these substances, it should 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 1,100°C) are already 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.

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 (ANZECC 1999).

Table 9 Stockpiling, storage and containment infrastructure

Description	Timeframe	Storage infrastructure for solid wastes and contaminated equipment	Storage infrastructure for liquid wastes
Transient	Less than 48 hours with no rain predicted	Covered stockpile or storage area on impervious bottom liner (e.g. tarp, plastic sheeting, membrane)	Packaged liquid containers or self-bunded containment vessels on impervious bottom liner (e.g. tarp, plastic sheeting, membrane)
Temporary	From 48 hours to 6 months	Managed stockpile, covered, on impervious, bunded hardstand, with effective stormwater controls (e.g. diversion drains, banks),	Self-bunded containment vessels covered, with lockable access, on impervious, bunded hardstand, with effective stormwater controls (e.g. diversion drains, banks)
Short-term	From 6 months to 2 years	Constructed stockpile with robust anchored covers, impervious bottom liner, and effective stormwater controls 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 to

Description	Timeframe	Storage infrastructure for solid wastes and contaminated equipment	Storage infrastructure for liquid wastes
			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	Packaged, double-walled containment vessels or self-bunded containment vessels, resistant to UV degradation, in engineered containment facility, with effective stormwater controls
Long-term	More than 5 years	Engineered containment facility, with effective stormwater controls	Packaged, double-walled containment vessels or self-bunded containment vessels, resistant to UV degradation, in engineered containment facility, with effective stormwater controls

Notes:

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.

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.

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, regulators 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, regulators may require that stockpiles comply with particular height, slope, quantity, duration and/or location requirements. There may also be requirements to immediately notify the environmental regulator if a loss of containment is detected.

10.1.1 Considerations for specific circumstances

Where the volume of material is minimal (for example, less than 10mPP3PP 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 materials 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. If the site is hydrogeologically appropriate, the PFAS contamination is below 50 mg/kg, the facility is appropriately designed and engineered, and ongoing monitoring is guaranteed, chemical immobilisation and on-site containment may be acceptable. 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 loss of containment, should be considered in determining acceptability. The relevant 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, PFASs 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 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 PFASs such as fluorotelomer alcohols and ketones are volatile. For these, air emissions need to be considered, noting 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 or human health exposure. The development of a sound conceptual site model (CSM) can help to identify the functional requirements for the site and thereby inform the design process. Specific infrastructure and design requirements should be proportionate to the level of risk that is posed by the PFAS-contaminated materials 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 materials 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 PFASs 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 via 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 (e.g. 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 for 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 materials and should be taken into account in the design process:

- materials should be stored or stockpiled, handled and transferred in a proper and efficient manner so as to minimise 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 (e.g. not exceeding 15 litres) 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 that 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 materials:

- 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 fire-fighting 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, and site management projects.

This guidance also applies to the design and construction of medium- to long-term containment of PFAS contaminated materials 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 materials 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 materials 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 via 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 ingress 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.

PFAS-contaminated materials, 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 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 10 000 L, together with 10% of the storage capacity between 10,000 L and 100,000 L, and 5% above 100,000 L. The essential criterion is to ensure all PFAS remains completely contained.

Storage and stockpiling of PFAS-contaminated materials, 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.

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:

- the physical characteristics of the site
- the site assessment outcomes
- the type of material that needs to be contained
- the duration of storage
- the PFAS chemicals present in the material
- their concentration, mass, volume, leachability and distribution
- ongoing storage requirements
- the relevant approvals required by regulators.

A comprehensive on-site environmental management plan 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 regulators and is only an option when:

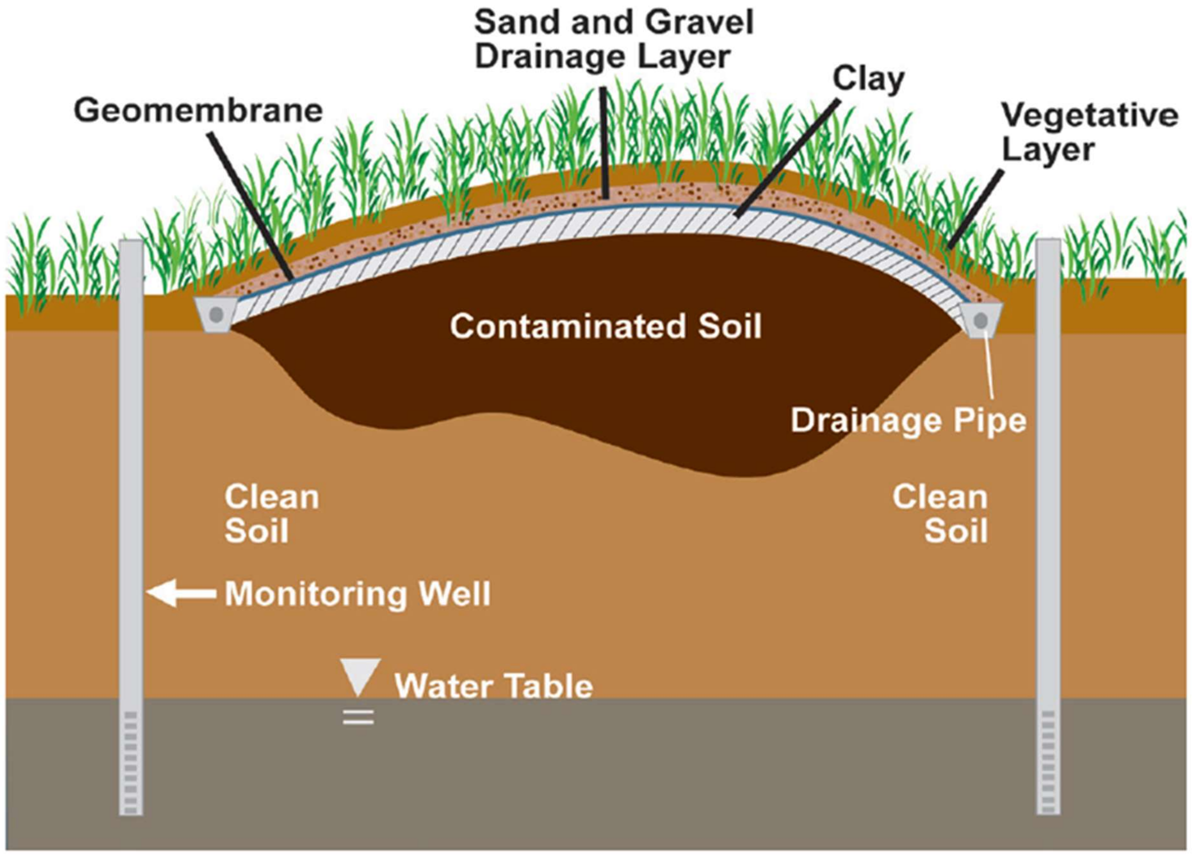
- the source site is hydrogeologically appropriate (with consideration of depth to water table and aquifer characteristics)
- it is possible to manage risks to on- and off-site beneficial uses (direct and indirect) and environmental values for soils, surface water, groundwater and biota
- there is capacity 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 (e.g. 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.

Figure 6 Example of a cap cover



Example of a 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, noting that a risk assessment undertaken by an appropriately qualified person may be required if potential exposure pathways to sensitive receptors are present:

- topography, geology and hydrogeology

- proximity to potential exposure pathways such as constructed drains, service trenches, natural rivers and streams, standing water bodies, groundwater and paleochannels
- proximity to sensitive receptors, such as key flora, fauna and ecological communities
- matters of national environmental significance and those protected by state and territory 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.

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 ANZECC (1999) and Section 12.3 of the NEMP 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 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 less 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 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. 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, 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 liners provided during the operational life of the facility prior to its closure.

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 materials.

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 materials. 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 materials

- 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 baseliner
- 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 and 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 the minimum amount practical 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 PFASs, or into food webs via 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 PFASs to the atmosphere. Non-volatile PFASs may also be transferred into the atmosphere via 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 of 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 (such as the use of leachate ponds, passive or active evaporation, filtration, aeration, ozonation, recirculation, etc.) 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 PFASs suggest a robust precautionary approach by 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; and 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, such as 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 and 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 and environmental considerations in accordance with relevant Commonwealth, national, state/territory and local requirements.

Technical documentation, such as design specifications, construction drawings, design reports, site investigations, impact assessments, site-specific risk assessments, environmental management plans (EMPs), PFAS Management Plans (PMPs), verification documentation, and 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 E.

11 Transport of PFAS-contaminated material

The transport of PFAS-contaminated material should be planned with regard to the characteristics, environmental risks and destination of the material in consultation with the environmental regulator, except where the environmental regulator has issued standing guidance to cover transport arrangements.

11.1 Waste code for PFAS contaminated materials

The transport and tracking of waste PFAS contaminated materials (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 (Movement of Controlled Waste 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 poly-fluoroalkyl 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, sufficient to accurately reflect the nature of the waste. Where multiple waste codes apply, the waste must be reported using the description ‘Per- and poly-fluoroalkyl substances (PFAS) contaminated materials, including PFAS-containing waste products and contaminated containers.

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

11.2 Considerations for transport

PFAS-contaminated materials must be transported in accordance with the requirements of the environmental regulator. Decisions regarding authorisations for the transport of PFAS contaminated materials, including interstate transport, must consider whether the receiving facility can lawfully receive these materials in relation to all the physical and chemical characteristics. These 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 materials should explicitly state this in the approval documentation.

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

12 Reuse of PFAS-contaminated materials including soils and water

Materials 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 (Commonwealth of Australia 2018). However, this must be discussed with the regulator as some may not approve reuse. If reuse is acceptable, many environmental regulators will require that an approval be granted.

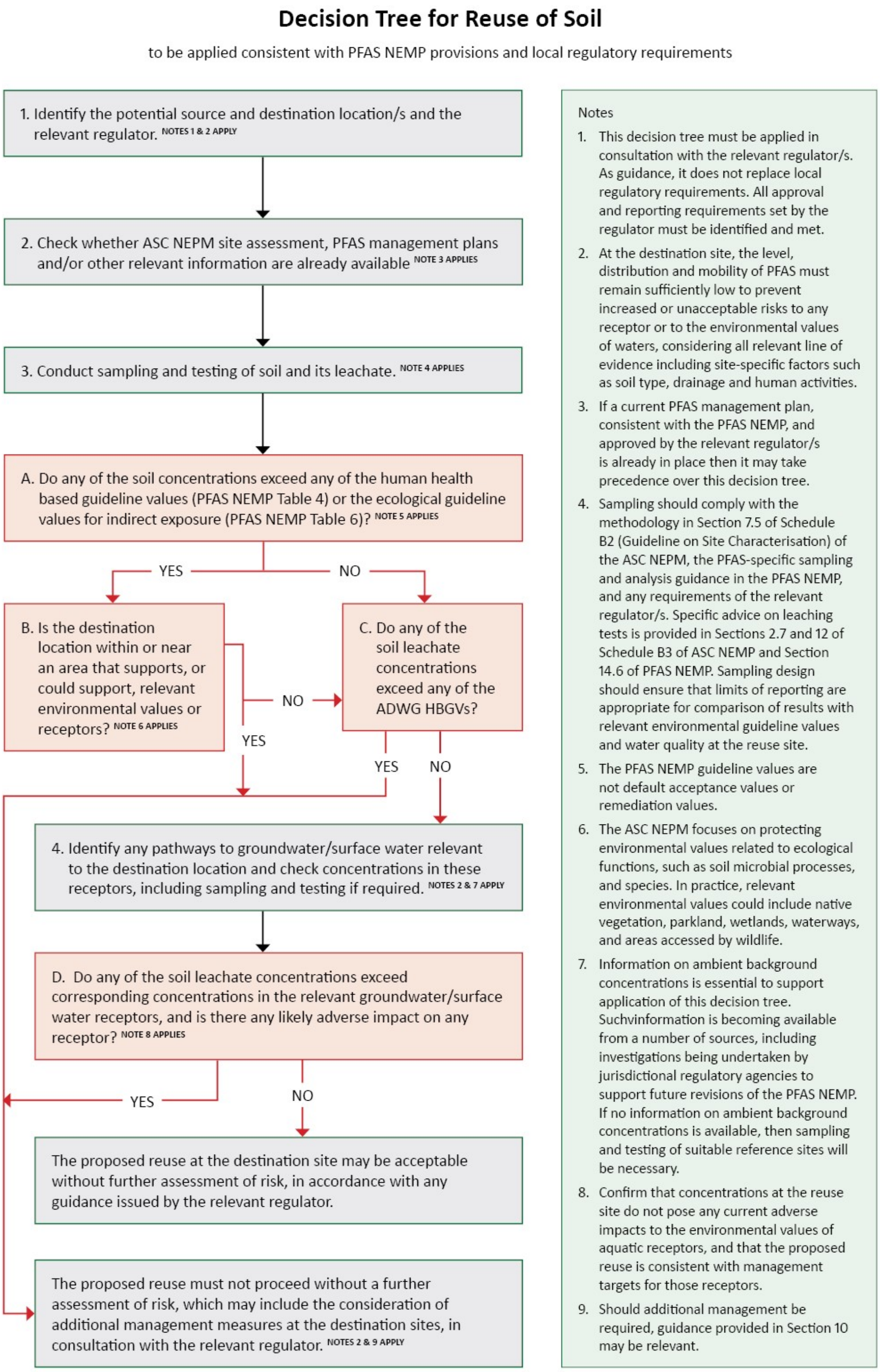
Assessment of reuse options for PFAS-contaminated materials will be based on the principles that reuse must not lead to an unacceptable risk to human health and/or the environment, or an increase in the level of risk at or near the location in which it is used. It is important to consider that PFAS can 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. These principles apply to all PFAS contaminated materials irrespective of source location and can include extracted material, virgin or otherwise.

