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Science Agency

Addressing the Challenges of PFAS

The Defence-CSIRO PFAS Collaborative Research Program: 2018-2025

A Summary of Research Outcomes and Benefits

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Executive summary

Between 2018 and 2025, the Department of Defence (Defence) and CSIRO conducted the Collaborative Research and Development Program (CRP) to support intensive per- and poly-fluoroalkyl substances (PFAS) contamination site investigations and management underway across 28 Defence sites nationally. This report summarises the key research activities and outcomes from the CRP.

The CRP was scoped to create critical knowledge for Defence and other agencies to manage the impacts of PFAS across the Commonwealth of Australia.

Over 25 staff across five key Australian partners completed research under four themes

> **Theme 1: Fate and transport.** To improve knowledge of PFAS movement in the environment to help in selecting soil and groundwater remediation options;
>
> **Theme 2: Management of concrete and asphalt**. To improve knowledge of how PFAS interacts with concrete and asphalt surfaces to inform management methods in lieu of demolition and replacement;
>
> **Theme 3: PFAS stabilisation / immobilisation in soils.** To improve knowledge on soil amendments as long-term management options to inhibit PFAS movement from soil to groundwater and surface water; and
>
> **Theme 4: Laboratory and field methods.** To establish laboratory and field methodologies to more effectively estimate the migration potential of PFAS from soils and concrete to surface water and groundwater.

Over 25 reports and 13 journal papers were produced and published containing key outcomes and research highlights.

Beyond Defence, the outcomes have been used nationally by state and territory, and Commonwealth agencies. More broadly, industry, water agencies and other organisations with related PFAS challenges have also benefited.

The CRP helped define practical approaches to mitigating PFAS impacts and prioritising management actions. The CRP provided assurances to communities and regulators that the best available approaches are being used to manage PFAS impacts.

The knowledge platform this program established is expected to continue. It has enriched connections with the United States of America's Federal PFAS research programs (SERDP/ESTCP) which will generate an even greater knowledge and technology base for Australian Defence to draw on into the future.

1 Introduction

1.1 Background to the research program

In 2016, Defence established the PFAS Investigation and Management (PFASIM) Branch to respond to environmental PFAS contamination at 28 bases across Australia resulting from historical use of PFAS-containing firefighting foams. Due to major uncertainties in understanding and responses to PFAS contamination at the time, no consistent guidance for environmental management existed in Australia, and guidelines were changing rapidly both nationally and globally.

In 2018, PFASIM entered into the Collaborative Research and Development Program (CRP) with the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Joint efforts across Defence and CSIRO addressed the urgent need for PFAS management nationally and especially across the Defence estate. The need and rationale included:

- *“The current state of the science and knowledge on PFAS is immature and includes significant knowledge gaps and uncertainty. Defence is looking to reduce these knowledge gaps and uncertainties to improve the management of PFAS across the Defence Estate by advancing research and development into PFAS.”*
- *“This will enable improved outcomes for Australian communities and the environment whilst improving value for money outcomes for the Commonwealth.”*
- *“The Commonwealth requires ongoing expert advice and services across a broad range of PFAS related priorities on a reactive basis to enable the ongoing management of the Defence Estate.”*

Overall, the intended benefits from the CRP to Defence were anticipated to reduce environmental risks, increase community and regulator confidence, and provide a science-based framework to underpin Defence decisions.

1.2 Purpose to this report

This report summarises the key research activities and outcomes from the CRP. The four research themes of the CRP are introduced in **Table 1.1** and presented in detail in the following sections of this report. For each theme, non-technical readers should focus on the introductory (motivation and questions addressed) and final (outcomes and benefits) sections. More technical readers can get a better understanding of the detail in the middle section (approach, methods and key results). Links to published papers are included in the Reference section.

Whilst a broad range of PFAS were investigated, most reported outcomes focused on perfluorooctanesulfonate (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexanesulfonate (PFHxS) being those PFAS with human health and ecological guidance values and those most focused on by environmental regulators in Australia.

Table 1.1 Four Themes in the CRP and focus.

#	Theme	Main focus
1	Fate and transport to support management decisions	To improve knowledge of PFAS movement in the environment to help in selecting soil and groundwater remediation options.
2	Management of concrete and asphalt impacted with PFAS	To improve knowledge of how PFAS interacts with concrete and asphalt surfaces to inform management methods in lieu of demolition and replacement.
3	PFAS stabilisation / immobilisation in soils	To improve knowledge on soil amendments as long-term management options to inhibit PFAS movement from soil to groundwater and surface water.
4	Laboratory and field methods for understanding PFAS mobility and leachability	To establish laboratory and field methodologies to more effectively estimate the migration potential of PFAS from soil and concrete to surface water and groundwater.

2 Theme 1: Fate and Transport to Support Management Decisions

2.1 Motivation and questions addressed

This theme addressed the need to better predict how the PFAS change and move after application by contaminating land uses. The theme considered soil, surface water and groundwater on Defence bases. Improving the ability to reliably predict PFAS movement in the environment would inform management decisions, such as on-going monitoring and precautionary advice to water users and passive or active remedial actions.

When the CRP started in 2018, understanding PFAS behaviour in the environment was in its infancy. Reports were beginning to appear in the scientific literature that the mobility of PFAS in the vadose zone (unsaturated surficial soils) was different to better studied contaminants such as petroleum hydrocarbons and chlorinated solvents. For example, at the time new science observations of PFAS accumulating at the air/water interface was important for explaining the common observation that PFAS tends to accumulate in the top metre or two of soil for long periods (decades or longer). Models for predicting PFAS in saturated soils (soils in perched water lenses or regional groundwater tables) were similarly undeveloped at that time. Therefore, there was a need to investigate if predictive modelling frameworks could be developed to inform management decisions and regulatory consultation.

To develop predictive models, key parameters were needed for how PFAS interacts with unsaturated and saturated soil materials, specifically the air/water interfaces. Laboratory work was undertaken using materials collected from several Defence bases to assess influences in where and how rapidly PFAS-impacted water moves throughout the subsurface profile.

Also important was a consideration of PFAS-impacted surface water (natural environmental flows and captured stormwater drains) moving throughout bases and discharging off-base. Surface water can also infiltrate vertically into the soil and act as a migration pathway of PFAS to regional groundwater tables. Understanding the relative importance of surface water transport versus infiltration to groundwater in Defence base source areas, was a key knowledge gap.

Primary questions being answered were:

- When and where do we operate (or cease) pump and treat remediation of groundwater plumes?
- When and how much do we seek to treat and/or remove source zone soils?

Subsidiary questions were:

- What are the time frames over which remediation efforts need to operate? How long do we need to operate to achieve remediation objectives?
- Will plumes continue to grow and expand? If we ‘do nothing’ what extension of groundwater plumes is likely?

- When will maximum PFAS concentrations in groundwater occur near boundaries or off-base under different remedial strategies?
- Why do key PFAS remain in soils when firefighting foams based on these PFAS were phased out from 2004?

2.2 Approach, methodology and key results

Data were examined from 16 bases that exhibited potential PFAS groundwater plumes, aiming to identify two bases for large-scale PFAS transport modelling. The two bases chosen were RAAF Base Edinburgh in South Australia and Swartz Barracks, Oakey in Queensland.

Field investigations, laboratory analysis and parameter estimation studies were conducted to fill data gaps necessary for modelling the two bases. The general overall schema is shown in **Figure 2.1** for RAAF Base Edinburgh, linking field coring and measurement, laboratory parameter estimation, geological modelling, groundwater flow model, observed field data, and then predictions of groundwater flows and contaminant plumes. The process was iterative, whereby the model was updated based on available data for comparison, calibration and verification.

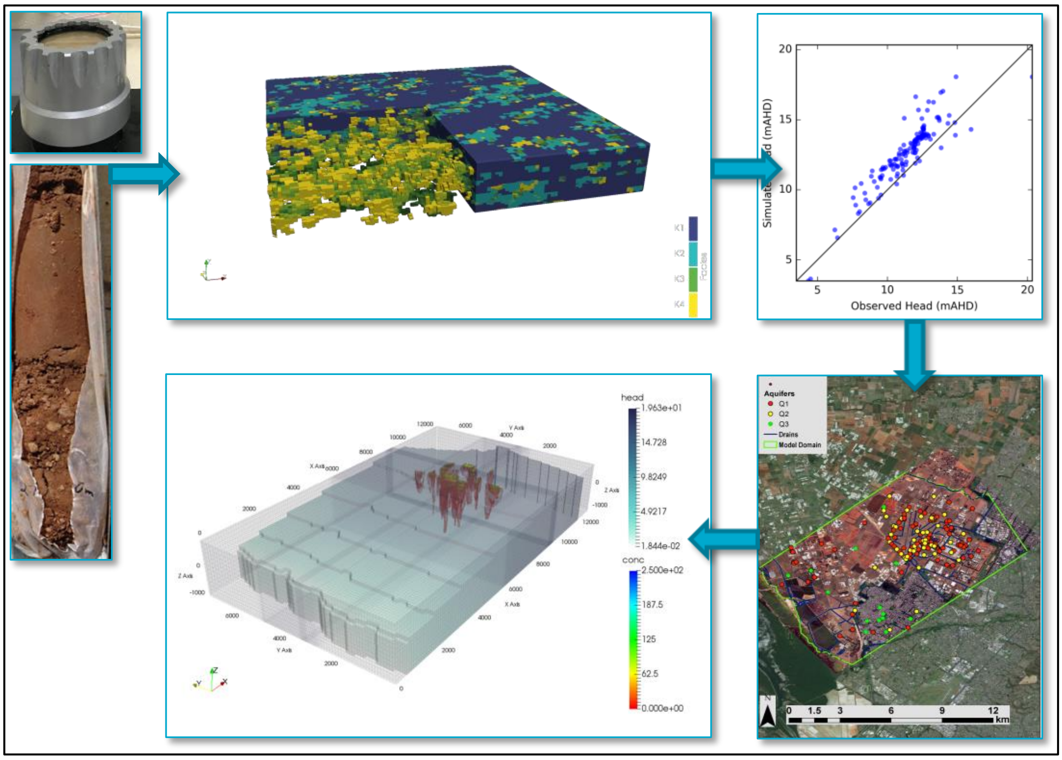


Figure 2.1. Schema outlining steps in characterisation and modelling for the case of Edinburgh. (From left following the blue arrows) samples recovered from the field, testing and measurements in the laboratory, creation of a geological and hydrogeological model, observed heads used to calibrate the resultant flow model for the site, determining PFAS source areas and PFAS transport parameters, resulting in plume prediction output.

2.2.1 Field Investigations for Improved Conceptualisations

Primarily, field investigations undertaken at Swartz Barracks were

(i) drilling to recover cores

(ii) groundwater quality measurement, and

(iii) assess environmental tracers;

and undertaken at RAAF Base Edinburgh were

(i) drilling to recover cores,

(ii) measurements of flow rates, EC and temperature of the main Helps Road drain to estimate surface water fluxes of PFAS,

(iii) an assessment of the hydraulics of the Helps Road drain as a recharge conduit to groundwater,

(iv) hydraulic conductivity and sorption estimates from core materials, and

(v) recharge estimates from mixing ratios of chemical components.

Data and outcomes from field investigations at Swartz Barracks are in a characterisation report (Martinez et al., 2022), and those for RAAF Base Edinburgh are contained within the modelling report (Wallis et al., 2021a,b).

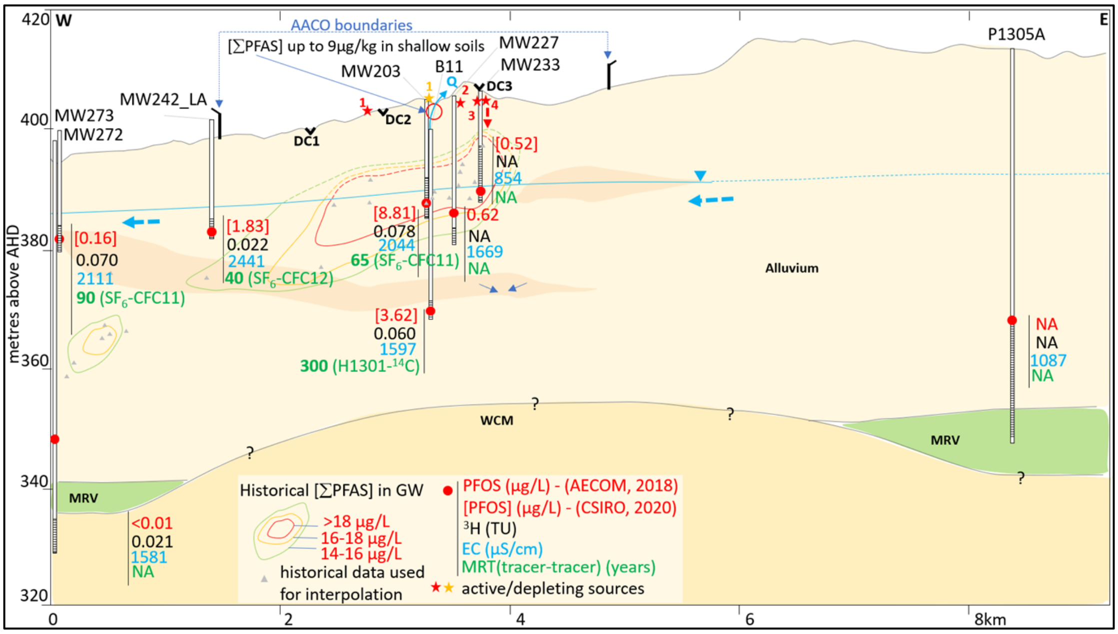


Figure 2.2 Conceptualisation and data as at 2020. West-East direction depth cross-section through the Oakey (Swartz Barracks) site showing bores and samples within a 200 m buffer zone. Downward red arrow suggests the potential entry point for PFAS into the alluvial groundwater and blue sub-horizontal arrow indicate groundwater flow direction. DC1-DC3 indicate the location of the main drainage channels on site. WCM = Walloon Coal Measures, MRV = Main Range Volcanics.

For Swartz Barracks, groundwater data available were combined with regional hydrochemical data to provide an augmented view of possible geochemical relationships between PFAS occurrence and other inorganic chemicals. Soil analyses confirmed a mean total porosity of 40% across the vadose zone, the occurrence of preferential flow paths (cracking soils) and the presence of centimetric scale precipitated minerals (carbonates and pyrite). Salinity and tracer data distributions suggested that the discharge channels traversing the site north-south correspond to potential primary and secondary sources that facilitate PFAS to reach the water table with evidence of connectivity to the underlying alluvial aquifer. The integrated interpretation of multiple tracers also guided the location of active PFAS sources in relation to drainage channels. Recharge estimates were also estimated from tritium vertical profiles. A cross-section summarising some of the data and conceptualisation as at 2020 is given in **Figure 2.2** (from Martinez et al., 2022). These observations and data were used to develop and constrain the modelling approach.

For RAAF Base Edinburgh, soil cores provided samples not only for estimation of hydrogeological parameters (e.g., hydraulic conductivity) but also provided depth profiles of PFAS concentrations and mass estimates which allowed calibration of vadose zone model simulations (**Figure 2.3**).

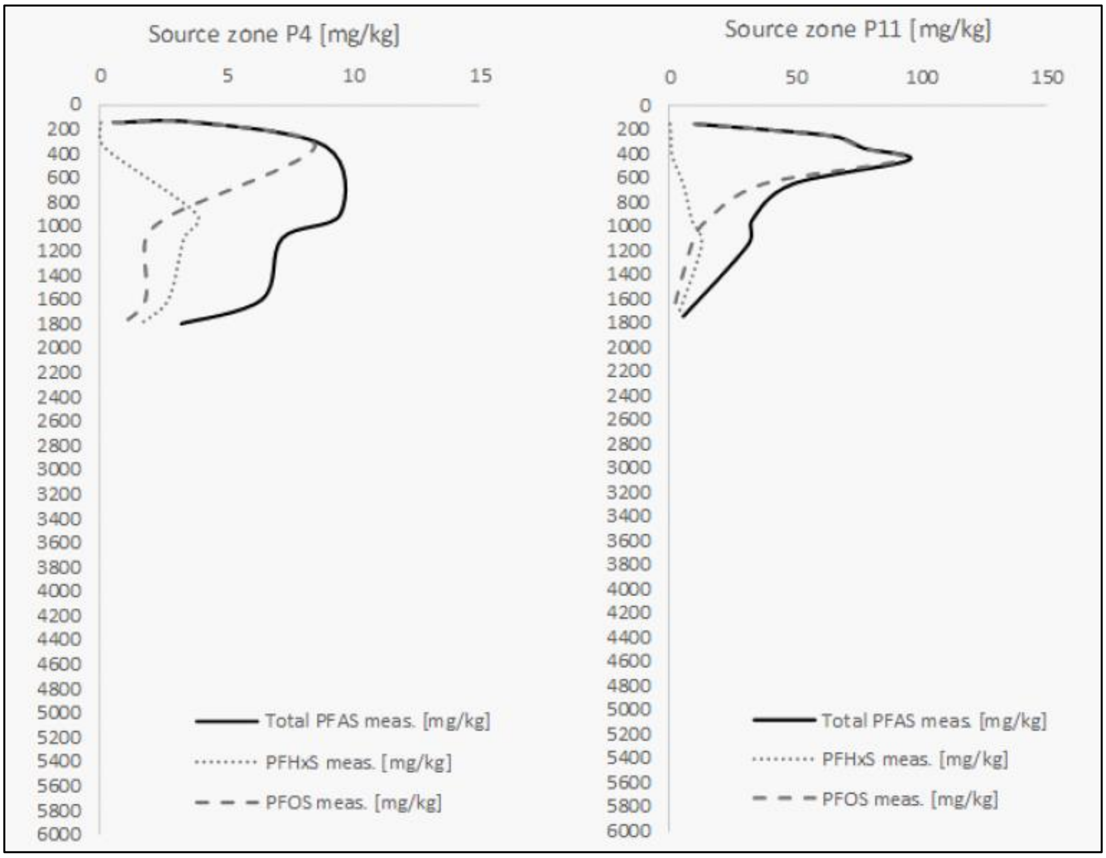


Figure 2.3 PFAS soil depth profile at two source zones (P4 and P11) at Edinburgh showing a chromatographic effect between different PFAS compounds, which can be ascribed to compound-specific sorption affinities. Y axis is millimetres below surface, while the x axis shows the PFAS concentration in mg/kg.

The simulations indicated the relative mobility of PFAS compounds like PFOS (less mobile) and PFHxS (more mobile) due to sorption and partitioning processes in the vadose zone. Permeability measurements were conducted at six selected locations along the Helps Road drain in conjunction with water level logger recordings in the drain and closely adjacent boreholes 5-15 m from the drain. These indicated that recharge to the aquifer from the drain was restricted to permeable windows within the otherwise predominantly low conductivity drain bed. Deeper boreholes did not hydraulically respond to increased flow in the drain. As such, clayey to silty lithologies were assigned lower recharge rates, compared to more permeable lithologies. Limited correlations between PFAS concentrations and major ions were observed, however, PFAS concentrations were positively correlated to elevated REDOX and oxygen content and negatively correlated to EC and temperature. This suggested that elevated PFAS concentrations would be associated with recharged rainwater. These findings were embedded into the groundwater model.

