PFAS Factsheet (Per and Polyfluoroalkyl Substances)

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8/01/2025	A	CWT	RM, SS, IR	Various CWT	First issue
3/02/2026	B	CWT	RM	RM	Updated with revised 2025 ADWG limits. Added Section 9 PFAS Waste Stream Disposal.

Contents

1 What Are PFAS and What Is The Concern?

Per- and polyfluoroalkyl substances are a group of over 4,000 synthetic, man-made chemicals that are more commonly referred to as 'PFAS'. Part of their structure is an extremely strong and thus stable fluorine-carbon bond that requires a significant amount of energy to break, and this energy demand is beyond that of nearly all existing treatment processes common in WTPs.

Due to their highly stable chemical composition, PFAS possess unique physical and chemical properties that make them resistant to heat, stains, grease, and water penetration. Their resistant and durable properties led to their widespread use from the mid-20th century in the manufacturing of a variety of industrial and consumer products that require or impart a protective barrier, such as:

- firefighting foams
- protective coatings and coating additives
- textiles and leather products
- pesticides
- cleaning products
- metal plating
- food packaging
- floor polishes
- shampoos
- cosmetics
- sunscreens
- denture cleaner
- photographic processes
- medical devices
- aviation hydraulic fluid

However, as a by-product of their stability and resilience to external factors, chemicals within the PFAS group take a long time to break down (some in excess of 1000 years), both in the environment and within organisms, leading to their being known as 'forever chemicals'. PFAS chemicals are concerning for water authorities due to their persistence in the environment and ability to spread from their original point of contamination.

With renewed attention and media coverage of PFAS detections across the Australian water industry, there has been a growing international consensus that the risks posed by PFAS are more significant than originally thought. While not yet proven through human medical studies, long term exposure to PFAS is suspected to be carcinogenic. Animal studies have shown that high doses of PFAS can cause cancer in animal subjects, delay physical development, cause endocrine disruption and increase neonatal (newborn) mortality, however the absence of human studies demonstrating a conclusive link between PFAS and 'adverse health outcomes' in humans has resulted in a lack of consensus with health authorities around the world setting different maximum acceptable exposure limits.

While global efforts are being encouraged to limit exposure and address the risks associated with PFAS chemicals, it is estimated that the majority of Australians already have a detectable concentration of PFAS in their blood.

2 Main PFAS Variants of Concern

Of the 4,000+ chemicals in the PFAS group, it is the 'long chain' variants which are thought to be of the most concern with perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS) and perfluorohexane sulfonate (PFHxS) the most well-known and with current available research suggesting that they are the most problematic.

Structurally, PFOA, PFOS and PFHxS are considered as 'long-chain' PFAS because they are comprised of long combinations of carbon atoms that are fully saturated with fluorine.

They are distinguished by their respective different functional groups at one end of the chain. It is these functional groups that play a significant role in the PFOA, PFOS and PFHxS molecules' relative toxicity.

Emerging evidence has also identified perfluorobutane sulfonic acid (PFBS) and hexafluoropropylene oxide dimer acid ammonium salt plus hexafluoropropylene oxide dimer acid (GenX chemicals) as requiring attention.

It is notable that not all PFAS variants pose a health risk with short carbon chains generally considered of lower concern than the longer chains (but still potentially dangerous). [1]

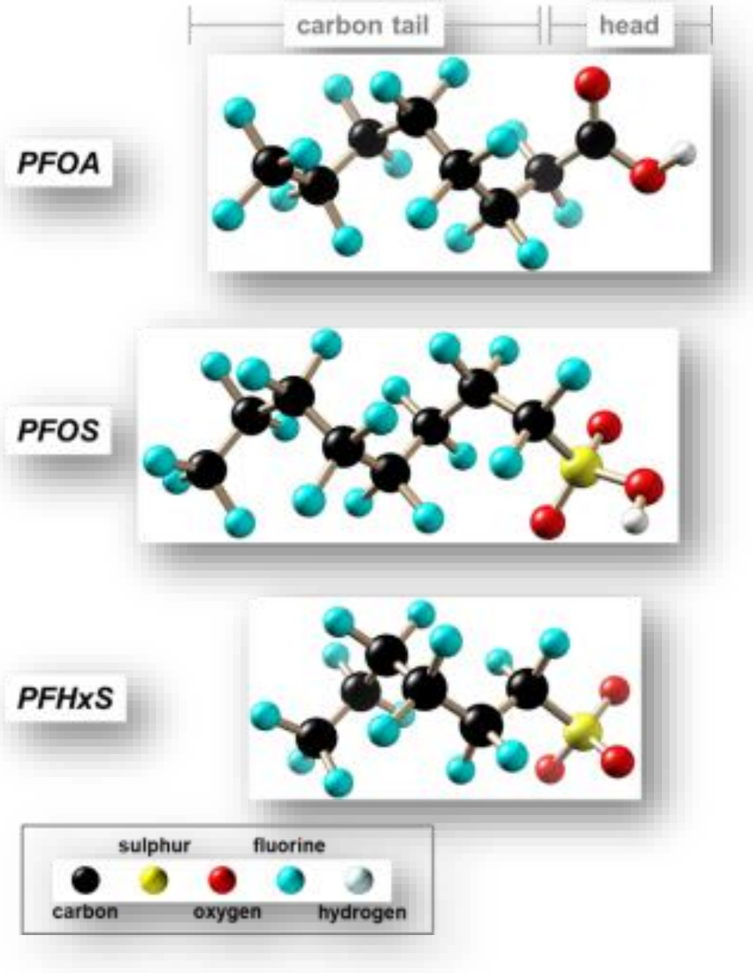

Figure 1. Molecular Structure of PFAS Variants of Concern (source: https://www.pfas.gov.au/about-pfas/faq)

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[1] Australian Government PFAS Taskforce 'Per- and Polyfluoroalkyl Substances (PFAS) Australian Information Portal', https://www.pfas.gov.au/about-pfas/faq, accessed 02/08/2024.

3 Routes of Exposure to PFAS

Most people come into contact with PFAS on a daily basis via trace amounts being present in dust and various consumer products. However, more significant exposure comes from consuming food which has been contaminated prior to harvest (having been grown from contaminated soil or untreated ground/surface water has been used in cultivating and/or manufacturing foodstuffs) or drinking inadequately treated water.

