



PATTLE DELAMORE PARTNERS LTD

RNZAF Base Ohakea PFAS Investigation: Comprehensive Site Investigation Report

New Zealand Defence Force

solutions for your environment



RNZAF Base Ohakea PFAS Investigation: Comprehensive Site Investigation Report

• Prepared for

New Zealand Defence Force

• August 2019



PATTLE DELAMORE PARTNERS LTD
Level 4, PDP House
235 Broadway, Newmarket, Auckland 1023
PO Box 9528, Auckland 1149, New Zealand

Tel +64 9 523 6900 Fax +64 9 523 6901
Website <http://www.pdp.co.nz>
Auckland Tauranga Wellington Christchurch



solutions for your environment

Quality Control Sheet

TITLE RNZAF Base Ohakea PFAS Investigation: Comprehensive Site Investigation Report

CLIENT New Zealand Defence Force

VERSION Final Version 2

ISSUE DATE 28 August 2019

JOB REFERENCE A02744805

SOURCE FILE(S) A02744805R001_Final_Version 2.docx

DOCUMENT CONTRIBUTORS

Prepared by

SIGNATURE

PP



Amber Simmonds

Aslan Perwick

Reviewed by

SIGNATURE

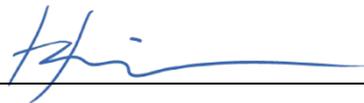


Nerena Rhodes

Andrew Rumsby

Approved by

SIGNATURE



Hamish Wilson

Limitations:

This report has been prepared by Pattle Delamore Partners Limited (PDP) on the basis of information provided by New Zealand Defence Force and [others (not directly contracted by PDP for the work), including Horizons Regional Council, Tonkin and Taylor, Coffey, Aurecon, Aecom, and Golder Associates. PDP has not independently verified the provided information and has relied upon it being accurate and sufficient for use by PDP in preparing the report. PDP accepts no responsibility for errors or omissions in, or the currency or sufficiency of, the provided information.

This report has been prepared by PDP on the specific instructions of New Zealand Defence Force for the limited purposes described in the report. PDP accepts no liability if the report is used for a different purpose or if it is used or relied on by any other person. Any such use or reliance will be solely at their own risk.

Executive Summary

New Zealand Defence Force (NZDF) has been investigating the potential for contamination of ground, water and biota associated with the use and storage of products containing per- and poly-fluoroalkyl substances (PFAS) at Royal New Zealand Air Force (RNZAF) Base Ohakea (the 'site' or 'Ohakea'). Investigations at Ohakea have identified PFAS in soil and water on base, as well as in the surrounding environment and neighbouring properties.

The sampling programme included several rounds of groundwater and surface water monitoring between 2015 and 2018. During the sampling programme 297 groundwater samples and 147 surface water samples were collected and analysed for PFAS. Sampling of soil, sediment, animal tissue and plant tissue was also conducted in various locations within the site (on-site samples) and in the vicinity of the site (off-site samples).

In summary:

- ∴ PFAS was detected in all media sampled with the exception of goat's milk.
- ∴ Exceedances of applicable guidelines and trigger values were observed for groundwater (drinking water), surface water, eggs, fish tissue and watercress.
- ∴ For all of the media tested on-site, PFOS concentrations were higher than any other PFAS compound measured.
- ∴ In biota and sediment sampled off-site, PFOS was present in greater concentrations than other PFAS compounds. However, in groundwater and surface water sampled off-site PFHxS concentrations were generally higher than PFOS concentrations.
- ∴ Comparison of the sample results on-site and off-site shows that a significant portion of the detectable PFAS mass in groundwater remains on-site. Median sum of PFOS + PFHxS measured in samples collected on-site (0.86 µg/L) is an order of magnitude higher than the median of off-site samples (0.093 µg/L). PFAS concentrations in groundwater off-site generally decreased with distance from the base with the exception of PFHxS.
- ∴ There is potentially significantly greater mass of PFAS in the unsaturated soil (i.e. soil above the water table) than in the groundwater.
- ∴ In general, PFAS concentrations in surface water decreased with increasing distance from the Base. The exception to this is the Makowhai Stream, where lower concentrations of PFOS were observed closer to the site, and the highest concentrations approximately 1.5 km downstream from the base, before decreasing again downstream. One potential mechanism for this is the influence of groundwater recharge where PFOS concentrations in the stream are highest

- ∴ The Makowhai Stream supports aquatic biota including eels (*Aguilla* sp.) and bullies (e.g. *Gobiomorphus cotidianus*), and has cultural significance for local iwi. Fish in the Makowhai Stream were shown to be accumulating PFAS in their tissue.
- ∴ Higher concentrations of PFOS were observed in the Makowhai Stream in the drier summer months and lower concentrations in the wetter winter months.
- ∴ Evidence of transformation (the breakdown of chemical from one chemical species to another) of PFAS was examined by comparing the molar concentration of PFAS from several groundwater wells extending south-west from the base.
- ∴ There is some limited evidence of transformation of PFAS compounds in the plume.

Predictions have been made for the existing and future groundwater plume with the assistance of a 3D groundwater flow and solute transport model:

- ∴ The existing plume (PFOS + PFHxS ≥ 0.06 ug/L) has an estimated area of 1100 ha to 1600 ha and has an estimated total PFOS + PFHxS mass (in solution) between 50 kg to 70 kg. An estimated 'above detection' extent has also been developed for the existing plume, with an estimated area of approximately 3600 ha. This estimate excludes other PFAS compounds. There is significant uncertainty associated with these estimates.
- ∴ Into the future, the plume is expected to continue migration and expansion before beginning a slow process of depletion. The plume is generally expected to continue advancing in the current direction of travel – generally west through south-southwest from Base Ohakea - until encountering a major groundwater discharge boundary (i.e. Rangitikei River or Makowhai Stream). Surface water is the primary receptor of the plume.
- ∴ The 'best estimate' of the likely time period for the existing plume (PFOS + PFHxS > 0.06 ug/L) to decrease below its current area is estimated to be in the order of 75 years (no retardation) to 100 years (with retardation).
- ∴ The time to halve the existing plume area (PFOS + PFHxS > 0.06 ug/L) is estimated to be greater than 100 years; best estimate 95 years (no retardation) to 125 years (with retardation).
- ∴ A maximum future extent of the plume area 'above detection' or ≥ 0.001 ug/L (PFOS + PFHxS) is estimated at approximately 4300 ha and predicted to occur > 50 years into the future. This extent should be considered as a probability extent e.g. PFOS + PFHxS detection outside of this extent is considered unlikely, but not impossible.

- ∴ A source zone removal prediction scenario was completed whereby the existing sources were assumed to have already completely depleted. This scenario is considered analogous to a 'Best Possible Case' estimate and its purpose is to provide a prediction which tends towards the fastest perceivable (but unlikely) plume depletion.
- ∴ Under this scenario plume depletion is likely to be significantly more rapid than for the 'best estimate' scenario, however plume depletion is still on the multiple decade scale.
- ∴ A longer source depletion prediction scenario where the existing sources were assumed to take longer to deplete than for the 'best estimate' scenario was also undertaken. This produced a plume with an overall similar shape and aerial extent (as per the 'best estimate'); however, plume depletion took significantly longer e.g. approximately twice the duration.

The following conclusions have been drawn following interpretation of the sample results and modelling of the groundwater plume:

- ∴ The results and the literature indicate that there is potentially significantly greater mass of PFAS in the unsaturated soil (i.e. soil above the water table) than in the groundwater. Leaching of PFAS from the unsaturated soil could potentially provide an ongoing and long term source of PFAS to groundwater.
- ∴ Surface water has been identified as an important pathway for the migration of PFAS into groundwater and vice versa. Surface water flow can move contaminants much faster than groundwater flow, and due to the strong connection between groundwater-surface water within the region, contaminant transport via surface water is a key influencing factor for the groundwater plume.
- ∴ Interconnectedness of groundwater and surface water is further illustrated in the Makowhai Stream where PFOS concentrations are lower near Ohakea, reaching their maximum approximately 1.5 km from the site, before decreasing with increasing distance from the site. One potential mechanism for this pattern is the influence of groundwater discharge (to the Makowhai Stream) where PFOS concentrations in the stream are highest.
- ∴ The plume of PFAS-containing groundwater emanating from historic use of AFFF at RNZAF Base Ohakea is expected to be constrained in the longer term by topography and higher groundwater pressures to the north, east and south and by the Rangitikei River to the west. It is expected that shallow groundwater in the investigation area is prevented from moving further south than approximately the Makowhai Stream and is instead directed towards the Rangitikei River. Plume migration/transport under and beyond these surface water bodies is

possible, but as these are the regional groundwater sinks, they are the ultimate receivers, and migration back into these surface water bodies would ultimately occur, albeit slightly further downgradient.

- ∴ The plume is expected to persist in concentrations > 0.06 ug/L for many decades.

Table of Contents

SECTION	PAGE
Executive Summary	ii
1.0 Introduction	1
1.1 Objectives and Scope	1
2.0 Background	2
2.1 Per- and Poly-fluoroalkyl Substances (PFAS)	2
2.2 PFAS in Aqueous Film Forming Foams	5
2.3 Fate and Transport of PFAS from Fire Training Areas	6
3.0 Site Description	9
3.1 Topography and Hydrology	10
3.2 Geology and Hydrogeology	12
4.0 AFFF use at Ohakea	15
5.0 Sampling Investigation	17
5.1 Methodology	17
5.2 Guidelines	20
5.3 Molar Calculations	24
5.4 Summary of Results	25
5.5 Discussion	39
6.0 Updated Conceptual Site Model	45
7.0 Groundwater Plume Modelling and Evolution Predictions	45
7.1 Approach to Plume Evolution Assessment	45
7.2 Key Assumptions	46
7.3 Existing Plume Interpretation	48
7.4 Best Estimate Future Plume Predictions and Interpretations	52
7.5 Source Zone Removal Scenario	58
7.6 Longer Source Depletion Scenario	62
7.7 Plume Predictions - Discussion and Summary	65
8.0 Summary and Conclusions	67
9.0 References	70

Table of Figures

Figure 1: Investigation Areas	75
Figure 2: On Site Sample Locations	76
Figure 3: Off Site Sample Locations	77
Figure 4: Groundwater Transect Location	78
Figure 5: Existing Shallow Groundwater PFOS + PFHXS Plume Estimate	79
Figure 6: Future Shallow Groundwater PFOS + PFHXS Plume Prediction (Maximum Extent)	80