2.2.2 Laboratory Investigations

Laboratory investigations included estimated sorption of PFAS, screening for the potential of colloidal movement of PFAS, and of the accumulation and partitioning of PFAS at the air-water interface.

Sorption measurements (Navarro et al., 2021a). Sorption of PFAS (primarily PFOS, PFOA, PFHxA, PFHxS) under saturated conditions to soil and aquifer sediment materials recovered from RAAF Base Edinburgh and Swartz Barracks were determined (Navarro et al., 2021a). PFOA, PFHxA and PFHxS showed low-moderate sorption in both soils and aquifer materials. The estimated sorption indicated that these PFAS would likely move at rates approximately 1.5 times slower than groundwater flow velocities. PFOS had greater sorption and had an inferred velocity of approximately 2-3 times slower than groundwater velocities. The values determined for each site were incorporated into modelling of the PFAS groundwater plumes.

Colloidal-assisted movement (Kookana et al., 2020). To provide an initial screening to test if PFAS sorbed to colloidal material was a significant transport mechanism, groundwater containing colloids were sampled from five sites. The samples were analysed with and without filtering and initial evaluation showed no significant difference indicating that colloidal transport was not significant. This allowed avoidance of undue sampling and analytical costs compared to the case where colloidal transport might have been significant.

Partitioning of PFAS to the air-water interface (Kookana et al., 2021). The importance of the air-water interface for partitioning of PFAS mass had been previously identified (Brusseau 2023). Experiments were undertaken under differing moisture conditions and soil types to confirm trends observed by others. The study showed that partially dried soils had greater partitioning, and the scale of the effect depended on soil type. It confirmed that the air-water interface contributes to the retention of PFAS in the vadose zone. This has implications for soil treatment strategies and PFAS longevity as a contaminant source to water.

2.2.3 Modelling - Swartz Barracks

The primary report is Cui et al. (2022). Available data was collated and reviewed, including the location of potential PFAS sources both onsite and offsite. An example depiction is in **Figure 2.4** (left panel). It was observed that concentrations in groundwater were different at different depths below the water table, and that it was possible that the nine soil source zones might have led to nine separate groundwater PFAS plumes – with some dispersion and merging of plumes further downgradient. At the time of the review some on-base groundwater concentrations were decreasing, but off-base concentrations were increasing. There was also evidence that PFAS was strongly migrating via drains but was also leaching through soils to groundwater (**Figure 2.4** right panel).

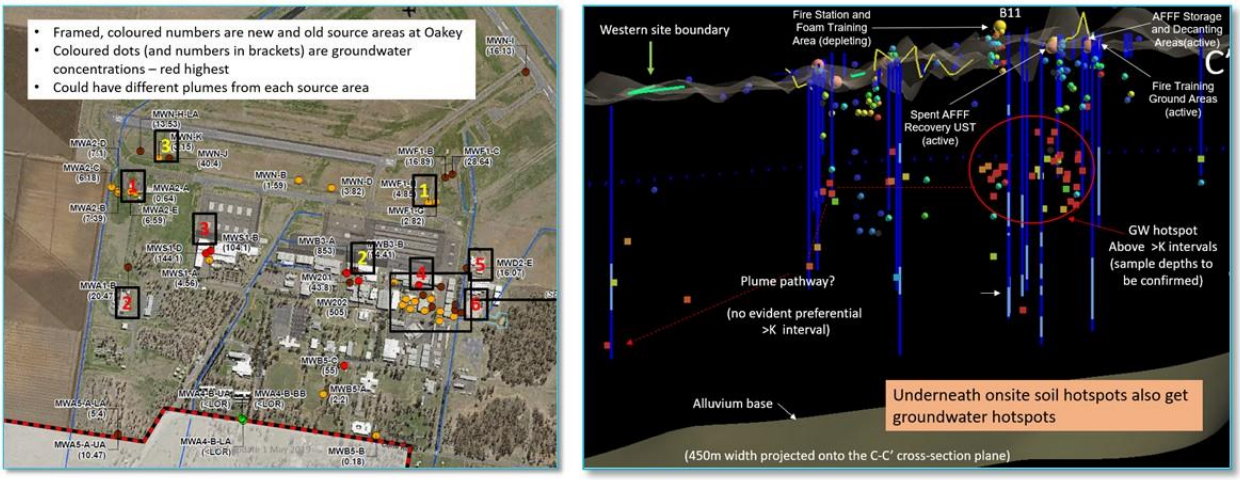


Figure 2.4 *Left Panel:* **Depiction of groundwater concentrations at Swartz Barracks, and labelling of potential soil source areas. This was part of an early review of base data to conceptualise if individual plumes might be likely from each source area.** *Right Panel:* **Depth section showing the range of PFAS concentrations at different depths noted against high and low hydraulic conductivity zones (K values).**

***The framework implementation*.** The modelling framework was able to incorporate available and new information to provide a probabilistic assessment of decision-relevant variables. The framework included:

- a geological model which incorporated the conceptual hydrostratigraphic understanding of the subsurface and the wider base area,
- a hydrogeological conceptual model which synthesised information encapsulated in the geological and unsaturated zone models, measured groundwater levels, PFAS concentration data, and expert knowledge from the literature,
- a numerical groundwater flow model which described the range of groundwater flow directions and hydraulic gradients,
- a dual-domain solute transport model which simulated PFOS advection, dispersion and sorption in groundwater, for a range of plausible groundwater flow characterisations.

Simulated management scenarios. After calibration to groundwater heads and available PFAS concentration data the modelling platform was used to assess five key remediation scenarios up to the year 2115. The results of an assemblage of 295 realisations were used. The five remediation scenarios were:

- Scenario 0 (base case): No remediation or active management is implemented.
- Scenario 1: Pumping of groundwater from wells impacted with PFAS and re-injection of treated (PFAS-free) groundwater, as was implemented at Oakey.
- Scenario 2: Removal of all suspected/known PFAS soil sources onsite and offsite in 2020, and operation of a groundwater pump and treat scheme similar to that simulated in Scenario 1.
- Scenario 3: Removal of five identified PFAS soil sources.
- Scenario 4: Same as Scenario 3, with additional operation of a groundwater pump and treat scheme until 2024, similar to that simulated in Scenario 1.

The plume distributions and concentrations for each scenario for the years 2050 and 2115 are shown in **Figure 2.5**. The estimated net mass flux at the western site boundary is also shown in **Figure 2.6**.

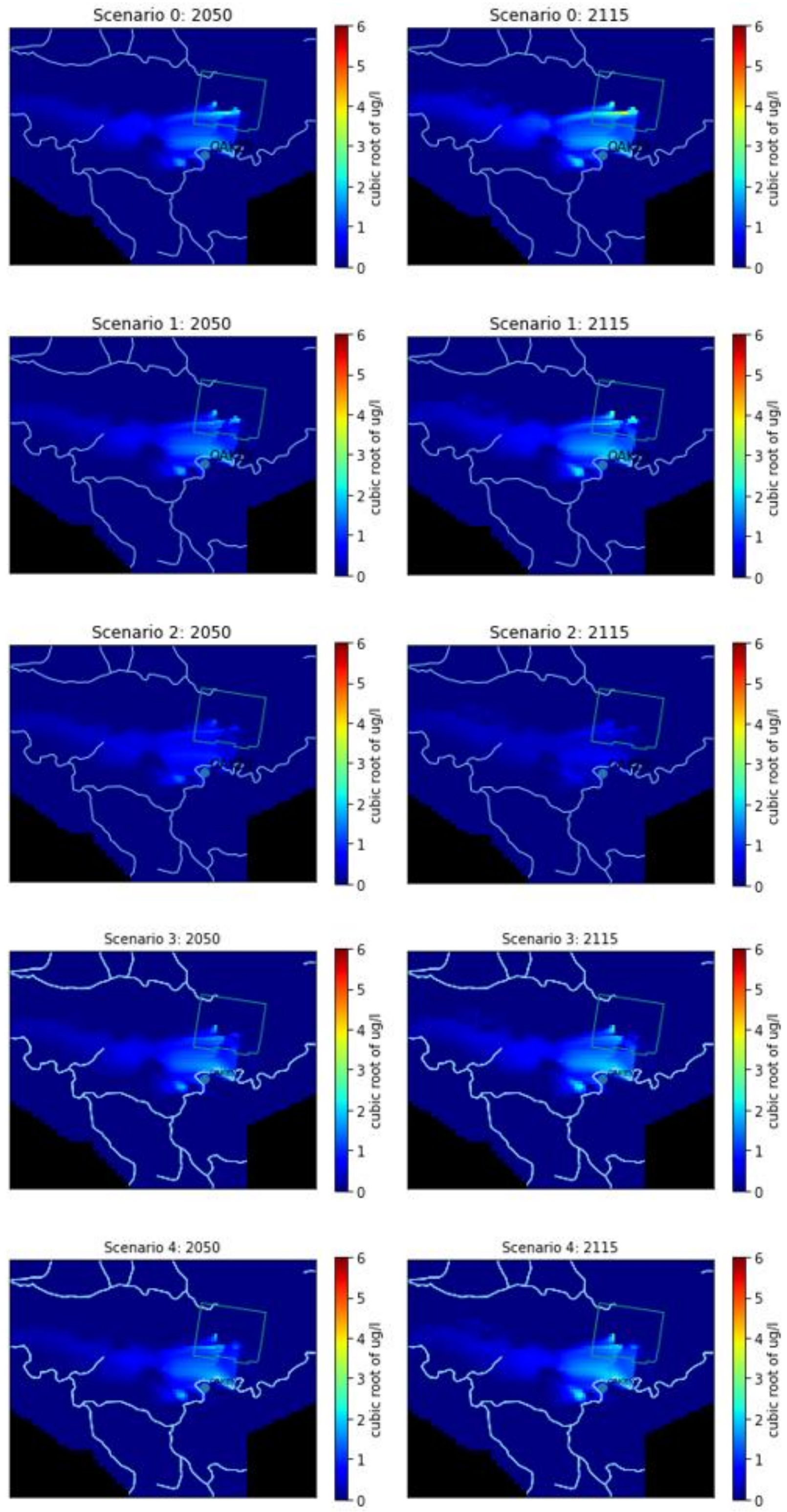


Figure 2.5 The spatial disposition of the plume in layer 2 of the model (realisation #250), in year 2050 and 2115 for the five modelled scenarios. The PFOS concentration scale is presented in units of the cubic root of the estimated concentration in µg/L to improve visualisation.

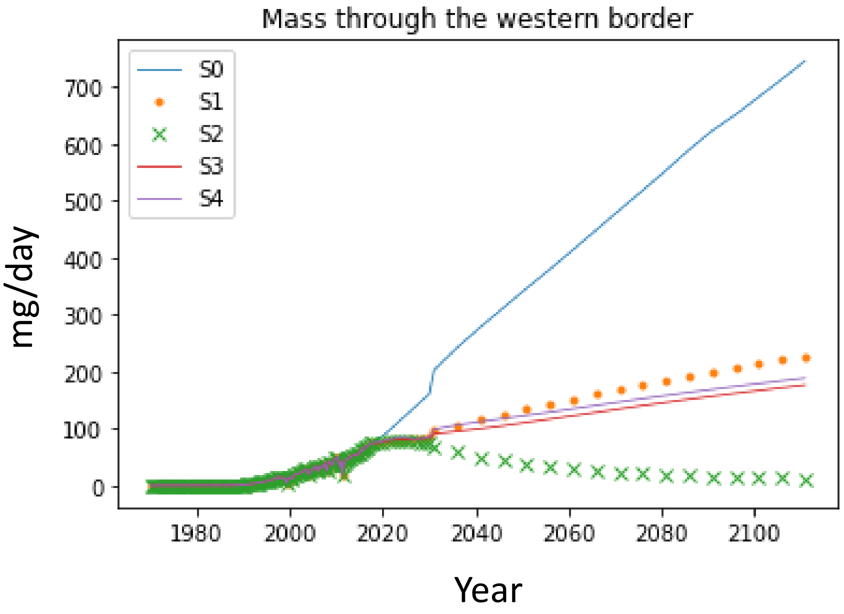


Figure 2.6 PFOS mass flux across the western site boundary for the five investigated scenarios. Note, that the results shown are only for realisation #250, and results vary across realisations. Scenarios 1, 2 and 4 used the same pumping scheme. As a result, their water flux exchanges across the borders are identical.

The key findings were (Cui et al. 2022):

- Scenarios 1, 3 and 4 were shown to marginally reduce the areal extent of the offsite PFOS-groundwater plume (i.e., the area at which a PFOS concentration >0.01 µg/L is present) by the end of the simulation period compared with the base case or 'do nothing' option.
- Scenario 2 achieved a 24% reduction in the areal extent and reduced the maximum offsite concentration significantly from 108 to 16 µg/L. This was obtained because future PFOS flux into the groundwater system was intercepted by complete removal of PFOS in soil from the vadose zone or via highly efficient capping.
- The onsite pump, treat and injection scheme was simulated to have a negligible impact on offsite PFOS mass by 2050. On the other hand, the operation reduced the onsite PFOS mass by about 35% on average within the 30 years until 2050. The remediation measures of Scenarios 3 and 4 showed a reduction of about 70% for the onsite PFOS mass.
- If all the PFOS loading from the vadose zone ceases from year 2020 onwards, the peak offsite concentrations were estimated to reduce by 50% over the following 20 to 40 years.
- Under Scenario 1, while the existing onsite pumping at the time could reduce the mass flux at the site boundary compared to no action under Scenario 0 (**Figure 2.6**), the trend for mass exiting the site along the western border was still predicted to be increasing over time. For Scenario 2, the mass flux through the western border decreased shortly after implementation of the remedial strategy. It is noted that the well configuration for pump, treat and reinjection was not optimised at the time, but if pumping was focused and aligned along the western border then significant mass might be additionally captured.

- Overall, the results can be used to indicate the relative performance of different management options, such as the locations of extraction and injection bores and the extent of soil treatment.

Future benefits of the developed modelling framework could be to incorporate all measured data to assess further plans for site management as well as the quantification of on and offsite groundwater concentration behaviours. It could also be used to direct the most efficient and effective sampling strategies. Despite remaining uncertainties, it is important to note that the modelling framework represented the most complete integration and interpretation of the available characteristics of the Swartz Barracks at the time.

2.2.4 Modelling - RAAF Base Edinburgh

The modelling undertaken is primarily reported in Wallis et al. (2021a,b). The two key elements were establishment of the PFAS vadose zone transport model that allowed estimation of PFAS flux into groundwater to enable modelling of PFAS plume behaviour. The vadose zone model accommodated known properties and PFAS mass distributions in soil and additionally (i) air-water partitioning within the vadose zone model, (ii) the surface slope of the soil to allow surface runoff in comparison to infiltration and (iii) climate (rainfall, evapotranspiration) forcing. The overall methodology used to establish the model framework is in **Figure 2.7**.

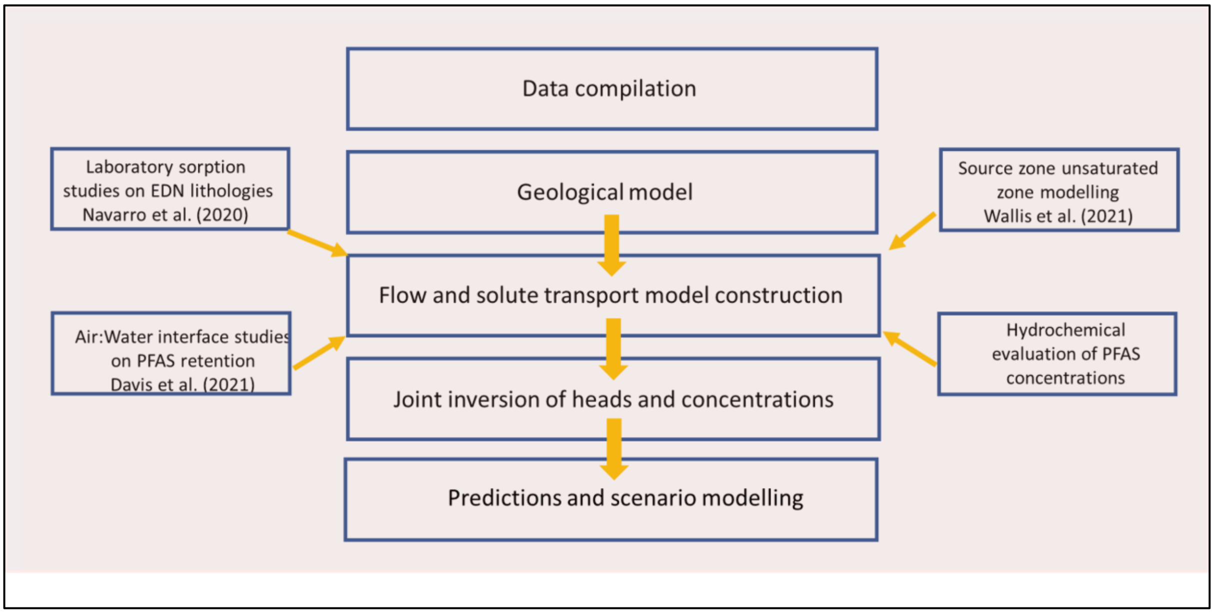


Figure 2.7 Methodological approach and interlinkages between the modelling framework and additional independent work packages within the modelling framework.

Soil source zone modelling (Wallis et al., 2021a; 2022). To inform PFAS migration rates and fluxes into groundwater, unsaturated zone modelling was employed. Specific air-water interface partitioning was incorporated into the model and applied to source zones to quantify the temporal PFAS migration across the vadose zone into the groundwater system. The key results of the unsaturated source zone flow and solute transport simulations revealed an overall decreased rate of movement of PFAS through the unsaturated zone (**Figure 2.8**). History matching of the simulated PFAS concentrations with the observed PFAS mass measured in soil profiles allowed ground truthing of the simulations. Simulations showed that the reduced downward migration is a consequence of the clay-heavy lithology of RAAF Base Edinburgh soils but additionally revealed that the PFAS mass is also retained within the shallow soil horizon due to upward migration of water and solutes during periods of low rainfall and high evapotranspiration. These periods are frequent in some climate regimes in Australia, and lead to PFAS being evapo-concentrated within the soil in the first ca. 0.5 m of the soil profile. This is consistent with the persistently high concentrations in shallow soil horizons that occur even years after terminating PFAS application.