The PFAS National Environmental Management Plan (NEMP [2]) was cowritten by the National Chemicals Working Group comprising the Heads of the EPAs from both Australia and New Zealand and summarises the PFAS exposure routes for humans in Figure 2 below.

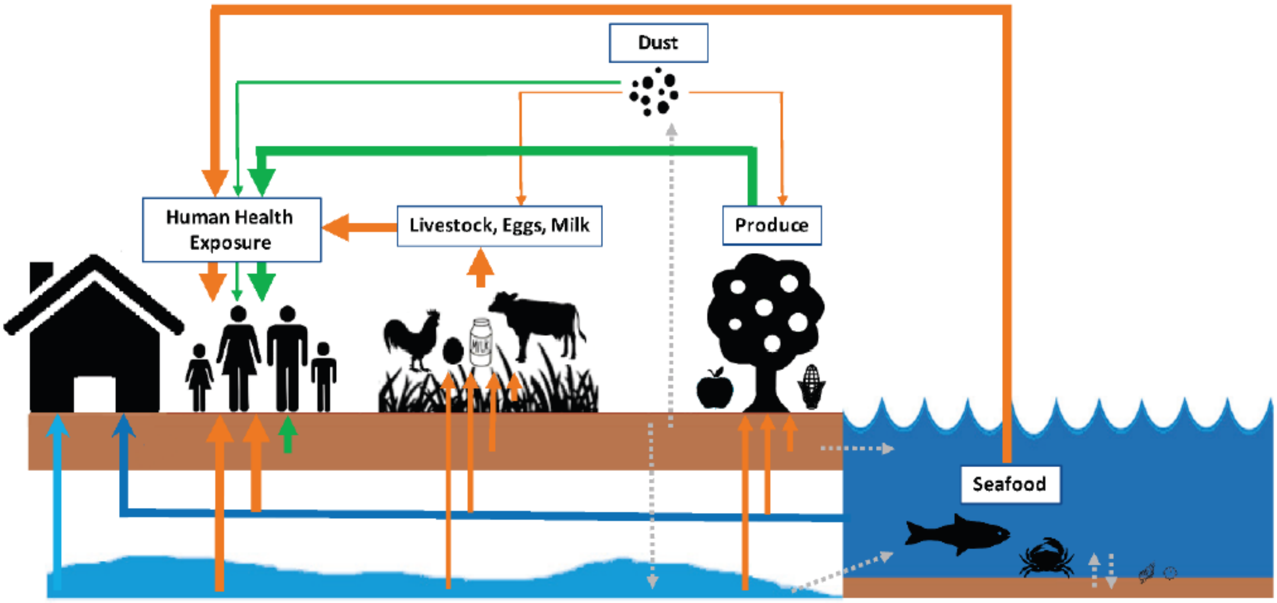

Figure 2 PFAS exposure routes for Humans (sourced from NEMP)

For the above NEMP figure:

- ⇨ Dotted grey arrows indicate PFAS transport mechanisms within the natural environment.
- ➡ Orange arrows indicate the potential PFAS exposure pathways to humans.
- ➡ Green arrows indicate the exposure pathways used in the NEMP to calculate health investigation levels for PFAS in soil.
- ➡ Blue arrows indicate pathways for potential direct (untreated) water delivery to households.

The thickness of arrows infers the relative magnitude of exposure for the route to humans.

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[2] National Chemicals Working Group of the Heads of EPAs Australia and New Zealand, 2020, PFAS National Environmental Management Plan v2.0, https://www.dcceew.gov.au/sites/default/files/documents/pfas-nemp-2.pdf

4 Health Effects of PFAS Exposure

While conclusive evidence of the health effects of PFAS on humans is yet to be delivered through controlled clinical or research trials involving human subjects, the consensus is that there is a correlation between PFAS compounds and detrimental impacts on health.

- Studies on human workers who have been exposed to high concentrations of PFAS show:
  - Higher blood cholesterol levels;
  - Impaired thyroid function; and
  - Changes in liver size.
- Studies on animals have shown that high doses of the PFAS variants PFOS and PFOA can:
  - Cause cancer;
  - Delay physical development;
  - Cause endocrine disruption; and
  - Increase neonatal (newborn) mortality.
- Health authorities in the US and Europe suggest that long-chain PFAS are linked to '*adverse health outcomes*', such as:
  - Lower birth weight in babies;
  - Higher levels of cholesterol and uric acid in the blood;
  - Reduced kidney function;
  - Thyroid disease;
  - Altered sex hormone levels;
  - Reduced vaccine response; and
  - Liver, kidney, and testicular cancers.
- While human medical studies are yet to be completed that demonstrate a conclusive link between PFAS and adverse impacts on human health, in 2023, the World Health Organization declared that PFOA is a class one human carcinogen.

Short-chain PFAS are less studied but suspected to also impact health due to structural similarities with long-chain PFAS but potentially less severe.

Conversely, the Australian NHMRC concluded that there is limited to no conclusive evidence that PFAS poses a clinically significant risk of harm to human health. They make the distinction between 'association' and 'causation': "*Please note: An 'association' to health outcomes does not confirm a direct cause. It is important to distinguish between:*

- *an* association – *a relationship between two factors*
- *causation – where one* factor *is directly responsible for change in the other.*" [3]

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[3] Australian Government, "Per- and Polyfluoroalkyl Substances (PFAS)", Department of Health and Aged Care, 21/10/2024, https://www.health.gov.au/topics/environmental-health/about/environmental-toxins-and-contaminants/pfas

5 Recommended Limits of Exposure Through Drinking Water

The Australian and US approaches to setting their respective limits for acceptable PFAS exposure follow different methodologies. While the United States Environmental Protection Agency (USEPA) and World Health Organisation (WHO) have based their approaches on the suspicion of PFAS being linked to '*adverse health outcomes*', the Australian approach has been to rely on the available clinical evidence (which is yet to conclusively link PFAS and adverse impacts on human health). As a result of the research available to date, the Australian NHMRC has set limits that have been less restrictive than the USEPA.