Table of Tables

Table 1: Kd Values of Common PFAS Compounds ^{1,2}	8
Table 2: Rangitikei River Flow Statistics	11
Table 3: Sample Summary 2015 - 2018	18
Table 4: Total Analytical Suite for PFAS	19
Table 5: Environmental and Human Health Guidelines - Water	21
Table 6: Health Canada drinking water screening values – other PFAS ¹	22
Table 7: Human Health Screening Values – Soil	22
Table 8: Norway Sediment Quality Guidelines ¹	23
Table 9: Human Health Trigger Points for Investigation – Plant and Animal Tissue	24
Table 10: Consumption Guidelines for Recreational Catch Freshwater Finfish ¹	24
Table 11: Groundwater Sampling Results Summary – On-Site	26
Table 12: Groundwater Sampling Results Summary – Off-Site	27
Table 13: Surface Water Sampling Results Summary – On-Site ¹	28
Table 14: Surface Water Sampling Results Summary – Off-Site	29
Table 15: Sediment Sampling Results Summary – On-Site	30
Table 16: Sediment Sampling Results Summary – Off-Site	30
Table 17: Soil Sampling Results Summary – On-Site	31
Table 18: Fish Sampling Results Summary – Off-Site	32
Table 19: Watercress Sampling Results Summary – Off-Site	33
Table 20: Egg Sampling Results Summary – Off-Site	34
Table 21: Meat Sampling Results Summary – Off-Site	35
Table 22: Offal Mammalian Sampling Results Summary – Off-Site	36

Table 23: Ratio of PFAS in Soil to Groundwater - Unsaturated Zone ¹	40
Table 24: Fish samples and associated surface water and sediment results ¹	45
Table 25: Summary of Generalised 'Best Estimate' Plume Evolution Predictions and Interpretations	55

Appendices

Appendix A: AFFF Results

Appendix B: Lab Results

Appendix C: Molar Concentration

Appendix D: CSM

1.0 Introduction

New Zealand Defence Force (NZDF) has been investigating the potential for contamination of ground, water and biota associated with the use and storage of products containing per- and poly-fluoroalkyl substances (PFAS) at Royal New Zealand Air Force (RNZAF) Base Ohakea (the 'site' or 'Ohakea'). Investigations at Ohakea have identified PFAS in soil and water on base, as well as in the surrounding environment and neighbouring properties.

A Preliminary Site Investigation and Detailed Site Investigation of the base Fire Training Area were completed in 2015 (PDP, 2015a; PDP, 2015b). Subsequently a PFAS-specific Preliminary Site Investigation was conducted over the remainder of the site (PDP, 2017a).

In 2017 a Detailed Site Investigation was conducted in locations identified during the PSI as having high Aqueous Film Forming Foam (AFFF) use (frequency of use and/or volume and/or locations near the site boundary (PDP, 2018a). Up to five rounds of groundwater sampling and four rounds of surface water sampling was conducted.

A separate groundwater assessment was conducted to assist NZDF to understand the groundwater flow regime around Ohakea (PDP, 2017b). The work included developing a geological model and 3D numerical groundwater model.

In December 2017 sampling was extended to private properties and public land adjacent to and down-gradient of Ohakea (the investigation area, Figure 1). The sampling programme included several rounds of groundwater and surface water monitoring between December 2017 and September 2018 (PDP, 2018b; PDP, 2018c; PDP, 2018d; PDP, 2018e). Sampling of soil, sediment, animal tissue and plant tissue was also conducted in various locations within the investigation area (PDP, 2018a; PDP, 2018b; PDP, 2018c; PDP, 2018d; PDP, 2018e; PDP, 2018f).

Pattle Delamore Partners Ltd (PDP) has been engaged by the New Zealand Defence Force (NZDF) to prepare a comprehensive site investigation report documenting the above PFAS investigation at Ohakea. The purpose of this report is to provide the results and assessment undertaken by PDP during the on and off-site investigations in a single report.

1.1 Objectives and Scope

The key project objectives were to:

1. Collate and compare all on-site and off-site PFAS sample data collected across all media.
2. Assess the likely 'status' of the PFAS plume at present including:
 - a. Partitioning of the mass in different media (soil and groundwater);

- b. Composition of the plume (in surface water and groundwater), including temporal and spatial trends and any evidence of transformation and attenuation of certain compounds.
3. Using the information available, assess the potential future behaviour (assuming no remediation / intervention) of the groundwater plume using modelling, focussing on the whether the extent and concentration of the groundwater plume is predicted to worsen, improve or remain largely the same.
4. Prepare an updated conceptual site model.

The scope to fulfil the project objectives was to:

- I. Collate and summarise all on-site and off-site PFAS sample data collected across all media during the investigation.
- II. Assess the PFAS mass in different media (soil and groundwater);
- III. Assess the composition of the plume (in surface water and groundwater), including an assessment of any trends evident in the results and assessment of the evidence for transformation and attenuation of PFAS compounds.
- IV. Update and re-calibrate the existing 3D groundwater flow and solute transport model. Using the information available, assess the potential future behaviour (assuming no remediation / intervention) of the plume in the short term (<5 yrs), medium term (5 - 25 yrs), and long term (25 - 100 yrs +) future, focussing on the whether the extent and concentration of the groundwater plume is predicted to worsen, improve or remain largely the same.
- V. Update the conceptual site model.
- VI. Prepare a comprehensive site investigation report documenting Ohakea PFAS Investigation.

2.0 Background

2.1 Per- and Poly-fluoroalkyl Substances (PFAS)

PFAS are a large group of several thousand human-made per and poly-fluorinated compounds used for the manufacturing of a wide variety of products (ITRC, 2018a). Two major groups of PFAS compounds (perfluoroalkyl substances and polyfluoroalkyl substances) are currently the focus of many PFAS investigations (refer to Diagram 1 for PFAS naming conventions). The basic structure of PFAS compounds is a fluorinated chain of two or more carbon atoms with a charged functional group (the group of atoms which defines the way a molecule reacts) at one end. The strong carbon-fluorine bond means they are highly persistent in the environment and resist degradation (ITRC, 2018a).

Diagram 1. Naming Conventions of Per- and Polyfluoroalkyl Substances (PFAS)

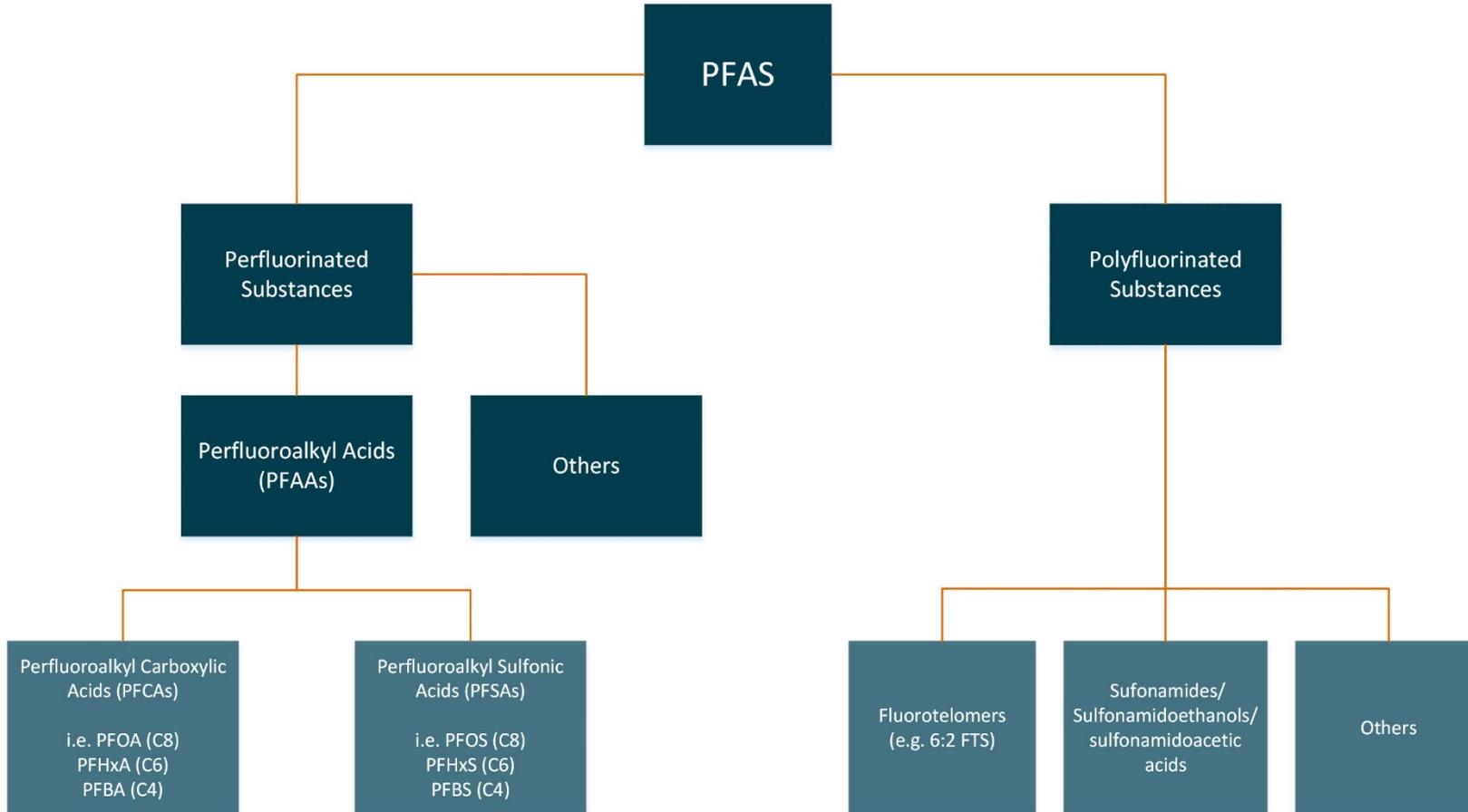
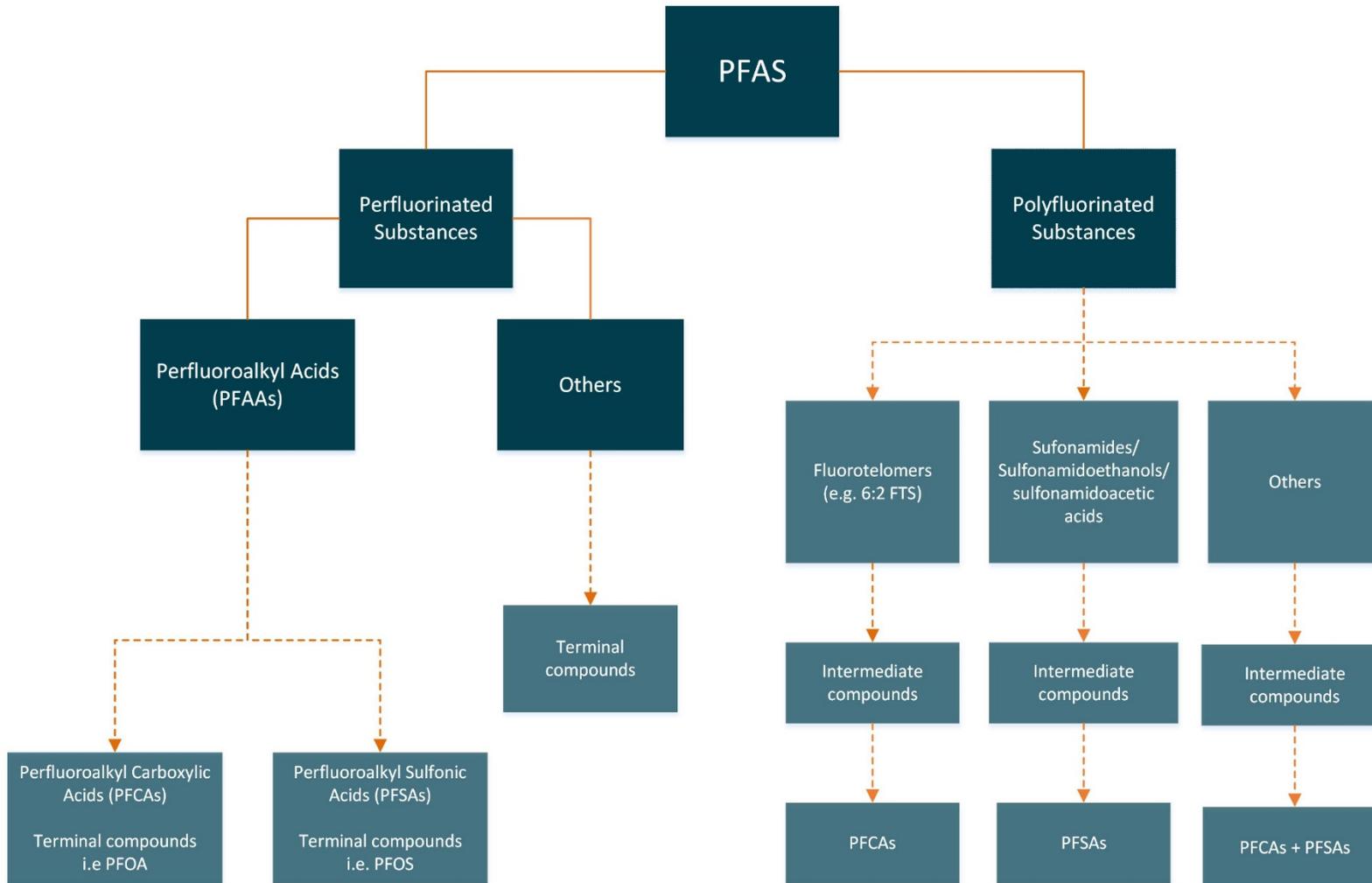