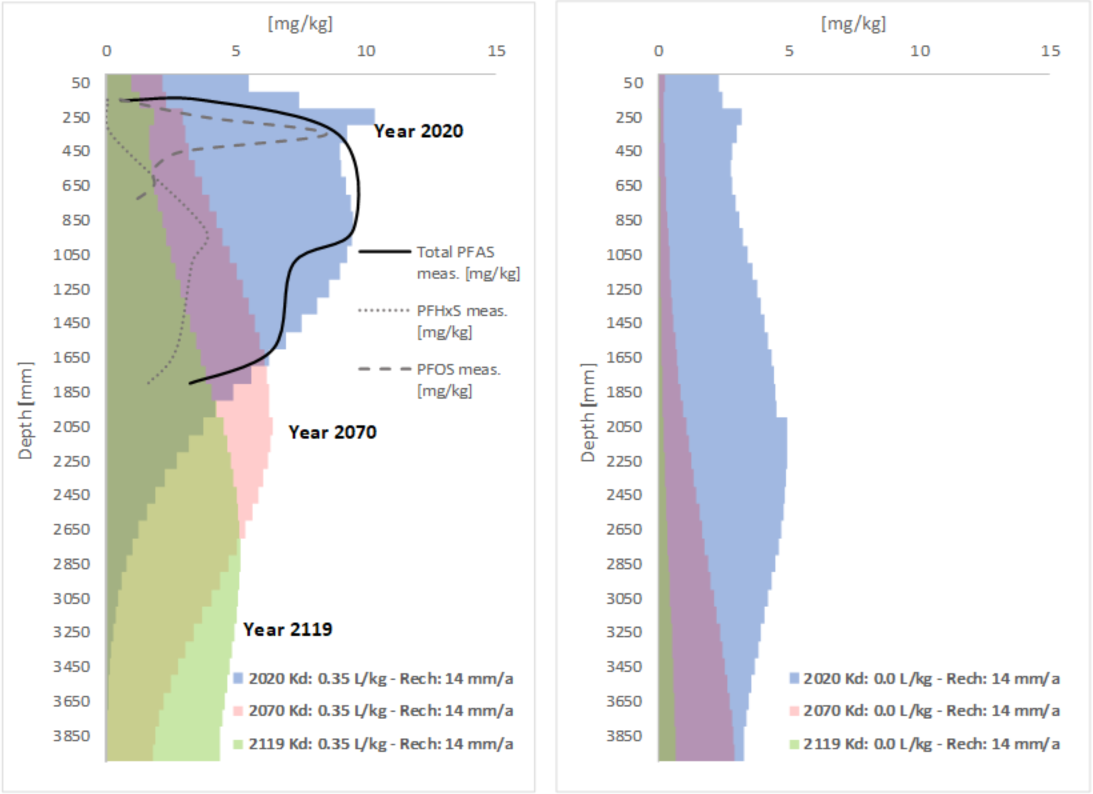


Figure 2.8 Simulated and observed (source zone P4) PFAS mass [mg/kg] with depth [mm] for the years 2020 (blue bars); 2070 (red bars) and 2119 (green bars) if a Kd of 0.35 L/kg or 0 L/kg is assumed. Also shown is the observed PFAS mass profile for PFOS and PFHxS.

Simulated management scenarios (Wallis et al., 2021b). The groundwater flow and transport model calibration involved an inverse modelling approach in which measured hydraulic heads and hydrochemical data (including PFAS concentrations) served as joint calibration constraints. History matching was undertaken as an iterative process with the objective of minimising differences between simulated and observed PFAS concentrations and head measurements through a successively improved estimation of model parameters and elimination of structural geological uncertainties. The simulations allowed for many geological facies' realisations, all compatible with what is known of the geological characteristics and hydraulic properties. This circumvented having to rely on one unique parameter field, which would be compromised by large variability in subsurface properties.

After calibration the modelling platform was used to assess four remediation scenarios up to 50 years to 2070:

- "Do-nothing" option (natural attenuation and migration of PFAS over time) with PFAS addition to groundwater ceasing at 2020.

- Soil removal/capping options for the six highest concentration source zones identified on site
- Soil removal/capping and groundwater pump and treat option, operable over two years.
- Soil removal/capping and groundwater pump and treat option, operable over five years.

The pump and treat scenarios consisted of six extraction wells and six re-injection wells that already existed on site, along with a possible additional 15 extraction wells and four re-injection wells. This complexity shows the value of the model in assessing mixed soil/groundwater pumping scenarios. **Figures 2.9** and **2.10** illustrate the estimated changes in masses and plume extents under the different scenarios.

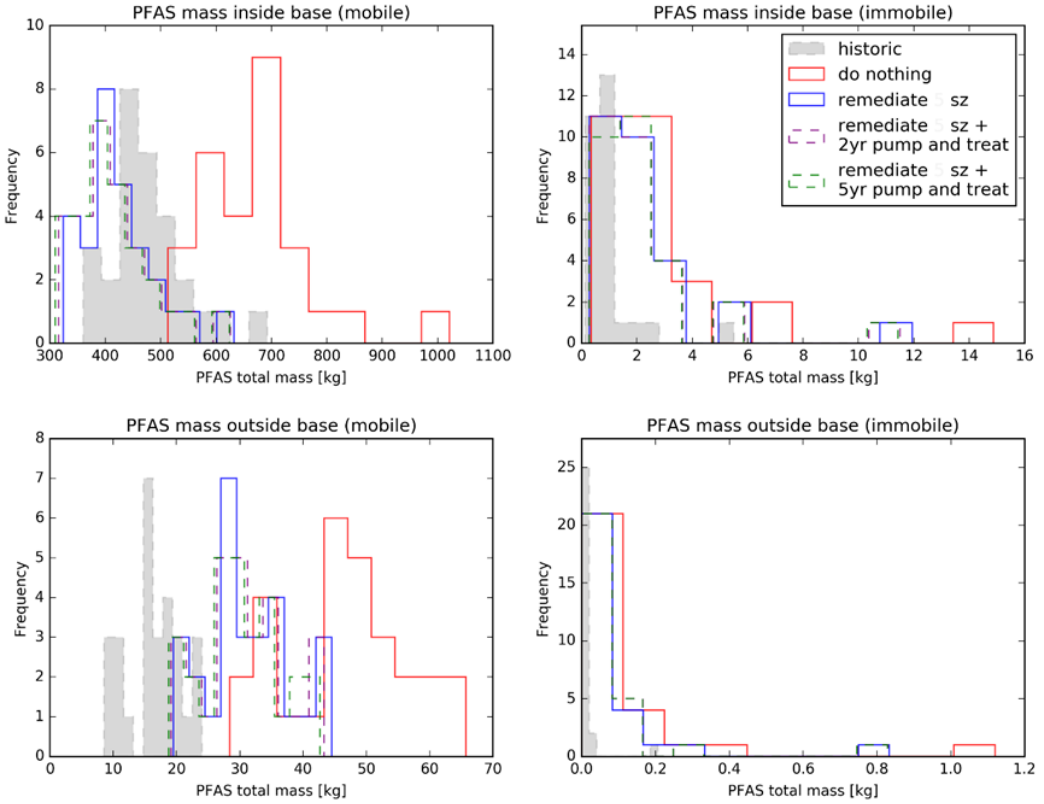


Figure 2.9 Ensemble distribution of the dissolved (mobile) mass of PFAS in groundwater and soils (immobile) located inside and outside of the base boundary for each of the four scenarios at the time 2070 with the historic distribution for 2020 shown for context ("historic").

In comparison with the historical distribution of PFAS mass in 2020, the remediation of six source zones was shown to lead to a notable reduction in dissolved PFAS mass inside the base at 2070 (**Figure 2.9**). This effect is striking when compared to the "do-nothing" scenario, with the PFAS mass inside the base simulated to be approximately halved. Within the immobile region, however, the PFAS mass was largely unchanged for all scenarios, indicating that PFAS mass remains in long-term storage in the immobile region of the soil profile requiring long-term management of this source.

Pumping was shown to reduce the PFAS mass further (**Figure 2.9**). However, with a 5 year maximum duration of pump and treat operations applying low pumping rates and with groundwater abstraction occurring where PFAS lower concentrations occurred in the aquifers, the simulated pump and treat operations are much less effective in reducing PFAS mass compared to the mass reduction achieved through the capping of high concentration source zones. However, if no remedial action is taken, PFAS mass in groundwater will nearly double by 2070 inside the base boundaries.

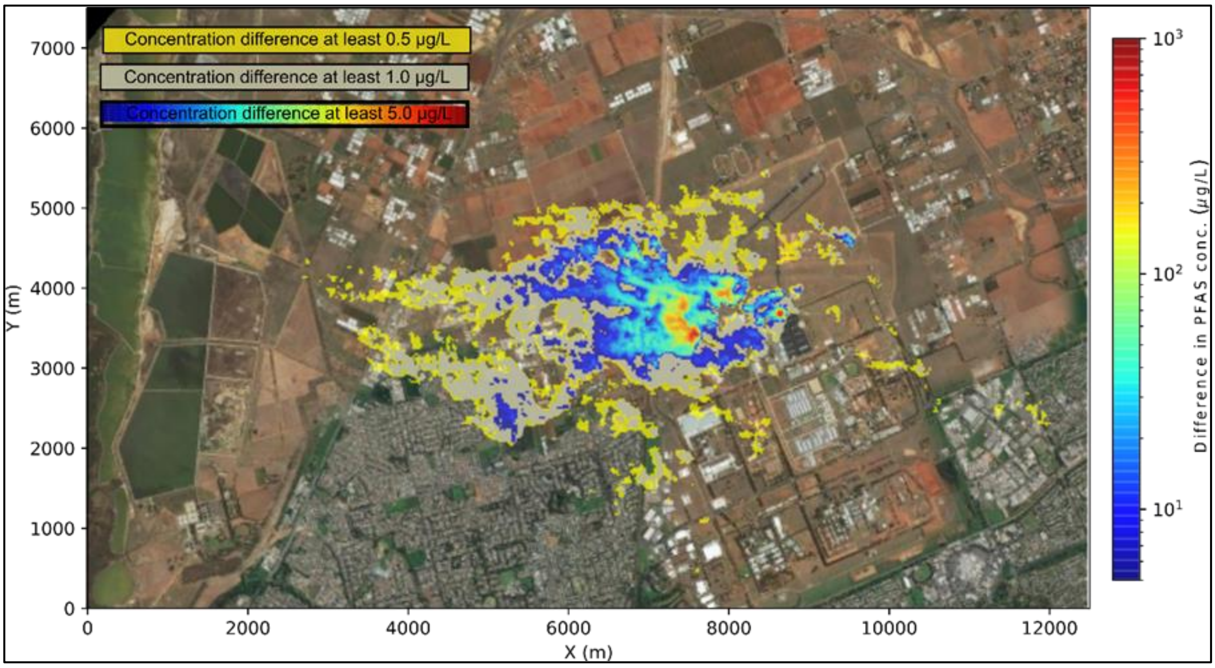


Figure 2.10 Example areal extent of predicted reductions in PFAS concentrations in 2070 based on a comparison between the "do-nothing" case and the "capping and pump and treat (5 yrs)" scenario. The reduction in PFAS concentrations is summed over model layers 5 to 9, which corresponds to the aquifer portion targeted under the simulated pump and treat configuration.

The reduction in the extent of groundwater plumes and PFAS concentrations, comparing the soil capping and groundwater pump and treat management scenario with the "do nothing" option, is shown in **Figure 2.10**. Predicted concentrations inside the base boundary reduce significantly. Concentrations outside the base boundary remain overall relatively low, even under the "do-nothing" scenario, as the plume disperses with time over an ever-larger region due to the pronounced sedimentary heterogeneity.

2.3 Outcomes and benefits

The laboratory work for this theme yielded several useful results, notably:

- PFAS transport on colloids (extremely fine particles) was ruled out as being important for PFAS in groundwater. This saved wasted effort and incorrect conclusions that may otherwise have results from including this in later modelling.
- An understanding of interactions of key PFAS (PFOS, PFOA, PFHxS and PFHxA) with soils typical of Defence Bases was obtained. This added to information from other studies and provided key inputs for the numerical modelling of PFAS transport.

The fieldwork provided detailed understanding of the subsurface environment necessary for modelling. This also added usefully to information obtained by Defence’s lead consultants for the environmental investigations.

Frameworks that linked geological understanding, flow, transport and partitioning processes were established for the two bases. Site specific assessments estimated how much PFAS moves across base boundaries over time, the shape of groundwater plumes and how that changes over time. Simulations using the models showed the effectiveness of soil source removal (or isolation) and pump and treat of groundwater and reinjection of treated groundwater on the size and extent of groundwater plumes. For example, the simulations helped provide justification for pump and treat of groundwater at RAAF Base Edinburgh.

A particularly significant scientific outcome was a better understanding of the processes that influence how PFAS behaves in unsaturated soil. Previous research by others had shown that PFAS downward movement with water in soil can be slowed due to PFAS accumulating at the interface of air and water between soil particles. Research for this program went a step further and demonstrated that water can move upwards due to evaporation and transpiration (plants taking up water). This evapo-concentration effect is better able to explain the observation at many sites, that more PFAS is being transported from source areas in the surface water than moving down to groundwater. The Commonwealth Department of Climate Change, Energy, the Environment and Water (DCCEEW) partnered to expand the capability of the PFAS transport modelling (Wallis et al., 2024) to quantify PFAS leaching for nationally relevant soil types, for possible PFAS masses in source soils, and across Australian climate regimes.

3 Theme 2: Management of Concrete and Asphalt Impacted with PFAS

3.1 Motivation and questions addressed

The management of PFAS-impacted concrete and asphalt was a major theme of the CRP, given the vast amount of concrete and asphalt across the Defence estate that may have come in contact with PFAS. Redevelopment or renewal of concrete or paved surfaces in the Defence estate requires decisions of how to manage significant amounts of potentially PFAS-impacted concrete and asphalt rubble. Rainwater or other applied water in contact with PFAS-impacted concrete or asphalt may continue to leach PFAS at concentrations over prolonged periods. Answering such questions is critical to understanding the risks for leaving in place, options for reuse, and implications of removal for long term stockpiling or landfilling.

When the CRP began in 2018, there was very little available information on PFAS in paving materials. Even the reliability of methods to analyse concentrations of PFAS in concrete and asphalt was not well understood at that time. There was almost no robust information on methods of remediating or treating impacted concrete and asphalt, despite claims from some sealant product manufacturers.

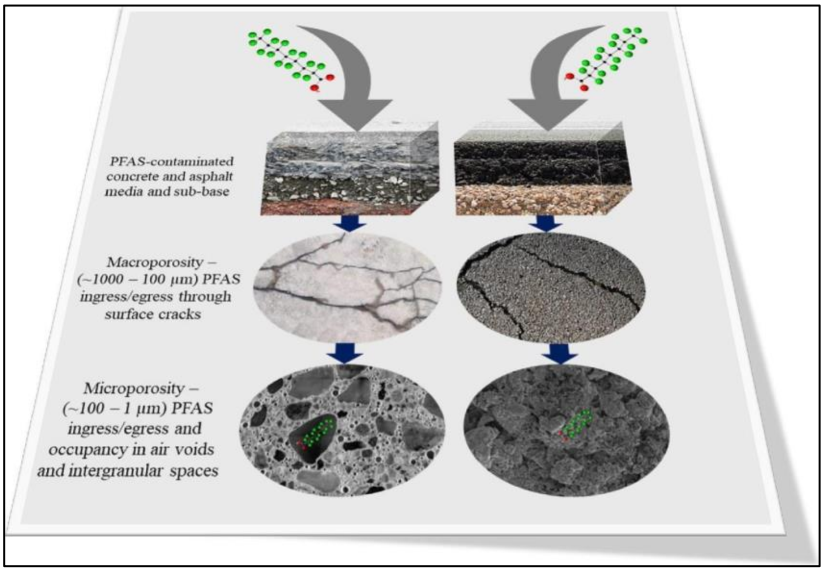


Figure 3.1. Schematic of PFAS interacting with example concrete and asphalt materials, considering macro- and micro-scale features and heterogeneities.

Addressing these questions commenced with:

- undertaking an extensive literature review to collate the knowledge base and conceptualise PFAS behaviour in concrete (**Figure 3.1**),
- advancing new analytical methods to extract and quantify PFAS in concrete and asphalt,
- using leaching methodologies to determine mass release from concrete and asphalt,

- investigating the values of sealants to limited PFAS release from in use surfaces, and
- undertaking extensive characterisation and field investigations of the concrete fire training facility at Bandiana, Victoria.

Key questions being answered were:

- What is the extent of PFAS contamination in concrete/asphalt?
- What do we need to do with PFAS in concrete/asphalt to safely re-use it?
- How do we manage or reuse our asphalt and concrete (*in situ* or off-site) where PFAS may be entrained?

Subsidiary questions were:

- What is the potential for PFAS to be mobilised from concrete and/or asphalt at levels that contribute to environmental risk?
- What are the mechanisms of PFAS interaction with concrete and asphalt materials that control PFAS retention and release by these media?
- Can PFAS mobilisation from concrete and/or asphalt be effectively mitigated using engineering approaches to allow repurposing or disposal?

3.2 Approach, methodology and key results

The staged approach adopted for the CRP was to first map the knowledge base related to PFAS in concrete and asphalt (Douglas et al., 2023a) and known plausible management options (Douglas et al., 2023b). The knowledge base enabled conceptualisation of how PFAS might behave and leach from concrete and asphalt and provided a basis for two main investigations (i) the leachability of PFAS from concrete and asphalt; and (ii) evaluation of management options for PFAS in concrete and asphalt. Both investigations involved detailed laboratory and field studies.

3.2.1 PFAS in Concrete and its Leachability

A focus site for samples and field investigations was the Firefighting Training Area (FTA) in the Bandiana Military Area in Victoria. Investigations determined the depth and spatial distribution of PFAS across the 18 cm thick concrete pad at Bandiana, the release of PFAS from concrete in laboratory leaching evaluations, and validated laboratory leaching methods via field-based water application trials at Bandiana onto portions of the concrete pad and whole of pad monitoring of rainfall and entrained PFAS in runoff waters across seasons. These are reported in brief here.

PFAS spatial distributions - Bandiana concrete pad (Williams et al., 2023). Multiple cores were recovered through the concrete pad at Bandiana, and surface (chip) samples of concrete were recovered across transects and more broadly to determine the spatial variability of PFAS. The surface samples are indicative of PFAS concentrations that are in contact with rain falling on the pad surface, and potentially PFAS that is leachable into runoff waters. The range of surface concentrations for four of the PFAS compounds are shown in **Figure 3.2**. PFOS and PFHxS dominate the concentrations observed and maximum concentrations of the four individual PFAS are not co-located across the pad.