5.1 Australia

For Australian drinking water, in 2018 the NHMRC introduced a recommendation for the accepted maximum health-based guideline values (HBGV) for PFOS, PFOA and PFHxS into the ADWG which was based on the available scientific evidence at the time. This informed drinking water regulators, local health authorities and water utilities as to the maximum safe concentration of PFAS that can be present in Australian drinking water.

With growing opinion that Australia needed to adopt much stricter limits that are more inline with the USEPA's, the NHMRC undertook a review of evidence that had been published since the 2018 inclusion of PFAS limits in the ADWG. In June 2025, following an extensive review of the available research, the ADWG health-based guideline values for PFAS species were revised, resulting in a lowering of the limits and the addition of values for two further classes of PFAS species, PFBS and GenX chemicals [4].

As of June 2025, the current health-based guideline values for PFAS in the ADWG are set as:

- PFOA (perfluorooctanoic acid): less than 200 parts per trillion (0.0002 mg/L | 0.2 µg/L | 200 ng/L)
    - Previous 2018 limit: less than 560 parts per trillion (0.00056 mg/L | 0.56 µg/L | 560 ng/L)
- PFOS (perfluorooctane sulfonic acid): less than 8 parts per trillion (0.000008 mg/L | 0.008 µg/L | 8 ng/L)
- PFHxS (perfluorohexane sulfonic acid): less than 30 parts per trillion (0.00003 mg/L | 0.03 µg/L | 30 ng/L)
    - Previous 2018 limit: less than 70 parts per trillion (0.00007 mg/L | 0.07 µg/L | 70 ng/L) for the *combined* total of PFOS and PFHxS
- PFBS (perfluorobutane sulfonic acid): less than 1000 parts per trillion (0.001 mg/L | 1 µg/L | 1000 ng/L)
- GenX chemicals (hexafluoropropylene oxide dimer acid and its ammonium salt): no health-based guideline value can be derived at this time.

The NHMRC provided the following explanation on how the above guideline values were derived (bolding by CWT for emphasis) [5]:

"The health-based guideline values included in this update are underpinned by high quality ***animal studies*** *that have examined the effect of PFAS exposure in animals.* ***The observed effects have been extrapolated to***

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[4] NHMRC https://www.nhmrc.gov.au/health-advice/environmental-health/water/PFAS-review

[5] Australian Government, "NHMRC Statement: Per- and polyfluoroalkyl substances (PFAS) in drinking water", NHMRC, 06/11/2024, https://www.nhmrc.gov.au/health-advice/environmental-health/water/PFAS-review/NHMRC-statement-PFAS

***humans** and used to derive health-based guideline values for drinking water.* ***Unlike some other international agencies, NHMRC did not consider the available studies in humans to be sufficiently reliable or appropriate** to derive Australian health-based guideline values for drinking water. Several limitations of these studies were identified, such as a small sample size, limited dose-response information and potential confounding by other chemicals (i.e. exposure to other chemicals might have caused the observed effects)."*

Note that the guideline values for PFAS are intended to reduce the risks to health from long term exposure through drinking water over a lifetime, not for acute exposure over short periods of time.

The Guidelines provide recommendations and do not carry mandatory or legal authority on their own; their adoption and implementation are subject to the discretion of individual states and territories, who can integrate them into their own governance and regulatory frameworks to make them enforceable.

However, Australian water utilities need to assess risk and implement measures to meet the updated guidelines in accordance with the ADWG Framework. It is advised that water utilities assess the risk of PFAS contamination to their water supply, consider testing to confirm compliance with the relevant standards, and take proactive measures to address any identified risks; an inadequately designed and performing treatment process can have implications on the ability of water authorities to mitigate their risk and sufficiently protect public health.

5.2 United States of America

The USEPA takes a much more restrictive approach as it considers there to be no safe level of exposure to PFAS and hence has adopted an aspirational target of zero. For the purposes of legislating and enforcing this, they have adopted the minimum limit of reporting for PFAS as their legislated maximum.

In April 2024, the USEPA revised their limits to be set at:

- a maximum of 4 parts per trillion (0.000004 mg/L | 0.004 µg/L | 4 ng/L) for the combined total of PFOA and PFOS in drinking water and which are legally enforceable (unlike the ADWG);
- a maximum of 10 parts per trillion (0.000010 mg/L | 0.010 µg/L | 10 ng/L) for PFHxS alone in drinking water and which is legally enforceable; and
- non-enforceable limits of 0 ng/L were also set for PFOA and PFOS. However, note that, being non-enforceable, these are aspirational rather than mandated targets.

5.3 World Health Organization

Recommendations for PFAS targets are yet to be included in the WHO's *Guidelines for drinking-water quality* with the most recent 4th edition being published in 2022 [6].

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[6] World Health Organisation, "Guidelines for drinking-water quality: fourth edition incorporating the first and second Addenda", World Health Organization; 2022, https://www.who.int/publications/i/item/9789240045064.

6 Management of PFAS Contamination

Source control to prevent additional PFAS contamination is generally lower cost, less energy intensive and more effective than implementing treatment technology to remove PFAS from drinking water. Restrictions have been introduced both nationally and internationally to restrict non-essential PFAS uses in an effort to limit the amount of new PFAS contaminations (however essential uses are still permitted). Some products that were previously manufactured with PFOS or PFOA may now be being made using alternative, supposedly less dangerous PFAS variants. The Australian Government has banned the manufacture, importation, exportation or use of PFOS, PFOA, and PFHxS from 1st July 2025. However, because of their longevity, PFAS compounds will remain in the environment for the foreseeable future.

While the use of PFOA and PFOS is being phased out, they remain present in environmental waters due to historical uses. As discussed further in Section 6.1, they are particularly concentrated in areas close to where firefighting foams have been routinely used and washed off or leached into the surrounding land and/or drains to nearby waterways (e.g., near airfields and department of defence sites) or near sites where industrial wastes have been released to the environment. PFAS are now commonly detected at trace levels in groundwater, surface water and soils in most urban areas worldwide.

Compared to other types of water contaminants, PFAS are particularly concerning because they are highly soluble in water and do not naturally break down in the environment. Their high solubility of PFAS means that they can readily leach from contaminated soil into groundwater aquifers through which they can disperse over long distances. When the groundwater reaches the surface, it merges with surface waters (creeks, rivers, lakes, dams), transferring the PFAS into these waterbodies. From these it then enters the food chain and is transferred from organism to organism. The aquifers and surface waters contaminated with PFAS include those that serve as raw water supplies for drinking water treatment plants.