In the 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 materials, which is covered in Section 10.

Environmental regulators may require that the reuse of PFAS-contaminated materials be informed by a site-specific risk assessment to ensure that the placement of PFAS contaminated materials 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 soils remains subject to state and territory oversight and the guidance provided here, including the decision tree in



Decision Tree for Reuse of Soil

to be applied consistent with PFAS NEMP provisions and local regulatory requirements

1. Identify the potential source and destination location/s and the relevant regulator. NOTES 1 & 2 APPLY

2. Check whether ASC NEPM site assessment, PFAS management plans and/or other relevant information are already available NOTE 3 APPLIES

3. Conduct sampling and testing of soil and its leachate. NOTE 4 APPLIES

A. Do any of the soil concentrations exceed any of the human health based guideline values (PFAS NEMP Table 4) or the ecological guideline values for indirect exposure (PFAS NEMP Table 6)? NOTE 5 APPLIES

B. Is the destination location within or near an area that supports, or could support, relevant environmental values or receptors? NOTE 6 APPLIES

C. Do any of the soil leachate concentrations exceed any of the ADWG HBGVs?

4. Identify any pathways to groundwater/surface water relevant to the destination location and check concentrations in these receptors, including sampling and testing if required. NOTES 2 & 7 APPLY

D. Do any of the soil leachate concentrations exceed corresponding concentrations in the relevant groundwater/surface water receptors, and is there any likely adverse impact on any receptor? NOTE 8 APPLIES

The proposed reuse at the destination site may be acceptable without further assessment of risk, in accordance with any guidance issued by the relevant regulator.

The proposed reuse must not proceed without a further assessment of risk, which may include the consideration of additional management measures at the destination sites, in consultation with the relevant regulator. NOTES 2 & 9 APPLY

Notes

1. This decision tree must be applied in consultation with the relevant regulator/s. As guidance, it does not replace local regulatory requirements. All approval and reporting requirements set by the regulator must be identified and met.
2. At the destination site, the level, distribution and mobility of PFAS must remain sufficiently low to prevent increased or unacceptable risks to any receptor or to the environmental values of waters, considering all relevant line of evidence including site-specific factors such as soil type, drainage and human activities.
3. If a current PFAS management plan, consistent with the PFAS NEMP, and approved by the relevant regulator/s is already in place then it may take precedence over this decision tree.
4. Sampling should comply with the methodology in Section 7.5 of Schedule B2 (Guideline on Site Characterisation) of the ASC NEPM, the PFAS-specific sampling and analysis guidance in the PFAS NEMP, and any requirements of the relevant regulator/s. Specific advice on leaching tests is provided in Sections 2.7 and 12 of Schedule B3 of ASC NEMP and Section 14.6 of PFAS NEMP. Sampling design should ensure that limits of reporting are appropriate for comparison of results with relevant environmental guideline values and water quality at the reuse site.
5. The PFAS NEMP guideline values are not default acceptance values or remediation values.
6. The ASC NEPM focuses on protecting environmental values related to ecological functions, such as soil microbial processes, and species. In practice, relevant environmental values could include native vegetation, parkland, wetlands, waterways, and areas accessed by wildlife.
7. Information on ambient background concentrations is essential to support application of this decision tree. Suchvinformation is becoming available from a number of sources, including investigations being undertaken by jurisdictional regulatory agencies to support future revisions of the PFAS NEMP. If no information on ambient background concentrations is available, then sampling and testing of suitable reference sites will be necessary.
8. Confirm that concentrations at the reuse site do not pose any current adverse impacts to the environmental values of aquatic receptors, and that the proposed reuse is consistent with management targets for those receptors.
9. Should additional management be required, guidance provided in Section 10 may be relevant.

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.

The decision tree is intended to be applied only to soil and should not be used to inform the use of other materials such as solid organic wastes, biosolids or other resource recovery materials. However, if the soils proposed for reuse have become PFAS contaminated due to incorporation of these materials into the soil, the decision tree is applicable to those soils. Note also, 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

A principle that must inform consideration of reuse of soil is 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. Thus, 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 is the application of the waste hierarchy whereby 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, noting 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 regulatory authority in exceptional circumstances where there is no feasible, practicable alternative. Where 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 regulatory authority to maximise confidence in application of the decision tree under such circumstances.

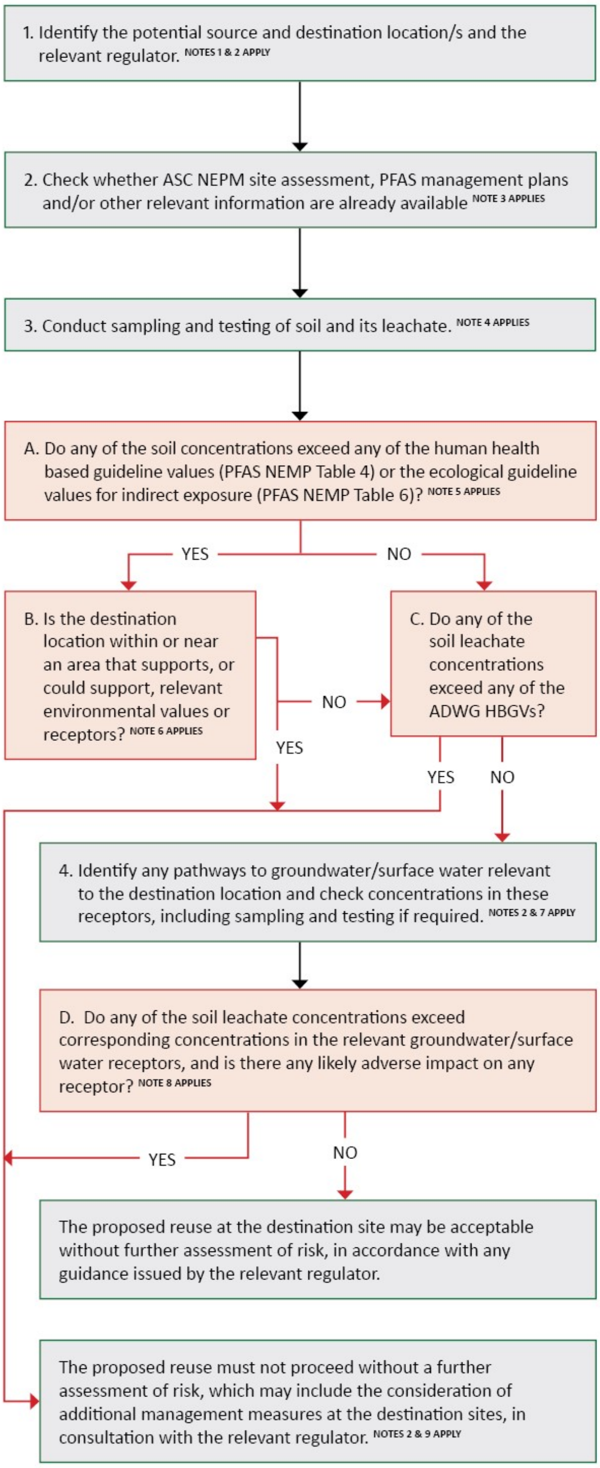
For large sites where soil excavation and reuse may be a recurring issue, the decision tree may be a useful tool to support development of overarching PFAS management strategies for the site, such as PFAS Management Plans (PMPs), through consultation with all relevant regulators.

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

Decision Tree for Reuse of Soil

to be applied consistent with PFAS NEMP provisions and local regulatory requirements



1. Identify the potential source and destination location/s and the relevant regulator. NOTES 1 & 2 APPLY

2. Check whether ASC NEPM site assessment, PFAS management plans and/or other relevant information are already available NOTE 3 APPLIES

3. Conduct sampling and testing of soil and its leachate. NOTE 4 APPLIES

A. Do any of the soil concentrations exceed any of the human health based guideline values (PFAS NEMP Table 4) or the ecological guideline values for indirect exposure (PFAS NEMP Table 6)? NOTE 5 APPLIES

B. Is the destination location within or near an area that supports, or could support, relevant environmental values or receptors? NOTE 6 APPLIES

C. Do any of the soil leachate concentrations exceed any of the ADWG HBGVs?

4. Identify any pathways to groundwater/surface water relevant to the destination location and check concentrations in these receptors, including sampling and testing if required. NOTES 2 & 7 APPLY

D. Do any of the soil leachate concentrations exceed corresponding concentrations in the relevant groundwater/surface water receptors, and is there any likely adverse impact on any receptor? NOTE 8 APPLIES

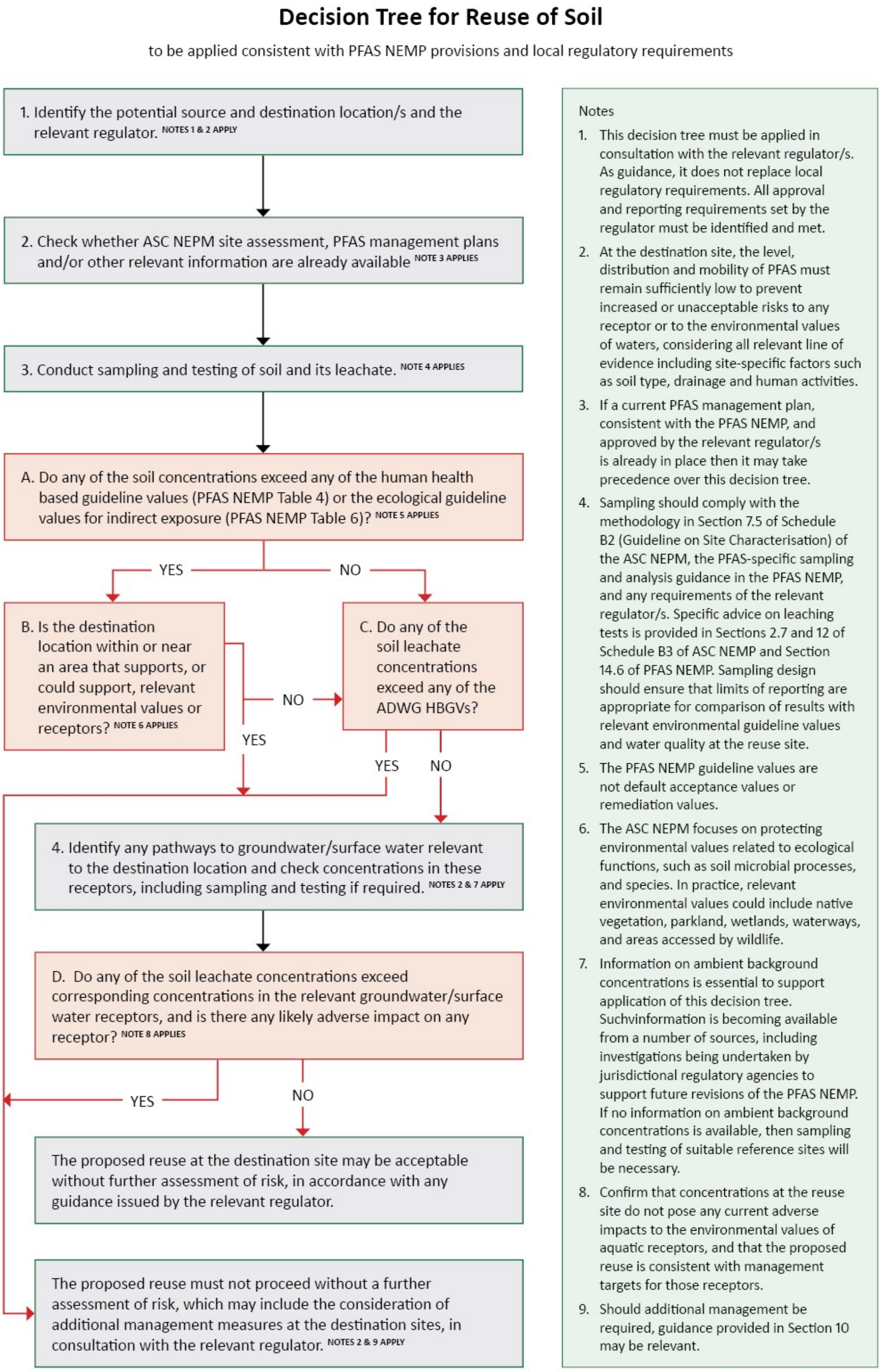
The proposed reuse at the destination site may be acceptable without further assessment of risk, in accordance with any guidance issued by the relevant regulator.