Diagram 2. Degradation and transformation pathways of Per- and Polyfluoroalkyl Substances (PFAS)



Perfluoroalkyl substances are fully fluorinated PFAS compounds and are among the most commonly detected PFAS compounds in the environment. PFAAs can enter the environment through the use of substances containing them or they can form due to the degradation of polyfluorinated precursors into perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs). PFCAs such as perfluorooctanoic acid (PFOA) and PFSAs such as perfluorooctane sulfonate (PFOS) are terminal degradation products of select precursor polyfluoroalkyl substances (refer to Diagram 2 for PFAS degradation pathways).

Polyfluorinated PFAS substances on the other hand are partially fluorinated, therefore making them more susceptible to degradation. Fluorotelomers are polyfluoroalkyl substances produced by the telomerization process. The degradation of fluorotelomer-based substances is a potential source of PFCAs in the environment (Buck *et al.*, 2011). 6:2 Fluorotelomer sulfonate (6:2 FTS) is known to break down into short chain PFCAs such as Perfluorohexanoic acid (PFHxA), Perfluoropentanoic acid (PFPeA) and Perfluorobutanoic acid (PFBA) via a series of intermediate compounds.

Long chain compounds can be more toxic than short chain compounds (particularly C8 compound, however toxicity may decrease in very long chain compounds). For PFCAs, carbon chains of eight carbon atoms (referred to as C8) or more (i.e. PFOA (C8)) are considered a long chain. Long chain PFSAs possess a carbon chain of six carbon atoms (referred to as C6) or more carbons (i.e. Perfluorohexane sulfonic acid, PFHxS (C6) and PFOS (C8) are both considered long chain sulfonic acids).

Whilst many PFAA precursors are monitored, numerous precursors are currently not measured due to a lack of analytical standards available.

2.2 PFAS in Aqueous Film Forming Foams

Some PFAS compounds are major components of Aqueous Film Forming Foams (AFFF) which are used to extinguish fuel-based fires (ITRC, 2018a). AFFF was adopted worldwide in the 1970's and 1980's as a primary firefighting agent due to its ability to quickly suppress most hydrocarbon fuel fires (Place and Field, 2012). The formulations of these foams are proprietary and contain complex mixtures¹ which vary year by year, manufacturing process and with manufacturer (Baduel *et al.*, 2015, Anderson *et al.*, 2016). The principal PFAS in many modern foams are various fluoroalkylthiamido sulfonates, fluoroalkylthiobetaine compounds and other related substances which are not reported as part of any current commercial analytical suites. Therefore, analysis of current foams may not accurately estimate the composition and concentrations of PFAS compounds released historically.

¹ Baduel *et al* (2017) have found more than 60 different PFAS chemicals from 12 different fluorochemical classes at one fire fighting training area.

Older AFFF developed between the 1960's and 2001 contained long chain 'C8' PFAS compounds such as PFOS and PFOA (ITRC, 2018b). PFOS and PFOA are persistent (i.e. they do not degrade or only degrade very slowly in the environment), mobile and bioaccumulate in organisms (ITRC, 2018b). In the early 2000's, 3M voluntarily phased out the manufacture of PFOS. By 2006, eight major companies had also committed to reducing other long chain compounds such as PFOA. In 2006, New Zealand prohibited the importing and manufacturing of firefighting foams containing PFOS or PFOA.

In 2009, the manufacture, import and use of PFOS was prohibited when the Annex B of the Stockholm Convention was amended to include PFOS. PFOA and PFHxS are currently proposed for listing.

In response to the phasing out of PFOS and PFOA containing AFFF, modern foams were developed containing fluorotelomer short chain (C6) PFAS which do not break down into long chain PFCAs such as PFOS. Shorter chain compounds are thought to be less bioaccumulative (Houtz *et al.*, 2016; ITRC, 2018b; Place and Field, 2012).

2.3 Fate and Transport of PFAS from Fire Training Areas

Fire training areas (FTAs) are potential areas of highly concentrated PFAS from AFFF where hydrocarbon fires were repeatedly extinguished during training exercises for many decades. The fate and transport of PFAS compounds released from AFFF is not well understood due to the uncertainty surrounding AFFF formulations and degradation pathways of PFAS compounds. Lack of historic AFFF application records also makes it difficult to discern how PFAS plumes may develop over time.

The behaviour of PFAS in the environment is site specific and international studies may not be directly applicable to the site at Ohakea, however some patterns can be observed:

- ∴ Some PFAS are highly soluble, making them very mobile in the environment, particularly in groundwater and surface water.
- ∴ Some PFAS compounds can sorb to solid surfaces.
- ∴ Some PFAS transform to terminal compounds. These terminal compounds are very persistent.

These attributes of PFAS are discussed further below.

2.3.1 Solubility

Water solubility of PFAS is dependent on the functional group. However, solubility tends to decrease with increasing molecular weight (the sum of the atomic weight values of the atoms in a molecule) and therefore generally decreases with the increasing length of the alkyl chain. Short chain PFAS

molecules such as PFHxA, PFPeA and PFBA are therefore generally expected to preferentially partition to water and therefore, be more mobile (Scher *et al.*, 2018). PFOS and PFHxS which are long chain PFAS are moderately soluble and therefore less mobile than short chain compounds.

2.3.2 Sorption

The ability of PFAS to sorb² onto solid surfaces such as soil and sediment affects the mobility of PFAS compounds and depends on the chain length (number of fluorinated carbons) and functional group. Additional factors influencing sorption include the pH of the soil, clay content and the presence of organic matter. Longer perfluorinated chain PFAS such as PFOS (C8) and PFNS (C9) more strongly sorb to soil and sediment than shorter chain compounds such as PFHxS (C6) and PFBA (C4). Shorter chain compounds are therefore more mobile in the environment (Gellrich *et al.*, 2012).

Numerous studies have attempted to determine soil: water partition coefficients (K_d) for PFAS compounds. The K_d value describes the preference for a compound to sorb to a solid (e.g. an aquifer matrix) or to remain in the liquid (e.g. the groundwater). It is typically defined by the equation below:

$$K_d = \frac{Conc_{soil}}{Conc_{water}}$$

Where:

- ∴ $Conc_{soil}$ is the concentration of a PFAS compound in the soil.
- ∴ $Conc_{water}$ is the concentration of a PFAS compound in the water.

A K_d value of < 1 indicates the concentration in the water is greater than the concentration in the soil (i.e. the compound does not sorb strongly to the aquifer matrix). A K_d value of > 1 indicates the compound is more likely to sorb to the soil than be present in the water.

The K_d values reported in the literature for some of the more commonly investigated PFAS compounds are presented in Table 1, and show a wide range in values, highlighting the complexity in predicting the sorption behaviour of these chemicals. Furthermore, it appears laboratory derived distribution coefficients often underestimate the sorption of PFAS compounds compared to values recorded in the field (e.g. Zareitalabad *et al.*, 2013). Field derived K_d values for PFOS and PFHxS at the Williamtown airbase were 1.19 L/kg and 0.11 L/kg respectively (AECOM, 2017).

² The ability to adhere to a surface/other substances.

Table 1: K _d Values of Common PFAS Compounds ^{1,2}	
Compound	K _d (pH 7)
PFOA	0 – 3.4
PFOS	0.1 – 97
PFHxS	0.6 – 3.2
<p>Note</p> <ol style="list-style-type: none"> 1. K_d values sourced from Wang <i>et al.</i> (2011). 2. All units in L/kg. 	