Because they are not readily broken down, PFAS bioaccumulate (i.e., their concentration within an organism increases with ongoing exposure, does not decrease with catabolism or excretion, and is passed on when they are consumed by predators).

6.1 Activities That Produce PFAS Contamination

The PFAS NEMP provides a list of the types of human activities that have contributed to PFAS contamination (see Figure 3 and Figure 4). However, given the pervasive use of PFAS, this list is not exhaustive.

Should water authorities be aware of such activities having been conducted within or close to their catchments (given the ability of PFAS compounds to disperse from their original point of contamination), then they may consider the risks posed to their raw water source/s from PFAS exposure to be elevated. In this scenario, instituting a risk-based PFAS monitoring program is recommended (see Section 0).

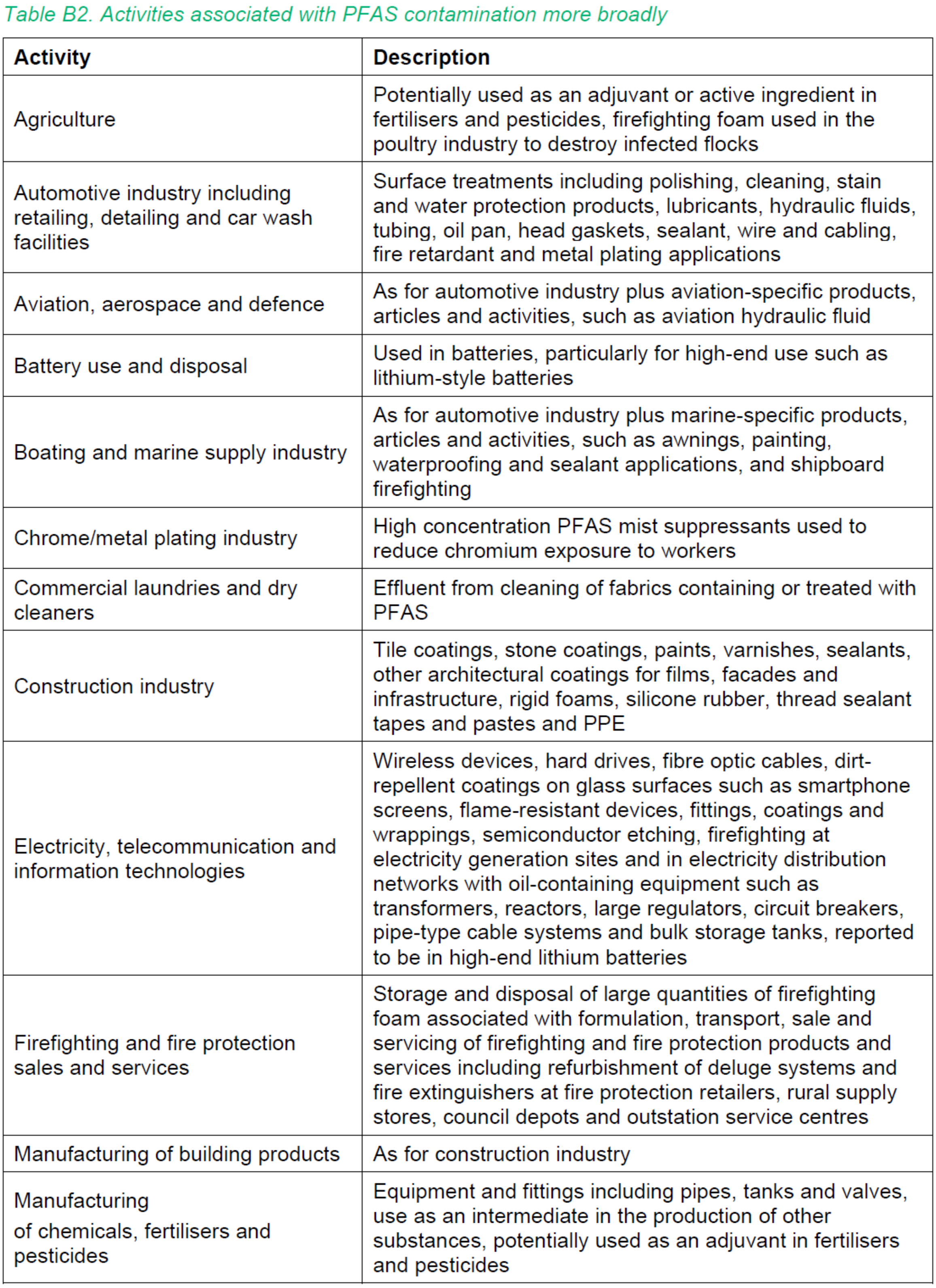

Table B2. Activities associated with PFAS contamination more broadly

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

Figure 3 PFAS contamination activities (sourced from NEMP)

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

Figure 4 PFAS contamination activities (continued)

6.2 PFAS Hotspots

Beyond locations where such activities as those identified in Section 6.1 occurred, increased levels of PFAS are commonly found near:

- Places where PFAS containing firefighting foams have been used either actively to put out fires or during demonstrations, and which include:
  - Airports
  - Department of Defence sites
  - Firefighting training grounds
  - Fuel refineries
  - Mining operations
  - Storage facilities
- Sewage treatment plants and locations where biosolids have been used.
- Landfills.

In locations around where PFAS have been used as an active ingredient in firefighting foams, there may be higher PFAS levels in the local environment. The foams are washed off surfaces where they penetrate into the surrounding land and then leach from the contaminated soil into aquifers or waterways and be dispersed, and/or directly into drains to nearby waterways. .

In the communities present in these surrounding areas, people are likely to have increased exposure to PFAS, especially if they drink PFAS-contaminated bore water, which may result in blood concentrations of the PFOS, PFOA and PFHxS variants above that of the general population.

6.3 Australia's Recommendations and Guidance Management Approach

The approach in Australia has historically been to provide recommendations and guidance rather than legislation, however, from 1st July 2025, the Australian Government has banned the manufacture, importation, exportation or use of PFOS, PFOA, and PFHxS.