The proposed reuse must not proceed without a further assessment of risk, which may include the consideration of additional management measures at the destination sites, in consultation with the relevant regulator. NOTES 2 & 9 APPLY

Notes

1. This decision tree must be applied in consultation with the relevant regulator/s. As guidance, it does not replace local regulatory requirements. All approval and reporting requirements set by the regulator must be identified and met.
2. At the destination site, the level, distribution and mobility of PFAS must remain sufficiently low to prevent increased or unacceptable risks to any receptor or to the environmental values of waters, considering all relevant line of evidence including site-specific factors such as soil type, drainage and human activities.
3. If a current PFAS management plan, consistent with the PFAS NEMP, and approved by the relevant regulator/s is already in place then it may take precedence over this decision tree.
4. Sampling should comply with the methodology in Section 7.5 of Schedule B2 (Guideline on Site Characterisation) of the ASC NEPM, the PFAS-specific sampling and analysis guidance in the PFAS NEMP, and any requirements of the relevant regulator/s. Specific advice on leaching tests is provided in Sections 2.7 and 12 of Schedule B3 of ASC NEMP and Section 14.6 of PFAS NEMP. Sampling design should ensure that limits of reporting are appropriate for comparison of results with relevant environmental guideline values and water quality at the reuse site.
5. The PFAS NEMP guideline values are not default acceptance values or remediation values.
6. The ASC NEPM focuses on protecting environmental values related to ecological functions, such as soil microbial processes, and species. In practice, relevant environmental values could include native vegetation, parkland, wetlands, waterways, and areas accessed by wildlife.
7. Information on ambient background concentrations is essential to support application of this decision tree. Suchvinformation is becoming available from a number of sources, including investigations being undertaken by jurisdictional regulatory agencies to support future revisions of the PFAS NEMP. If no information on ambient background concentrations is available, then sampling and testing of suitable reference sites will be necessary.
8. Confirm that concentrations at the reuse site do not pose any current adverse impacts to the environmental values of aquatic receptors, and that the proposed reuse is consistent with management targets for those receptors.
9. Should additional management be required, guidance provided in Section 10 may be relevant.

Figure 7 below.



Decision Tree for Reuse of Soil

to be applied consistent with PFAS NEMP provisions and local regulatory requirements

1. Identify the potential source and destination location/s and the relevant regulator. NOTES 1 & 2 APPLY

2. Check whether ASC NEPM site assessment, PFAS management plans and/or other relevant information are already available NOTE 3 APPLIES

3. Conduct sampling and testing of soil and its leachate. NOTE 4 APPLIES

A. Do any of the soil concentrations exceed any of the human health based guideline values (PFAS NEMP Table 4) or the ecological guideline values for indirect exposure (PFAS NEMP Table 6)? NOTE 5 APPLIES

B. Is the destination location within or near an area that supports, or could support, relevant environmental values or receptors? NOTE 6 APPLIES

C. Do any of the soil leachate concentrations exceed any of the ADWG HBGVs?

4. Identify any pathways to groundwater/surface water relevant to the destination location and check concentrations in these receptors, including sampling and testing if required. NOTES 2 & 7 APPLY

D. Do any of the soil leachate concentrations exceed corresponding concentrations in the relevant groundwater/surface water receptors, and is there any likely adverse impact on any receptor? NOTE 8 APPLIES

The proposed reuse at the destination site may be acceptable without further assessment of risk, in accordance with any guidance issued by the relevant regulator.

The proposed reuse must not proceed without a further assessment of risk, which may include the consideration of additional management measures at the destination sites, in consultation with the relevant regulator. NOTES 2 & 9 APPLY

Notes

1. This decision tree must be applied in consultation with the relevant regulator/s. As guidance, it does not replace local regulatory requirements. All approval and reporting requirements set by the regulator must be identified and met.
2. At the destination site, the level, distribution and mobility of PFAS must remain sufficiently low to prevent increased or unacceptable risks to any receptor or to the environmental values of waters, considering all relevant line of evidence including site-specific factors such as soil type, drainage and human activities.
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7. Information on ambient background concentrations is essential to support application of this decision tree. Suchvinformation is becoming available from a number of sources, including investigations being undertaken by jurisdictional regulatory agencies to support future revisions of the PFAS NEMP. If no information on ambient background concentrations is available, then sampling and testing of suitable reference sites will be necessary.
8. Confirm that concentrations at the reuse site do not pose any current adverse impacts to the environmental values of aquatic receptors, and that the proposed reuse is consistent with management targets for those receptors.
9. Should additional management be required, guidance provided in Section 10 may be relevant.

Figure 7 Decision tree for soil reuse

12.2 Reuse with a detailed risk assessment

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

- potential for pre-existing 'background' 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 and the actual and potential beneficial uses of groundwater
- proximity of the destination site to pathways such as open drains, storm water 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, noting that risks should be assessed for stormwater runoff that may mobilise PFAS
- use as fill material in areas where background 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, e.g. 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 and would therefore normally be considered unacceptable uses for PFAS contaminated material, based on risks to the environment and human health.

The environmental regulator may consider these uses 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 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 2 m above the seasonal maximum groundwater level
- reuse within 200 m 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 protected under the 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, e.g. food production areas.

The reuse of PFAS-contaminated material above the Stockholm Convention low content limit of 50 mg/kg 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 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 context may include, for example, the following materials:

- biosolids
- food organics and garden organics (FOGO)
- organic fraction of municipal solid waste (MWOO)

- waste from paper manufacturing
- digestate (products of anaerobic digestion)
- animal waste.

Organic waste recovery materials can be reused in a variety of applications, with the most common beneficial reuse being 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 collects in municipal wastewater and at wastewater treatment plants, and PFAS can move through the treatment process into sewage sludge and biosolids.

Any wastes originating from activities associated with PFAS contamination (e.g. those listed in Appendix C) have a high likelihood of containing PFAS and 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 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. However, Table 10 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 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, for example, 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. 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, 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 human health, the environment and 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, and 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 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.

Table 10 provides a general guide to the level of assessment that may be required for considering suitability for reuse of different organic waste types. The relative placement of different waste types within the ‘levels of assessment’ hierarchy in Table 10 is intended as a general guide only, being based on general 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 materials 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.

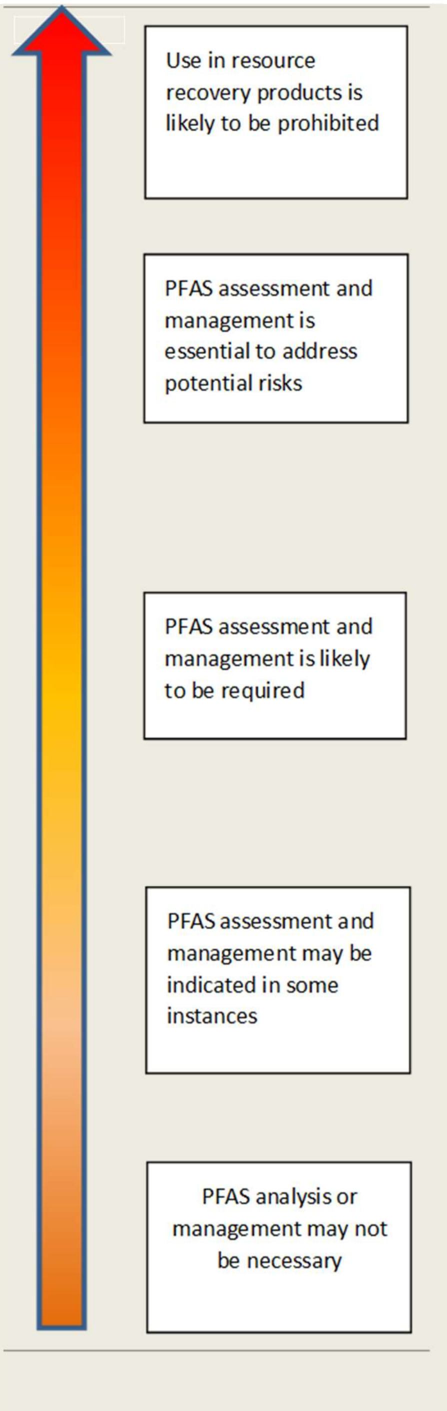
Feedstock management plans

Resource recovery products (e.g. compost and other soil amendment products) are often formed by blending organic waste materials from different sources. 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, including 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. A feedstock management plan may include a range of components aimed at managing risks other than PFAS content; however, 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 required for some common organic waste types with respect to potential PFAS content

Waste type	Examples[b]	Level of assessment required
Organic-derived (industrial) liquid wastes	Interceptor trap waste; textile effluent and residues; industrial wash waters; solvents	
WWTP solid outputs	Biosolids[c], sludge cake	
Septage waste	Liquid or solid components from pump-out of septic tanks	
Paper waste	Paper, cardboard, paper pulp, paper processing sludge.	
Domestic organic wastes	MWOO, FOGO	
Animal wastes	Manure; abattoir wastes, animal bedding organics	
Treated timber waste	Waste from timber composite materials[d]	
Natural (untreated) timber wastes	Wood packaging, woodchips, sawdust, shavings	
Natural fibrous organics	Peat, seed hulls/husks, straw	
Green waste/mulch derived from controlled collections	Grass, leaves, tree prunings	

Notes:

a. This table provides a guide to potential risks associated with PFAS only. Other contaminants that may be present in organic waste materials should be assessed separately.

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

c. Use of resource recovery products containing biosolids must comply with concentration criteria and 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 F on wastewater treatment, which also discuss 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 human health and/or the environment. 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 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 and impacts on process emissions and product.

Where reuse involves the discharge of PFAS-contaminated water to land, the risk assessment should not only consider the potential for PFAS transport to off-site sensitive receptors, but also 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 (i.e. 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 (Commonwealth of Australia 2018) 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

The following guidance should be read in conjunction with sections relating to site investigation (Section 9) and the management of PFAS-contaminated water, including, for example, sections on containment (Section 10) and reuse of PFAS-contaminated water (Section 12). This guidance is intended to ensure that construction water is appropriately evaluated and managed, to minimise the risk of harm to human health and the environment.

In this context, construction water means 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 or dewatering. Re-use 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, for example lowering the water table, may change conditions so as to 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 via 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 down gradient environmental values. Regulators should be consulted when potential PFAS contamination or actual impacts are identified. 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 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, for example, staging excavation to avoid wet seasons, limiting periods where bare soil is left uncovered, and minimising the time that excavations are left unfilled, directing stormwater around or away from PFAS-contaminated areas, and separating PFAS-contaminated material from uncontaminated material. Measures to minimise groundwater disturbance during construction, for example, 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 human health and/or the environment 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, 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 (i.e, not to allow increases in concentration up to the guideline value; ANZ QWG 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 offsite, where practicable and available, or via 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 at below current detection levels.

Management measures such as reuse, re-infiltration, re-injection, release or discharge to soil, surface water or groundwater of PFAS-contaminated construction water may require specific approval from environmental or other regulators. 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.

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.

13 PFAS Remediation and Management

Remediation is generally considered ‘any action undertaken for eliminating, reducing, controlling, or mitigating the risks resulting from contamination’ (UNEP, 2021).

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 sections set 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. PFASs 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. PFASs also bioaccumulate in biota, and hence consideration of effects on secondary consumers is also critical.

Because of these behaviours, the following sections, 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 these sections 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, land owner, land manager, entity disturbing the contamination, leasee or similar entity.

13.1 Context – International obligations

Australia and New Zealand are parties to the Stockholm Convention on Persistent Organic Pollutants (POPs), and the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, 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; if remediation of those sites is undertaken it shall be performed in an environmentally sound manner. While ultimately this means that the Commonwealth is responsible for establishing what activities meet the Convention’s obligations for environmentally sound, all Australian jurisdictions are collectively involved in setting up frameworks and requirements around environmentally sound practices.

Currently PFOS, its salts and PFOSF, and PFOA, its salts and PFOA-related compounds, are listed under the Stockholm Convention. PFHxS and its salts and PFHxS related compounds were listed by the Conference of the Parties in 2022.

13.2 Australian jurisdictional requirements

In Australia, the Commonwealth and the states and territories have differing responsibilities; and different legislation in relation to contamination and remediation. It is important to understand and follow the requirements in the relevant jurisdiction/s.

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 (e.g. PFAS phase out) or compliance audit.

In some cases, immediate action to address offsite 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 (2019) notes that considerations for remediation and/or management are protection of human health and the environment, 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. These 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, i.e. 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 hence risks into the surrounding area offsite 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), then this uncertainty should be factored into the decision and accurately reported and communicated, noting that a 'reasonable worst case' precautionary approach may be warranted. These are unpacked in more detail in Appendix D.

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.

The goals of remediation should be focused on an overall reduction of risk both on-site and, if PFASs are potentially or actually migrating, off-site. 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 offsite chemical transport pathways, 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 on or offsite destruction
- source control – for example treatment and/or other methods to contain the contamination or limit its migration
- 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, and/or other methods focussed 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, noting that the choices made at each site will differ depending on the circumstances at the site and the relevant jurisdictional requirements.

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

2) They 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 elaborated 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 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 [draft] guidance on best available techniques (BAT) and best environmental practices (BEP) notes that the best remedial option is one 'using the best available techniques, using environmentally sustainable methods, while not entailing excessive costs, reducing as much as possible the environmental risks' (UNEP 2021).

Source management (i.e. 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, PFASs are often distributed unevenly throughout a site and potentially offsite. 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 offsite 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 materials 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 POPs from the environment. Highly preferred may not always mean that it is possible or selected 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.

Least preferred options 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, noting that the conditions in some landfills may affect immobilisation chemistry. Acceptance of PFAS-contaminated materials 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 and Stockholm Conventions, 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 content limits 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 Government 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 Australia for fixation, thermal desorption, thermal destruction, and so on. 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 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 current undergoing field trials for different media. For soil, thermal treatment, soil washing, sorption, containment and secure landfill are the most common options. Remediation strategies combining two or more treatment technologies (‘treatment trains') are likely needed to provide an appropriate approach to managing PFAS impacted soils (Bolan et al. 2020). 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 materials. 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 materials should be managed so as not cause any unacceptable or increased risk to human health and/or the environment, or breach of any environment protection requirements. Once disturbed, disposal or treatment of the contaminated soil, water, or other material is the preferred option. Placing contaminated material without appropriate treatment back onto or into the site may not be consistent with environmental legislation. Any re-placement must not cause a new or additional risk to human health and/or the environment, and may not increase the risk at or near the location at which any contaminated material is stored, transported, or re-used. It should also be consistent with relevant environmental duties. Considerations on potential re-use are set out in Section 12.