2.3.3 Persistence

PFOS and PFOA are considered to be persistent compounds which bioaccumulate in organisms (ITRC, 2018b). In 2009, the manufacture, import and use of PFOS was prohibited when the Annex B of the Stockholm Convention on Persistent Organic Pollutants was amended to include PFOS. Persistent Organic pollutants are defined as synthetic, organic compounds that, to varying degrees, resist photolytic, biological, and chemical degradation (ITRC, 2017). Currently, PFOA and PFHxS are also proposed for listing.

2.3.4 Transport

Due to the mobility and persistence of PFAS in environment, PFAS can form large plumes depending on the hydrological and geological setting (ITRC, 2018b). Surface water and groundwater contamination from point source discharges of PFAS has been shown to extend for many 10's of kilometres (Awad *et al.*, 2011; Kwadijk *et al.*, 2014; AECOM, 2017; AECOM, 2018). The mobility of PFAS can be further influenced by the presence of other co-contaminants such as petroleum hydrocarbons (McKenzie *et al.*, 2016).

Despite the high mobility of PFAS, in the case of AFFF, a significant portion of the PFAS mass is thought to be retained at the source where it is sorbed to soil in both the saturated and unsaturated zone. PFAS then slowly migrates down gradient with the flow of groundwater. Baduel *et al.*, (2015) estimated the source half-life³ of PFAS to be 25 years, indicating that a small amount of PFAS could continue to be discharged from the source area for up to hundreds of years (Baduel *et al.*, 2015). It should be noted that Baduel *et al.* (2015) derived this value based on kinetic model which used site specific soil leaching data and rainfall/runoff conditions which might be very different to those present at Ohakea. However, there is no information of leaching half-lives in any of the other literature that PDP reviewed. Most literature reviewed said that leaching

³ Half-life is defined as the time taken for the concentrations of PFAS compounds at the source to halve.

of PFAS soils can be a significant source of PFAS compounds for several decades after the use of these compounds has ceased at the site.

2.3.5 Transformation

Unmeasurable⁴ precursors of PFAS compounds are capable of breaking down after they have been discharged into the environment (i.e. 6:2 FTS is a precursor compound which can breakdown into PFHxA and PFBA). Precursors are defined as a substance recognised as having the potential to transform into PFCAs or PFSAAs (Casson and Chiang, 2018). These precursor compounds can account for a large amount of unknown PFAS mass in the environment. Precursors have been found to account for 41 – 100% of total PFAS concentrations in AFFF formulations (Casson and Chiang, 2018). As such, the potential ecological impacts of discharged firefighting foams may be under-estimated by analysing for the traditional 27 PFAS suite which only measure a small percentage of the total mass of PFAS. More recently an analytical method has been developed which oxidises samples in the laboratory to provide an indication of how PFAS in a sample might degrade and transform over time (refer to Section 4). The reliability of this method is the subject of ongoing scientific debate.

3.0 Site Description

Ohakea is a large, operating airforce base with on-site residential dwellings alongside the buildings and infrastructure associated with the airfield. The majority of the site is composed of the runways and the associated open grassed areas and accessways for aircraft (Figure 2). Located at the edge of the runway apron to the north are various structures associated with the airbase operations including three large aircraft hangars, the fire flight complex, the airport terminal and the motor transport yard and fuel tanker storage bay.

In the east of the site is another large aircraft hangar associated with the No. 3 Squadron (SQN) hangar, and the MSS maintenance and repair complex. The bulk fuel storage site is located to the north of No. 3 SQN hangar.

In the north of the site are numerous buildings including offices, residential dwellings for site personnel, recreational facilities and maintenance yards.

Two closed landfills are located on-site, north and west of the runway respectively.

The sewage treatment plant is located northwest of the main base, between the Base and the Rangitikei River.

⁴ Laboratories typically analyse for between 25 – 35 individual PFAS, the remaining PFAS, estimated to be several thousand, are generally not measured and are referred to in this report as ‘unmeasurable’.

3.1 Topography and Hydrology

The regional topography near the Rangitikei River is dominated by a succession of river terraces that step down to the current level of the river. Being located on one of these terraces, the majority of Base Ohakea is flat; except in the west of the site where the land slopes steeply to the lower river terrace approximately 10 m below.

Topographic elevations within the wider project investigation area range between approximately 10 m (relative level) RL and 100 m RL. The highest elevation areas are present north-east through east of Base Ohakea, where the landscape transitions from raised floodplain to incised hill country. Base Ohakea resides on a relatively flat relic (raised) floodplain at approximately 45 m RL to 50 m RL. West of Base Ohakea, topography lowers by approximately 10 m at a pronounced terrace / escarpment, to the present-day Rangitikei River floodplain.

The Rangitikei River is approximately 350 m from the northern boundary of the site. The river curves around the location of the base to be 1 km west of the western boundary of the site (Figure 1). The Makowhai Stream runs along the eastern boundary of the base in a general southerly direction, eventually discharging to the Rangitikei River approximately 9 km downstream. Numerous open drainage ditches run through the base, particularly alongside the runways. In the south of the site these drainage ditches discharge into the Makowhai Stream.

The Rangitikei River is predominantly a shingle/gravel braided river which is confined/semi-confined in the upper reaches and un-confined in the lower reaches (Alexander, 2012). The Rangitikei River is the third longest river in the North Island with a total length of 241 kilometres. The Rangitikei is the sixth largest river in the North Island when ranked by average flow. The source of the Rangitikei River is in the Kaimanawa range, rising from springs on Ngapuketuru. Its total catchment area is approximately 3,925 km²; with the catchment area above Ohakea being approximately 3,547 km².

A hydrological description of the Rangitikei River taken from Alexander (2012) is summarised below:

- ∴ The headwaters flow through open tussock country and gorges (along the eastern margin of the NZ Army Waiouru training area). The bed of the river at this stage is shingle.
- ∴ The middle portion of the river has eroded down to mudstone and sandstone, with vertical cliffs below a series of terraces. The country used to be covered in native forest, but much has been cleared for farm development.

- ∴ The lower reaches of the Rangitikei River, near Ohakea, are dominated by a meandering braided river which has deposited large amounts of gravel and shingle that have been eroded from the upstream ranges.

The Rangitikei River has many significant tributaries, namely; Moawhango River, Hautapu River, Ngaruroro River, Pohangina River, Oroua River, Mangapapa River, Waitangi Stream and Kiwitea Stream.

3.1.1 Rangitikei River Flow Data

The Rangitikei River is currently monitored by Horizons Regional Council (HRC) in the vicinity of Ohakea at the following stations:

- ∴ Rangitikei at Onepuhi
- ∴ Rangitikei at McKelvies

The Rangitikei River at Onepuhi monitoring site is located approximately 23 km upstream (north) of Ohakea. The Rangitikei River at McKelvies monitoring site is located approximately 17 km south of Ohakea. Flow data for these two sites is summarised in Table 2.

Table 2: Rangitikei River Flow Statistics		
Statistic	Flow (m ³ /s)	
	Rangitikei at Onepuhi ¹ (upstream)	Rangitikei at McKelvies ¹ (downstream)
Mean Annual Low Flow (MALF)	11.74	10.56
Mean Flow	65.13	72.18
Summer Median Flow²	23.4	22.57
Winter Median Flow²	106.32	118.43
Maximum Flow	718 (19/09/2010)	1,018 (21/06/2015)
Minimum Flow	8.95 (12/03/2013)	8.62 (12/03/2013)
<i>Notes:</i> <ol style="list-style-type: none"> 1. Length of record from 16/06/2006 – 03/07/2017. Total sample size 4,036. 2. Summer period January to March, Winter period July to September. 		

3.2 Geology and Hydrogeology

The Geological Map of the Taranaki Area (Townsend et al., 2008) indicates that the investigation area is underlain by Late Pleistocene river (deposits around 500,000 to 120,000 years old) comprised of poorly to moderately sorted gravel with minor sand and silt underlying terraces and includes minor fan deposits and loess (windblown deposits of silt).

West of the prominent river terrace, on the present floodplain, younger river deposits have been emplaced by the Rangitikei River; but overall the unit contains a similar mix of gravel, sand, silt and clay sediments.

The hill country in the north- eastern portions of the investigation area comprises older (Early Pleistocene) ocean/marine deposits of the Rangitikei Supergroup. This unit also primarily comprises sands, silts, gravels and peats.

In the south of the investigation area (south of the Makowhai Stream), an area of relic dunes creates a region of elevated topography.

Analysis of bore and hand auger logs from previous investigations completed at Ohakea and available HRC driller logs, indicate the following:

- ∴ Beneath the majority of the runway area, gravelly SAND is the dominant shallow (approximately 0 – 50 m bgl) geology;
- ∴ West of the runway area, sandy GRAVEL is the dominant shallow geology;
- ∴ East of the runway area, sandy SILT/CLAY is the dominant shallow geology;
- ∴ Isolated areas/lenses of CLAY/SILT/PEAT are likely and can be present anywhere within the floodplain geology.
- ∴ Deeper geology (i.e. greater than 50 m bgl) is dominated by sandier units or silt/clay units.

3.2.1 Groundwater Flow

Available groundwater level (head) data from HRC and Ohakea site monitoring covers a range of over 50 m (relative levels). Higher groundwater levels (around 60 m RL) are associated with higher topography in the north, and lower groundwater levels (around 10 m RL) are associated with lower topography in the south-west.

Analysis of the groundwater level data in coordination with the topographic, geologic and hydrological information indicates the following key features:

- ∴ Groundwater head distribution and flow direction from the Ohakea site is primarily in the westerly to southerly direction.

- ∴ Groundwater flow directions within the shallow groundwater system i.e. <50 m bgl, can be influenced by local 'sinks'. These sinks are primarily the Rangitikei River, streams/channels which incise the project area, and pumping bores. The presence of these sinks can locally alter groundwater flow directions towards these sinks.
- ∴ The shallow groundwater system is primarily an unconfined aquifer i.e. an aquifer that forms a 'water table' or phreatic surface.
- ∴ Higher topography and groundwater pressures exist north, east and south of the site. Consequently, it is expected that shallow groundwater in the investigation area is prevented from moving further north, and groundwater is not expected to move much further south or east than approximately the Makowhai Stream.
- ∴ The Rangitikei River presents a groundwater discharge boundary to the west and shallow groundwater in the investigation area is also not expected to move much further west than the Rangitikei River.
- ∴ Groundwater head distribution and flow direction within the deeper groundwater system i.e. below 100 m bgl, displays a generally north-east-to-south-west oriented gradient, and is not expected to be locally influenced by surface water sinks (as they are too hydraulically disconnected to be an influence).
- ∴ The deeper groundwater system beneath the floodplain landscape is however typically higher pressure than the shallow system, and consequently - on a regional scale – deeper groundwater is generally up-welling e.g. deeper groundwater is moving upwards and into the shallow portion of the groundwater system.
- ∴ The deep groundwater system is primarily a confined aquifer, or potentially a series of increasingly confined aquifers with depth.