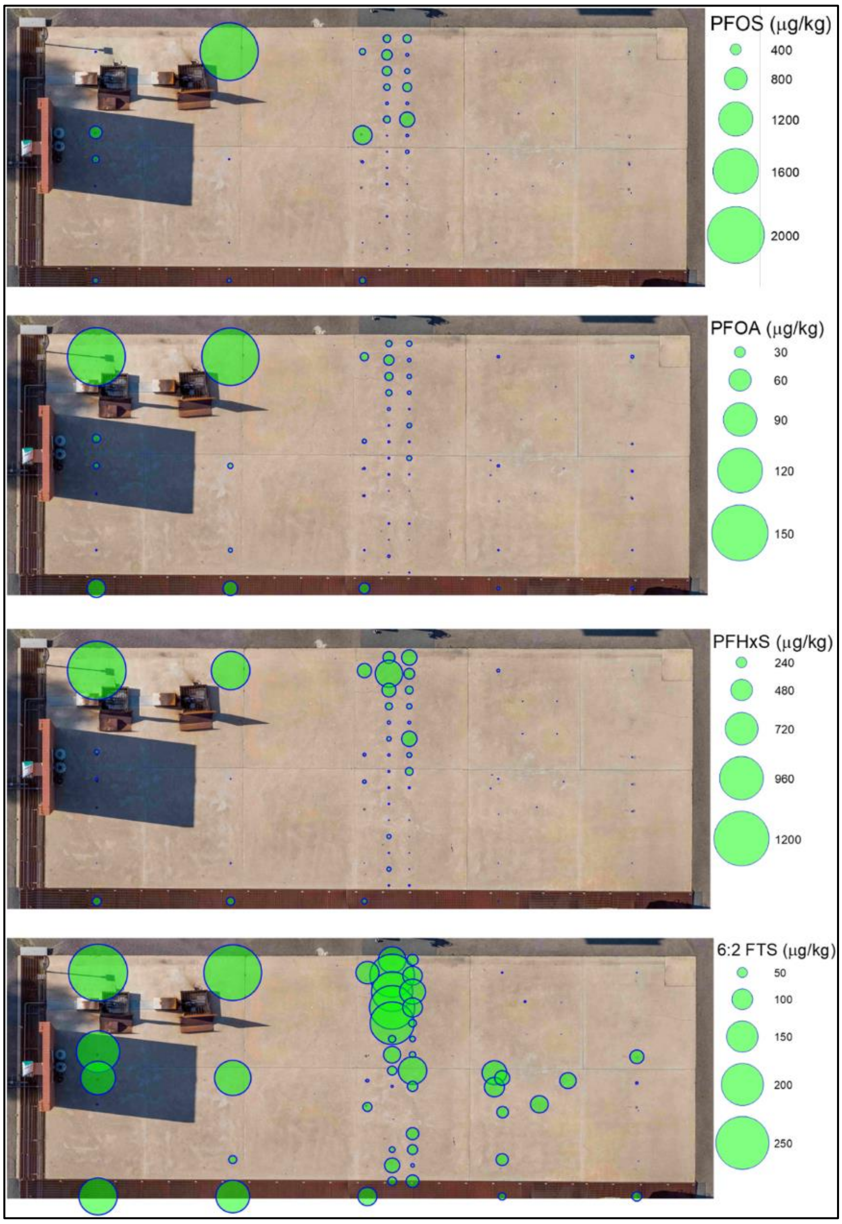


Figure 3.2 Concentrations of PFOS, PFOA, PFHxS and 6:2 FTS (µg/kg) across the pad surface (top 25 mm).

Depth profiles for two clusters of triplicate cores are shown in **Figure 3.3**. Cores 16, 17 and 18 show remarkably consistent depth profiles across all four PFAS shown, with peak concentrations at an approximate depth of 50-70 mm of the 120 mm depth profile. Cores 13, 14 and 15 have greater variability, and core 13 has the highest PFOS concentration of 700 µg/kg at the top surface of the pad. In general, there was no strong differential of the depth of penetration of PFAS based on C=F chain length. The total mass estimate for the concrete pad was approximately 27 g ± 17 g (1 std dev).

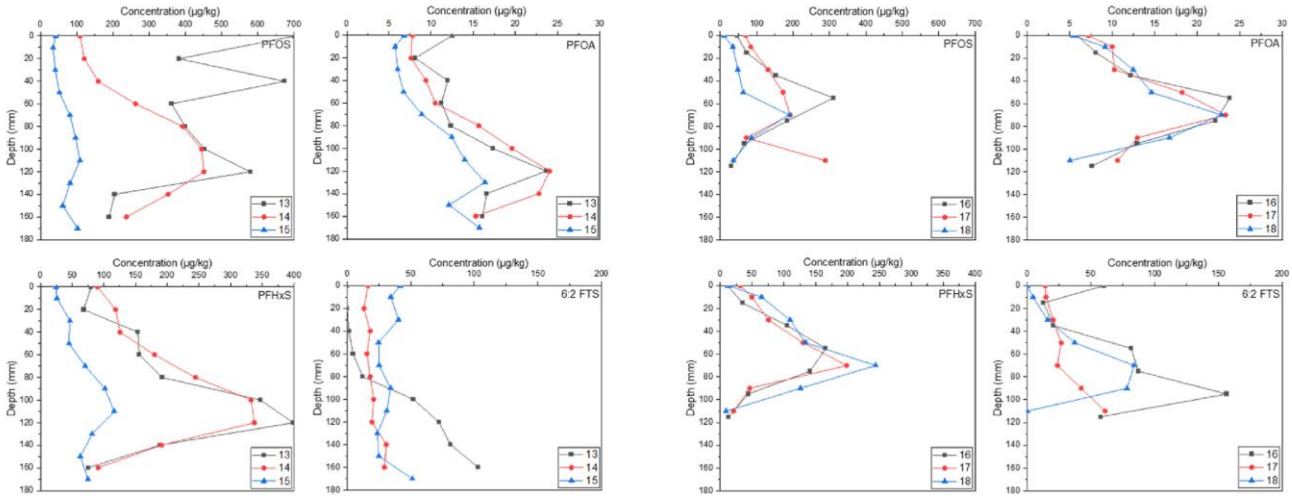


Figure 3.3 PFOS, PFOA, PFHxS and 6:2 FTS concentrations (µg/kg) depth profiles for two clusters of triplicate cores 1 m apart (numbered 13-15 and 16-18). The x axis scale differs across the compounds.

Leachability of PFAS from concrete (Srivastava et al., 2022a; 2024). To assess the leachability of PFAS from concrete two primary methods were used:

- the Leaching Environmental Assessment Framework (LEAF),
- Australian Standard Leaching Procedure (ASLP).

These were used to examine the leachability of PFAS, specifically PFOS, PFOA, PFHxS and PFHxA from aqueous film-forming foam (AFFF) contaminated concrete that had high (~2100 µg/kg), medium (960-1400 µg/kg) and low (600-670 µg/kg) PFOS+PFHxS concrete concentrations. In general, PFAS readily leached from concrete monoliths using the LEAF 1315 method giving maximum concentrations in the water bath for PFOS of about 10 µg/L, with PFOA below 0.4 µg/L (**Figure 3.4**). The cumulative proportion (%) leached decreased in the order: PFHxA (>95%) > PFOS (26–84%) ≈ PFHxS (14–78%) > PFOA (<1–54%). The duration of exposure to water (0.5–48 h) and temperature (25 °C and 50 °C) had little influence on the proportion of PFAS leachability from powdered concrete. A higher proportion of PFAS leached from a <2 mm concrete powder size fraction as compared to 2–20 mm and 20 mm size fractions.

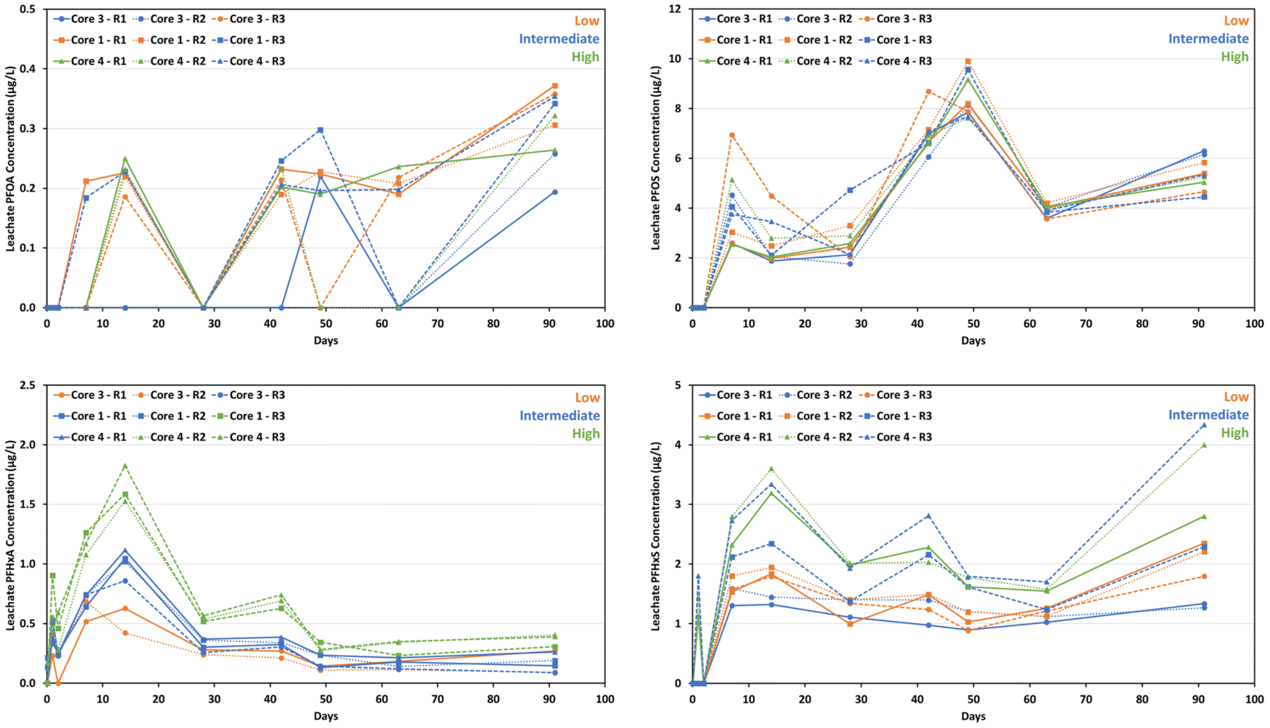


Figure 3.4 PFAS concentrations (µg/L) in leachates during the LEAF 1315 testing at each sampling time point (d). Note that at each sampling point the water bath was replaced with PFAS free water. The x-axis is the cumulative time across all time intervals. Low, intermediate and high refer to concentration ranges in the cores undergoing leach testing.

Bandiana field PFAS discharge trials. To accommodate the spatial distribution of PFAS in concrete observed in earlier studies, two sets of tests were undertaken in the field to directly measure the PFAS concentration in water in contact with larger areas of the concrete paved surface – to measure what PFAS might be released from the pad and the FTA. The two tests involved (i) adding water to discrete 4 and 9 m^2 bunded areas of the concrete pad surface with periodic sampling of the equilibrated water, and (ii) measurement of PFAS discharge in runoff water from the whole FTA under natural rainfall conditions over an 11-month period to evaluate real conditions.

PFAS leaching via water application onto portions of the concrete pad at Bandiana (Douglas et al., 2025a). The trials added water to discrete 1, 4 and 9 m^2 bunded areas of the concrete pad surface with periodic sampling of the equilibrated water to determine PFAS concentration increases. Cores were also recovered in or near the quadrants trials to provide concrete concentration data local to each bunded area, and particularly at the surface. In water samples, a slightly higher sum of PFAS concentrations were seen in the 1 m^2 quadrants (436 ng/L after 48 h) compared to 4 or 9 m^2 (274-326 ng/L). The range of mean % PFAS leached/day (**Figure 3.5**) from concrete surfaces in this study are similar to those reported by Srivastava et al. (2024) using LEAF 1315 for medium to high PFAS contaminated concrete.

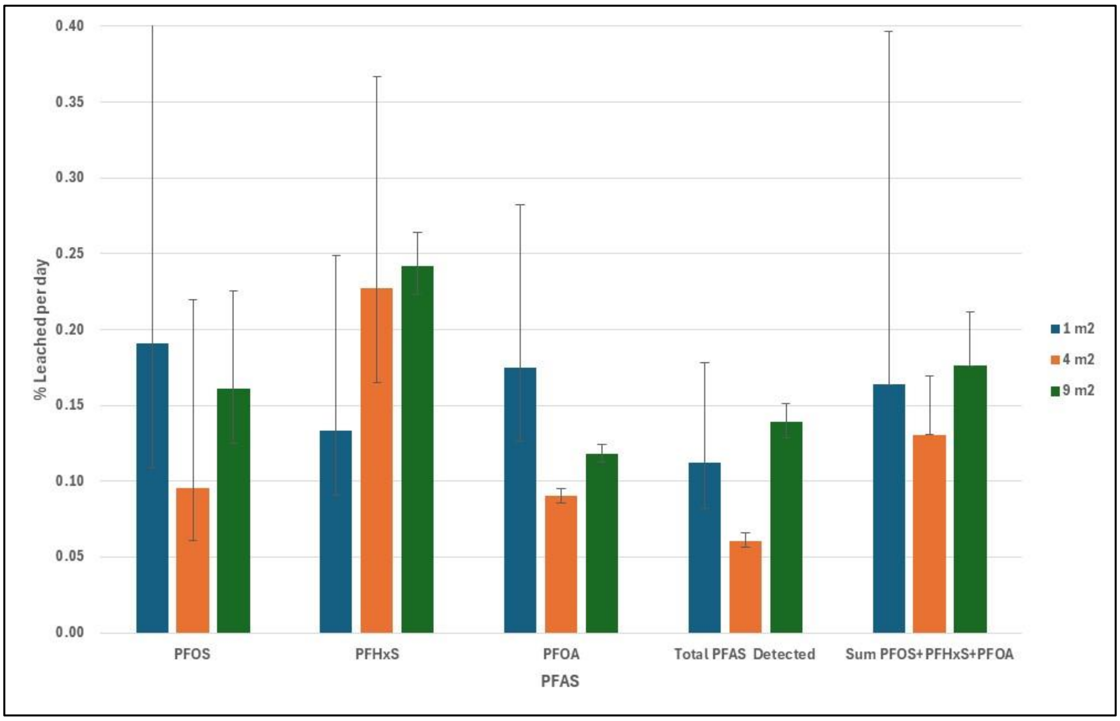


Figure 3.5 PFAS leached per day from quadrant concrete surfaces as a percentage of the mass in the concrete surface within the 1, 4 and 9 m^2 quadrants.

Whole of pad washoff trials (Douglas et al., 2025b,c). Rainfall and runoff water flow from the entire FTA at Bandiana Military Area was monitored for more than a year and, for 11 months of this time, 232 samples of runoff were recovered and analysed for 32 PFAS. Greater than 30 rainfall events occurred totalling 759 mm inducing runoff with a peak flow of 1.75 L/s. An example event is given in **Figure 3.6**. Comparing samples recovered at the start and end of the 11-month period, PFAS concentrations in runoff water did not vary significantly, commonly being in the range 1.0-3.8 µg/L (but a maximum of 11 µg/L) and for PFOS was 0.50-1.7 µg/L. During individual events (**Figure 3.6**), concentrations did decrease at higher runoff flow rates and increased again as flow rates decreased after a rainfall-runoff event.

Regardless of flow rate, over the entire period of the investigation, the fractional composition of PFAS discharging in runoff did not vary greatly, with PFOS dominant at 40-60% of the total PFAS, and PFHxS, 6:2 FTS and PFHxA each between about 3 and 20%. Based on estimates of PFAS mass discharge from the FTA and the total PFAS mass in the concrete pad, and assuming the year of monitoring was representative of weather at Bandiana Military Area, the concrete was estimated to have the potential to continue to discharge PFAS at greater than 1 µg/L over centuries. Preliminary modelling (Douglas et al., 2025c) also suggested decadal to century time frames. This suggests natural depletion over time cannot be relied on to meaningfully reduce discharges, and this should be considered when making decisions on whether active management via removal, sealing or ongoing capture and treatment of discharge water may be warranted.

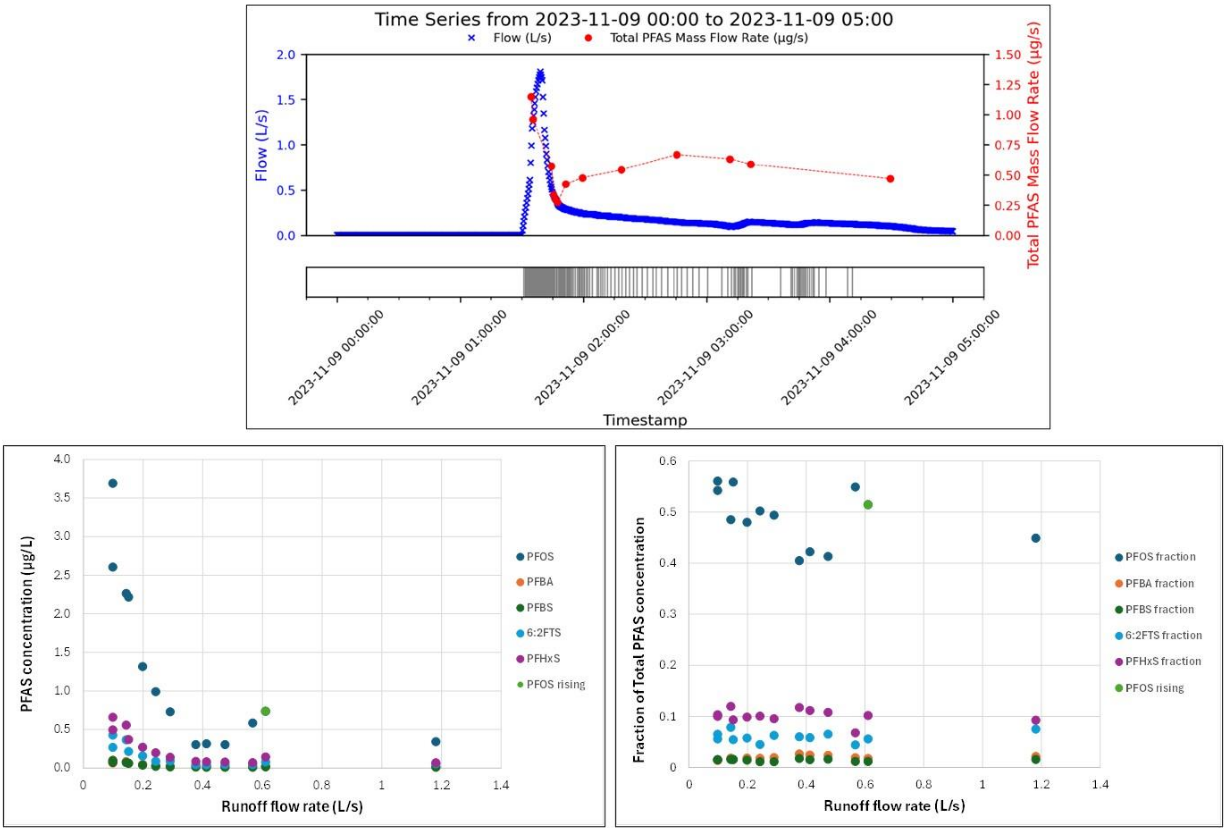


Figure 3.6 Flow rate and total PFAS mass flux estimate (top panel), selected PFAS concentrations (bottom left panel) and fraction of the total PFAS concentrations for individual PFAS (bottom right panel) compared to flow rates over the 12 samples recovered across the rainfall/runoff event on 9th November 2023. The single green data point for PFOS is the one sample on the rising limb of the hydrograph.