- The ADWG provides recommended limits to inform health and water authorities although these do not carry mandatory or legal authority on their own.
- The PFAS NEMP:
  - Provides guidance about the environmental management of PFAS with a focus on preventing further contamination while managing the existing PFAS levels.
  - Focuses on PFOS, PFOA, and PFHxS, and their direct and indirect precursors, as these are the most widely studied and are usually the primary indicators of the presence of a broad range of PFAS compounds.
  - Recognises the need to evolve with scientific developments, including regular reviews.

- Recognises that it is not only the primary sources of PFAS contamination that need to be addressed but also the secondary sources that include facilities that receive waste and wastewater containing PFAS from other sources, such as landfills and wastewater treatment plants.
- Considers the identification and implementation of site- and catchment-specific PFAS risk management actions while recognising that managing PFAS is part of, and should be integrated into, the management of contaminants of concern more broadly.
- Leaves environmental regulators to develop and enforce restrictions in the use and management of PFAS-containing products (i.e. legislation).

6.4 International Obligations

Australia is a signee to the Stockholm Convention on Persistent Organic Pollutants, a multilateral environmental agreement to protect human health and the environment from persistent organic pollutants. The convention sets globally accepted standards for the use and management of persistent organic pollutants, such as PFAS, with specific obligations tailored to each listed chemical.

Australia is also a party to the Basel Convention and the Rotterdam Convention which address other aspects of the management and international trade of chemicals, pesticides and wastes.

Note that signees to the Conventions are required to *consider* the standards, not enforce them. The Australian Government is still reviewing the uses of PFOS, PFOA, and related compounds included in the Stockholm Convention's listings and how they relate to a national phasing out of PFAS usage.

7 PFAS Removal

7.1 Drinking water

While the research remains young, the consensus is that the removal of PFAS by existing conventional water treatment processes is typically inadequate due to their high solubility and very strong chemical structure. The ADWG cites a 2016 Canadian study that "*Standard water treatment technologies including coagulation followed by physical separation, aeration, chemical oxidation, UV irradiation, and disinfection have little or no effect on PFOS or PFOA concentrations" (Dickenson and Higgins, 2016; Health Canada, 2016)*[7].

NHMRC's 2024 literature review of PFAS research papers[8] identified 14 studies that were conducted between 2012 and 2023 that had concluded that "*Standard/traditional treatment at a Water Treatment Plant is ineffective*".

In recent years, research on the treatment of PFOS, PFOA, and PFHxS, all of which are long-chain PFASs, in drinking water has increased, and certain studies have shown that granulated activated carbon (GAC) filtration may sufficiently reduce levels to below the limits mentioned in Section 4. The US EPA published

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[7] NHMRC, "Australian Drinking Water Guidelines 6 2011 National Water Quality Management Strategy (version 3.8 updated September 2022). NHMRC, National Resource Management Ministerial Council, 2022.

[8] National Health and Medical Research Council, "Evidence Evaluations for Australian Drinking Water Guidelines Chemical Fact Sheets – PFOS, PFHxS, PFOA, PFBS, and GenX Chemicals", SLR Consulting Australia, 17/10/2024.

Technologies and Costs for Removing Per- and Polyfluoroalkyl Substances (PFAS) from Drinking Water [9] in March 2024, which presents and summarises the research done on PFAS removal from drinking water, including percent removal for GAC.

7.1.1 Granulated Activated Carbon

Granular activated carbon (GAC) works by passing contaminated water through a filter bed containing carbon, to which PFAS then adsorbs to, removing it from solution. As filter runtime goes on, these sites gradually become blocked (through adsorption of PFAS along with other organic compounds (such as NOM, TOC, colour, taste and odour compounds) and any solid particles remaining in suspension) resulting in decreased capacity for further adsorption. To remove the accumulated deposits and return the media's capacity, routine backwashing is required, ideally including air scouring.

Regardless of the thoroughness of the backwashing process, over time the GAC media's condition degrades and/or become irreversibly saturated (with PFAS or other compounds); this impacts the number of available sites on the carbon and with limited capacity left for additional PFAS adsorption, and the GAC must be replaced.

In the NHMRC's literature review, GAC was identified as "… *one of the few treatment processes demonstrating significant PFAS removal from water but can be exhausted and must be replaced and disposed or reactivated and reused thus can be costly to operate and maintain.*" The papers identified as supporting this were Belkouteb et al. (2020), Brun et al. (2023), Eschauzier et al. (2012), Gobelius et al. (2019), Hyamen et al. (2023), Heidari et al. (2021), Hopkins et al. (2018), Inyang and Dickenson (2017), Li et al. (2020), Liu et al. (2021), McCLeaf et al. (2017), McNamara et al (2018), Najm et al. (2021), Park et al. (2021b), Pontius (2019), Singh and Singh (2017), Siriwardena et al. (2021), Sorengard et al. 2020, Xiao et al. (2017), Yuan et al. (2022), and Zeng et al. (2019).

The papers covered in the NHMRC literature review do not include any research correlating a GAC's iodine number to PFAS adsorption capacity. For GAC, the iodine number is a test method used to indicate the available surface area and porosity of the activated carbon and therefore its capacity to adsorb contaminants (with iodine being the surrogate measured in the test). Determining the frequency with which GAC filter media needs to be replaced is complicated by other factors that influence its condition (e.g. the degree of competition for adsorption sites from NOM, production flowrate, routine backwash frequency and duration), so research papers are few and inconclusive. The most often cited papers are Belkouteb et al. (2020) and Pontius, F. (2019).

- In a full-scale WTP study involving GAC filters (Belkouteb et al., 2020 [10]), 'young' GAC (i.e. only 30 days of operation) effectively removed 92 to 100% of all PFAS to levels below the limit of detection. In contrast, older GAC (360 days of operation) demonstrated an average PFAS removal efficiency of 67%, with PFOA removal at 22% and PFOS and PFHxS removal at 72%.

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[9] United States Environmental Protection Agency, "Technologies and Costs for Removing Per- and Polyfluoroalkyl Substances (PFAS) from Drinking Water", USEPA Office of Water, Office of Groundwater and Drinking Water, Standards and Risk Management Division, 2024.

[10] Belkouteb, N. et al. "Removal of per- and polyfluoroalkyl substances (PFASs) in a full-scale drinking water treatment plant: Long -term performance of granular activated carbon (GAC) and influence of flow-rate." Water Res, 182, 2020.