Because PFASs are highly mobile, consideration also must be given to the off-site impacts of the contaminant. In some jurisdictions, re-placing excavated materials may be considered pollution, and 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.

It is noted that there may be co-benefits of undertaking treatment of materials disturbed during the development, as it can contribute to improving 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, such as when unacceptable risks to human health or the environment have been 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 balance.

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

- address data gaps
- 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 regulators should demonstrate that remediation goals and objectives have been met. This will often require a site audit by a suitable qualified and experienced person such as a contaminated site auditor (see, for example, ASC NEPM, Schedule B9 – Site Auditors).

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

13.7 Long-term management strategies

In addition to remediation, some sites (or parts of a site) may require a long-term management strategy, particularly where PFASs remain on site. This may result in restrictions on land use now and in the future. The implementation of a long-term management strategy (such as long-term environmental monitoring, fencing, security and signposting) and an associated environment plan for on-site 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 (e.g. determined via a site-specific risk assessment) and long-term management can effectively eliminate or reduce the PFAS contamination risks to human health and the environment
- 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 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.

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 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 materials 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 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 waste streams means that the PFAS specific characteristics (e.g. 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, which may result in a refusal to accept solid PFAS contaminated-materials 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 materials:

- 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 materials directly into the receiving landfill cell, where they 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 materials 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 materials. If regulatory requirements do not exist, monitoring programs should include PFAS.

Information on PFAS is likely to be found in different media at landfills together with 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 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 understanding PFAS risks. FTCA are included in some extended suites offered by commercial laboratories in Australia. A TOP Assay in which the extraneous organic content does not exhaust the oxidant is an additional option.

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.

It is important to recognise that only ionic, non-volatile PFASs are quantified by LC-MS/MS and thus 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 background 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). 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, such as 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 materials 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 for total concentration have been capped at 50 mg/kg. This is based on the Stockholm Convention, which requires the following:

- 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 (Stockholm Convention on Persistent Organic Pollutants, Article 6, paragraph 1(d)(ii)).
- Waste is not permitted to be subjected to disposal operations that may lead to recovery, recycling, reclamation, direct reuse or alternative uses of persistent organic pollutants (Stockholm Convention on Persistent Organic Pollutants, Article 6, paragraph 1(d)(iii)).

Further to this, the Basel Convention on the Transboundary Movements of Hazardous Waste and Disposal provides the low content limit for PFOS wastes for the purposes of Article 6, paragraph 1(d)(ii) of the Stockholm Convention at 50 mg/kg. The guidelines are available from the Basel Convention web site at: http://www.basel.int/Implementation/POPsWastes/TechnicalGuidelines/tabid/5052/Default.aspx.

The following criteria do not provide permission for any landfill to receive solid PFAS contaminated materials. 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 materials, considerations include:

- ensuring the landfill is not located on a vulnerable groundwater system (see Australian Government (2013) and, for PFAS-specific advice, DER (2017) adapted from Appleyard (1993)
- depending on the landfill liner design, whether the landfill is located within 1,000 m of a surface water body that supports an aquatic environment (including groundwater dependent ecosystems), or within 1,000 m 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

3021 **Table 11 Landfill acceptance criteria**

Landfill type	Concentration type	Interim landfill acceptance criteria (a)(b)		Comments
		Sum of PFOS + PFHxS (c)	PFOA	
Unlined	ASLP leachable concentration (µg/L)	0.07 µg/L	0.56 µg/L	Drinking water x 1 (Department of Health 2017)
	Total concentration (mg/kg)	20 mg/kg	50 mg/kg	Soil – Human health industrial/commercial x 1 Total concentration for PFOA of 50 mg/kg based on the low content limit
Clay/single composite lined	ASLP leachable concentration (µg/L)	0.7 µg/L	5.6 µg/L	Drinking water x 10 (Department of Health 2017)
	Total concentration (mg/kg)	50 mg/kg	50 mg/kg	Soil – Human health industrial/commercial x 10 Total concentration for PFOS + PFHxS and PFOA of 50 mg/kg based on the low content limit
Double composite lined	ASLP leachable concentration (µg/L)	7 µg/L	56 µg/L	Drinking water x 100 (Department of Health 2017)
	Total concentration (mg/kg)	50 mg/kg	50 mg/kg	Soil – Human health industrial/commercial x100 Total concentration for PFOS + PFHxS and PFOA (including related substances) of 50 mg/kg based on the low content limit

3022 Notes:
3023 (a) Waste concentrations must be less than both the relevant leachable concentration and the total concentration values
3024 for the type of landfill.
3025 (b) Where significant PFAS are present beyond PFOS, PFHxS and PFOA, these solid PFAS-contaminated materials may not be
3026 acceptable for landfill disposal. This should be discussed with the environmental regulator.
3027 (c) Where the criteria refer to the sum of PFOS and PFHxS, this includes PFOS only, PFHxS only, and the sum of the two.

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, work is underway to establish a framework for controlling the import, sale, use and disposal of industrial chemicals in Australia. Additional work is also underway to communicate to industry regulatory intent in relation to phasing out the use of particular PFAS in Australia.

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) and the Australian and New Zealand Water Quality Guidelines (Australian Government 2018). Using a framework provides a systematic way to plan, develop and manage performance.

The NWQMS and the Guidelines 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 (e.g. trade waste and domestic wastewater)

- wastewater processing (e.g. infrastructure and biological treatment processes)
- wastewater outputs (e.g. 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, noting 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 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 F. 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 via wastewater utility conditions of license.

15.2 Additional management tools

Drawing on the advice provided in this plan, in the 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, PFASs 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 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. Detailed 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 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 and in local waters as frothy bubbles and contaminated the wastewater treatment system infrastructure.

To manage further contamination of the wastewater treatment plant, 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 wastewater treatment plants
- 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 wastewater treatment plants. Currently, most biosolids meeting existing criteria for beneficial re-use 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 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 the Supporting Document on Biosolids). This work has led to the derivation of criteria and guidance for all jurisdictions to consider and 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 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 Chapter 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 that reported significant increases in PFCA in biosolids analysed via 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 – Biosolids). 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. 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 perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), and human health risks from the sum of PFOS and perfluorohexane sulfonate (PFOS + PFHxS), and PFOA. 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 the Supporting Document on Biosolids. The outcome of the HHERA was that criteria for restricted 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 11. The most sensitive pathways were used to derive the criteria 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 re-use in agriculture. It is proposed that the MASCCs are used to calculate a contaminant limited biosolids application rate (CLBAR) for PFAS. The criteria were derived at three margins of safety, 1, 2 and 5-fold. The selection of the most suitable margin of safety should consider the following:

- the criteria in Table 11 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 margin of safety may be informed by the total PFAS concentrations present
- the presence of additional individual PFAS or PFAS classes may warrant a larger margin of safety 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 regulators to implement a tiered approach where criteria can be reduced over time to encourage biosolids producers to manage and reduce PFAS inputs.

Table 11 Criteria for PFOS+PFHxS and PFOA in biosolids and maximum allowable soil contaminant concentrations (MASCC) based on a 1, 2 and 5-fold margin of safety

Criteria type	Margin of safety	PFOS+PFHxS (µg/kg)	PFOA (µg/kg)
Biosolids threshold restricted use	5	6.2	25
	2	15	65
	1	31	130
Biosolids threshold unrestricted use*	5	0.22	1.0
	2	0.55	2.5
	1	1.1	5
MASCC	5	0.22	1.0
	2	0.55	2.5
	1	1.1	5

* 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 (e.g. short chain PFAS and Total Extractable Organic Fluorine in Queensland).

15.4.4 Additional requirements

Note that biosolids application should provide a benefit to soil (e.g. meet crop nutrient requirements when used in agriculture) and not constitute opportunistic disposal of waste into soil. This may restrict the beneficial re-use 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 your jurisdiction for further advice.

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

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 and 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 to formally establish a structured way of sharing data and information arrangements.

17 PFAS notification

Many environmental regulators require mandatory or voluntary notification of PFAS-containing products, PFAS-contaminated material stockpiles and/or sites. These requirements are based on the relevant environmental legislation (e.g. 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 human health or the environment or PFAS have caused land contamination.

Notification is not further considered in the 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

The Northern Territory Environment Protection Authority applies the general environmental duty (Section 12) and the notification requirements (Section 14) in the *Waste Management and Pollution Control Act 1999*. 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. The Northern Territory Contaminated Land Guideline, Sections 6 and 7, provides further detail about how this is applied in practice.

18 PFAS sampling

The approach to PFAS sampling should be generally consistent with established methods for contaminated site investigation, as outlined in the ASC NEPM Schedule B2 – Guideline on Site Characterisation and references therein (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 a processing (Section 18.2.2)
    - Considerations for sampling different environmental media (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, the 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 12 for a summary of specific NEMP sections relevant by 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 12 General guidance on sampling environmental media and materials and reference to relevant NEMP sections by media

Environmental media and materials	Relevant 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	Section 8 PFAS environmental guideline values, specifically: 8.5.2 Human health investigation levels for soil 8.7.1 Ecological soil guideline values 8.7.4 Sediment Quality

PFAS adsorption will differ based on different soil types. For soils the potential of PFAS to leach is also a critical compone nt of the assessment. 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 regulator.	8.6.4 Estuarine and marine sediment quality – guidance Section 9 PFAS contaminated site assessment, specifically: 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Re-use of PFAS-contaminated materials, 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
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 regulator.	Section 5 PFAS monitoring, specifically: 5.1 Planning and designing monitoring programs 5.2 Ambient monitoring programs Section 8 PFAS environmental guideline values, specifically: Section 9 PFAS contaminated site assessment 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Re-use of PFAS-contaminated materials, 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 (e.g. fillet vs whole fish, composite, or individual samples).	Section 8 PFAS environmental guideline values, specifically 8.4.1 Consideration of bioaccumulation 8.6.2 Biota guideline values Section 9 PFAS contaminated site assessment 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
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	Section 9 PFAS contaminated site assessment 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Re-use of PFAS-contaminated materials Section 18 PFAS sampling, specifically:

integrity, as well as considering how samples may need to be processed (e.g. 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.	18.3 Assessing PFAS leachability Section 19 PFAS analysis
Organic waste and and 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 re-use of material is considered, understanding the potential 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 Management of PFAS compounds and mixtures Section 9 PFAS contaminated site assessment 9.2 Risk assessment Section 10 On-site stockpiling, storage, and containment Section 12 Re-use of PFAS-contaminated materials, specifically 12.4 Organic waste and resource recovery materials Section 14 PFAS disposal to landfill, specifically 14.4 Monitoring at landfills Section 15 PFAS in the wastewater treatment system, specifically 15.4 PFAS criteria in biosolids Section 18 PFAS sampling, specifically: 18.3 Assessing PFAS leachability Section 19 PFAS analysis

For PFAS 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 QAQC, 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. The PFAS Contamination Response Protocol, (which is an Appendix to the Intergovernmental Agreement on a National Framework for Responding to PFAS Contamination) 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.
- 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 (i.e. greater than the 1 sample in 20 recommended in AS4482.1-2005 Guide to the investigation and sampling of sites with potentially contaminated soil and 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 ten primary samples. Inter-laboratory blind replicates, and re-submission of previously analysed samples, should also be used to confirm reproducibility of analytical results. More details can be found in the PFAS Analysis section (Section 19).

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

18.2.1 Preventing sample contamination

Environmental guideline values for PFAS for ecosystem protection and thresholds for the use of biosolids are generally very low (i.e., maximum allowable soil contaminant concentrations for the use of biosolids, see Table 12). As a result, PFAS investigations will often require quantification of analytes at concentrations close to the practical limits of reporting 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, including new clothing, footwear, PPE and treated fabrics stain and water-resistant products, sunscreen, moisturisers, cosmetics, fast food wrappers, polytetrafluoroethylene (PTFE) materials (such as TeflonPP©PP), sampling containers with PTFE-lined lids, foil, glazed ceramics, stickers and labels, inks, sticky notes, waterproof papers, drilling fluids, decontamination solutions and 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, 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.

18.2.2 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.
- During sample processing and storage, minimise the exposure of the sample to light.
- Chemical or gel-based coolant products (e.g. BlueIce®) to maintain samples at 4°C following sample collection is not recommended.

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.

18.2.3 Considerations for sampling different environmental media

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

Groundwater

Conventional groundwater drilling and well development practices are generally suitable for monitoring wells where groundwater samples will be analysed for PFAS (e.g. 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 250 mL per USEPA (2009).

Sampling requirements may vary by laboratory and analytical method. Prior to sampling, always confirm requirements with the selected analytical laboratory.

- For drinking water, each 250 mL sample bottle may be required to contain a small amount (1.25 g) of TrizmaPP®PP, a buffering reagent that removes free chlorine from chlorinated finished water (USEPA 2018), 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.
- 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 (i.e. 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 materials or personnel are PFAS free, including when detergents are being used and secondary containers.
- Larger sample volumes and/or additional sampling bottles may be necessary if the required LOR are ultra-trace and/or a TOP Assay or TOF Assay analysis is to be performed on the same sample.