3.2.2 PFAS in Asphalt and its Leachability

Three field sites were a focus for asphalt sampling and investigation – RAAF Base Williamtown, RAAF Base Edinburgh, and Bandiana Military Area. Similar to the concrete program of activities, the distribution of PFAS in selected cores was determined, and LEAF and other leaching testing were undertaken. To ensure quality data, additional efforts established a new method for reliable analysis of PFAS in asphalt (Williams et al., 2021b; Srivastava et al., 2022b).

Williamtown runway asphalt cores (Williams et al., 2021a). Of thirty-four cores collected at Williamtown, PFAS was quantifiable in nine cores. The main runway had the lowest range (0.4-9.9 µg/kg), while concentrations on the taxiways and driveways had a much higher range (1-1950 µg/kg). Depth profiles were variable – with one core only having PFAS in the top 50 mm, while five cores had PFAS throughout the vertical profile (up to 400 mm). Depth profile data from four cores along the runway are shown in **Figure 3.7**. PFOS was the dominant PFAS.

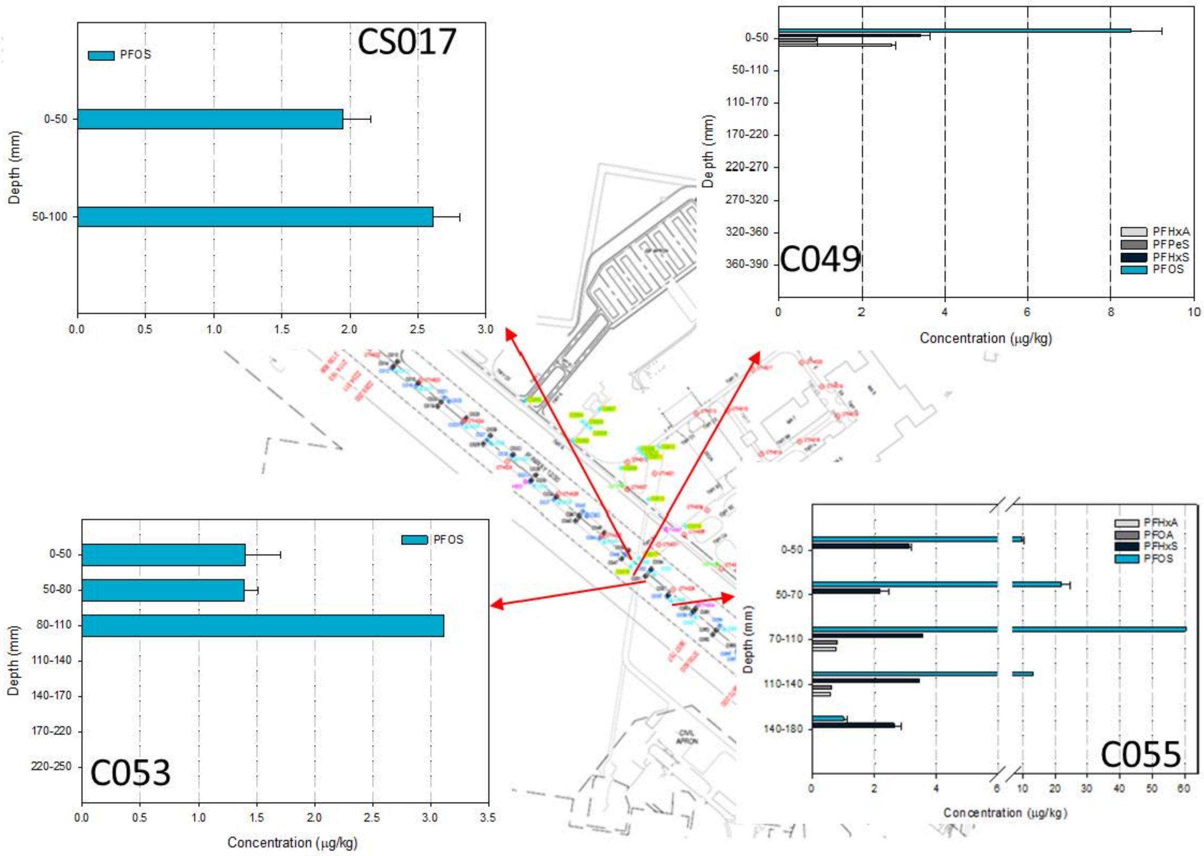


Figure 3.7 Concentrations of PFAS in vertical profile of asphalt samples collected from runway locations sampled at various depths of respective cores.

Leachability of PFAS from asphalt (Srivastava et al., 2025). As with the concrete leaching in section 3.2.1, ASLP and LEAF 1315 leach tests were undertaken on asphalt core material. In this case cores recovered from the Bandiana site had a range of concentrations (as shown in **Figure 3.8**). Leached PFOS concentrations ranged from 0.15 µg/L to 0.8 µg/L (**Figure 3.8**) across a range of asphalt concentrations in cores and across a range of LEAF 1315 leaching periods (time spans of a few hours to 14 days). We note that this concentration range is an order of magnitude lower than the concentration range seen during the concrete leaching tests. A contributor to this is that the PFAS concentration in the lowest (‘low’) concrete cores were higher than the highest (‘high’) concentration asphalt cores.

Additionally, unlike the concrete leaching, for asphalt, changes in leached concentrations occurred at different temperatures and depended somewhat on the duration of leaching.

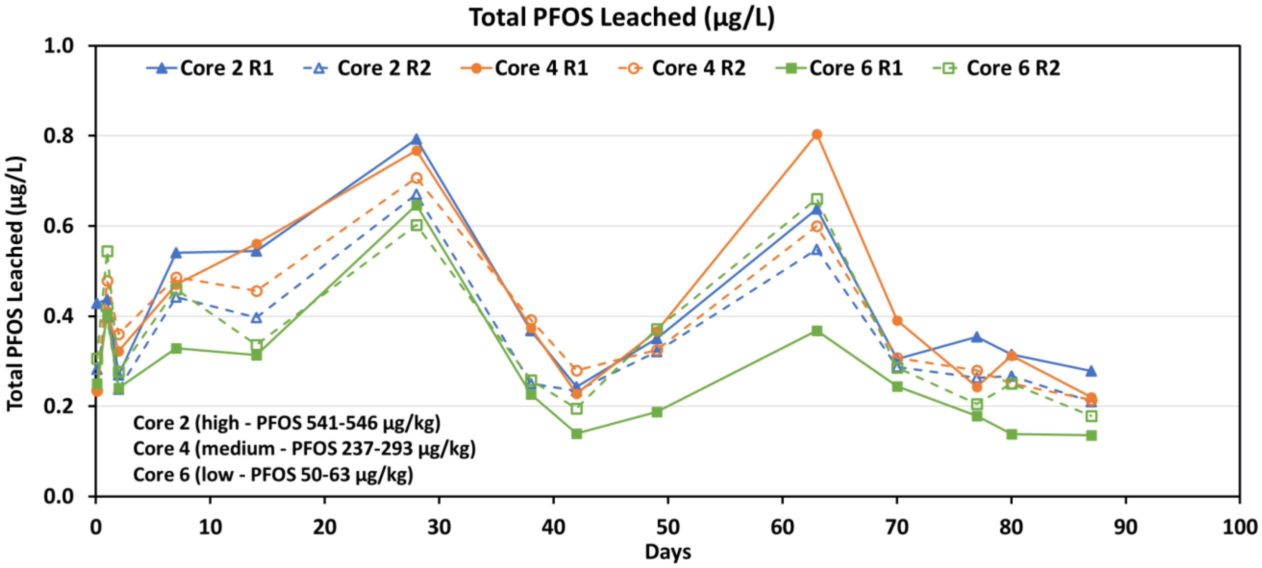


Figure 3.8 PFOS concentrations (µg/L) in asphalt leachates during the LEAF 1315 testing at each sampling time point (d). Note that at each sampling point the water bath was replaced with PFAS-free water. The x-axis is the cumulative time across all time intervals. Low, medium and high refer to concentration ranges in the asphalt cores undergoing leach testing. R1 and R2 are replicates.

3.2.3 Sealants to Manage PFAS in Concrete

A literature review and earlier studies identified sealants as viable management options to reduce leachability of PFAS from concrete and to prolong the life of concrete impacted by PFAS. Laboratory studies screened sealant options, and two likely options were trialled in the field.

Laboratory testing of sealants for concrete (Douglas et al. 2024). Laboratory leaching (egress tests from sealed PFAS impacted concrete pucks) and imbibition (ingress of PFAS into clean sealed concrete pucks) investigations revealed that six of eleven commercially available sealants were viable options for pilot- to field-scale trials to mitigate PFAS release from contaminated concrete. A summary of outcomes is in **Figure 3.9**. Bitumen-based sealants were the best-performing sealants, however, use may be restricted due to their potential flammability, inherent low reflectivity and susceptibility to heating. Three polymer-based sealant classes (epoxy, acrylic, polyaspartic), even though not as high performing as the bitumen sealants, demonstrated low PFAS leachability and penetration into concrete. The epoxy and acrylic polymers meet several functional requirements for concrete, including high chemical and weathering resistance, and high-water repellence. Whilst the polyaspartic polymer was marginally less effective at preventing PFAS leachability, compared with other polymer-based polymer sealants, this sealant satisfies a wider range of functional requirements for concrete (e.g., UV resistance, wear/trafficability, heat resistance and adhesion).

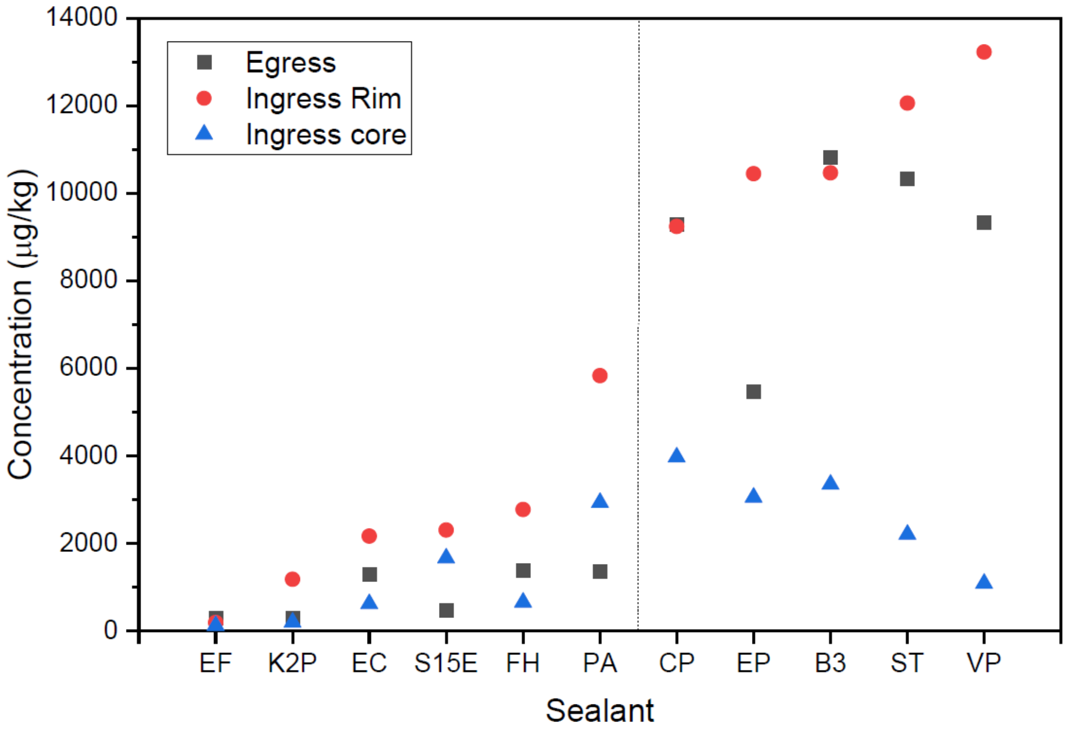


Figure 3.9 Compilation of results of PFAS egress from AFFF-exposed, sealant-treated concrete and PFAS ingress into sealant-treated concrete from AFFF exposure for a range of sealants. Sealants are ranked by increasing rim ingress concentrations. Dotted line delineates a demarcation between sealants with good performance in at least two of the three categories (Egress, Ingress Rim, Ingress Core).

Bandiana field trials (Donn et al., 2025). Two sealant options were trialled at Bandiana – (i) a three-layer epoxy primer, epoxy basecoat and polyaspartic topcoat and (ii) an inorganic silicate penetrating binder (lithium densifier) with two polyaspartic topcoat layers. The concrete pad was divided into three bunded cells each approximately 41.25 m^2 (**Figure 3.10**). Water was added to each bunded cells prior to applying sealants to determine 'background' PFAS concentrations coming off each cell. Subsequently, the sealant combinations were applied to two bunded cells and water was reapplied into each bund.

Both sealants reduced the leachability of PFAS into the ponded water relative to release during the pre-sealant washdown and to the control cell. The epoxy/polyaspartic cell outperformed the inorganic silicate/polyaspartic cell. This performance reflects the observations from laboratory testing outlined above (Douglas et al. 2024). Accompanying the reduction in the PFAS released the proportion PFAS compounds that were leached also changed following sealant application with fewer compounds measured.

Wet-dry cycling experiments run 3.5 months after the post-sealant washdown showed that sealants were still affective at reducing PFAS leaching, however there was no systematic relationship between the duration of drying and the quantity of PFAS mass released.

Figure 3.10 Sealed and unsealed areas of the concrete pad – Cell 1 = Epoxy/Polyaspartic, Cell 2 = Control, Cell 3 = Lithium densifier/Polyaspartic. Dimensions in metres.

3.3 Outcomes and benefits

Early research for this theme provided confidence in analytical methods for PFAS in concrete and asphalt, and the literature review provided a robust knowledge platform to steer further efforts.

For asphalt, extensive sampling and analysis of the RAAF Base Williamtown runway and taxiways was very important in providing an understanding of the general level of the problem faced by Defence. This work indicated may areas were not impacted and impacted areas had very low concentrations, highlighting the potential for asphalt to be safely reused on base.

For concrete, detailed sampling of a firefighting training pad at Bandiana Military Area was very helpful in demonstrating that in some cases PFAS can penetrate deep into the concrete structure and concentrations can vary greatly over small distances. These results conflicted with some other published work and were very useful for informing the nature of sampling needed to understand risks or meet compliance for offsite disposal. Such information can save significant costs for remediation and estate works programs, due to better understanding how more detailed delineation of concentrations can help segregate material suitable for reuse versus disposal.

Laboratory work identified leachable concentrations and rates of leaching. While PFAS partitioning to water from concrete was expected due to its porous nature, somewhat surprisingly, PFAS was also readily leachable from asphalt despite its bituminous nature. For concrete, outcomes for in-place pavements and for different particle sizes were established, which informs understanding for different reuse or disposal options.

Field work showed how PFAS is leached from concrete over time and the impact of periodic rainfall events. These studies indicated that leaching might be maintained for decades to centuries, helping justify the need for active management of impacted concrete at Defence bases.

A small lab study considered the possibility that heating and capturing the PFAS driven off may be a simple and cost-effective means of managing PFAS in asphalt. This was because organic solvents in the asphalt could change PFAS to be the easier to drive into the air at lower temperatures. A simple proof of principle test ruled out this possibility, without the need for expensive more-detailed study.

Potential sealants to mitigate PFAS leaching from concrete left in place were investigated. Sealants were identified, screened in laboratory test and two with the highest potential for success, were applied in field trials. A key consideration was testing sealants relevant to Defence needs for other characteristics (such as maintaining friction for safety, or chemical resistance for storage areas) and commercial availability to ensure ability to supply at the needed scale. Even though further development work is needed, early results have identified promising types of sealant and other sealants that perform very poorly as PFAS sealants. Promising sealants identified in laboratory trials have been shown to be affective in field application, though long-term effectiveness still needs to be assessed. This information has been provided to contractors to help advise projects which type of products to adopt or avoid, thereby helping manage risks for Defence.

The concrete and asphalt research has built capability in Australia to allow success in obtaining funding from the US Department of Defense Strategic Environmental Research and Development Program (SERDP). These include a project to (i) validate LEAF leaching methods for PFAS in concrete and asphalt, to field-assess PFAS leaching from asphalt and to model mass transfer and transport processes in concrete and asphalt, and (ii) to further test and evaluate sealants. Such efforts will yield additional data for use by Defence and will further validate approaches already of value in Australia. The SERDP linkages also ensure knowledge and technologies of value to Australian Defence can be appropriated rapidly.

4 Theme 3: PFAS Stabilisation/Immobilisation in Soils

4.1 Motivation and questions addressed

Sorbents have been available for over a decade to stabilise and immobilise contaminants in soils. When the CRP was started, there was little available information to support the use of immobilisation for PFAS (commonly called soil stabilisation). Given the unusual characteristics of PFAS compared to contaminants such as metals, it is understandable that regulators and other stakeholders would have concerns about applying this strategy for PFAS. At the time, there was considerable pressure to find remediation strategies for soil, as investigations were revealing that it was not just immediate source areas impacted but also soil at quite some distance due to spreading by surface water. Digging up and disposing of such large volumes of soil would not only be cost prohibitive but also a waste of soil as an important resource.

Given that PFAS such as PFOS and PFOA don't break down in the environment there were questions about the longevity of immobilisation offered by sorbents. Also, as many PFAS are taken up by plants and animals, effectiveness to prevent such uptake was a key information gap.

To address these gaps, this theme comprised six elements (**Figure 4.1**). These included lab studies of the longevity of a range of sorbents but focusing on activated carbon, assessing the effectiveness of activated carbon for reducing PFAS uptake by plants, worms and ants, and examination of shallow implementation as an alternative to ex-situ and re-emplacement of treated soil. Collectively, these activities aimed to improve understanding of the efficacy of different soil stabilisation treatments to both inform Defence's soil stabilisation practices and support regulator acceptance of this as a remediation approach.