- The Belkouteb study also indicated that reducing the flow rate could enhance total PFAS removal efficiency, with the extent of improvement depending on the age of the GAC – decreasing the flow rate from 39 to 29 L/s increased the removal rate by 14% for older GAC but only by 6.5% for younger GAC.
- Pontius (2019 [11]) concluded that "*Fresh GAC is effective at removing PFOA and PFOS. Use of GAC over one year was not effective in removing PFOA and PFOS*."
- Yuan et al. (2022 [12]) reported 20-55% PFOS and PFOA removal with 6 year-old GAC filters, but showed negligible removal of PFOA with 9 year-old GAC.
- Söderberg (2023 [13]) found that a two-stage GAC filtration process resulted in higher PFAS removal efficiency, as well as increasing the amount of time needed before GAC regeneration is required. The study found that, overall, two-stage GAC filtration, averages of 84%, 95%, and 94% of PFOA, PFHxS, and PFOS were removed. It was also determined that a two-stage system could treat approximately 3.5 times as many bed volumes as a single filter until the total PFAS concentration in the filtered water reached 4 ng/L.

As GAC will also remove other organic compounds, these will compete with the PFAS for the adsorption sites and should be minimised upstream where possible. To lengthen the operating lifespan of the media (and hence the frequency with which the media needs to be replaced), GAC is normally located towards the end of the treatment process so that other contaminants which may compete with the PFAS for the adsorption sites have already been reduced.

Some studies report that, as it ages, GAC adsorbs long-chain PFAS better, meaning short-chain PFAS don't get removed as effectively.

Pontius also considers powdered activated carbon (PAC): "*Compared to GAC, PAC exhibits a higher adsorption capacity and faster adsorption kinetics due to its fine particle size*", however using PAC contributes significantly to solids loading with implications for coagulation, flocculation, filtration and wastewater systems.

Key points

- GAC filtration is very efficient in removing PFAS.
- GAC filtration efficiency declines with GAC age.
- Conclusively determining a universal age at which carbon media needs replacement is not possible due to the complex factors that influence media condition; following a risk-based approach with an emphasis on ongoing monitoring of PFAS removal efficacy is recommended to guide decisions on the need for carbon media replacement.

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[11] Pontius, F. (2019). "Regulation of Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonic Acid (PFOS) in Drinking Water: A Comprehensive Review." Water, 11(10), 2003.

[12] Yuan, J. et al., "Evaluating perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) removal across granular activated carbon (GAC) filter-adsorbers in drinking water treatment plants.", Sci Total Environ, 838(Pt 3), 2020.

[13] Söderberg, J. "Evaluation of two-stage GAC filtration for PFAS reduction in drinking water", 2023.

7.1.2 Coagulation

Coagulation/sedimentation and filtration will provide some level of PFOS and PFOA removal, depending on type and dosage of coagulant.

One study (Pramanik et al., 2015 [14]) looked into the combination of coagulant (polyaluminium chloride (PACl), effectively a less concentrated version of (poly)aluminium chlorohydrate, ACH) and PAC/GAC dosage into the water, and found that this method significantly increased the percentage removal of PFOS and PFOA to 91% and 95% respectively. The study had a PAC contact time of 10 minutes and a PACl dosage of 5 mg/L at pH 7. With the same contact time and coagulant dosage, the use of GAC together with the coagulant increased PFOS and PFOA removal to 86% and 92% respectively. The study did not look into PFHxS.

Another study (Hubert et al., 2024 [15]) compared the removal efficiency of 6 different coagulants – PACl, zirconium oxychloride octahydrate, cationic polyacrylamide, anionic polyacrylamide, Polyclay 685, and *Perfluor Ad* – at different doses in PFAS-spiked soil wash water. The study found that 100mg/L of the specially designed coagulant *Perfluor Ad* performed the best out of all coagulants, removing over 99% of the long-chain and over 68% of the short-chain PFAS. Dosage between 25 and 150 mg/L consistently removed over 95% of long-chain PFAS. These results were obtained at a pH of 5.96. The average removal efficiency for all PFASs and turbidity decreased as *Perfluor Ad* dosage increased past 100 mg/L. The same study showed that PACl removed up to 48% (removal at 369.9 mg/L) of short-chain and up to 61% (removal at 123.3 mg/L) of long-chain PFAS at pH 6.47.

Removal efficiency has been observed to be improved as the coagulant dose is increased and coagulation pH is decreased (enhanced coagulation). As the pH decreases, the flocs get positively charged, inducing the electrostatic attraction with the anionic (negatively charged) PFOS and PFOA species. However, trials were limited and the pHs targeted were ~pH 4, far below a practical application at WTP scale and at heightened risk of water corrosivity. Within the more realistic coagulation pH range of 5.5-6.5, the expected improvement in the removal of natural organic matter (NOM) could result in improved PFAS adsorption to carbon media as there would be less competition from NOM particles for the available adsorption sites.

Key points

- Specifically designed coagulants are the most effective at removing PFAS, however they are yet to be endorsed for use in Australia.
- Of coagulants not specifically designed for PFAS removal, medium to high doses of PACl can remove 48-61% of PFAS. Given the similarity in their composition, it is thought that ACH would likely share at least comparable efficacy as PACl.
- Combining coagulation (PACl) and PAC/GAC can result in higher removal efficiencies (≥86%).
- Enhanced Coagulation may improve PFAS removal, potentially as a result of improved NOM removal leading to reduced competition for adsorption sites on carbon media.

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[14] Pramanik, B.K.; Pramanki, S.K.; Suja, F. "A comparative study of coagulation, granular- and powdered activated carbon for the removal of perfluorooctane sulfonate and perfluorooctanoate in drinking water treatment." Environ. Technol.,36, 2610–2617, 2015.

[15] Hubert, M. et al. (2024) 'Per- and polyfluoroalkyl substance (PFAS) removal from soil washing water by coagulation and flocculation', Water Research, 249. doi:10.1016/j.watres.2023.120888.

7.1.3 Ozone and Biological Activated Carbon

Biological Activated Carbon (BAC) is formed when bacteria utilise the surface of GAC as a growth matrix, forming a biofilm. This occurs gradually as the GAC ages. The bacterial colonies will then metabolise certain contaminants (such as manganese), removing them from solution.