3.2.2 Groundwater Sources and Sinks

The primary groundwater sources within the project area are:

- ∴ Groundwater inflow – from 'upgradient' groundwater located to the north and east of the project area. This inflow will occur year-round.
- ∴ Groundwater recharge – primarily from rainfall percolation through the soil zone. This will primarily occur during the wetter months i.e. April through October, when rainfall accumulation is higher and soil moisture deficits are lower. Percolation from irrigation is also possible.
- ∴ Surface water bodies – from surface water flowing into the project area during or post rainfall events via the Rangitikei River and its tributaries. Through this mechanism, water leaks from the surface water body into the surrounding shallow groundwater system. By volume, this is

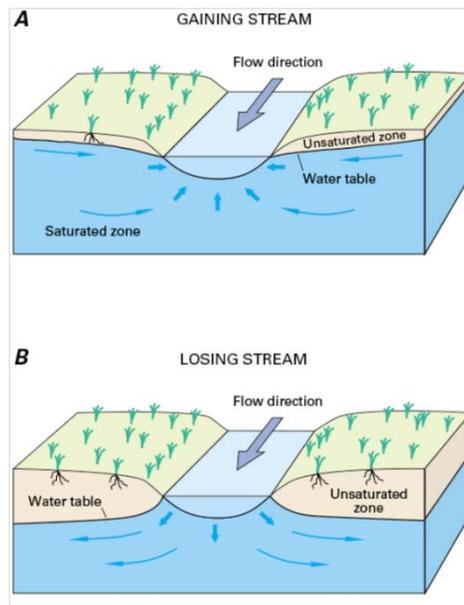
expected to be significantly less than groundwater inflows or rainfall recharge.

The primary groundwater sinks within the project area are:

- ∴ Groundwater outflow – to ‘downgradient’ area south and west of the project area. This outflow will occur year-round.
- ∴ Surface water bodies – discharge of water from the shallow groundwater system into the Rangitikei River and streams/channels which incise the topography (to sufficient depth). This will occur year-round but greatest when surface flows are not as influenced by rainfall.
- ∴ Groundwater abstraction – groundwater abstraction from the numerous bores within the project area. By volume, this is likely to be the smallest of the sinks, however bores which abstract high flows can be very influential on a local scale. HRC bore construction data indicate that groundwater abstraction is occurring from both the shallow and deep groundwater systems.

It should be noted that surface water bodies act as both a groundwater source (losing streams) and groundwater sink (gaining streams) depending on river stage level relative to the local shallow groundwater level. As described in Section 3.1.1, the Rangitikei River gauging data show median flow rates are slightly greater at the upstream Onepuhi site than they are at the downstream McKelvies site. This indicates that there is on average a ‘net loss’ of river water to the adjacent shallow groundwater system. During large rainfall events, the flow difference can be more pronounced and significant volumes of surface water may be ‘lost’ to shallow groundwater. However, over the drier months, the opposite trend is dominant whereby downstream flow is greater than upstream flow, indicating the river is being fed primarily by groundwater discharge or baseflow.

Local to the Rangitikei River i.e. within approximately 100 m, groundwater and surface water interaction is expected to be dynamic, with water easily able to migrate between the river and shallow groundwater in either direction.



Gaining streams (A) receive water from the ground-water system, whereas losing streams (B) lose water to the ground-water system. From https://pubs.usgs.gov/circ/circ1186/html/gw_effect.html

3.2.3 Bore Search and Ground water Use

Groundwater bore data from Horizons Regional Council (HRC) borehole database was used to determine the number and location of bores within a 10 km radius of the centre of the site (data extracted by HRC in July 2017).

Many of the bores contained in the HRC database do not have a use listed. For those that do, the primary use in the surrounding area is for stock drinking water and irrigation water, with some use for potable supply. The potable supply for Base Ohakea comes from a shallow bore (11 m deep) located north of the base near the Rangitikei River (WS2, Figure 2). A deeper bore (160 m deep) is located within the site and is used for non-potable supply, in particular for the sprinkler systems (WS3, Figure 2).

4.0 AFFF use at Ohakea

AFFF has been used on base for firefighting, fire prevention and firefighting training since the 1980's. AFFF has been stored for use in emergencies in both static systems, fire service vehicles and smaller storage containers. Fire training exercises at Ohakea have been carried out at multiple areas at the base on bare ground and concrete. The direct application of AFFF to bare soil can result in the contamination of soil and groundwater through leaching and surface water via runoff. PFAS compounds are known to leach from fire training pads over multiple decades (Baduel *et al.*, 2015).

Raw product samples were collected from a variety of AFFF products at Ohakea and on other NZDF camps and bases. A summary of the PFAS concentrations in AFFF sampled from Ohakea is provided in Table A1, Appendix A. Samples were collected from the following foams⁵:

- ∴ Solberg RFS 3% (fluorotelomer based) (C6)
- ∴ 3% Angus Tridol-S (fluorotelomer based) (C6)
- ∴ Tridol M 3% (fluorotelomer based) (C6)
- ∴ Anuslite 3% (fluorotelomer based) (C6)
- ∴ Chemguard.

Historically, NZDF used PFOS containing products such as Lightwater and Angus Alco Seal. Samples were also collected from Lightwater stored at other NZDF sites (refer to Table A2, Appendix A). NZDF have advised that foams such as Lightwater and Alco Seal were used at Ohakea between the years 1980 to 2002. Post 2002, and prohibition of PFOS containing foams, newer foams with fluorotelomers, such as those listed above, were likely to have been used.

Based on existing records and anecdotal evidence NZDF provided an estimate of 1 m³ per annum of AFFF used during fire training exercises at Ohakea between the years 1980 to 2015.

To better understand how foams used at NZDF sites might degrade and transform over time, a Total Oxidizable Precursor Assay (TOPA) analysis was conducted on a variety of AFFF samples from several NZDF sites. The TOPA analysis chemically oxidizes samples using a hot persulphate digest under alkaline conditions (pH greater than 12 pH units (Houtz and Sedlak, 2012)). The purpose of oxidising AFFF samples is to simulate how PFAS compounds (and unmeasurable precursors) may break down over time in the environment. However, it is important to note that the conditions created during TOPA may never actually occur in the natural environment therefore TOPA should be considered to provide a conservative indication of potential degradation of PFAS only.

A sample of Angus Tridol from Ohakea was analysed. The results showed there was no PFOS present in the foam before or after oxidation, however, PFOA did increase post- TOPA. In the AFFF samples, Post -TOPA analysis, a number of precursor breakdown products such as PFPeA, PFHxA and PFBA increased substantially after oxidation. This indicates the modern fire fighting foams do have the potential to breakdown into a number of different terminal PFCA compounds.

⁵ Several samples were taken from unlabelled storage containers and are therefore unidentified. See Appendix A.

For comparison, stored Lightwater was also analysed. Analysis of 3 M light water revealed that it contained high concentrations of PFOS and PFHxS. Post- TOPA, PFOS and PFHxS did not degrade/change, however, there was an increase in PFHxA concentrations.

5.0 Sampling Investigation

5.1 Methodology

Sampling of groundwater, water supply, wastewater, surface water, sediment and soil was conducted at Ohakea during a two PFAS-specific Detailed Site Investigations completed by PDP (2015b and 2018a).

Sampling was undertaken in conjunction with other consultancies, in groundwater, surface water, sediment, soil, plant and animal tissue from multiple locations adjacent to Ohakea over four sampling events (PDP, 2018b; PDP, 2018c; PDP, 2018d; PDP, 2018e).

Further animal tissue (freshwater fish), surface water and sediment pore water samples were collected and analysed for PFAS in 2018 (PDP, 2018f).

Due to the ubiquitous presence of PFAS in the environment, sampling of groundwater, water supply and surface water was undertaken following the methodology outlined in the *Sampling Protocols for Monitoring Per and Poly-fluorinated Compounds in Groundwater and Surface Water for New Zealand Defence Force* (PDP, 2018g) and the guidance documents referenced therein.

Sampling of other media was undertaken following procedures developed by PDP which were used as the basis for sampling advice outlined in *Sampling and Analysis of Per – and Poly – fluorinated Substances (draft)*, Ministry for the Environment, 2018.

The location of all groundwater, surface water, sediment and soil samples collected from Ohakea (on-site samples) are shown on Figure 2. The location of groundwater, surface water, sediment, plant and animal tissue samples collected on private and public properties and waterbodies within the investigation area (off-site samples) are shown on Figure 3. A summary of all the sampling locations is in Table 3.

Due to the very low detection limits of PFAS required for this investigation, a robust quality assurance / quality control (QA/QC) programme was required. The results of QA/QC programme including analysis of duplicate and blank samples are described in the primary investigation reports (PDP, 2015; PDP, 2018 a – g).

Table 3: Sample Summary 2015 - 2018

Monitoring Zone	Number of Samples	Number of Locations	Sample Media
On-site	56	21	Groundwater
	25	7	Surface Water
	3	3	Sediment
	34	26	Soil
Off-site	241	83	Groundwater
	122	47	Surface Water
	16	11	Sediment
	7	5	Fish
	31	NA	Eggs
	6	6	Watercress
	8	NA	Meat
	2	NA	Offal
	2	NA	Milk

5.1.1 Contaminants of Concern

The analytical suite is listed below in Table 4 where both the linear and branched isomers of PFOS and PFHxS are combined it is reported as T-PFOS and T-PFHxS. The WA DER⁶ guidelines recommend a suite of minimum target compounds in the analytical suite which are bold in the table below.

Analytical detection limits for water and ground water samples are 0.001 µg/L and 0.025 µg/g or less for sediment and soils samples.

⁶ Western Australia Department of Environment Regulation. Interim Guidance on the Assessment and Management of Perfluoroalkyl and Polyfluoroalkyl substances (PFAS). Contaminated Sites Guidelines.