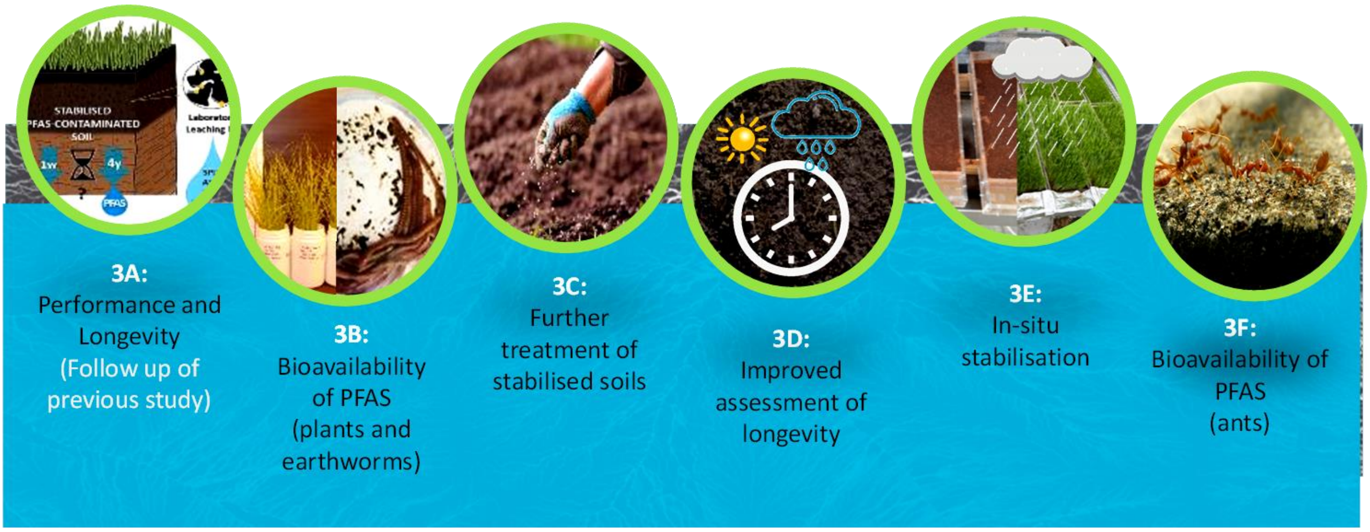


Figure 4.1 Overview of activities (3A to 3F) within the PFAS Stabilisation/Immobilisation in Soils theme.

Key questions for this theme were:

- How effective are currently available soil stabilisation treatments over the long term, and how do they perform under varying leaching conditions?
- Are sorbents that reduce PFAS leachability also effective in reducing PFAS uptake by soil organisms?
- Do treated soils continue to support essential biological functions (e.g., plant growth)? If not, how should treated soils be managed on-site?
- What are the key conditions that affect sorbent performance over time, and how effective are these soil stabilisation treatments under such conditions?
- Is shallow *in situ* GAC emplacement a viable and effective strategy for managing PFAS-contaminated soils?

4.2 Approach, methodology and key results

This theme adopted a multi-faceted approach to evaluating soil stabilisation performance. Leachability was assessed under both short- and long-term conditions using multiple leaching methodologies that simulated a range of leaching scenarios—from worst-case, aggressive leaching to more representative environmental exposures (i.e., static leaching). Incubation conditions were also conducted to simulate various aging processes, including natural weathering and aging accelerated by physical, chemical or biological factors. To inform improved implementation practices, the feasibility of shallow *in situ* amendment application (e.g., GAC) was examined as a potentially lower-cost alternative to conventional ex-situ approaches. Treatment efficacy was also evaluated in terms of risk reduction through bioavailability assessments across taxa with distinct exposure pathways and uptake mechanisms, including plants, earthworms, and ants.

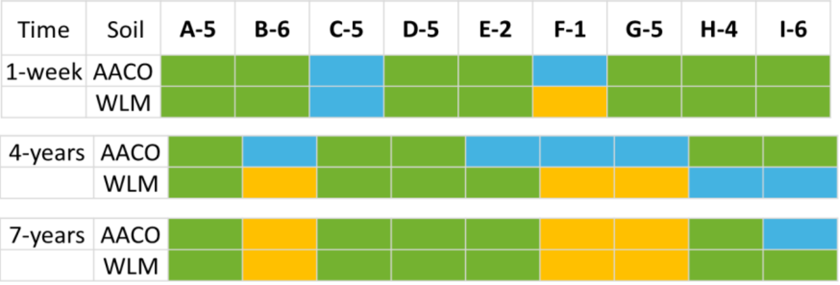
Here we report outcomes under three key headings:

- Leaching of PFAS from stabilised soil (Themes 3A and 3D)
- Shallow emplacement of amendments subjected to controlled rainfall (Theme 3E)
- Bioavailability (Themes 3B and 3F)

4.2.1 Leaching of PFAS from Stabilised Soil

Effectiveness of stabilisation treatments for PFAS in soils (Navarro et al., 2021b, 2021c, 2023, Navarro and Davis 2023). The first activity under this theme was a blind study designed to evaluate the long-term effectiveness of soil stabilisation treatments for PFAS. It involved leachability assessments on samples from bench-scale trials conducted by AECOM in 2016, using two soils (WLM and Swartz Barracks) treated with nine different sorbent amendments (Navarro et al. 2021b). To rigorously test treatment performance, leachability assessments 4-years post-treatment involved multiple standard leaching methodologies that simulated a range of conditions: (1) Synthetic Precipitation Leaching Procedure (SPLP using unbuffered acidic solution) was used as this method was used in the earlier study and allowed comparison with the AECOM data; (2) Australian Standard Leaching Procedure (ASLP) using both Deionized (DI) water and buffered alkaline solution was selected as this method is recommended in the PFAS National Environmental Management Plan (NEMP) for landfill acceptance characterisation; (3) Multiple Extraction Protocol (MEP) which involves repeated leaching events in sequence using a buffered alkaline solution was selected as this is often used as a surrogate measurement to estimate the long-term performance of stabilised soils; and (4) Leaching Environmental Assessment Framework Method 1313 (LEAF 1313) to assess leaching under a wider range of environmentally relevant pH conditions (4 to 10.5).

Key results, expressed as percent reduction in PFAS leaching, are summarised in **Figures 4.2** and **4.3**. While some treatments retained high effectiveness four years post-treatment, others showed a marked decline in performance over time. First-tier sorbents—A, C, and D (at 5% dose) and E (at 2% dose)—consistently achieved >95% reduction in PFHxS, PFOS, and PFOA leaching across both soils in SPLP and ASLP tests. Based on detailed assessment 4-years post-treatment (**Figure 4.3**), these sorbents also exhibited minimal changes in leachability following ageing and remained effective across a wide pH range (4–10.5), as demonstrated by LEAF testing.



Time	Soil	A-5	B-6	C-5	D-5	E-2	F-1	G-5	H-4	I-6
1-week	AACO	🟩	🟩	🟦	🟩	🟩	🟦	🟩	🟩	🟩
	WLM	🟩	🟩	🟦	🟩	🟩	🟨	🟩	🟩	🟩
4-years	AACO	🟩	🟦	🟩	🟩	🟦	🟦	🟦	🟩	🟩
	WLM	🟩	🟨	🟩	🟩	🟩	🟨	🟨	🟦	🟦
7-years	AACO	🟩	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟦
	WLM	🟩	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟩

Figure 4.2 Reductions in leaching of PFAS (PFHxS, PFOS and PFOA) from different sorbent amendments as assessed 1-week, 4-years, and 7-years post treatment following SPLP. Category 1: % reduction ≥95%, Category 2: % reduction 85-94%; Category 3: % reduction <85%.

Soil	Test	A-5	B-6	C-5	D-5	E-2	F-1	G-5	H-4	I-6
	SPLP	1*	2	1	1*	2$^{\#}$	2	2	1*	1
	ASLP	1*	2	1	1*	1*	2	2	1*	1
	MEP	1*	3	3$^{\#}$	1	3$^{\#}$	3	3	3	3$^{\#}$
	LEAF	3$^{\#}$	3	3$^{\#}$	2$^{\#}$	3$^{\#}$	3	3	3	3
WLM	SPLP	1*	3	1	1*	1*	3	3	2	2
	ASLP	1*	3	1	1*	1*	3	3	2	2
	MEP	1	3	1	1	1	3	3	2	2
	LEAF	1	3	1	1	1	3	3$^{\#}$	2	1

Sorbents were categorised as follows: **Category 1**: % reduction ≥95%; **Category 2**: % reduction 85-94%; **Category 3**: % reduction <85% for at least 1 of the three target compounds (PFHxS, PFOS and PFOA). For MEP, % reduction was based on cumulative concentrations leached. For LEAF, % reduction was based on average percentage reductions at 5 different pH values.
Sorbents that were able to exceed 99% reduction are noted by an asterisk "*".

$^{\#}$ Categorised accordingly because of 1 compound; otherwise, sorbent amendment would fit in the higher tier of category of performance.

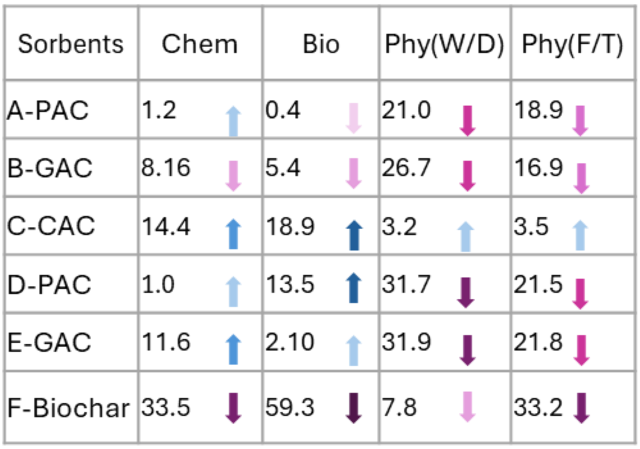
Figure 4.3 Categorisation of sorbent amendments across all leaching tests and Swartz Barracks and WLM soils as assessed four years post-treatment.

These high-performing sorbents were subsequently identified as activated carbon-based products sourced from different suppliers. The lowest-performing sorbents were biochars. Categorisation of activated carbon-based sorbents as top performers were corroborated by results from a 2023 evaluation conducted seven years post-treatment (Navarro and Davis 2023). In the same study, assessments showed that the performance of some treatments (G-5, H-4, and I-6) improved with higher treatment moisture content, underscoring the critical role of moisture in enhancing treatment performance. In line with these findings, batch testing of soils under long-term storage should incorporate wet-dry cycles to better simulate incubation processes occurring under field conditions.

Effectiveness of soil stabilisation treatments under normal and accelerated aging conditions (Navarro et al. 2025a). To better understand the factors and mechanisms influencing treatment longevity, follow-up investigations assessed ageing effects under both ambient and accelerated conditions. Soils from RAAF Base Pearce and RAAF Base Edinburgh were amended with five activated carbon (AC) products (1% w/w), comprising two powdered (PAC), two granular (GAC), and one colloidal (CAC) material sourced from different suppliers. A biochar was included as a negative control, based on the limited performance observed in the 2021 study. Natural aging involved storage of treated and untreated soils in a glasshouse (15–50 °C) and controlled moisture cycles to simulate environmental wet-dry conditions over time. Accelerated aging involved promoting chemical, physical, and biological processes compared to natural conditions and was used as a means of assessing long-term performance of the different sorbent treatments.

Results were consistent with the results from the Navarro et al. (2021b, 2021c) study. PAC sorbents were the most effective in reducing PFAS leachability by up to 98% after 1-year of incubation. PAC also reduced the release of PFAS precursors, as indicated by total oxidisable precursor assay results comparing leachates from treated and untreated soils. This demonstrates the capacity of PAC to immobilise a broader suite of PFAS than typically monitored. Performance of the AC sorbents generally improved over time during the 1-year incubation, with the exception of biochar treatments, which showed declining performance. These trends were consistent across both aggressive (ASLP) and static (saturate-and-spin) leaching assessments. Some differences were observed between soil types (clayey vs sandy) that affected the kinetics of PFAS sorption to sorbent and resulting PFAS reductions.

Among all the accelerated aging tests, physical aging (wetting to saturation followed by drying at 70°C for 21 cycles) had the greatest impact on sorbent performance – regardless of whether sorbents were aged before or after mixing with soil. This treatment significantly reduced the sorbent's specific surface area (**Figure 4.4**), increased oxygen content, and mostly remained positively charged (zeta potential) across a range of pH values (2-10). In terms of PFAS reductions, the most pronounced impact was observed for PFOS, followed by short-chain PFAS, particularly PFCAs with low partitioning coefficients (K_d). While sorbent origin had minimal influence under natural aging, differences became more apparent under accelerated aging conditions. For example, coal-based sorbents were generally more resistant to performance loss than nut- or shell-based alternatives. Although both PAC sorbents performed well under natural aging, the coal-based sorbent may offer greater long-term effectiveness.



Sorbents	Chem	Bio	Phy(W/D)	Phy(F/T)
A-PAC	1.2 ↑	0.4 ↓	21.0 ↓	18.9 ↓
B-GAC	8.16 ↓	5.4 ↓	26.7 ↓	16.9 ↓
C-CAC	14.4 ↑	18.9 ↑	3.2 ↑	3.5 ↑
D-PAC	1.0 ↑	13.5 ↑	31.7 ↓	21.5 ↓
E-GAC	11.6 ↑	2.10 ↑	31.9 ↓	21.8 ↓
F-Biochar	33.5 ↓	59.3 ↓	7.8 ↓	33.2 ↓

Figure 4.4. Changes in the surface area of individual sorbents subjected to different aging methods. Blue arrows indicate an increase in surface area, while pink arrows denote a decrease. The colour gradient of the arrows represents the extent of increase or reduction in surface area.

Overall, these findings strengthen the case for using AC-based amendments to treat PFAS-contaminated soils at Defence sites. Under all the conditions tested, PAC was still the most effective among all sorbents, followed by CAC and GAC, while the biochar used was largely ineffective. However, for sites where short-chain PFAS are a priority, alternative sorbents or combined strategies should be evaluated for suitability and effectiveness. Given the challenges of long-term bench trials, this study highlights the potential of accelerated aging, particularly physical aging, as a conservative approach to assess treatment durability under harsh conditions and to identify sorbents with superior long-term stability.

4.2.2 Shallow Emplacement of Amendments Subjected to Controlled Rainfall

Building on earlier work by Ventia and the University of Adelaide using laboratory-simulated rainfall, the effectiveness of *in situ* GAC application was evaluated for reducing PFAS release through infiltration and runoff (Navarro, Kabiri, 2025). It focused on two key aspects: (1) assessing treatment longevity under repeated wetting and drying cycles by progressively increasing intervals between rainfall events; and (2) examining the influence of groundcover (perennial ryegrass) on PFAS transport via soil particulates, given prior evidence that suspended solids can carry PFAS (Richardson et al., 2022). GAC was applied at a 1% amendment rate directly onto clayey (RAAF Base Edinburgh) and sandy (RAAF Base Pearce) soils, with some trays later covered with grass. Each treatment received five simulated 1-in-100-year rainfall events over the course of six to eleven months, allowing for natural drying between events to mimic field-relevant moisture cycling.

The 1% GAC treatment substantially reduced PFAS concentrations in both runoff and infiltration over time in both soils, indicating its effectiveness in limiting PFAS mobility. GAC alone effectively reduced the sum of PFAS concentrations by up to 97% in runoff and up to 99% in infiltration, even after multiple wetting and drying periods. In the presence of groundcover, treatment achieved >99% reduction in PFAS concentration in runoff and infiltrates with plant effects becoming more pronounced after 60 days (**Figure 4.5**). Particulates recovered from runoff and infiltrates in untreated soils contained PFAS, particularly long-chain PFSAs and PFCAs, indicating that mobilised particles can act as carriers of PFAS. Plant cover significantly reduced the mass of particulates transported via runoff and infiltration. In D-EDN soil, this effect became apparent after root systems were well-established (from Day 30 onward), whereas in D-PEA soil, reductions were observed consistently throughout the study. Consistent with results from Task 4B (section 4.2.3), ryegrass accumulated PFAS in untreated soils. Treatment with GAC did reduce PFAS uptake in plants across all compounds. and soils, but some short chain compounds (PFBA) remained bioavailable.

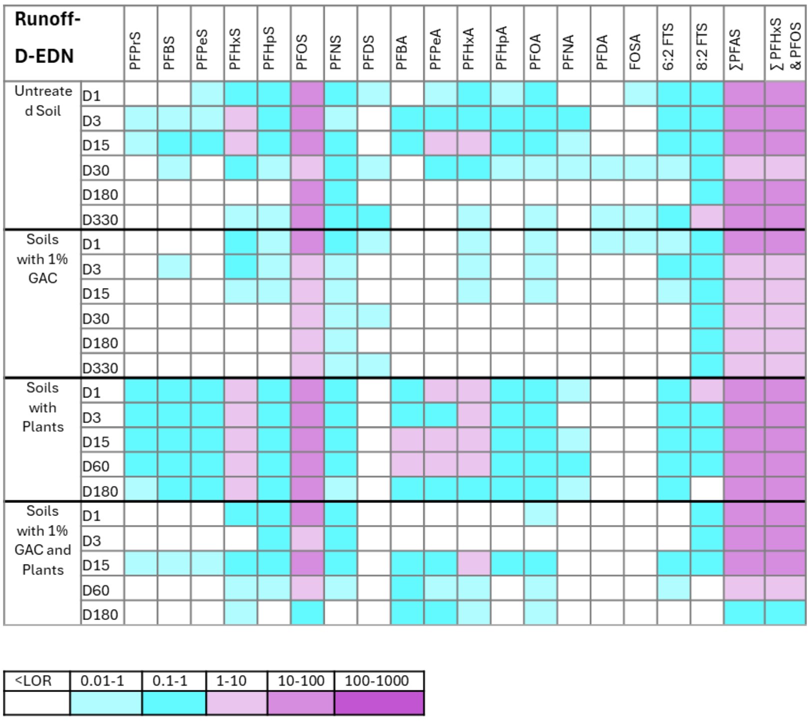


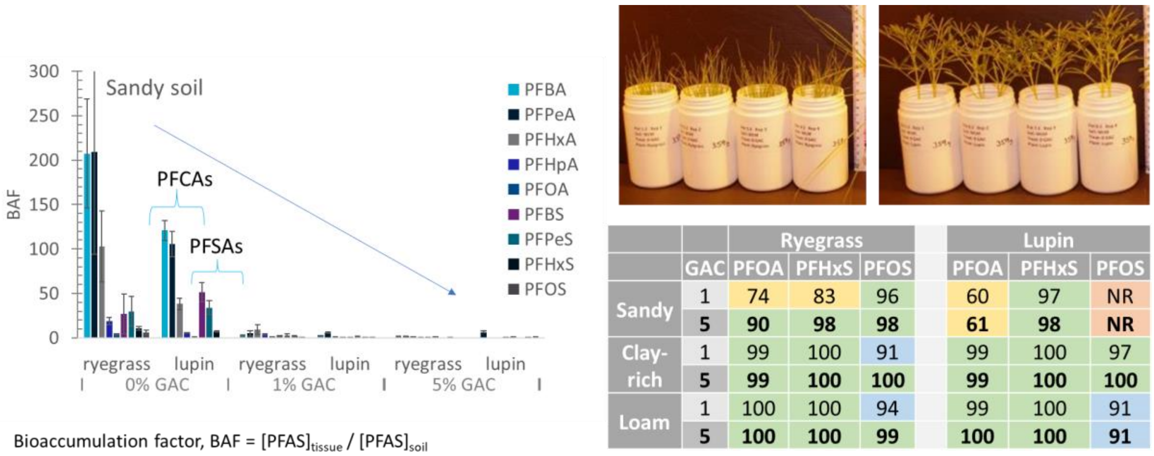
Figure 4.5. Heat map of PFAS concentrations (µg/L) in runoff collected from D-EDN.