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.

- For each sample, the required minimum amount of soil or sediment is at least 5 g on a dry weight basis, per ASTM (2017). The soil in the sampling container (minimum 50 ml container) must be well mixed prior to removing the subsample for analysis. These sampling requirements may vary by laboratory. Prior to sampling, confirm sample size requirements with the analytical laboratory. If leach testing (e.g. ASLP, toxicity characteristic leaching procedure) of soils is required, a larger sample size is required (see Section 18.3).
- For drinking water, each 250 mL sample bottle may be required to contain a small amount (1.25 g) of TrizmaPP®PP, a buffering reagent that removes free chlorine from chlorinated finished water (USEPA 2018), 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 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 (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 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 materials or personnel are PFAS free.
- Other quality assurance samples for water sampling 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 TOP Assay analysis 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 Appendix B for guidance on biota sampling for human health risk assessment.

If analysis is intended to inform human health assessment, edible portions should be sampled (e.g. 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.

18.3 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, re-use 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 including 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 (e.g. 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 (e.g. 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 field -based (Table 14) and laboratory based (Table 15) leachability methods available for PFAS. The National Chemicals Working Group commissioned a review of methods to assess PFAS leachability in soils and other solid materials. A summary of different types of leachate assessment methods, their advantages and limitations is 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.

Further, this section should be read alongside Section 5.2 (Ambient monitoring programs), Section 5.3 (Site-specific monitoring programs), Section 9 (PFAS contaminated site assessment), Section 12 (Reuse of PFAS-contaminated materials including soils and water), Section 13 (PFAS Remediation and Management) and Section 14 (PFAS disposal to landfill).

18.3.1 Leaching methods

A leaching assessment is performed to gain an understanding of the leaching behaviour of chemicals. This can provide an estimate of the extent and rate of release of a chemical through water-pathways, give insights on material durability (e.g. 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 leachate methods. For example, ASLP may be required to enable consistent data comparisons (as different methods are not directly comparable), though other methods are likely to be 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 re-use 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 available methods to assess the leaching of PFAS from soils and solid material. Note, the tables do not reflect an exhaustive list of options to assess leaching, but rather discusses the most common methods used for PFAS in Australia. The information presented is summarised from the literature review commissioned by the National Chemicals Working Group in 2021. Further details on the benefits and limitations for each leachate method listed in Table 14 and Table 14 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 circumstance and question being addressed. Further, jurisdictions may have specific regulatory requirements for the use of leachate methods.

To date, ASLP is the most common method applied for PFAS leachate analysis in Australia, and additional information on the use of ASLP for PFAS are presented in the following section. ASLP was designed to determine the potential leaching of chemicals under landfill conditions. As general guidance, ASLP can be used as an initial screening test to determine if PFAS is leachable from solid materials. For contaminated site assessments and when determining site management/remediation options, applying multiple leaching methods may enable 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

For investigations and comparisons of leachable PFAS, the preferred batch method used is ASLP, where the relevant worst-case pH is selected, noting that generally PFAS leachability increases with pH. But it should be noted, that ASLP (and other batch leachate methods) may not be suitable as the only line of evidence for assessing leachate. Further specific guidance for the ASLP leachate test are:

- Representative sample(s) need to be collected based on soil type to ensure site/scenarios are adequately represented – 100 g of solid is recommended for a more representative sample at <2.4 mm particle size.
- Samples should be adequately homogenised after drying to minimise variability in leaching results.
- Drying samples to determine a consistent solid to liquid ratio avoids variability in results due to different moisture contents in samples.
- Volume of leaching solution appropriate for the material/site/environment to be evaluated unless this is already specified by the regulator or regulation.
- Leachate should not be filtered prior to analysis to avoid PFAS loss over the filter and sample contamination. Leachate should be centrifuged at a g-force that will allow separation of natural colloids <0.45 µm.

- QAQC 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.
- ASLP (and other batch leachate methods) may not be suitable when the total concentration in the sample is near or below the laboratory limit of reporting.

Table 13 Examples of laboratory-based leachate methods available to assess the leaching of PFAS from soils and solid material. For further details on each method see Appendix G

Laboratory leachate 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 (i.e. variable L/S (f), 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. L/S ratios and other method aspects also may need to be considered in data interpretation • For PFAS, the preferred batch method is ASLP for consistency, where the relevant worst-case pH is 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 (g) – 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 (h) – Columns in up-flow or down-flow mode	• 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
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 (i) – ponding experiments (j)	• Can be used for compacted soils or infrastructure materials (based on environmental conditions, e.g. compaction and material size more relevant to the environmental scenario) • Ability to investigate desorption rate (based on environmental conditions, e.g. using volumes of water adjusted to local precipitation)

(a) ASLP: Australian Standard Leaching Procedure. Australian Standards 2019. AS4439.3
(b) TCLP: Toxicity Characteristic Leaching Procedure. US EPA 1992a, 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: SW-846, Liquid-solid partitioning as a function of extract pH using a parallel batch extraction procedure
(e) LEAF 1316: Leaching Environmental Assessment Framework. US EPA 2017b. Method 1316: SW-846, Liquid-solid partitioning as a function of liquid-to-solid ratio in solid materials using a parallel batch procedure
(f) L/S: Liquid-to-solid ratio
(g) MEP: Multiple extraction procedure. US EPA 1992b. Method 1320: SW-846, test methods for evaluating solid waste, physical/chemical methods
(h) LEAF 1314: Leaching Environmental Assessment Framework. US EPA 2017c. Method 1314: SW-846, Liquid-solid partitioning as a function of liquid-solid ratio for constituents in solid materials using an up-flow percolation column procedure
(i) LEAF 1315: Leaching Environmental Assessment Framework. US EPA 2017d. Method 1315: SW-846, Mass transfer rates of constituents in monolithic or compacted granular materials using a semi-dynamic tank leaching procedure
(j) Example: Baduel et al. 2015

Table 14 Examples of field-based leachate methods available to assess the leaching of PFAS from soils and solid material. For further details on each method see Appendix G

Field based leachate 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 remdial 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 (i.e. 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 be used to assess remedial success

(a) Davis et al. 2021
(b) Example: Sörengård et al. 2021
(c) Example: NOT PUBLISHED YET (only cite if it is published on time) Kabiri et al. (in progress)

18.3.3 Using information gained from leaching assessments

When performing leachate 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 projects 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 leachate 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 leachate 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 leachate 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 a 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 <9.5 mm. 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 lab ware and sorption of PFAS to filters. The preferred approach is to collect leachate after centrifugation at a g-force that will allow separation of natural colloids <0.45 µm
- the soil to water 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 leachate 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 (e.g. Davies et al. 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, and 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 materials (see Section 12) based on jurisdictional requirements

- comparison of PFAS concentrations to relevant site-specific trigger values or guideline values (see Section 8), for example estimating soil pore water PFAS concentration for a site risk assessment
- 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.

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, and Appendix A on the PFAS family. 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. Standard methods of analysis and selected non-standard methods are listed in Table 15. Specifically, Table 15 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 15 Methods of PFAS analysis – standard and selected non-standard methods

Method	Use	Sample matrices	Limitations	Analytes	Internal standards	References
USEPA Method 537.1-1 (a) Determination of selected per- and polyfluorinated alkyl acids in drinking water by SPE and LC-MS/MS	To analyse for specific analytes in drinking water	Drinking water, 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, PFTrDA, PFUnA, PP^{11}PPCl-FP3OUdS, PP^{9}PPCL-PFRR$_3$RRONS, ADONA, PFTrA, PFTeA,	PP13PPCRR2RR-PFOA, PP13PPCRR4RR-PFOS and dRR3RR-NMeFOSAA	Shoemaker and Tettenhorst (2018)
USEPA Method 1633 Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and	To analyse for specific analytes in aqueous, solid, biosolids and tissue samples	Aqueous, solid, biosolids and tissue samples	Currently only single laboratory validated and subject to revision	1 PFCAs 8 PFSAs 3 FTSs 3 FOSAs 2 FOSAAs 2 FOSEs 5 PFECAs	24 extracted internal standards 7 non-extracted internal standards	US EPA 821-D-21-001 Draft Method 1633

Method	Use	Sample matrices	Limitations	Analytes	Internal standards	References
Tissue Samples by LC-MS/MS				3 PFESAs 3 FTCAs		
Total Oxidisable Precursor Assay (TOP Assay)	Can be used in conjunction with a USEPA 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 (b) 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
Total Organic Fluorine Assay (TOF Assay) as combustion ion chromatography (the most common method available)	Can be used in conjunction with a USEPA method to understand the total presence of organic fluorine in a sample and compare this to the organic fluorine equivalent detected by the USEPA method	Water samples and extracts including soil, biota, firefighting foam products and wastes	Cannot be used to target exact PFAS precursor compounds	Total organic fluoride corrected to remove inorganic forms	Linear and branched isomers should be included	Laboratory reported methods only

(a) The 2018 USEPA 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 USEPA Method 537 or 537.1 to obtain additional analytes, such as 6:2 and 8:2 fluorotelomers.

(b) 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 USEPA are most commonly used in Australia. These methods test for a standard analytical suite of PFAS in each case, using LC-MS/MS with additional methodological adaptations for specific environmental media. The USEPA 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 USEPA Method 537 and 537.1 and USEPA Method 821-R-11, or modified methods, including proprietary methods such as ASTM Method D7968-17a and Method ASTM Method D7979-17. These methods include additional sample media or additional PFAS. Any modifications to the USEPA methods that result in poorer method performance are not supported (e.g. see Shoemaker and Tettenhorst 2018, p.3.).

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 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 spectroscopy (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 (i.e. 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 and 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.

In general, the limit of reporting (LOR) for PFAS available at standard commercial rates is 0.01–0.05 µg/L for water, 1–5 µg/kg for soils, 0.3–0.5 µg/kg for biota, and 5–20 µg/kg for biosolids. Trace and ultra-trace analyses, which are more sensitive, are also available, usually at a higher cost, and may be necessary depending on the purpose of the assessment. The LOR obtainable is dependent on the matrix and method.

The limit of reporting 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 limit of reporting depends on the sample type. For example, a sample with very low levels of PFAS will need to be submitted for trace analysis (i.e. with a lower LOR) compared to a firefighting foam that has a high concentration of PFAS.

Not all Australian 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 up to 33 of the more than 4,700 PFAS compounds known to exist (OECD 2018). 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 (e.g. 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 materials 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 QA/QC reporting). For example, as specified in Table B-15 in QSM 5.3 (USDoD and USDoE, 2019). Importantly, QSM 5.3 is not an analytical method - it provides quality control criteria to manage uncertainty and provide assurance of confidence and consistency in laboratory reporting
- details on accreditation or validation of the method. Schedule B3 of the ASC NEPM states that comparable established methods from recognised sources such as Standards Australia, the US EPAUSEPA, the American Public Health Association (APHA), ASTM International (formerly the American Society for Testing and Materials (ASTM) and the International Standards Organisation (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 (e.g. 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 (e.g. 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 (e.g. for USEPA 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% (± 50%) depending on media and the specific analyte.

- if undertaking TOP Assay, that validation of the methods of oxidation using detectable oxidisable precursors (e.g. 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 of up to 10% might be expected due to normal analytical variability
- 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 (e.g. 6:2 FtS, FOSA) are detectable post oxidation, signifying complete oxidation
- 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 USEPA 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 USEPA 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 USEPA 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 USEPA 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 limit of reporting (LOR) when compared to that usually available with the TOP Assay and hence may not be suitable with low screening levels. However, it may be a helpful screening tool for higher impact source zones and circumstances where information on the approximate carbon chain length is not required; an understanding of the amount of precursors may be sufficient.

The TOF Assay can also be used to check the degree to which TOP Assay analysis accounts for potential precursors, noting that any PFAS with a carbon chain length shorter than C4 and longer than C14 would be missed by either TOP Assay or standard LC-MS/MS analysis.

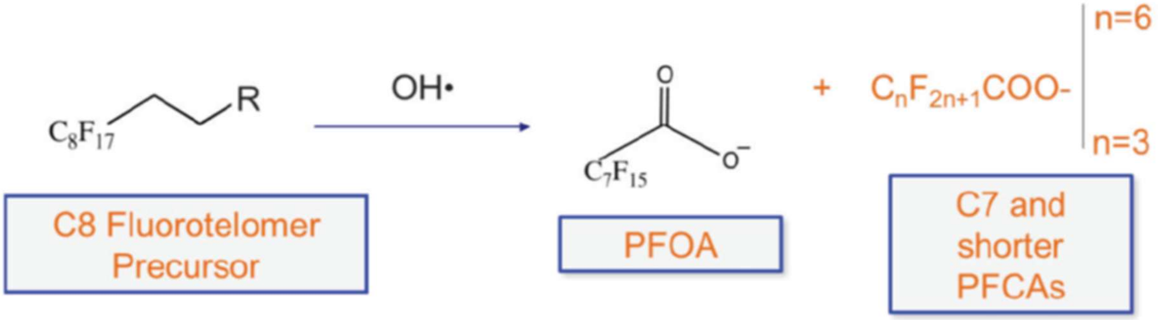
19.3.3 Interpreting results

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.

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. 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 ECF process contain both linear and branched isomers, whereas those produced by telomerisation contain no branched perfluoroalkyl chains.