Table 4: Total Analytical Suite for PFAS			
Abbreviation	Compound Name	Abbreviation	Compound Name
PFPrS	Perfluoropropanesulfonic acid	PFBA	Perfluorobutanoic acid
PFBS	Perfluorobutanesulfonic acid	PFPeA	Perfluoropentanoic acid
PFPeS	Perfluoropentanesulfonic acid	PFHxA	Perfluorohexanoic acid (PFHxA)
di-PFHxS	Total Perfluorodimethylbutane sulfonic acids	PFHpA	Perfluoroheptanoic acid
mono-PFHxS	Total Perfluoromethylpentane sulfonic acids	PFOA	Perfluorooctanoic acid
L-PFHxS	Linear Perfluorohexanesulfonic acid	PFNA	Perfluorononanoic acid
T-PFHxS	Total Perfluorohexanesulfonic acid	PFDA	Perfluorodecanoic acid
PFHpS	Perfluoroheptanesulfonic acid	PFUnDA	Perfluoroundecanoic acid
di-PFOS	Total Perfluorodimethylhexane sulfonic acids	PFDoDA	Perfluorododecanoic acid
mono-PFOS	Total Perfluoromethylheptane sulfonic acids	PFTTrDA	Perfluorotridecanoic acid
L-PFOS	Linear Perfluorooctanesulfonic acid	PFTeDA	Perfluorotetradecanoic acid
T-PFOS	Total Perfluorooctanesulfonic acid	PFOSA	Perfluorooctanesulfonamide
PFNS	Perfluorononanesulfonic acid	NEtFOSA-M	N-ethylperfluoro-1-octanesulfonamide
PFDS	Perfluorodecanesulfonic acid	NMeFOSA-M	N-methylperfluoro-1-octanesulfonamide

Table 4: Total Analytical Suite for PFAS			
Abbreviation	Compound Name	Abbreviation	Compound Name
4:2 FTS	1H,1H,2H,2H-perfluorohexanesulfonic acid	NEtFOSAA	N-ethylperfluorooctanesulfonamidoacetic acid
6:2 FTS	1H,1H,2H,2H-perfluorooctanesulfonic acid	NMeFOSAA	N-methylperfluorooctanesulfonamidoacetic acid
8:2 FTS	1H,1H,2H,2H-perfluorodecanesulfonic acid	NEtFOSE-M	2-(N-ethylperfluoro-1-octanesulfonamido)-ethanol
		NMeFOSE-M	2-(N-methylperfluoro-1-octanesulfonamido)-ethanol

5.2 Guidelines

5.2.1 Water

The interim guideline for drinking water quality adopted by the Ministry of Health is presented in Table 5.

The adopted guideline is the health based guidance value developed by the Australian Government Department of Health (2017). The value is based on the tolerable daily intake developed by FSANZ. These guidelines are based on the following assumptions:

- ∴ Up to 90% of the tolerable daily intake can be a result of non-drinking water sources (i.e. food consumption).
- ∴ The average weight of the person is 70 kg.
- ∴ Assumes that an individual is drinking 2 Litres per day of the water from the site for over a 70 year period (lifetime exposure).

Surface water sample results have been compared to the draft ANZECC guidelines for the protection of 95% of species. The 90 and 99% species protection guidelines have been included in Table 5 below for completeness. While comparison to the 99% protection guidelines is recommended for bioaccumulative substances, any concentrations of PFOS above the laboratory limit of reporting would exceed the 99% ecosystem protection value⁷. The guidelines have been derived using a species sensitive distribution using chronic toxicity data.

⁷ Currently the draft ANZECC/ANZGWQG are under revision, which is likely to result in the 99% ecosystem protection value being higher than the current draft 95% ecosystem protection value (Batley *et al.*, 2018). Therefore, the current draft 95% ecosystem protection value has been used in this assessment.

Table 5: Environmental and Human Health Guidelines - Water					
Media	Sum of Total PFOS + PFHxS	PFOA	Total PFHxS	Total PFOS	Source
Drinking Water	0.07 µg/L	0.56 µg/L	-	-	MoH ¹ AGDoH ²
Ecological Freshwater Guideline 95% ecosystem protection	-	220 µg/L	-	0.13 µg/L	HEPA ³
Ecological Freshwater Guideline 90% ecosystem protection	-	632 µg/L	-	2 µg/L	HEPA ³
Ecological Freshwater Guideline – 99% ecosystem protection	-	19 µg/L	-	0.00023 µg/L	HEPA ^{3,4}
<p>Notes:</p> <ol style="list-style-type: none"> 1. Ministry of Health (MoH, 2017) Interim Guidance Level for Drinking Water, PFOA, PFOS and PFHxS. 2. Australian Government Department of Health (AGDoH, 2017) Health Based Guidance Values for PFAS for Use in Site Investigations in Australia. 3. Australian and New Zealand Guidelines for Fresh and Marine Water Quality – technical draft guideline values in PFAS National Environmental Management Plan – Table 5. The Heads of EPAs Australia and New Zealand (HEPA), January 2018. 4. 99% ecosystem protection guideline has been shown for completeness. However, this guideline has not been compared to in the results. 					

Recent additions made to the Health Canada Drinking Guidelines have included drinking water screening levels for nine additional PFAS compounds (See Table 6). Screening values can be used as a rapid assessment to help identify a level at which no health effects are expected. However, these screening values have not been validated in New Zealand. The screening values have been compared to off-site groundwater samples for completeness as there are no New Zealand guidelines for these compounds (See Section 5.4.1.1).

Table 6: Health Canada drinking water screening values – other PFAS ¹	
PFAS compound	Drinking water screening value (µg/L)
PFBA	30
PFBS	15
PFHxS	0.6
PFPeA	0.2
PFHpA	0.2
PFNA	0.02
6:2 FTS	0.2
8:2 FTS	0.2
Notes: 1. Health Canada (HC, 2019). Health Canada's Drinking Water Screening Values for Other PFAS. https://www.canada.ca/en/services/health/publications/healthy-living/water-talk-drinking-water-screening-values-perfluoroalkylated-substances.html Accessed. 4/06/19.	

5.2.2 Soil

The results of soil samples collected on-site were considered in this report. Soil samples collected on-site were compared to the screening values in the PFAS National Environmental Management Plan by the Heads of EPAs Australia and New Zealand (HEPA, 2018) for commercial/industrial land use. The commercial/industrial screening value assumes potential soil exposure of 1 hour per day.

The screening values are based on 20% of the Food Standards Australia New Zealand's (FSANZ) tolerable daily intake (and therefore assume 80% of PFAS exposure comes from other sources).

Table 7: Human Health Screening Values – Soil					
Media	Sum of Total PFOS + PFHxS	PFOA	Total PFHxS	Total PFOS	Source
Industrial / commercial	20 mg/kg	50mg/kg	-	-	HEPA ¹
Notes: 1. PFAS National Environmental Management Plan. Heads of EPAs Australia and New Zealand (HEPA), January 2018.					

5.2.3 Sediment

The Norway Sediment Quality Guideline was developed by Bakke *et al.* (2010) for PFOS. However, these guidelines have been derived using a theoretical relationship and have not been validated by ecotoxicological data. For this reason, the Norwegian guidelines have been used as an initial screening criterion only. These have been provided in Table 8.

Compound	Toxic Effects Following Chronic Exposure	Toxic Effects Following Short Term Exposure	Source
PFOS	0.22 mg/kg	0.63 mg/kg	FSANZ ¹

1. Norway Sediment Quality Guidelines. Obtained from Bakke, T., Kailquist, T., Ruus, A., Breedveld, G. and Huylland, K. (2010). *Journal of Soils and Sediment*, 10, pp 172-178.

5.2.4 Biota

Biota samples including animal tissue (i.e. chicken eggs, finfish flesh, mammalian meat), watercress and milk were compared to the Food Standards Australia New Zealand's (FSANZ) trigger points (for further investigation); these are provided in Table 9. The "trigger points" are the maximum concentration level of these chemicals that could be present in individual foods or food groups so that even high consumers of these foods would not exceed the relevant TDI [tolerable daily intake]" (FSANZ, p.2, 2017). For fish, the trigger points are based on consumption, by a child 2 – 6 years old, of 73 g per day of fish.

Fish samples were additionally compared to the consumption guidelines for recreational catch freshwater finfish produced by the Ministry for Primary Industries (MPI, 2018). These guidelines were developed to minimise the food safety risk associated with recreational catch freshwater finfish. MPI state that, on average, adults consume freshwater fish less than twice a month (MPI, 2018). The guidelines are provided in Table 10.

Table 9: Human Health Trigger Points for Investigation – Plant and Animal Tissue

Media	Sum of Total PFOS + PFHxS	PFOA	Source
Poultry eggs	11 µg/kg	85 µg/kg	FSANZ ¹
Finfish (all)	5.2 µg/kg	41 µg/kg	
Meat mammalian	3.5 µg/kg	28 µg/kg	
Offal mammalian	96 µg/kg	264 µg/kg	
Vegetables (all)	1.1 µg/kg	8.8 µg/kg	
Milk	0.4 µg/kg	2.8 µg/kg	

1. *Assessment of potential dietary exposure to perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) occurring in foods sampled from contaminated sites – Table 8, Supporting Document 2. Food Standards Australia New Zealand (FSANZ), April 2017.*

Table 10: Consumption Guidelines for Recreational Catch Freshwater Finfish¹

Average PFOS concentration (µg/kg)	Child (2-10 years) (1 serving = 100g)	Adult (1 serving = 150g)
30-45	Limit of 3 servings/month	No advice necessary
45-60	Limit of 2 servings/month	
60-90	Limit of 1 serving/month	Limit of 3 servings/month
90-125	Limit of 1 serving/month	Limit of 2 servings/month
125-250	Do not consume	Limit of 1 serving/month
>250		Do not consume

Notes:

1. *Ministry for Primary Industries. Accessed on 07/01/2019 from <http://www.mfe.govt.nz/sites/default/files/media/Land/marine-freshwater-fin-fish-PFOS-thresholds.pdf> on 07/01/2019.*

5.3 Molar Calculations

PFAS results for several wells were converted to molarity or molar concentrations to look for evidence of transformation of PFAS in the groundwater plume. Comparing results in molar concentrations instead of mass concentration is considered more useful when discussing transformation of molecules because molarity is not affected by changes on molecular weight of different compounds (this is important as transformation results in one compound being converted into another compound which has a different molecular weight).

To convert concentrations to molarity the following calculation was made:

$$\text{Molarity} \left(\frac{\text{mols}}{\text{L}} \right) = \frac{\text{mass (g)}}{\text{Volume (L)}} \times \frac{1}{\text{Molar Weight (g/mol)}}$$

5.4 Summary of Results

All samples across all media were summarised in Tables 11 to 22 below. Samples collected from RNZAF Base Ohakea (on-site) have been tabulated separately to samples collected from adjacent private and public properties and waterbodies within the investigation area (off-site samples). The median concentration reported in the tables below was calculated from the samples that were above the laboratory limit of reporting (LOR) only.