These results suggest that shallow *in situ* GAC treatment with plant groundcover, could be used to enhance PFAS mitigation by reducing soil erosion and limiting the movement of PFAS-bound particles. This approach will be beneficial in clay-rich or fine-textured soils, where high runoff and low infiltration can lead to significant PFAS transport. Though groundcover initially increased PFAS concentrations in runoff in this soil type, it could be suitable as a long-term remediation solution. Plant/root establishment will be critical in ensuring the plants are able to effectively stabilise the soil, minimise erosion, and reduce PFAS transport via particulate-bound runoff. Together with earlier work (Richardson et al., 2022), this study strengthens the evidence for both *in situ* and ex-situ GAC applications as effective approaches to reduce PFAS mobilisation, with and without vegetation. It offers a practical option for Defence and other stakeholders managing low-to-medium PFAS contamination in surface soils, especially where excavation is impractical.

4.2.3 Bioavailability in Stabilised Soils

Assessing the bioavailability of PFAS in treated soils is essential when considering their potential reuse in environments where ecological exposure may occur. To address this, two activities were undertaken as described below (Navarro et al. 2022; Navarro et al. 2025c; Navarro et al. 2025d).

Bioavailability of PFAS in stabilised soils to plants and earthworms (Navarro et al. 2022). This investigation was undertaken of PFAS uptake in two non-edible plant species (ryegrass and lupins) and earthworms, exposed for 28 days to GAC-treated (1% and/or 5%) and untreated WLM (sandy), Swartz Barracks (clay-rich), and EDN (loam) soils. Results showed that treated soils were generally able to reduce the availability of PFAS to both plants and earthworms, with higher reductions observed at higher (5%) amendment rates (**Figure 4.6**). Treated soils were also able to support growth of plants albeit ryegrass appeared to be more sensitive to the application of GAC. In PFAS-free soils, ryegrass growth was significantly reduced in sandy soils amended with GAC, suggesting nutrient competition or sorption effects. In contrast, lupins were less affected, likely due to their ability to fix atmospheric nitrogen and store it in their roots. Addition of nutrients can improve plant growth (i.e., increased biomass) without increasing the uptake of PFAS in the treated soils. Improved growth could be beneficial to reduce other impacts (e.g., soil run-off from lack of vegetative cover, section 4.2.2) from shallow emplacement of treated soils. The potential for PFAS mobilisation due to the plants' root environment which could be due to plant root exudates, was evident in WLM soil treated with 1% GAC with ryegrass where $\frac{\text{PFAS in plant PW}}{\text{PFAS in no plant PW}} \gg 1$. This suggested that in sandy soils with lower sorbent rates, plant activity could remobilise previously stabilised PFAS. In the case of earthworms, survival was not impacted over the 28-day exposure period; however, GAC applied at 5% appeared to reduce cocoon production across both soil types.

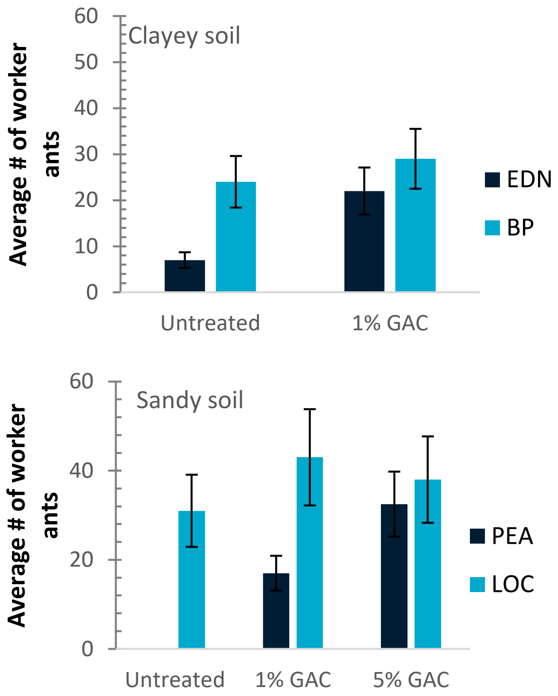


Bioaccumulation factor, BAF = $[\text{PFAS}]_{\text{tissue}} / [\text{PFAS}]_{\text{soil}}$

		Ryegrass				Lupin		
	GAC	PFOA	PFHxS	PFOS		PFOA	PFHxS	PFOS
Sandy	1	74	83	96		60	97	NR
	5	**90**	**98**	**98**		**61**	**98**	**NR**
Clay-rich	1	99	100	91		99	100	97
	5	**99**	**100**	**100**		**99**	**100**	**100**
Loam	1	100	100	94		99	100	91
	5	**100**	**100**	**99**		**100**	**100**	**91**

Figure 4.6 Plant bioaccumulation factors from untreated and treated soils, and equivalent reductions in bioavailability for PFOS, PFHxS and PFOA. Photos show ryegrass and lupins grown in WLM soil.

Bioavailability of PFAS in stabilised soils to ants (Navarro et al. 2025c, Navarro et al. 2025d). This study focused on ants due to their ecological relevance in semi-arid and arid regions. Tropical queen fire ants were allowed to colonise GAC-treated (1% and 5%) and untreated EDN (clay-loam) and PEA (sandy) soils over a two-month period. While GAC presence did not affect colony size, reduced colony growth was observed in untreated PFAS-contaminated soils. Similar to findings with plants and earthworms, GAC at both 1% and 5% reduced PFAS bioavailability to ants and helped mitigate impacts on colony development (**Figure 4.7**).



	Tropical Fire ants		
	PFOA	PFHxS	PFOS
PEA @1%	100	99.7	95.7
PEA @5%	100	99.9	99.8
EDN @1%	100	96.7	57.2

Figure 4.7 Worker ant abundance in untreated and treated soils, alongside reductions in PFOS, PFHxS, and PFOA bioavailability. The photo shows two queen ants on the soil surface, with visible food and ant trails indicating colony activity.

Overall, GAC applied at 1 and 5% reduced the bioavailability of PFAS to plants, earthworms, and ants. GAC not only reduced PFAS leachability in the soils tested, but also PFAS bioavailability across the taxa, with greater reductions observed at 5% sorbent rate.

4.3 Outcomes and benefits

The studies for this theme indicated that different forms of activated carbon can greatly reduce the mobility of PFAS from soil at amendment rates appropriate for field application (1 to 5%), based on laboratory assessments simulating a range of leaching conditions. This effect was retained for over seven years in soil stored under laboratory conditions. In general, more finely divided (powdered) activated carbon had a greater effect at low application rates (1%) than granular activated carbon. This result played an important part in achieving confidence for field implementation of soil stabilisation, which has now occurred at several Defence sites.

Studies of uptake by soil organisms showed that activated carbon greatly reduces PFAS uptake into plants, earthworms and ants and diminished evidence of toxicity from PFAS, especially in the ants. The presence of activated carbon caused lower plant growth and worm reproduction, which was assumed to be due to the activated carbon also immobilising nutrients. Adding nutrients overcame this issue for plants but was not tested for worms. This information further supported the value of this approach for managing PFAS in soil, but suggested care might be taken if surface application is to be adopted in future. The studies were useful in supporting the approach generally adopted by Defence of re-emplacement below the root zone of plants.

Studies aimed at understanding shallow implementation indicated that maintaining plant cover provides better overall impact than activated carbon alone, with improving performance over the time tested (6-11 months).

Overall, the studies for this theme have played an important part in demonstrating the effectiveness of this remedial approach. Most notably on choice of sorbent or amendment rate (noting not all available sorbents were tested) and sensible limits on application approaches. This has resulted in the treatment of large volumes of soil in areas (and at times) when other disposal options were not available or practical. This has allowed Defence to move quickly to implement effective remediation of source areas whilst other technologies were in development.

5 Theme 4: Laboratory/Field Methods for Understanding PFAS Mobility

5.1 Motivation and questions addressed

A key concern at commencement of the CRP was the lack of rapid and reliable methods to estimate and measure the leaching and mobility of PFAS in field soils and other solid materials such as concrete. To date, most methods used for PFAS rely on aggressive extraction approaches that maximise the PFAS extracted from the soil. This approach has been typically used for characterising soil or concrete to send to landfill, to know what type of landfill is appropriate (e.g. a hazardous waste facility versus general solid waste). Such methods are useful for this purpose, as a conservative measure is needed of all the substances that may leach out over a very long period of time. For some purposes, however, it is more useful to understand the concentrations leaching out at a point of time. This is helpful when comparing against a concentration-based guideline value, or when assessing risks to land users or nearby ecology from reusing materials. The lack of suitable point-in-time leaching methods being commercially available means that projects have resorted to the more conservative batch processes. This can add massively to costs by overestimating the volume of materials needing disposal, or a higher level of treatment/disposal, or even completely rule out reuse options.

In Theme 4, the CRP advanced and established new laboratory and field methods that better represented field conditions. A focus was on attempting to develop a method that was relatively simple and could be implemented readily by commercial laboratories. Efforts were also made to better understand field measurements for assessing PFAS movement through the soil (suction lysimeters) that have been in Defence investigations. Results from the field measurements were useful as a guide of what the lab measurements should be able to replicate. This is depicted in part in **Figure 5.1**.

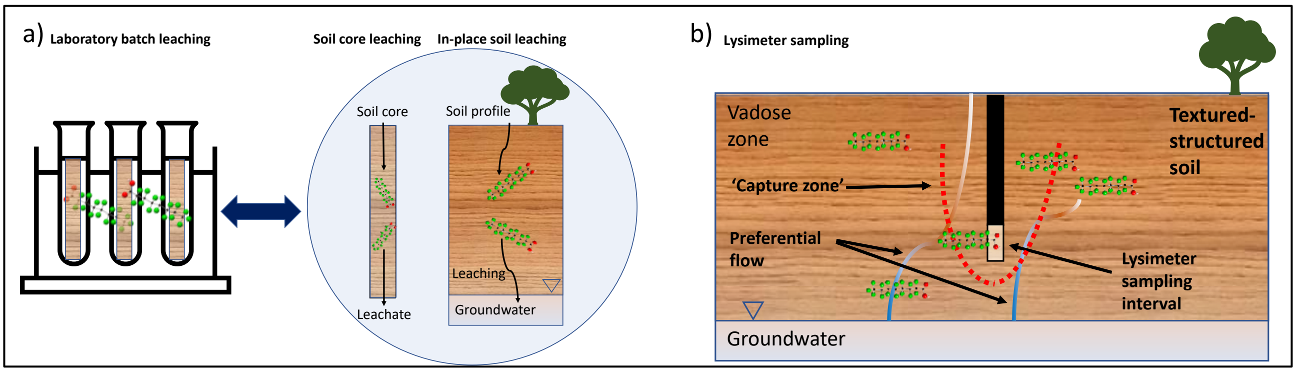


Figure 5.1 Schematic depicting the scales of measurement that were compared to represent PFAS leaching from source zone soils towards groundwater, with a focus on a) laboratory equivalence and b) suction lysimeter deployment.

Key questions to be answered included:

- What is a reasonable test of PFAS leachability from soils?

- What laboratory leaching methods best represent field conditions?
- How much PFAS continues to leach out of source area soils?

To address these questions, a new soil batch laboratory method was developed and tested against field measurements and existing leaching methods. Lysimeter investigations allowed further comparison of laboratory methods to field measurements of PFAS pore water concentrations in vadose zone soils (**Figure 5.1**).

5.2 Approach, methodology and key results

Using a variety of methods, the approach was to compare leachate and pore water PFAS concentrations from field and laboratory investigations to indicate which method may best represent PFAS behaviours in soil. A new laboratory soil leaching method was validated and further applied to PFAS leaching from concrete.

5.2.1 Soil Leaching Method Comparison

Details are in Slee et al. (2021) and Rayner et al. (2022a). Thirty-seven field soils from five sites were assessed for PFAS leaching using new and existing laboratory leaching methods to provide alternative methods better reflecting PFAS risks posed by its leaching and movement. Dominant PFAS in the field soils were PFOS, PFHxS and PFHxA. Leaching from intact soil cores (Exp 1) was taken to reflect field conditions (see **Figure 5.1a**). These were compared to two new laboratory batch tests, static leach (Exp 2) and tumble leach (Exp 3), and two standard approaches; ASLP (Exp 4) and LEAF (Exp 5) (**Figure 5.1a**). The tests varied in terms of liquid:soil ratio, tumbling time and pH of the starting solution, with LEAF-1313 conducted across seven pH values (2−12).

Key results across the tests are seen in **Figure 5.2**. The PFAS mass leached as a fraction of the total increased such that:

- Soil core leaching (27 %) < saturate-spin (30 %) < saturate-tumble-spin (65 %) ≤ LEAF-1313 (65 to 88 % at pH 5–9) < ASLP (90 %).
- As a fraction of individual PFAS compounds in leachate compared with soil, the shorter chain PFAS (e.g., PFBA) were higher in the leachate in all tests.
- Across all tests, the static-leach test (Exp 2) most closely represented intact soil core leaching (Exp 1) (**Figure 5.2**) and therefore was shown to potentially provide a measure more analogous of *in situ* soil leaching at field sites.

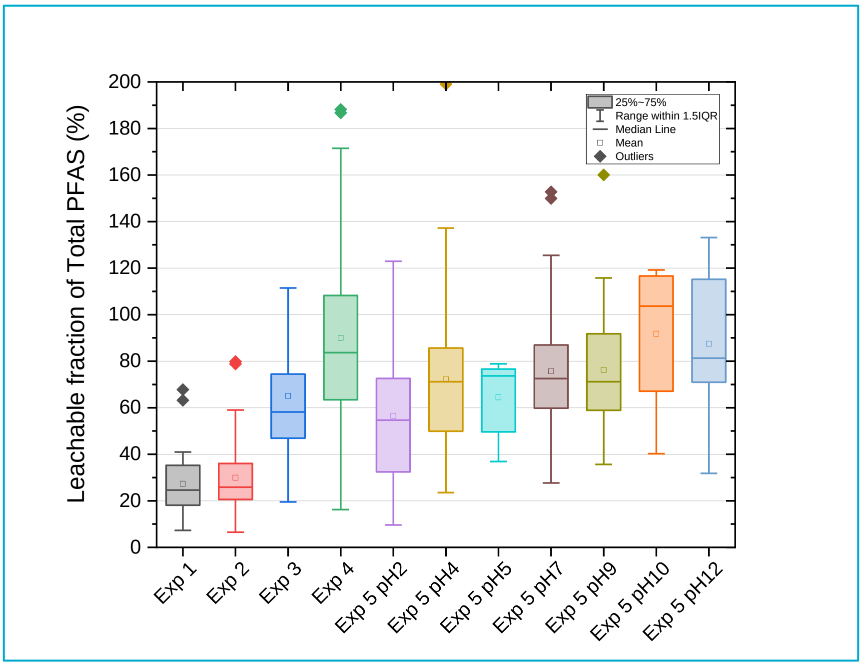


Figure 5.2 PFAS leachate concentrations from Exp 1 to 5 expressed as a fraction of total PFAS extracted. Descriptive statistics for the box plot are shown in the legend.

5.2.2 Lysimeters for Soil PFAS Monitoring

Details are in Rayner et al. (2022b; 2024). Suction lysimeters are designed to be installed in unsaturated soil profiles to recover soil pore water samples for analysis of pore water chemistry. Lysimeter pore water concentrations can provide complementary data to soil core or groundwater concentration measurements in assessing contaminant management options at sites. Pore water concentrations can also provide early notification of the potential leaching of PFAS through soil towards groundwater and may be usable in measuring reduced contaminant migration through soil pore water subsequent to soil source zone remediation activities.

Over a six-month period in 2020, forty-seven suction lysimeters were installed across six Defence sites (HMAS Albatross, RAAF Base Parce, RAAF Base Richmond, RAAF Base Townsville, RAAF Base Wagga, RAAF Base Darwin) and evaluated as to their performance in measuring PFAS pore water concentrations. A range of rainfall and climatic conditions, soil types and depths of installation, and soil and pore water concentrations were investigated.

Key was understanding the comparative performance of lysimeters with alternate laboratory leaching methods as described in section 5.2.1. As shown in **Figure 5.3**, broadly, longer chain (higher K_d) PFAS behaved differently to shorter chain (lower K_d) PFAS. In addition, some sulfonates showed greater sorption than their corresponding carboxylates, but this also seemed to be more prevalent with longer chain equivalents species. Exceptions did appear in the data (e.g., PFNA). Of the 15 PFAS shown, most showed a leachable fraction in pore water from the lysimeters that was higher and in some cases many times higher (1.5 to 6 times) than from the leachable concentrations determined from ASLP or the static leach tests. Notably, contrary to this, the leachable fraction of PFOS recovered from lysimeter pore water samples (fraction <1) was less than that seen from ASLP and static leach tests (fraction >1). Some selective sampling of the compounds during sampling of the lysimeters are evident. Direct comparison requires estimation of the volume of capture from the lysimeter which will depend on soil texture and soil moisture.

Differences may also be associated with the liquid:solid ratio—with ASLP being 20:1, static being 3:1 and lysimeters being likely <0.5:1.

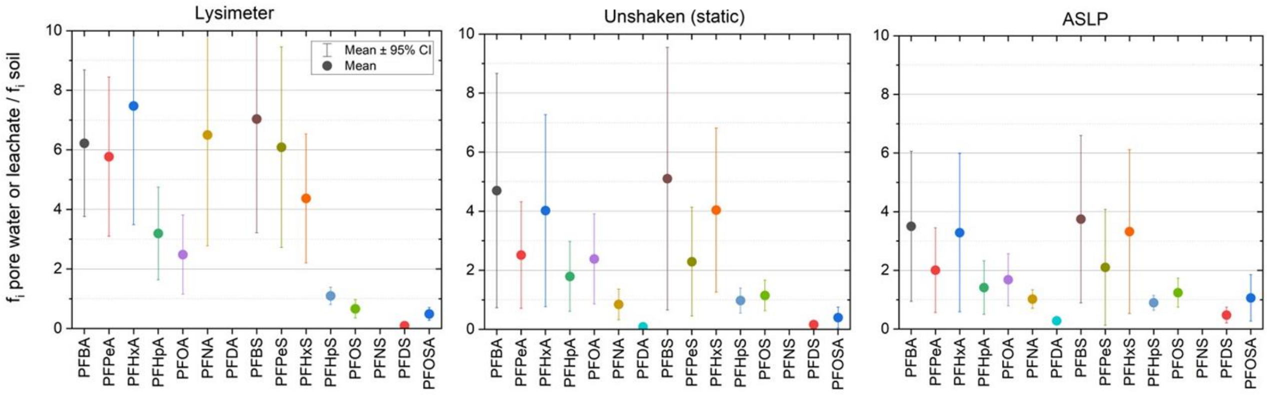


Figure 5.3 Mean fraction of the total mass of PFAS in leachate/pore water samples compared to that in soil (central dots are the means, and the vertical lines are the 95% confidence interval). Centre – Static leach method; Right - ASLP leachate data (data for both images are from Rayner et al. 2022). Left - Lysimeter pore water data. No data is presented for PFNS as it was not detectable in both soil and pore water samples

Soil pore water concentrations were compared to soil core concentrations, and some variability was observed. Lysimeters are seen as an attractive approach and a valid line of evidence for assessing migration of soil PFAS to groundwater. It is a method with some residual challenges but challenges that can be addressed with focused efforts to do so.