However, given the strength of the carbon-fluorine bond and the energy required to break it, there are no known bacteria species which are effective in reducing PFAS through direct metabolism. A research paper by Sundaram and Pagilla (2019) [16] noted that removal of PFOS through the ozone BAC process was due to adsorption to the carbon media rather than any biological activity, demonstrating that BAC provides no benefit over GAC for PFAS removal.

Ozone can be used ahead of BAC to break down some organic compounds into shorter length carbon chains or elements which BAC organisms can then metabolise and remove from solution.

However, ozone is not powerful enough to disrupt the carbon-fluorine bonds that saturate the PFAS compounds and which grant them their durability. As a result, ozone is not effective in reducing PFAS.

7.1.4 Reverse Osmosis and Nanofiltration

Reverse osmosis (RO) and nanofiltration (NF) can both be effective at removing PFAS (particularly shorter chain), however they are high pressure and energy intensive which incurs a high OPEX cost. They also produce a reject (brine) stream that is highly contaminated with concentrated PFAS and which requires disposal and/or further treatment. Generally, the volume of the contaminated brine is ~20% of the influent water with a corresponding ~5 fold increase in the concentration of the PFAS.

In the NHMRC's literature review, RO was nominated as a "*Proven technology for removing PFOA and PFOS, achieving up to >99% removal".* The papers supporting this were Brunn et al. (2023), Choi et al. (2021), Hopkins et al. (2018), McCLeaf et al. (2023), Pontius (2019), and Singh and Singh (2017).

RO/NF is normally located at the end of the treatment process so that other contaminants have already been reduced and to protect the integrity of the membranes.

Given the comparison against the need for replacing spent GAC on an ongoing basis, the CAPEX and OPEX of installing, operating and maintaining a suitably sized RO or NF system would require a detailed NPV analysis.

7.1.5 Ion Exchange

Although more commonly used in industrial applications than in drinking water treatment, ion exchange (IEX) has been shown to be an effective method for removing PFAS. IEX works by passing contaminated water through a vessel that contains anion exchange resin media. In passing through the resin, anions from the media (typically chloride or hydroxide) are exchanged and substituted for the PFAS. When the supply of anions from the exchange media is exhausted, the media needs to be replaced (and as it is now saturated with PFAS, requires disposal and/or further treatment).

In the NHMRC's literature review, IEX was nominated as "*Can be effective for removing PFOA, PFOS, and other PFAS*." The papers supporting this were Boyer et al. (2021), Conte et al. (2015), Cornelson et al. (2021),

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[16] Sundaram, V., & Pagilla, K. (2020). Trace and bulk organics removal during ozone–biofiltration treatment for potable reuse applications. Water Environment Research, 92(3), 430-440. https://doi.org/https://doi.org/10.1002/wer.1202

Dixit et al. (2019, 2020), Hayman et al. (2023), Heidari et al. (2021), Hopkins et al. (2018), Liu et al. (2022, 2022b), McCLeaf et al. (2017), Pontius (2019), Zaggia et al. (2016), and Zeng et al. (2019).

To lengthen the operating lifespan of the media (and hence the frequency with which the media needs to be replaced), as with the other processes, IEX is normally located towards the end of the treatment process so that other contaminants which may compete with the PFAS for the exchange anions have already been reduced.

The footprint for an IEX system is typically about ¼ that of an equivalently effective GAC system. Removal is strongly dependent on the pH at which it occurs with better removal achieved at more acidic pHs.

However, given the CAPEX and OPEX costs, maintenance requirements, and impact on plant hydraulics involved, a detailed NPV analysis would need to be carried out before considering whether IEX would be considered a viable option for a WTP.

7.2 Wastewater

For wastewater treatment, most current wastewater treatment plants do not reduce PFAS. As a consequence, PFAS can be present in:

- Biosolids;
- Treated water discharged to the environment; and
- Recycled water.

As PFAS can persist through the wastewater treatment process, the risks posed through the reuse of recycled water and biosolids needs to be considered, especially if they are to be used for agricultural and food cultivation purposes.

8 PFAS Monitoring

The NHMRC recommends taking a site-specific and risk-based approach to monitoring PFAS in drinking water supplies. This approach is outlined in the ADWG risk management framework and is based on the need to tailor management of the specific risks posed by each catchment’s unique circumstances and the capability of the WTP to adequately manage the risks through treatment.

The ability of PFAS compounds to move easily through ground and surface waters, combined with the historical (and often undocumented) introduction of PFAS into the environment and the potential for ongoing contamination from landfill and biosolid applications means that unexpected PFAS detections may sometimes occur.

8.1 In Raw Waters

The concentrations of PFAS across available raw water sources should be monitored so as to identify when levels are elevated and become problematic.

Should elevated levels of PFAS be detected in raw water within a catchment, it is recommended that additional testing of hotspots be introduced to trace and potentially isolate (if possible) sources of contamination from other available raw water sources.

8.2 In Soils

Should water testing close to confirmed hotspots be found to have elevated PFAS concentrations, then soil sampling to confirm the accumulation of PFAS in the surrounding soils and sediments could be undertaken. Results from this would inform the need for pursuing remediation and/or options to isolate the water body.

8.3 In Treated Waters

Given the growing concerns around PFAS contamination, it is recommended that PFAS testing be incorporated into the standard monthly water quality assessments.

Once it has been established that the WTP is producing treated water that comfortably meets the ADWG PFAS targets (or other more stringent targets should the water authority decide to pursue them), a risk assessment could be undertaken to review the frequency of the monitoring.

8.4 Note on Sampling Protocols to Ensure Accurate PFAS Testing

When collecting samples for PFAS testing, the potential for sample contamination during both sample collection and analysis is very high due to the prevalence of PFAS being used in the manufacturing of the involved products (e.g., plastic sample containers and their waterproof labels, disposable gloves, laboratory consumables, etc). As a result, appropriate sampling, storage and transportation are critical for accurate analysis and therefore should be carried out by trained personnel.