Results for all samples are included in Appendix B.

5.4.1 Groundwater

Groundwater samples were collected from on-site and off-base locations between July 2015 and July 2018. Further groundwater samples were also collected off-site during September 2018. A total of 297 samples (56 on-base and 241 off-site, from 104 locations) were analysed for PFAS during multiple sampling investigations. The results were compared to the interim drinking water guideline of 0.07 µg/L for the sum of PFOS + PFHxS and 0.56 µg/L for PFOA (MfE, 2018).

During the investigation uncertainty of measurement (UOM) was assessed through comparison of duplicate samples both inter- and intra-lab, lab replicates and blanks (PDP 2018a, PDP 2018b, PDP 2018c, PDP 2018d, PDP 2018e, PDP 2018f).

Through this assessment an UOM of 10% was calculated. Because of the potential human health concerns with respect to drinking water, the UOM was applied to the results from all drinking water wells during the investigation. Therefore, all groundwater samples collected off-site were compared to a concentration of 0.06 µg/L for the sum of PFOS + PFHxS to provide confidence that groundwater used for drinking water did not exceed the interim drinking water guideline.

The results are summarised in Table 11 and 12.

Of the 297 groundwater samples collected:

- ∴ PFOS concentrations were above the LOR in 49 of the 56 samples (73%) collected on-site, and 107 of the 241 samples (44%) collected off-site.
- ∴ To account for the uncertainty of measurement of ± 0.01 µg/L, samples whose combined concentration of PFHxS and PFOS of greater than 0.06 µg/L where assumed to have potentially exceed the interim drinking

water standard. Sixty-five of the groundwater samples collected off-site potentially exceeded the interim guideline for drinking water.

- ∴ Thirty-one analytes were recorded above the LOR (Appendix B). The highest concentrations of individual compounds observed were for PFHxS at 26 µg/kg, followed by PFOS, 6:2 FTS, PFHxA and PFPeA.
- ∴ The median concentration of the sum of PFOS + PFHxS was 0.86 µg/L on-site and 0.093 µg/L off-site.
- ∴ The median concentrations for PFOS, PFHxS, PFOA and sum of PFOS + PFHxS of samples collected on-site were an order of magnitude higher than the median concentrations of the samples off-site. It is noted that the median concentrations were calculated from samples above the LOR.
- ∴ The median PFOA concentration of on-site and off-site samples was below both the median PFOS and PFHxS concentrations. It is noted that the median concentrations were calculated using only samples that exceed the LOR.
- ∴ The 65 off-site samples that exceeded the drinking water guideline (when taking the UOM into account) were collected from a total of 19 groundwater bores. Of those, 8 bores were identified (by the occupants of the property) as being used for drinking historically, occasionally or currently (at the time of sampling).
- ∴ All off-site samples that exceeded 0.06 µg/L for the sum of PFOS + PFHxS were collected from groundwater bores that also exceeded the actual drinking water guideline of 0.07 µg/L.

Table 11: Groundwater Sampling Results Summary – On-Site

Number of Samples	Compound	Concentration Range ¹	No. Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Guideline
56	PFOA	< LOR - 2.87	49	0.15	NA
56	PFOS	< LOR - 14	48	0.44	NA
56	PFHxS	< LOR - 26	50	0.33	NA
56	PFOS + PFHxS	< LOR - 31.7	49	0.86	NA

Notes:

1. All values in µg/L.
2. Only samples above the Limit of Reporting (LOR) were included in the calculations. The median concentration was not calculated when there were less than three samples above LOR.

'NA' – Not Applicable

Table 12: Groundwater Sampling Results Summary – Off-Site					
Number of Samples	Compound	Concentration Range ¹	No. Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Guideline ²
241	PFOA	< LOR - 0.15	91	0.02	0
241	PFOS	< LOR - 0.84	107	0.028	NA
241	PFHxS	< LOR - 1.2	112	0.066	NA
241	PFOS + PFHxS	< LOR - 1.3	114	0.093	65 ⁴

Notes:

- All values in µg/L.
- Only samples above the Limit of Reporting (LOR) were included in the calculations. The median concentration was not calculated when there were less than three samples above LOR.
- Exceeds Interim Guidance Level for Drinking Water, MoH 2017. Guideline sourced from Australian Government Department of Health - Health Based Guidance Values for PFAS accessed on 01/06/2017 from: [www.health.gov.au/internet/main/publishing.nsf/content/A12B57E41EC9F326CA257BF0001F9E7D/\\$File/PFAS-interim-health-reference-values-june2016.pdf](http://www.health.gov.au/internet/main/publishing.nsf/content/A12B57E41EC9F326CA257BF0001F9E7D/$File/PFAS-interim-health-reference-values-june2016.pdf).
- Total number of samples that exceed 0.06 µg/L.

'NA' – Not Applicable

5.4.1.1 Health Canada Water Screening Values for other PFAS

Recent additions made to the Health Canada Drinking Guidelines (HC, 2019) have extended to include drinking water screening values for nine more PFAS compounds (refer Table 6), there are no New Zealand guidelines for these compounds. The screening values were compared to off-site groundwater samples.

- ✦ No off-site samples exceeded the screening values for PFBS, PFBA and 8:2 FTS.
- ✦ Thirty-eight samples were above the screening values for PFPeA.
- ✦ Twenty-five samples were above the screening values for PFHxA.
- ✦ Fifteen samples were above the screening values for PFNA.
- ✦ Eight samples were above the screening values for PFHpA.
- ✦ Four samples were above the screening values for 6:2 FTS.

5.4.2 Surface Water

Surface water samples were collected from on-site and off-site locations between May 2015 and September 2018.

A total of 147 samples were taken (25 on-site and 122 off-site) were analysed for PFAS. The results have been compared to the ANZECC 95% ecological protection guideline of 220 µg/L for PFOA and 0.13 µg/L for PFOS. The results are summarised in Table 13 and 14.

Of the 147 surface water samples collected:

- ∴ PFOS concentrations were above the LOR in 24 of the 25 samples collected on-site, and 92 out of the 122 samples collected off-site. These samples were collected from 47 different locations.
- ∴ As discussed in Section 5.2.1, all samples where PFOS concentrations were above LOR exceeded the ANZECC 99% species protection guideline. Some of the samples below the LOR could potentially have exceeded the ANZECC 99% species protection guideline.
- ∴ Twenty-seven analytes were recorded above the LOR (Appendix B). The highest concentrations of individual compounds observed on-site were for PFOS and off-site were for PFHxS.
- ∴ The median concentration for PFOS was an order of magnitude higher for the surface water samples collected on-site than the off-site samples. The median concentrations for PFHxS and the sum of PFOS + PFHxS were the same order of magnitude for samples collected on-site and off-site.
- ∴ 14 of the 25 on-site samples (56%) exceeded the ANZECC 95% species protection guideline for PFOS.
- ∴ 31 of the 122 off-site samples (25%) exceeded the ANZECC 95% species protection guideline for PFOS.

Table 13: Surface Water Sampling Results Summary – On-Site ¹					
Number of Samples	Compound	Concentration Range ²	No. Sample > LOR	Median Concentration of Detects ^{2,3}	Exceeds Guideline ⁴
25	PFOA	< LOR – 0.78	22	0.069	0
25	PFOS	< LOR – 2.6	24	0.205	14
25	PFHxS	< LOR – 2.2	24	0.103	NA
24 ⁵	PFOS + PFHxS ⁵	< LOR – 4.8	24	0.32	NA

Notes:

1. A sample, Int1, was removed from the summary statistics as the water sample came from the inceptor which treated water from the fire training area.
2. All values in µg/L.
3. Only samples above the Limit of Reporting (LOR) were included in the calculations.
4. Exceeds the ANZECC 95% Ecological Protection Guideline. Referenced in HEPA, 2018. PFAS National Environmental Management Plan. Heads of EPA Australia and New Zealand. January 2018.
5. Where the PFOS + PFHxS was not reported in the laboratory report the result was calculated manually.

'NA' – Not Applicable

Table 14: Surface Water Sampling Results Summary – Off-Site					
Number of Samples	Compound	Concentration Range ¹	No. of Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Guideline ³
122	PFOA	0.001 - 0.76	89	0.019	0
122	PFOS	0.001 – 2.3	92	0.047	31
122	PFHxS	< LOR – 2.4	95	0.07	NA
122	PFOS + PFHxS ⁴	< LOR - 4.5	95	0.12	NA

Notes:

- All values in µg/L.*
- Only samples above the Limit of Reporting (LOR) were included in the calculations.*
- Exceeds the ANZECC 95% Ecological Protection Guideline. Referenced in HEPA, 2018. PFAS National Environmental Management Plan. Heads of EPA Australia and New Zealand. January 2018.*
- Where the PFOS + PFHxS was not reported in the laboratory report the result was calculated manually.*

NA – Not Applicable

5.4.3 Sediment

Sediment samples were collected from stormwater infrastructure on-site and from stormwater drains, ponds and natural waterways off-site between April 2017 and June 2018. A total of 19 samples were taken (3 on-site and 16 off-site) were analysed for PFAS. The results have been compared to the Norway Sediment Quality Guideline for chronic exposure of 0.22 mg/kg for PFOS. The results are summarised in Tables 15 and 16.

Of the 19 sediment samples collected:

- ∴ Fifteen analytes were recorded above the LOR (Appendix B). The highest concentrations of individual compounds observed were for PFOS with 0.11 mg/kg, followed by PFHxS, 6:2 FTS, 8:2 FTS and PFHxS.
- ∴ PFOS concentrations were above LOR in all three samples collected on-site, and seven of the 16 samples collected off-site.
- ∴ The median concentration for PFOS and the sum of PFOS + PFHxS had the same order of magnitude for samples collected on-site and off-site. The median concentrations for PFOA and PFHxS from samples collected on-site and off-site were not compared as the median concentrations for the on-site samples were not calculated.
- ∴ The maximum concentration of PFOS observed in a sample collected on-site was 0.032 mg/kg, the maximum concentration in a sample collected off-site was 0.11 mg/kg.
- ∴ No samples exceeded the sediment quality screening value.