5.2.3 Validating the Static Leaching Method

The static leach method developed and compared to other leaching methods as described in section 5.2.1, was further validated for commercial laboratory use and adoption for leaching PFAS from soils and concrete (Rayner et al., 2025).

For Soils: To validate the soil static leach method, five different soils from Defence sites (RAAF Base Edinburgh, Albury Wodonga Military Area - Bandiana, RAAF Base Pearce, RAAF Base Tindal, RAAF Base Williamtown) were sourced and evaluated using the static leach method in comparison to ASLP and to centrifuge extraction of pore water. Up to seven repeats per soil type were undertaken for the static leach, and three repeats for each was undertaken for ASLP. The leachable fraction of total PFAS for all soils for all leachate methods is presented in **Figure 5.4**. For all soils ASLP leached more PFAS mass than the static method with the leached amount for each method being consistent across soil types.

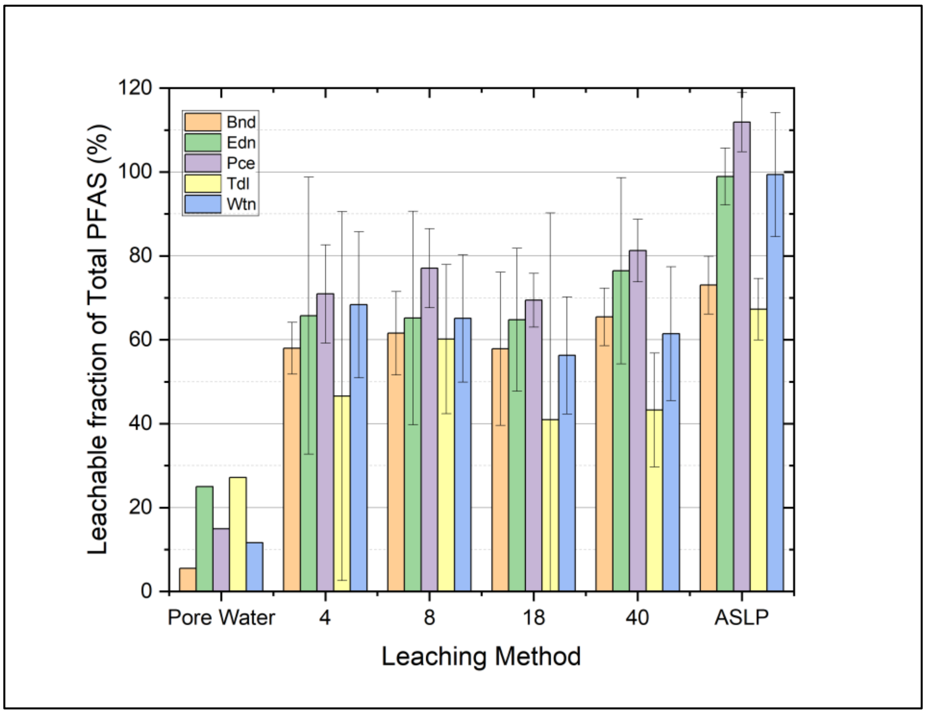


Figure 5.4 Leachable fraction of total PFAS (sum of 33 compounds). The leachable fraction is the mass of PFAS in the leachate as a fraction of the total mass in the soil.

Notably, there is a strong linear relationship between the PFAS concentrations in the soil and PFAS concentrations in the leachate from all 3 methods (**Figure 5.5**). The concentration in the leachate is determined by the concentration in the soil, the liquid: soil ratio and the effectiveness of transfer of PFAS from the soil into the liquid phase (see ranges in **Table 5.1**). If all the PFAS mass in the soil enters the liquid phase, then the slope of the line is the theoretical soil:liquid ratio reflected in the leaching method used. The ratio between the measured slope and the slope predicted if all the mass enters the solution phase (i.e. the soil:liquid ratio) approximates the leachable fraction.

In the case of ASLP, the slope is c. 0.05 which is very close to the 20:1 liquid:soil ratio used for ASLP indicating that almost all the PFAS mass in the soil entered the liquid phase. Conversely for the pore water method, only around 17% of the total PFAS mass in the soil entered the liquid phase. This seems counter intuitive given the high concentrations in the leachate, but it needs to be considered that in these pore water tests between 600 to 800 g of soil was used and between 100 to 230 mL of water added.

Table 5.1 Liquid:soil ratios and % leached for the 3 methods applied to soil leaching tests. The Pore Water (PW) liquid:soil ratio is an average across all 5 soils as the amount of water added depends on the soil texture.

Method	Liquid:Soil ratio	Soil:Liquid ratio	slope of line	Effective Liquid: Soil ratio	Effective % leached	Average % leached from all data measured
Pore Water	0.20	5.00	0.83	1.21	16.6	16.8
Static	3.00	0.33	0.23	4.41	68.1	62.8
ASLP	20.00	0.05	0.05	20.08	99.6	90.1

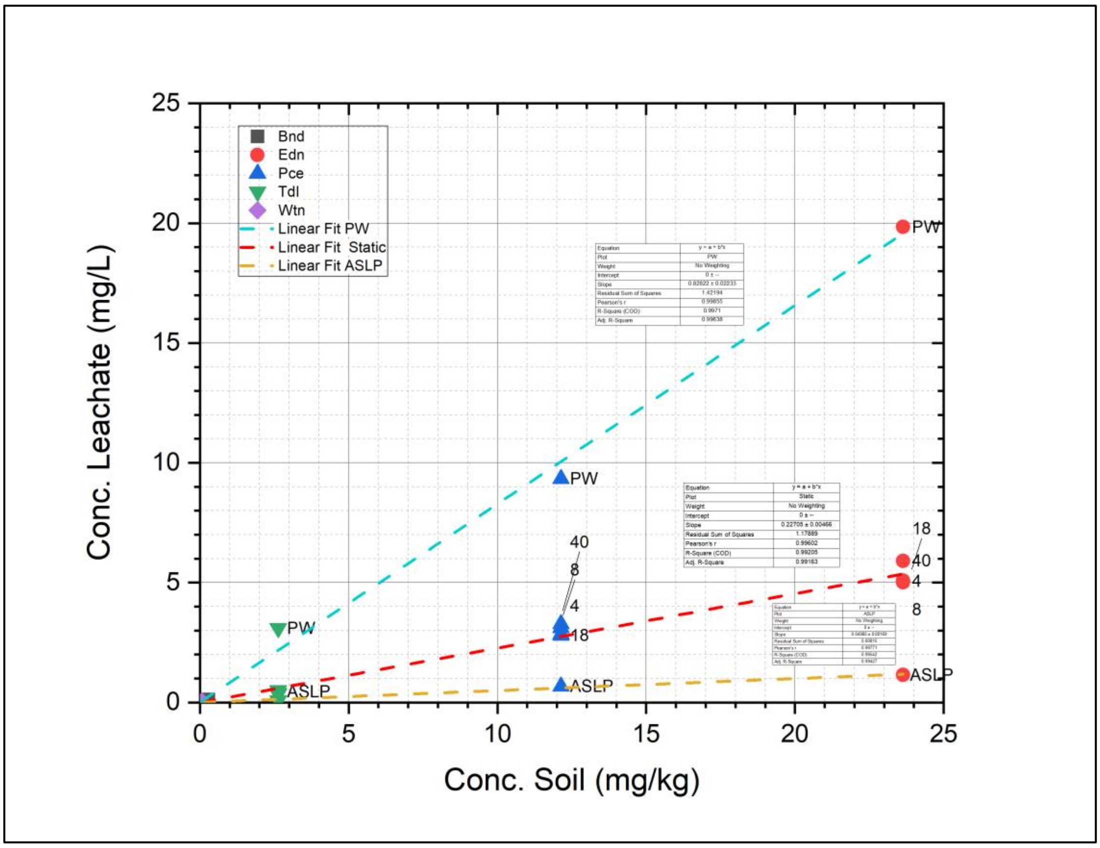


Figure 5.5 Summed PFAS concentration in soil vs summed PFAS concentration in 3 leaching methods: static leachate (each cluster of symbols for static leachate represents 4, 8, 18 and 40 hours), ASLP and Pore Water (PW). A linear fit to each method is shown along with the fitting parameters.

Whilst the static test better represents *in situ* soil leaching compared to ASLP, it produces a higher concentration upon leaching than ASLP (**Figure 5.5**). Note that the centrifuged pore water yielded a higher concentration again, but this water was extracted under significant suction and as such would not be readily mobile in the soil.

For Concrete: The static leach method was also further evaluated for PFAS in concrete. Four different concrete core and rubble materials from Defence sites were sourced and evaluated using the static leach method in comparison to ASLP (Lavarack Barracks, RAAF Base Tindal, Albury Wodonga Military Area - Bandiana, Blamey Barracks – RAAF Base Wagga Wagga). Three repeats were undertaken per concrete type for both leaching tests. Concentration ranges for Total and TOPA are shown in **Figure 5.6**, indicating in some cases considerable differences across the two analysis methods.

Unlike the leaching tests for soils, those for concrete typically do not yield a strong linear trend between the leachate concentration and the total concrete concentration. Although, ASLP was approximately linear. Concrete size ranges created variable leached fractions over the different time intervals. Preparation of samples and sample size would need to be standardised. Reuse of concrete at variable sizes would need greater consideration.

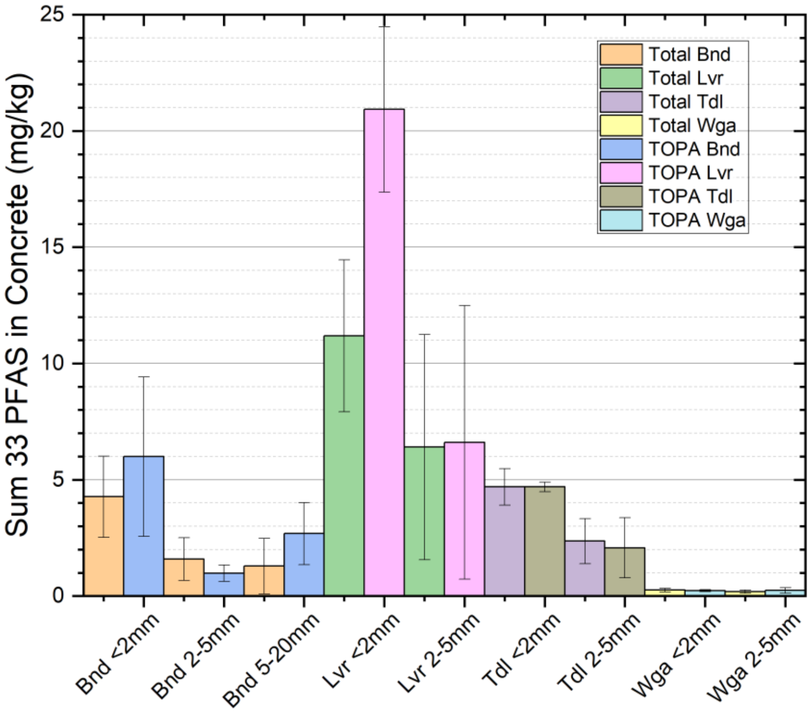


Figure 5.6. Sum of 33 PFAS concentrations in concrete showing both Total and TOPA analysis with particle size.

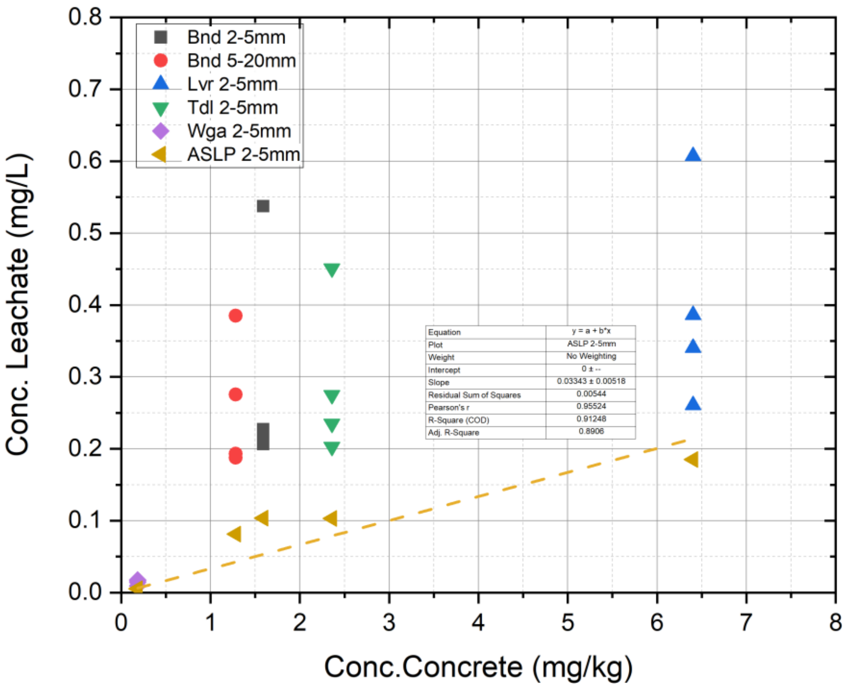


Figure 5.7 Summed PFAS concentration in concrete vs summed PFAS concentration in static leachate and ASLP. Each cluster of symbols for static leachate represents 4, 8, 18 and 40 hours. ASLP results are also shown. ASLP data has a linear fit.

5.3 Outcomes and benefits

New field and laboratory methods were established and tested for broader adoption. The field method (suction lysimeters) was shown to have promise in direct measurement of soil pore water PFAS concentrations and may be generally preferred to modelling approaches for estimating PFAS movement which have considerable uncertainties.

A laboratory leaching method was developed which more closely reflected PFAS leachability in field testing compared to current more aggressive leach test methods. When promoted and standardised, it offers a practical laboratory-based method for PFAS leaching from *in situ* soils and concrete that could be adopted by commercial laboratories for broader assessment. For soils it offers a method applicable to undisturbed soils, but also to soils with amendments such as addition of biosolids to soils for soil beneficiation.

Intercomparison across field measurements using lysimeters and laboratory batch measurements brings confidence to PFAS investigations and remediation decisions. Broader application of the soil batch method developed for this theme is being adopted by NMI with demand for use of the method from contaminated site consultants and auditors. Defence is likely to get further benefit from the outcomes of this theme if the developed approach is incorporated into future versions of the PFAS NEMP.

6 Key Outcomes and the Future

6.1 Summary of outcomes

The Defence-CSIRO PFAS Research Program concluded in 2025 with significant outcomes, presented below.

- **A soil and groundwater modelling framework tailored to PFAS behaviour.** It showed the importance of climate drivers in comparison to PFAS retention at the air-water interface in vadose zones for water and PFAS movement. Evapo-concentration was shown to be critical in semi-arid or Mediterranean climates. Application at two Defence sites demonstrated the framework's ability to distinguish and forecast the effectiveness of different remedial options, including soil removal/treatment and groundwater pumping strategies.
- **Determination of the variability and leachability of PFAS in concrete and asphalt.** Expected leachable concentration ranges, that might be regulated, were quantified and validated against field-based investigations. Sealants for managing PFAS-impacted concrete were evaluated and trialled at both laboratory and field scales to assess their effectiveness in reducing PFAS release.
- **Identification and quantification of the value and effectiveness of carbon-based (vs other types of) amendments in stabilising PFAS in soils.** Across nine amendment types, the effectiveness over seven years was quantified, and subsequently with aged stabilising amendments. GAC reduced the bioavailability of PFAS to plants, earthworms and ants, the latter particularly relevant to Australia's semi-arid environments.
- **A new laboratory leaching method, that was more representative of PFAS movement in soils and concrete.** The static batch method was developed and validated by comparison with standard measurements and in-field sampling. A framework for advancing the use of lysimeters for measurement of PFAS concentrations in vadose zone soil pore water was also proposed.

Additionally, the CRP delivered outcomes that were disseminated nationally and internationally, and enabled engagement and future R&D that will bring additional benefits to Australia and Defence in management of PFAS. For example:

- Upskilling and knowledge advancement across Australian researchers, government agencies, consultants and contractors.
- Input to other Commonwealth agencies in shaping their approach to PFAS. For example, The Department of Infrastructure, Transport, Regional Development, Communications, Sport and the Arts used CRP outcomes to inform upcoming investigations of airports and associated facilities nation-wide. DCCEEW used insights to progress considerations around future policy and R&D needs.
- Presentations to the National Chemicals Working Group contributed to the development of the updated PFAS NEMP 3.0.

- Success at securing SERDP projects on PFAS release from concrete and asphalt, and management via use of sealants. It also enabled competitive SERDP and ESTCP scopes on PFAS transformation in soils and the longevity of effectiveness of soil stabilisation at US field sites. Engagement with US-based researchers and US Defense will continue to deliver data, technology, tools and know-how back to Defence and Australia for dissemination and use.
- Journal publications (see reference list) from the CRP raised the credentials of Australian research and fostered collaboration and knowledge exchange with international research groups, US military agencies, and regulatory authorities.

6.2 Reflection and the future

Partnering across the two Commonwealth agencies (Defence and CSIRO) has enabled a strong focus on delivering the best available science to underpin practical, evidence-based outcomes for PFAS management across the Defence estate. When the CRP began seven years ago, the national knowledge base on PFAS fate, exposure and remediation was limited. The CRP has since made substantial progress in closing critical knowledge and technology gaps and providing Defence with tools, data and confidence to make informed decisions.

The Program also provides a model for future partnerships whereby scientific knowledge is scarce and uncertainty constrains effective decision-making. Globally, there are many such challenges that require this type of coordinated, science-enabled approach. In the area of waste and contaminant management, a compelling example is the aspiration for reuse of materials and waste in our circular economy, but where reuse materials and waste entrain chemicals with uncertain risk. Addressing these complexities will increasingly require the kind of integrated, cross-agency collaboration exemplified by the CRP.

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Appendix 1: Researchers that contributed

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Dr Rai Kookana	CSIRO	Co-Director and researcher
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Mr John Rayner	CSIRO	Research Lead – Theme 4
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Dr Joanne Vanderzalm	CSIRO	Researcher – Theme 2
Dr Michael Donn	CSIRO	Researcher – Theme 2
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