9 PFAS Waste Stream Disposal

9.1 PFAS Removal and Destruction Technologies

Reducing the PFAS concentration of contaminated water via treatment process/es transfers the risk to the waste stream handling system rather than eliminating it altogether; depending on the removal method used, while the concentration present in the water has been reduced, the removed PFAS is still present, be it adsorbed upon GAC or IEX media, in filter backwash water, accumulated in sludge (including PAC), or concentrated in a UF/NF reject brine.

If this waste stream is not managed correctly, then it is possible that the removed PFAS could be reintroduced through recirculation back into the process, discharges to and/or through leaching back into the environment.

Additionally, some removal and disposal technologies may alter the composition of the PFAS compounds present, where shortening the length of carbon chains can actually make the PFAS compounds more soluble and, if they are not contained and destroyed, they will pose a continued threat if they are allowed to recontaminate the water.

The NEMP v3.0 outlines the preferred remediation hierarchy as:

1. Separation and treatment for destruction of the PFAS-contaminated material on-site
2. Destruction off-site at an appropriately licenced facility
3. On-site containment (less preferred)
4. Off-site removal to landfill (least preferred)

Table 9-1 below has been adapted from the NEMP v3.0 and summarises the limited PFAS treatment technologies (for both direct removal from water as well as waste stream handling) which are currently available in Australia.

Table 9-1 Currently Available PFAS Treatment Technologies Identified by NEMP v3.0 (Table D1)

Process / Approach	Technology	Definition	Application	Media	Status
Destruction or transformation	Pyrolysis and oxidative thermal destruction (Ross et al. 2018)	Alteration of chemical composition to convert to inorganic fluoride using high temperature in the absence or presence of limited oxygen	Removal ex-situ (offsite) and then high temperature plasma arc, cement kilns to break the C-Fl bonds	Soil, aqueous film-forming foam concentrates, solid concentrates from adsorption, liquid concentrates from reverse osmosis, nanofiltration and ion exchange	Facilities are available in Australia and trials are underway to improve efficiency and to make it more portable
	Electrochemical oxidation/reduction (AsA n.d.; Ross et al. 2018)	Defluorination of PFAS using electrodes	In-situ	Water and wastewater	Currently available and effective for wastewater treatment. Under further development to increase effectiveness in other media
Separation and concentration (requires concentrated PFAS to be managed appropriately)	Adsorption (Tan et al. 2022; Ross et al. 2018; Appleman et al. 2013)	Adhesion of PFAS to the surface of an adsorbent	In-situ or ex-situ using GAC or PAC, resins, IEX polymers or proprietary absorbents	Water and wastewater	Currently available and further trials to improve technique
	Foam fractionalisation/ separation (ozofractionation) (Australian Government 2016)	Separation of PFAS from groundwater and wastewater into a foam using air or ozone bubbles	Ex-situ. The removed PFAS must be managed appropriately (in combination with an additional technology)	Surface, groundwater and wastewater	Currently in use for water and in trial for wastewater

Process / Approach	Technology	Definition	Application	Media	Status
	Reverse osmosis and nanofiltration (Liu et al. 2021; Ross et al. 2018; Appleman et al. 2013; Thompson et al. 2011)	Removal of PFAS from water using semi-permeable membranes	Ex-situ. The removed PFAS must be managed appropriately (in combination with an additional technology)	Water and wastewater	Various systems are available and currently in use with wastewater
	Thermal desorption (often first stage of thermal destruction)	Separation of PFAS from solid materials using high temperatures to increase the volatility of the PFAS	Ex-situ. Indirect and direct-fired thermal desorption. Once PFAS is removed it must be managed appropriately	Soil and waste	Not being used in Australia as a stand-alone option at this stage
	Soil washing (Høisæter et al. 2021)	Removal of PFAS through washing with water, followed by treatment of the water to remove PFAS	Ex-situ. The soil must be removed and often cannot be returned to the original site	Soil	Currently available
Stabilisation and immobilisation	Immobilisation (Bräunig et al. 2019 and 2021; Ross et al. 2018)	Addition of a binding agent to soil to reduce PFAS mobility	Ex-situ using GAC/PAC, or proprietary adsorbents followed by return of material. In-situ using modified clays	Soil and waste	Available and under further development including in-situ application
	Stabilisation (Australian Government 2016)	Minimising the movement of PFAS contaminated material by adding a physical barrier	In-situ using cement or polymers	Soil and waste	Available

9.2 External Services

Having removed and contained PFAS from the water, water utilities may prefer to engage a suitably licensed external hazardous waste processing service for the destruction of the resulting PFAS laden waste stream rather than attempting to process it themselves.

9.2.1 Onsite Stockpiling, Storage and Containment of PFAS Waste Streams

The PFAS NEMP sets out requirements for the onsite stockpiling, storage and containment of waste streams containing PFAS.

Table 9-2 has been adapted from the PFAS NEMP and includes provisions depending on the duration of stockpiling.

Table 9-2 Onsite Stockpiling, Storage and Containment of PFAS Waste Streams

Duration	Solid Waste Infrastructure	Liquid Waste Infrastructure
Transient – Less than 48 hours with no rain predicted	Covered stockpile or storage area on impervious bottom liner (e.g. tarp, plastic sheeting, membrane etc.)	Packaged liquid containers or self-bunded containment vessels on impervious bottom liner (e.g. tarp, plastic sheeting, membrane etc.)
Temporary – From 48 hours to 6 months	Managed stockpile, covered, on impervious bunded hardstand, with effective stormwater controls (e.g. diversion drains, banks, etc.)	Self-bunded containment vessels covered, with lockable access, on impervious, bunded hardstand, with effective stormwater controls (e.g. diversion drains, banks, etc.)
Short-term – From 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 impact 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 ensure that rainwater and sheet flow do not contact contaminated liquids

9.2.2 Offsite Transfer of Waste

Any PFAS contaminated wastes transferred from site are to be managed under Waste Code M270 and in accordance with requirements of the Environmental Regulator(s).

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

Factsheet Authors and Its Use

This factsheet was compiled by City Water Technology (CWT) based on consideration of the information available and known to CWT on PFAS at the time of writing. It is intended to summarise and present information on PFAS, its treatment and management, but given the evolving and emerging research and knowledge base on PFAS, its content should not be considered exhaustive or conclusive.

The advice in this report is provided within the context of the time it was written and with the information available at the time of writing. The specific circumstances of individual water treatment facilities may affect the applicability of the information provided.

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