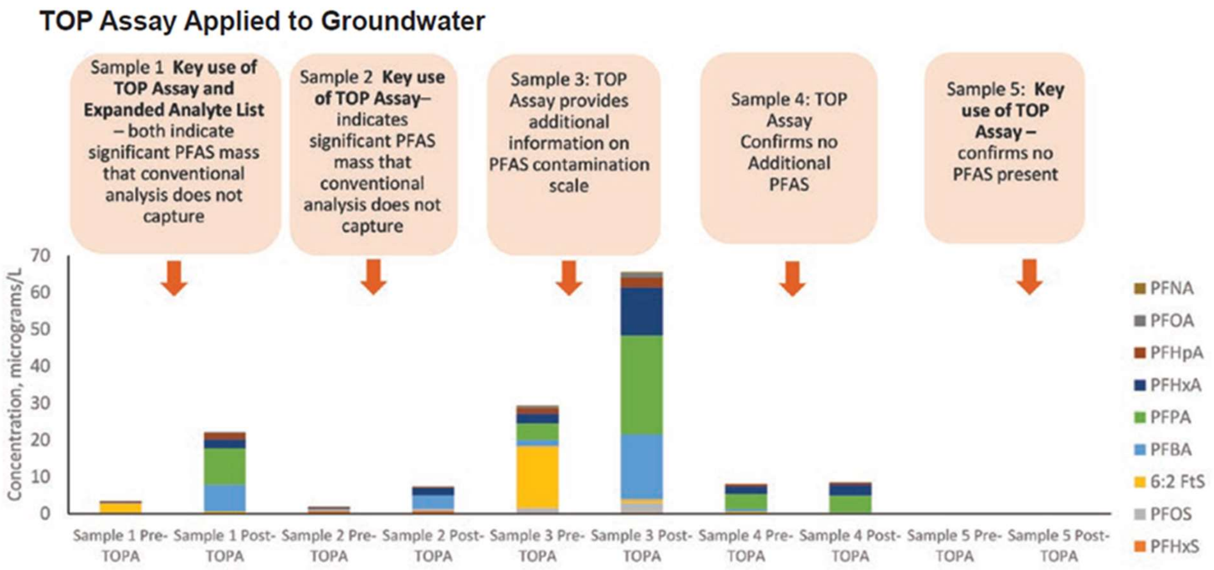
These differences can be detected if the quantification of PFASs uses both branched and linear isomeric analytical standards of perfluoroalkyl carboxylates in the analysis.

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 Erica 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 the 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 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 PFSAs in sewage sludge and biosolids from the USEPA (EPA 821-R-11-007, now replaced by CWA Method 1633 and ASTM (D7979-20), which can give some guidance; however, these methods 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 quality control and quality assurances. 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; the suite of PFAS to be analysed; the method of extraction used; and the 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 (more on matrix interferences below). 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 currently only presents

data derived from a single-laboratory validation study, and the recoveries will be updated in a subsequent revision.

  - 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 can help to monitor method performance. For example, the National Institute of Standards and Technology provides a sludge material with certified concentrations of PFAS (NIST Sludge SRM 2781).
- 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. Another 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. Values higher than 100 indicate an enhancement of the signal, whereas values 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 analysis, 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 interlaboratory 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 (e.g. 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

The 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 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 TOPA, 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 the NCWG 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 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

The NEMP is a living document designed to reflect the current state of knowledge. It will be updated regularly to reflect new scientific evidence and guidance.

21.1 Informal review

The NCWG, in consultation with other working groups appointed by HEPA, will:

- monitor PFAS research and information
- monitor relevant developments in other national frameworks and policy processes
- consider lessons learned from 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.

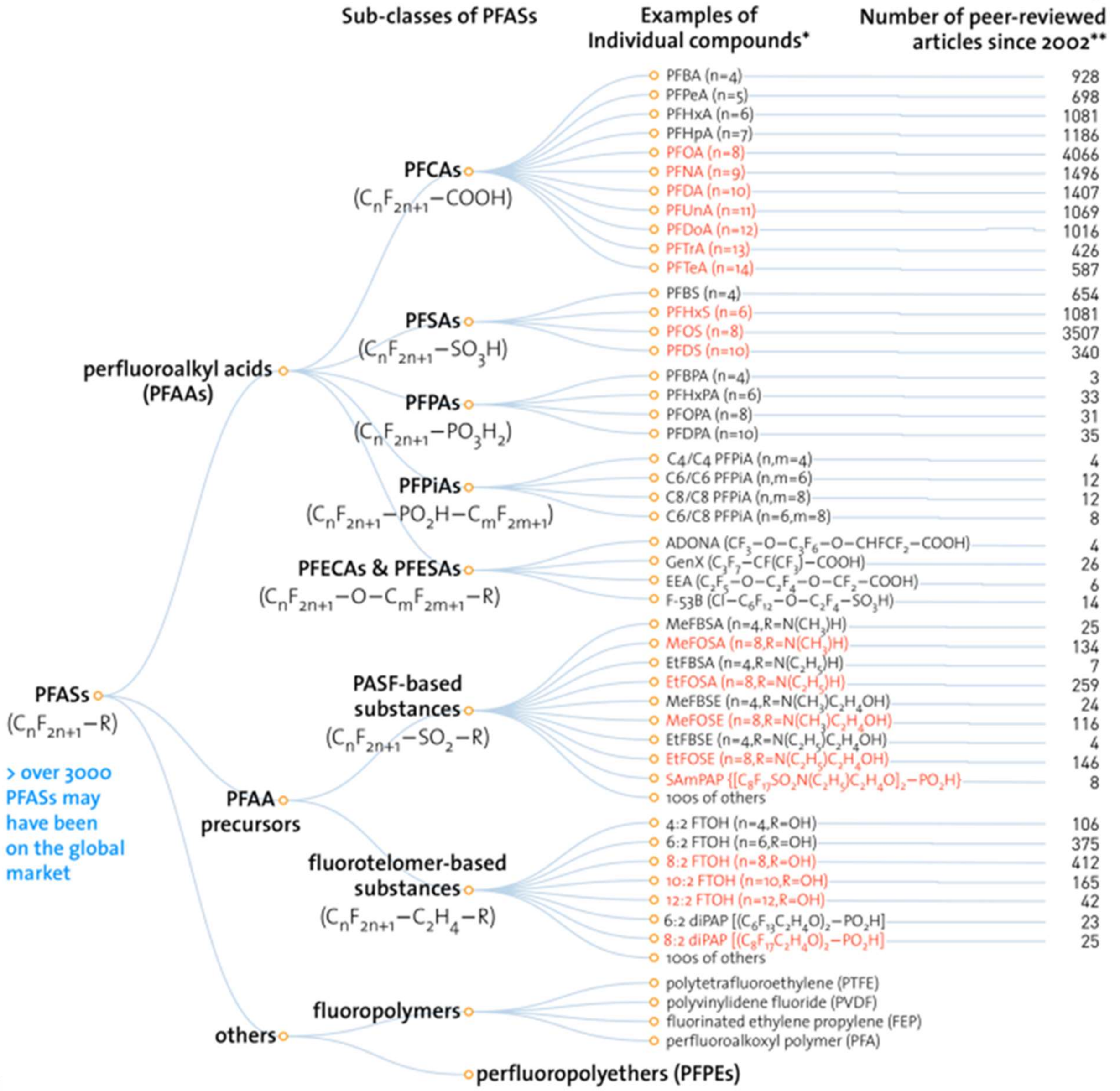
21.2 Formal review

The NEMP will be subject to a formal review every five years, with the first formal review due in 2023.

Appendix A The PFAS chemical family

For detailed information about the PFAS compounds on the Australian Inventory of Chemical Substances see www.nicnas.gov.au

Figure A - 1 The PFAS chemical family with examples of individual compounds



* PFASs in **RED** 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.

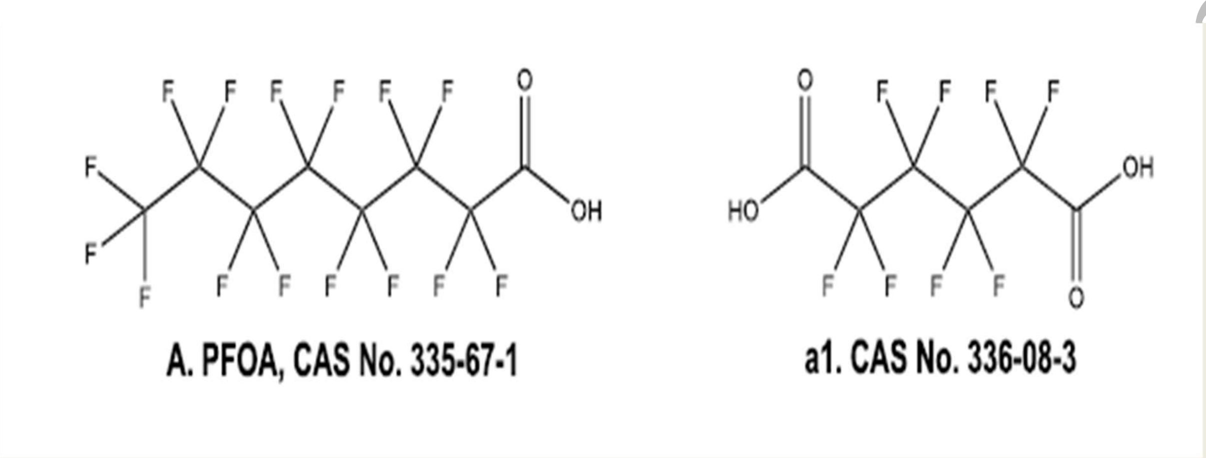
From Wang et al. (2017). See also Buck et al. (2011), ITRC (2018), and OECD (2018, 2021).

Numerous classes of fluorinated substances outside the scope of the Buck (2011) primary structure (i.e. C_nF_{2n+1}) are now recognised as PFAS (OECD 2021). Examples are given below.

A fully fluorinated saturated carbon moiety is connected with functional groups on both ends instead of one (compound a1 at right has no terminal (–CF3) group).

Figure A - 2 Alkyl chain with 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 below at right compared to PFOA on the left. Unlike PFOA, the right hand compound does not contain a (–CF3) group (circled in PFOA).

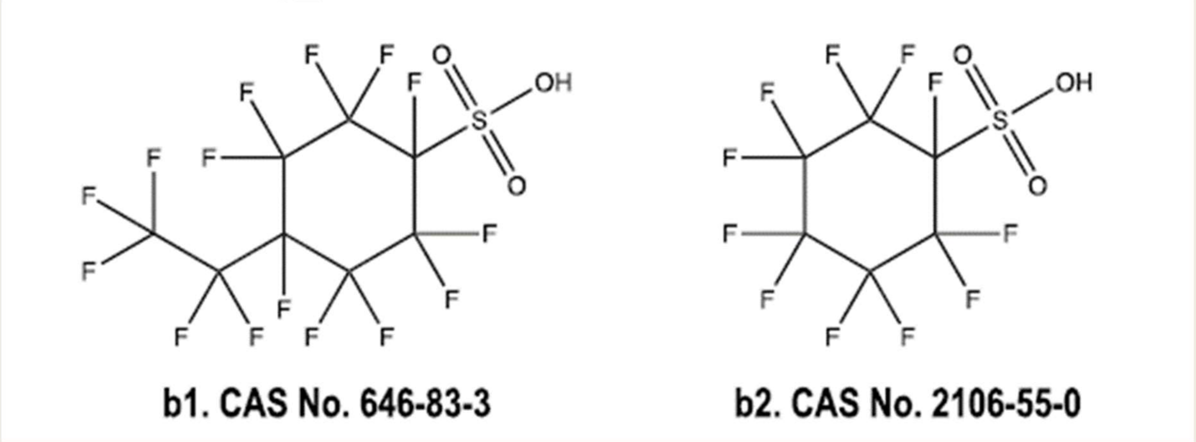

A. PFOA, CAS No. 335-67-1

a1. CAS No. 336-08-3

A fully fluorinated aliphatic cyclic compound that does not contain a fully fluorinated alkyl side chain (compound b2 at right has no side (–CF3) group).

Figure A-3 Cyclic compounds with and without a fully fluorinated alkyl side chain

In this example, two fully fluorinated aliphatic cyclic compounds are contrasted. The compound on the right b2 does not contain a fully fluorinated alkyl side chain whereas compound b1 on the left contains a side (–CF3) group (circled).


b1. CAS No. 646-83-3

b2. CAS No. 2106-55-0

Table A - 1 Common PFAS abbreviations

Group	Abbreviation	Meaning
Sub-classes	FTS	fluorotelomer sulfonate

Group	Abbreviation	Meaning
	PFAA	perfluoroalkyl acid
	PFCA	perfluorocarboxylic acid
	PFSA	perfluoroalkane sulfonic acid
PFSA	PFBS	perfluorobutane sulfonic acid
	PFDS	perfluorodecane sulfonic acid
	PFHxS	perfluorohexane sulfonate, or perfluorohexane sulfonic acid
	PFHpS	perfluoroheptane sulfonate
	PFOS	perfluorooctane sulfonate, or perfluorooctane sulfonic acid
	PFPeS	perfluoropentane sulfonic acid
PFCAs	PFBA	perfluorobutanoic acid
	PFDA	perfluorodecanoic acid
	PFDoA or PFDoDA	perflurododecanoic acid
	PFHpA	perfluoroheptanoic acid
	PFHxA	perfluorohexanoic acid
	PFNA	perfluorononanoic acid
	PFOA	perfluorooctanoate, or perfluorooctanoic acid
	PFPeA	perfluoropentanoic acid
	PFUnA or PFUnDA	perfluoroundecanoic acid
	PFTeDA	perfluorotetradecanoic acid
	PFTrDA or PFTriDA	perfluorotridecanoic acid
FTS	N:2 FTSAs	N:2 fluorotelomer sulfonic acids
	4:2 FTS	1H,1H,2H,2H-Perfluorohexanesulfonic Acid
	6:2 FTS	1H,1H,2H,2H-Perfluorooctanesulfonic Acid
	8:2 FTS	1 H,1H,2H,2H-Perfluorodecanesulfonic Acid
	10:2 FTS	1H, 1H, 2H, 2H-perfluorododecane sulfonate
Other	9Cl-PF3ONS	9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid
	11CL-PF3OUdS	11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid
	ADONA	4,8-dioxa-3H-perfluorononanoic acid
	HFPO-DA	hexafluoropropylene oxide dimer acid
	FOSA or PFOSA	perfluorooctane sulfonamide
	N-EtFOSA	N-ethyl perfluoro-1-octane sulfonamide
	N-EtFOSAA	N-ethyl perfluorooctanesulfonamidoacetic acid
	N-EtFOSE	2-(N-ethylperfluoro-1-octane sulfonamido)-ethanol
	N-MeFOSA	N-methyl perfluoro-1-octane sulfonamide
	N-MEFOSAA	N-methyl perfluorooctanesulfonamidoacetic acid
	N-MeFOSE	2-(N-methyl perfluoro-1-octane sulfonamido)-ethanol

Appendix B PFAS Ambient sampling guideline

B.1 Objectives

This document details a guideline to undertake sampling for per- and poly-fluoroalkyl substances (PFAS) in locations that are defined as ambient or not directly impacted by point sources. 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 NEMP to ensure a consistent approach is taken for the sampling and analysis of PFAS. This document is not intended for use in sampling known contaminated sites or investigation areas although may provide useful context for the design of monitoring programs for offsite 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.

NEMP 3.0 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 (e.g. industrial, agricultural etc.). Sample sites should be classified by land use areas using the Australian Land Use and Management Classification scheme (ALUMC) 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 NEMP Sections 18 and 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 including catchment layers, slope/terrain, land cover, stream type 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 to access historical data. Locations should be chosen at least 1 km from the known extent of plumes from point sources of PFAS (see NEMP 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
- 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 B - 1 is an example of how to record this information.

Table B - 1 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 and 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 (e.g. seasonality of rainfall, temporal vs 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 for a particular laboratory should be based on the objectives of the sampling program, including guideline levels, risk to human health or environment 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 (e.g. passive sampling). For ambient sampling, the generally available and recommended LORs are provided in Table B - 2.

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 30 PFAS (see Table B - 2). 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 B - 2 Typical suite of PFAS compounds and LOR currently analysed by commercial laboratories (grouped by PFAS compound class)

PFAS Class and Compounds	Liquid (Ultra-trace) (µg/kg)	Solids (Low-level) (µg/kg)	Biota (Standard) (µg/kg)
Perfluoroalkyl carboxylic acids (PFCAs)			
Perfluorobutanoic acid (PFBA)	<0.01 to <0.005	<2 to <0.5	<2 to <0.5
Perfluoropentanoic acid (PFPeA)	<0.007 to <0.001	<2 to <0.1	<2 to <0.5
Perfluorohexanoic acid (PFHxA)	<0.005 to <0.0005	<1 to <0.1	<1 to <0.5
Perfluorooctanoic acid (PFOA)	<0.007 to <0.0005	<1 to <0.1	<5 to <0.3
Perfluoroheptanoic acid (PFHpA)	<0.005 to <0.001	<1 to <0.1	<0.5 to <0.1
Perfluorononanoic acid (PFNA)	<0.007 to <0.0005	<1 to <0.1	<2 to <0.5
Perfluorodecanoic acid (PFDA)	<0.001 to <0.005	<1 to <0.1	<5 to <0.5
Perfluorododecanoic acid (PFDoDA or PFDoA)	<0.001 to <0.005	<1 to <0.1	<5 to <0.5
Perfluoroundecanoic acid (PFUnDA or PFUda)	<0.001 to <0.005	<2 to <0.1	<2 to <0.5
Perfluorotridecanoic acid (PFTrDA)	<0.05 to <0.001	<2 to <0.1	<2 to <0.5
Perfluorotetradecanoic acid (PFTeDA)	<0.02 to <0.001	<2 to <0.1	<5 to <0.5
Perfluoroalkyl sulfonic acids (PFSAs)			
Perfluoropropanesulfonic acid (PFPrS)	<0.001 to <0.0005	<1 to <0.1	<0.5 to <0.1
Perfluorobutanesulfonic acid (PFBS)	<0.001 to <0.0005	<1 to <0.1	<0.5 to <0.1
Perfluoropentanesulfonic acid (PFPeS)	<0.001 to <0.0005	<1 to <0.1	<1 to <0.5
Perfluorohexanesulfonic acid (PFHxS)	<0.001 to <0.0002	<1 to <0.1	<2 to <0.3
Perfluoroheptanesulfonic acid (PFHpS)	<0.001 to <0.0005	<1 to <0.1	<1 to <0.5
Perfluorooctanesulfonic acid (PFOS)	<0.0001 to <0.0002	<2 to <0.1	<1 to <0.3
Perfluorononanesulfonic acid (PFNS)	<0.001 to <0.0005	<1 to <0.1	<2 to <0.5

Perfluorodecanesulfonic acid (PFDS)	<0.001 to <0.0005	<1 to <0.1	<2 to <0.5
Perfluoroalkyl sulfonamido substances			
2-(N-ethylperfluoro-1-octane sulfonamido)-ethanol (N-EtFOSE)	<0.02 to <0.005	<5 to <0.5	<40 to <0.5
2-(N-methylperfluoro-1-octane sulfonamido)-ethanol (N-MeFOSE)	<0.005	<5 to <0.5	<5 to <0.5
N-ethylperfluoro-1-octane sulfonamide (N-EtFOSA)	<0.005	<5 to <0.5	<5 to <0.5
N-ethyl-perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	<0.002 to <0.005	<2 to <0.2	<5 to <0.5
N-methylperfluoro-1-octane sulfonamide (N-MeFOSA)	<0.02 to <0.005	<2 to <0.5	<5 to <0.5
N-methyl-perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	<0.005 to <0.002	<2 to <0.2	<5 to <0.5
Perfluorooctane sulfonamide (FOSA)	<0.005 to <0.002	<2 to <0.5	<2 to <0.5
n:2 Fluorotelomer sulfonic acids (n:2 FTSAs)			
Sodium 1H,1H,2H,2H-perfluorohexane sulfonic acid (4:2 FTSA)	<0.005 to <0.001	<1 to <0.1	<1 to <0.5
Sodium 1H,1H,2H,2H- perfluorooctane sulfonic acid (6:2 FTSA)	<0.005 to <0.001	<1 to <0.5	<1 to <0.5
Sodium 1H,1H,2H,2H-perfluorodecane sulfonic acid (8:2 FTS)	<0.005 to <0.001	<1 to <0.1	<1 to <0.5
Sodium 1H,1H,2H,2H-perfluorododecane sulfonic acid (10:2 FTS)	<0.005 to <0.001	<2 to <0.1	<10 to <0.5

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 B - 3. 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 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 and for example, if a sample is field filtered, the field blank will also be filtered. It is recommended that water is 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 (e.g. trowel to collect soil or sediment) to assess potential contamination from the equipment.

Other field quality control samples

- Blind replicates – Duplicate (or triplicate) results provide an estimate of the error associated with the subsampling/splitting process and laboratory analysis and are a measure of precision. Duplicate or triplicate samples should be sent in as blind samples to the laboratory. Blind samples are collected by sampling at exactly the same time and place. 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) – Certified reference materials are available for some PFAS analytes in some matrixes. Certified reference materials can be used to assess laboratory accuracy and precision. Samples should be sent in as a blind sample. The concentration of analytes in the CRM 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 B - 3 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 (e.g. 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 twenty 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.
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 nitrile gloves. To mitigate the risk of sample contamination it is mandatory that staff wear non-powdered/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.

Refer to Table B - 2 for details of materials, clothing and equipment that must not be used or taken on site during sampling.

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), 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 10 cm below the water surface and 10 cm above the bed to avoid elevated concentrations of PFAS in sediments and surface films. If the water depth is less than 30 cm, 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.

Check all information on the sample bottle and 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 2–5 cm 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) before and after sampling using PFAS-free water. Rinsate blank samples should be collected for 1 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 (e.g. using micro-purge pump)
- passive sampling (e.g.) 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 (HDPE tubing and silicon) to 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. O-rings may be re-used after rinsing, but a fresh bladder and tubing should be used for each sampling location. All instrumentation and equipment (ie. 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 in the direct flow path from the bore to the sample bottle (i.e. the flow cell and multiprobe meter) need not be rinsed with PFAS-free water.

For every ten 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 levels (from top of casing) are to be recorded for each bore location. The pump is to be lowered to approximately 1 m 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 to 4 litres per minute.

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 wells should be purged before sampling commences. The groundwater sample for lab analysis is to be collected once purging has removed all stagnant water is removed 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.

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 and location taken. Record sample location, date and time on sample jar/bag labels. Check all information on the sample 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:

- 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 Fishing Requirements below for more information).
- Only edible species that are typically consumed from the area of interest must be used.
- 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 100 g.
- 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-TexTM 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 (e.g. 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 human health risk assessment from ecological risk assessment to help ensure a sufficient number of specimens appropriate for human health risk assessment 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 NEMP 3.0 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 20 g), although the number of individuals and their weights should be recorded.

Sampling for PFAS requires strict procedures to prevent cross contamination due to the ubiquitous nature of these compounds in everyday materials. The tables below present the standard requirements for cross-contamination mitigation measures (WA, 2016). These measures need to be strictly followed.

Appendix C Activities associated with point sources of PFAS contamination

Table C - 1 and Table C - 2 identify activities associated with PFAS contamination, with a focus on primary and secondary sources.

Table C - 1 Activities associated with PFAS contamination due to a risk of fire

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
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 C - 2 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 PPE
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
Manufacturing of safety gear	Widespread use of fluorinated compounds to provide stain, water and fire protection for Personal Protective Equipment (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

Table D - 1 provides a summary of PFAS treatment technologies which are currently available in Australia.

The PFAS treatment technologies listed in Table D - 2 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 D - 1 PFAS treatment technologies currently available in Australia

Process		**Definition**	**Application**	**Media**	**Status**
Destruction or transformation	Pyrolysis and oxidative thermal destruction (DER 2017)	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 viewed 2022)	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

Process		Definition	Application	Media	Status
Separation and concentration (requires concentrated PFAS to be managed appropriately)	Adsorption (DER 2017)	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) (DoEE 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
	Reverse osmosis and nanofiltration (DER 2017)	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) (DER 2017)	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 at this stage, as a stand-alone option
	Soil washing (Åse 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 &2021)	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

Process		Definition	Application	Media	Status
	Stabilisation (DoEE 2016)	Minimising the movement of PFAS contaminated material by adding a physical barrier	In situ using cement or polymers	Soil and waste	Available

Table D - 2 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) (DoEE 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 (DoEE 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, 2021)	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

Process		Definition	Application	Media	Status
	Photocatalysis (Merino et al. 2016)	Uses catalysts to mineralise PFAS to inorganic fluoride with visible or ultraviolet radiation	Laboratory	Water and wastewater	Current laboratory development

Appendix E Matters to inform selection of management and remediation options

There are different remedial technologies and treatments available (see Appendix D). In selecting 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:

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

These matters are expanded on below.

E.1 The likelihood of the hazard or the risk occurring

The site investigations and risk assessments (see Section 9.2) will help determine the environmental values to be protected, receptors, exposure pathways and 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, 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 ‘reasonable worst case’ precautionary approach may be warranted.

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 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 PFASs are transported? For example, will they travel along the vadose zone and into other surface bodies, are PFAS likely to go through fractured rock 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 balance 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 that 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 The degree of harm that might result from the hazard or the risk, and/or the level of protection that may be required

Harm includes any adverse impact on the environment of any degree or duration. This includes impacts that add up over time or are caused by a number of sources (known as ‘cumulative’ impacts) or factors.

The Conceptual Site Model will help to identify receptor pathways, and the HHERAs 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 Indigenous Australians 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 PFASs are persistent, bioaccumulative, and mobile, 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 ‘reasonable worst case’ precautionary approach may be warranted.

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 offsite potentially affected?
- Are there sensitive areas, or environmental values such as waterways affected?

- What 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, but if above, has a detailed risk assessment been done?
- What precursor load is present and is that included in the risk assessment? How have other contaminants been considered?
- How long will exposure be likely to be? Will animals and plants be exposed for weeks, months and/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 The availability and suitability of practical mechanisms to eliminate or minimise the 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/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 it and is feasible to implement. Modelling, lab research, bench tests, pilot studies and field trials can be important components of developing treatment technologies. However, many would not in themselves constitute demonstrated long term effectiveness for the site.

A way of eliminating or minimising a hazard or risk (e.g. 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 PFASs 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 PFASs. 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 impacted waste materials generated (or intended to be generated) during remedial works been 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?
- Has the mass balance likely to be removed or remaining 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 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 The costs and benefits associated with available ways of eliminating or minimising the risk

All reasonably foreseeable hazards and risks must be considered when identifying what is the sufficient level of clean up including consideration of:

- likelihood of risks eventuating in the event of no treatment or remediation being undertaken, including uncertainty regarding long term risks
- degree of harm resulting from risk eventuating in the event of no or minimal treatment or remediation being undertaken.

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 Economic cost considerations

Economic costs of remediation can be high, so tools have been developed to maximise the benefits of remediation using limited resources, including:

- risk assessments of multiple areas within a single site to direct resources to those areas that present the highest risk to public health and the environment
- 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, human health or the environment, or enhancing the beneficial use, amenity or ecological value of an area, benefits may include reductions in external costs/damages caused to parties off site such as loss of land value/loss of use of a resource/loss of recreational resource or amenity impacts. These 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 (e.g. truck movements associated with off site management)
- external costs/damages caused to parties off site, for example loss of land value/loss of use of a resource/loss of recreational resource/amenity impacts etc.

Appendix F Example stockpiling, storage and containment checklist and framework

Table F - 1 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 NEMP or reference to other legislation for more information and assistance.	

Table F - 2 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 licenses/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 PFOS, PFOA or PFHxS content <50 mg/kg – relevant in terms of managing wastes in accordance with the Stockholm Convention on Persistent Organic Pollutants.
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.
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

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 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 poly-fluoroalkyl 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 has 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 (NEMP), agreed by all Australian environment ministers, provides the expert guidance that underpins this framework. The framework is consistent with the [Month Year] version of the 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 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 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 and
  - 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 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 is 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 (PFASs 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 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 below in Section 7.1.

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 the use or handling of PFAS-containing products such as foam suppressants or aqueous film forming foam (AFFF) specific businesses. 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. The resulting additional quantities may impact the effectiveness of biological treatment processes and other aspects of 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). 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 G - 1) is a high-level summary to inform detailed risk assessments for each wastewater treatment plant (WWTP) with its catchment area. It will be updated with additional information as these detailed risk assessments are developed.

Table G - 1 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 Environmental Financial	Potential harm to health Environmental harm Financial costs
Beneficial reuse of biosolids/sludge affected due to elevated PFAS	Health Environmental Financial	Potential harm to health Environmental harm Financial costs
Biosolids/sludge disposal to landfill or other disposal method affected due to elevated PFAS	Health Environmental Financial	Potential harm to health Environmental harm 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 Legal	Financial costs 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, i.e. 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 NEMP. The aim is to generate a representative picture of PFAS and its 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 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 Assay (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, i.e. 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 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 PFASs of high concern, such as PFOS, PFOA and 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. However, 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, PFAS types 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 such as additional environmental sampling, diversion of effluent, and 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 it reaches 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 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 and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality 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 the Environment and Energy in relation to Matters of National Environmental Significance.

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 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 perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) and any other PFAS identified as being of high concern(it is noted; 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 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 National Water Quality Management Strategy.

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 market place. 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 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 (i.e. residential, commercial and industrial settings) and the discharge of recycled water to stormwater and groundwater (i.e. 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 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 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 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 leaches out of soil and other solid materials to reach groundwater and aquatic ecosystems offsite. As PFAS behaves differently than other contaminants, existing management controls are unlikely to be sufficient as there is also the potential for a proportion of sedimentary particles from the biosolids to be transported offsite 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 NEMP provides further guidance, including national criteria for landfill acceptance of PFAS-containing 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 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 laboratory-based leaching methods commonly applied and commercially available in Australia

Table H - 1 Overview of laboratory-based leaching methods commonly applied and commercially available in Australia. Standard methods are marked with #. (refer to Section 18.3 in the NEMP)

Leaching method and description*	**Potential application** **Note: Jurisdictions may have specific requirements for the use of listed methods**	**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 soil 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 soils may be a more conservative than using field-fresh samples (Lange et al. 2020). As consistency is important, drying samples to determine solid to liquid 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 **Limitations** • For PFAS investigations, centrifugation is recommended for removal 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

Leaching method and description*	Potential application Note: Jurisdictions may have specific requirements for the use of listed methods	Advantages and limitations
		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 • ASLP (and other leachate methods) are not suitable for assessing leachate concentrations when the total concentration in the sample is near or below the laboratory limit of reporting
Batch test – standard method **TCLP#** Toxicity characteristic leaching procedure US EPA Method: USEPA 1311	For PFAS, the preferred batch method is ASLP for consistency, where the relevant worst-case pH is selected, noting that generally PFAS leachability increases with pH.	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

Leaching method and description*	**Potential application** **Note: Jurisdictions may have specific requirements for the use of listed methods**	**Advantages and limitations**
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 soil ratio This method is typically used in the classification of waste for disposal in a landfill containing putrescible material. Designed to simulate leaching from a landfill		• Can be modified to use leach solution relevant to simulate circumstances of concern
Batch test – standard method **SPLP#** Synthetic precipitation leaching procedure Method: USEPA 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 soil 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	For PFAS, the preferred batch method is ASLP for consistency, where the relevant worst-case pH is selected, noting that generally PFAS leachability increases with pH.	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
Batch test – standard method **MEP#** Multiple extraction procedure Method: USEPA 1320 Mass transfer-based batch leaching method in acidic conditions, repetitive batch extraction with agitation at 20:1 liquid to soil ratio (24h x 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 (i.e. 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**

Leaching method and description*	**Potential application** **Note: Jurisdictions may have specific requirements for the use of listed methods**	**Advantages and 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 L/S 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 regulators
Batch and column tests – standard method **LEAF#** Leaching Environmental Assessment Framework Integrated set of testing methods which comprise of both static (batch) and column leaching tests under various pH	Specifically designed for inorganic chemicals, but has been used for PFAS in • Assessing worst-case leaching • Soil reuse evaluation • Evaluation of remediation effectiveness	**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 (e.g. pH relevant to site can be chosen)

Leaching method and description*	**Potential application** **Note: Jurisdictions may have specific requirements for the use of listed methods**	**Advantages and limitations**
conditions and L/S ratio scenarios (see details below). Designed to work individually or to be integrated as a set **LEAF 1313 (USEPA 1313)** Liquid solid partitioning as a function of extract pH using a parallel batch extraction procedure **LEAF 1314 (USEPA 1314)** Liquid-solid partitioning as a function of liquid-solid ratio for constituents in solid materials using an up-flow percolation column procedure **LEAF 1315 (USEPA 1315)** Mass transfer rates of constituents in monolithic or compacted granular materials using a semi-dynamic tank leaching procedure **LEAF 1316 (USEPA 1316)** Liquid-solid partitioning as a function of liquid-to-solid ratio in solid materials using a parallel batch procedure	Assessment of leaching closer to field conditions (site investigations) (LEAF 1314) Suitable for monolithic and compacted materials (LEAF 1315)	• 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, e.g. 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
Non-standardised batch tests Non-standardised or modified methods with varying liquid to solid ratios, pH, variable extraction times, with or without tumbling Selected standardised methods used for PFAS presented below	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

Leaching method and description*	Potential application Note: Jurisdictions may have specific requirements for the use of listed methods	Advantages and limitations
Modified methods have not been listed but have varying sample preparation (homogenisation, tumbling sample or saturating sample)		**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 regulators
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	For PFAS this test has been used to investigate leaching and transport from contaminated soils	**Advantages** • Simulate leaching closer to environmental conditions • Provides information on the rate of desorption • Provides a more accurate representation of the concentration of the target analyte in the leachate

Leaching method and description*	Potential application Note: Jurisdictions may have specific requirements for the use of listed methods	Advantages and limitations
Designed to evaluate release of chemicals under either local equilibrium or advection conditions as a function of time		• 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
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	For PFAS this test has 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 **Limitations** • No standardised protocols are available • Not practical for routine assessments

Table H - 2 Overview of field-based leaching methods commonly applied and commercially available in Australia.

Standard methods are marked with #. Section 18.3

Leaching method and description*	Potential application Note: Jurisdictions may have specific requirements for the use of listed methods	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 in 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 (e.g. 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 pore-water 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

Leaching method and description*	Potential application Note: Jurisdictions may have specific requirements for the use of listed methods	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

Appendix I Abbreviations and Glossary

See also the list of PFAS abbreviations in Appendix A.

Table I - 1 Abbreviations

Abbreviation	Meaning
µg	micrograms (10PP–6PP g)
ADWG	Australian Drinking Water Guidelines
AELERT	Australasian Environmental Law Enforcement and Regulators network
AFFF	aqueous film-forming foam
ASC NEPM	National Environment Protection (Assessment of Site Contamination) Measure
ASLP	Australian Standard Leaching Procedure
ASTM International	Former American Society for Testing and Materials
Bw	body weight
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
CSM	conceptual site model
DoEE	Australian Government Department of the Environment and Energy
DGV	default guideline value
DW	drinking water
ECF	electrochemical fluorination
EMP	Environmental Management Plan
enHealth	Environmental Health Standing Committee of the Australian Health Protection Principal Committee
EPA	Environmental Protection Agency/Environment Protection Authority
EPBC	Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth)
EqP	Equilibrium Partitioning
FOGO	Food Organics and Garden Organics
FSANZ	Food Standards Australia New Zealand
GAC	granular activated carbon
GIS	geographic information system
HBGVs	health-based guidance values
HDPE	high-density polyethylene
HEPA	Heads of EPAs Australia and New Zealand
HHGVs	human health guideline values (proposed change to all occurrences of this acronym from HBGVs – health-based guidance values)
HIL	health investigation level

Abbreviation	**Meaning**
HPLC	high performance liquid chromatography
IBC	intermediate bulk container
Kg	kilogram
Km	kilometre
K_d	partition coefficient. The ratio of a contaminant concentration in a sediment (or soil) to that in water at equilibrium
Kow	octanol:water partition coefficient; used as a measure of the hydrophobicity or lipophilicity of an organic compound.
L	litre
LC-MS	liquid chromatography - mass spectrometry
LC-MS/MS	liquid chromatography - tandem mass spectrometry
LOQ	limit of quantitation
LOR	limit of reporting
Mg	milligrams (10PP−3PP g)
MWOO	Mixed Waste Organic Outputs
NATA	National Association of Testing Authorities
NCWG	National Chemicals Working Group
NEMP	National Environmental Management Plan
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
Ng	nanograms (10PP−9PP g)
NHMRC	National Health and Medical Research Council
NMI	National Measurement Institute
NWQMS	National Water Quality Management Strategy
OC	organic carbon
PAH	polycyclic aromatic hydrocarbons
PCB	polychlorinated biphenyl
PFAA	perfluoroalkyl acid – refer to Appendix A for information on the PFAS chemical family
PFAS	per- and poly-fluoroalkyl substances – refer to Appendix A for information on the PFAS chemical family
PMP	PFAS Management Plan
PNEC	predicted no effect concentration
POP	persistent organic pollutant
PPE	personal protective equipment
PSI	preliminary site investigation
QA/QC	quality assurance/quality control
RAAF	Royal Australian Air Force
RWQ	recreational water quality

Abbreviation	Meaning
SSD	species sensitivity distribution
SPE	solid phase extraction
TDI	tolerable daily intake
TOF Assay	total organic fluorine assay
TOP Assay	total oxidisable precursor assay
UF	uncertainty factor
UNEP	United Nations Environment Programme
WQG	Water Quality Guidelines (Australian and New Zealand Guidelines for Fresh and Marine Water Quality)
Ww	wet weight

Table I - 2 Glossary

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 (see, for example, Schedule B1 and B5b of the ASC NEPM [2013]).
ambient monitoring	monitoring program producing chemical, physical and/or biological condition data
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 ASC NEPM 1999: [2013]). 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 (see, for example, Schedule B1 and B5b of the ASC NEPM [2013]).
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 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

Term	Definition
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
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 by stormwater contacting disturbed contaminated soils, defined in the Australian Work Health and Safety Regulations 2011 , 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 or human health
diffuse	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
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 (i.e. prior to kerbside collection)

Term	Definition
groundwater system	groundwater and associated processes, including recharge, flow, discharge and interaction with other aquifers and surface water, at a specific location
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
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 (IBC)	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
isotainer	a tank container, built to an ISO (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 5 years – also used for a very long timescale such as greater than 20 years
Mass flux (J)	the rate that a mass of chemicals (e.g., contaminants, amendments, tracers, NORMs, and other chemical additives) pass through a defined cross-sectional area over a measured period of time (ITRC 2010: 7). The symbol for mass flux is J and the SI units are kg m−2 s−
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: D-2). Mass balance as a quantitative estimation of the source ‘strength’ (i.e. 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 2008 and 2010: 30).
medium term	2–5 years
Mesocosm	artificial systems containing complex and self-sustaining populations or communities set in natural environmental conditions (ANZG 2018: https://www.waterquality.gov.au/anz-guidelines/guideline-values/derive/field-effects).
MWOO	the product of a practice aiming to separate the organic waste fraction of household domestic waste from other waste types
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 poly-fluoroalkyl 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)

Term	Definition
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	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
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
temporary	up to 6 months – see also transient
toxicity	the degree to which a substance is toxic (i.e. 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 ≤3 m while a highly vulnerable aquifer has sand and limestone with a shallow to intermediate water table ≤30 m, or fractured rocks with a high permeability ≥40 m/d or a shallow to intermediate water table ≤30 m (DER 2017 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

Term	Definition
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

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