Table 15: Sediment Sampling Results Summary – On-Site					
Number of Samples	Compounds	Concentration Range ¹	No. of Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Guideline ³
3	PFOA	< LOR - 0.0016	2	NC	NA
3	PFOS	0.0049 - 0.032	3	0.016	0
3	PFHxS	< LOR – 0.004	2	NC	NA
3	PFOS + PFHxS	0.0049 - 0.036	3	0.019	NA

Notes:

- All values in mg/kg (Dry Weight).
- Only samples above the Limit of Reporting (LOR) were included in the calculations. The median concentration was not calculated when there were less than three samples above LOR.
- Exceeds Norway Sediment Quality Guidelines. Obtained from Bakke, T., Kailquist, T., Ruus, A., Breedveld, G. and Huylland, K. (2010). *Journal of Soils and Sediment*, 10, pp 172-178.

'NA' – Not Applicable
'NC' – Not Calculated

Table 16: Sediment Sampling Results Summary – Off-Site					
Number of Samples	Compound	Concentration Range ^{1 1}	No. of Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Guideline ³
16	PFOA	< LOR - 0.0025	3	0.0015	NA
16	PFOS	< LOR - 0.11	7	0.01	0
16	PFHxS	< LOR - 0.0081	3	0.0054	NA
16	PFOS + PFHxS	< LOR - 0.12	7	0.01	NA

Notes:

- All values in mg/kg (dry weight).
- Only samples above the Limit of Reporting (LOR) were included in the calculations.
- Exceeds Norway Sediment Quality Guidelines. Obtained from Bakke, T., Kailquist, T., Ruus, A., Breedveld, G. and Huylland, K. (2010). *Journal of Soils and Sediment*, 10, pp 172-178.

'NA' – Not Applicable

5.4.4 Soil

Thirty-four soil samples were collected on-site and analysed for PFAS. The results are summarised in Table 17. The results were compared to the human health screening value for commercial/industrial soils of 50 mg/kg for PFOA and 20 mg/kg for sum of PFOS + PFHxS.

Of the soil samples collected:

- ∴ PFAS concentrations were above the LOR in 26 samples. Twenty-one analytes were recorded above the LOR (Appendix B).
- ∴ The highest concentrations were of PFOS at 0.65 mg/kg, followed by 6:2 FTS, 8:2 FTA, PFUnDA, PFNA.
- ∴ No samples on-site exceeded the soil screening guideline for commercial/industrial areas for the sum of PFOS + PFHxS.

Table 17: Soil Sampling Results Summary – On-Site					
Number of Samples	Compound	Concentration Range ¹	No. of Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Guideline ³
34	PFOA	< LOR - 0.034	21	0.0039	0
34	PFOS	< LOR - 0.65	25	0.012	NA
34	PFHxS	< LOR – 0.015	13	0.0019	NA
34	PFOS + PFHxS	< LOR - 0.66	26	0.0117	0

Notes:

1. All values in mg/kg (Dry Weight).
2. Only samples above the Limit of Reporting (LOR) were included in the calculations.
3. Exceeds the Human Health Screening Values – Industrial / Commercial. Referenced in HEPA, 2018. PFAS National Environmental Management Plan. Heads of EPA Australia and New Zealand. January 2018.

'NA' – Not Applicable

5.4.5 Biota

5.4.5.1 Fish

Seven fish samples were collected from the following species *Anguilla sp.*, (Eel) *Cyprinus carpio* (Carp), and *Gobiomorphus cotidanus* (Common Bully) at five off-site locations. The results have been compared to the human health trigger points for investigation for finfish of 5.2 µg/kg for sum of PFOS + PFHxS and 41 µg/kg for PFOA.

Of the seven fish samples collected:

- ∴ PFAS compounds were detected in all seven samples. Sixteen analytes were recorded above the LOR (Appendix B).
- ∴ The highest concentration was for the sum of PFOS + PFHxS with a maximum of 81 µg/kg in sample FS2.2 (a carp).

- ∴ All seven samples were above the FSANZ human health trigger level for investigation for PFOS and sum of PFOS+ PFHxS.
- ∴ The average PFOS concentration of fish (FS2.1, FS2.2 and FS4.1) in the Makowhai Stream was 45 µg/kg. When comparing to the MPI consumption guidelines, the applicable MPI consumption category is to limit consumption of fish caught in the Makowhai River for children to three servings per month (MPI, 2018). All other fish samples, with the exception of OHA_ADJ_FS04.2 were below 30 µg/kg and therefore below the consumption guideline. The total PFOS concentration of FS04.2 was 31 µg/kg which exceeds the first level of the consumption guideline, however as only one sample was collected from this site the average PFOS concentration cannot be calculated.

Table 18: Fish Sampling Results Summary – Off-Site

Number of Samples	Compound	Concentration Range ¹	No. of Samples > LOR	Median Concentration of Detects ¹²	Exceeds Trigger Value ³
7	PFOA	< LOR - 0.48	4	0.4	0
7	PFOS	11 - 80	7	23	7
7	PFHxS	< LOR – 5.1	7	1.9	NA
7	PFOS + PFHxS	13 – 81	7	23	7

Notes:

1. All values in µg/kg.
2. Only samples above the Limit of Reporting (LOR) were included in the calculations.
3. Exceeds FSANZ Trigger Value for Further Investigation. Assessment of potential dietary exposure to perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) occurring in foods sampled from contaminated sites – Table 8, Supporting Document 2. Food Standards Australia New Zealand (FSANZ), April 2017.

'NA' – Not Applicable.

5.4.5.2 Watercress

Six samples of watercress were collected off-site. The results have been compared to the human health trigger points for investigation for vegetables of 1.1 µg/kg for sum of PFOS + PFHxS and 8.8 µg/kg for PFOA.

Of the six watercress samples collected:

- ∴ PFAS compounds were above LOR in two samples. Eleven analytes were recorded above the LOR (Appendix B).
- ∴ The highest concentration was PFPeA with 4.7 µg/kg, followed by PFHxA, PFBA, sum of PFOS + PFHxS and PFOS.

- ∴ One sample, collected from a roadside drain, exceeded the FSANZ human health trigger level for investigation.

Table 19: Watercress Sampling Results Summary – Off-Site

Number of Samples	Compound	Concentration Range ¹	No. of Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Trigger Value ³
6	PFOA	< LOR - 0.57	1	NC	0
6	PFOS	< LOR - 0.7	1	NC	0
6	PFHxS	< LOR - 0.48	1	NC	NA
6	PFOS + PFHxS	< LOR – 1.2	1	NC	1

Notes:

- All values in µg/kg.
- Only samples above the Limit of Reporting (LOR) were included in the calculations. Median concentration was not calculated when there were less than three samples above LOR.
- Exceeds FSANZ Trigger Value for Further Investigation. Assessment of potential dietary exposure to perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) occurring in foods sampled from contaminated sites – Table 8, Supporting Document 2. Food Standards Australia New Zealand (FSANZ), April 2017.

'NA' – Not Applicable.
'NC' – Not Calculated.

5.4.5.3 Eggs

Eggs were collected from a nearby farm and compared to the Human Health Trigger Points for Investigation for poultry eggs of 11 µg/kg for sum of PFOS + PFHxS and 85 µg/kg for PFOA.

Of the 31 egg samples collected:

- ∴ PFAS compounds were above LOR in 29 samples.
- ∴ Nine analytes were recorded above the LOR (Appendix B).
- ∴ The highest concentrations of individual compounds observed were for PFOS with 16 µg/kg, followed by PFHxS, PFNA and PFHpS.
- ∴ The maximum sum of PFOS + PFHxS concentration was 18 µg/kg.
- ∴ Seven samples were above the FSANZ human health trigger level for investigation for sum of PFOS+ PFHxS.

Table 20: Egg Sampling Results Summary – Off-Site					
Number of Samples	Compound	Concentration Range ¹	No. of Samples > LOR	Median Concentration of Detects ^{1,2}	Exceeds Trigger Value ³
31	PFOA	< LOR - 0.3	2	NC	0
31	PFOS	< LOR – 16	29	6.3	1
31	PFHxS	< LOR – 4.7	28	1.85	NA
31	PFOS + PFHxS	< LOR – 18	29	7.8	7

Notes:

- All values in µg/kg.
- Only samples above the Limit of Reporting (LOR) were included in the calculations. Median concentration was not calculated when there were less than three samples above LOR.
- Exceeds FSANZ Trigger Value for Further Investigation. Assessment of potential dietary exposure to perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) occurring in foods sampled from contaminated sites – Table 8, Supporting Document 2. Food Standards Australia New Zealand (FSANZ), April 2017.

'NA' – Not Applicable.
'NC' – Not Calculated.

5.4.5.4 Meat

Eight samples of various animal tissue were collected from private properties off-site. Meat samples included beef meat, lamb meat and pork meat. The results have been compared to the human health trigger points for investigation for mammalian meat of 3.5 µg/kg for sum of PFOS + PFHxS and 28 µg/kg for PFOA.

Of the eight meat samples collected:

- ∴ PFAS was above LOR in six samples.
- ∴ Six analytes were recorded above the LOR (Appendix B). The highest concentrations of individual compounds observed were for PFOS at 1.2 µg/kg, followed by PFHxS. No samples were above the FSANZ human health trigger level for investigation for PFOS and the sum of PFOS + PFHxS.

Table 21: Meat Sampling Results Summary – Off-Site					
Number of Samples	Compound	Concentration Range ¹	No. of Sample > LOR	Median Concentration of Detects ^{1,2}	Exceeds Trigger Value ³
8	PFOA	< LOR	0	NC	0
8	PFOS	< LOR – 1.2	4	0.0.37	0
8	PFHxS	< LOR – 0.38	3	0.38	NA
8	PFOS + PFHxS	< LOR – 1.4	6	0.38	0

Notes:

1. All values in µg/kg.
2. Only samples above the Limit of Reporting (LOR) were included in the calculations. Median concentration was not calculated when there were less than three samples above LOR.
3. Exceeds FSANZ Trigger Value for Further Investigation. Assessment of potential dietary exposure to perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) occurring in foods sampled from contaminated sites – Table 8, Supporting Document 2. Food Standards Australia New Zealand (FSANZ), April 2017.

'NA' – Not Applicable.
'NC' – Not Calculated.

5.4.5.5 Offal (Mammalian)

Two samples of mammalian offal tissue were collected off-site. The results have been compared to the human health trigger points for investigation for mammalian offal of 96 µg/kg for sum of PFOS + PFHxS and 264 µg/kg for PFOA.

Of the two offal samples collected:

- ∴ PFAS was above LOR in both samples.
- ∴ Six analytes were recorded above the LOR (Appendix B). The highest concentrations of individual compounds observed were for PFOS 7.9 µg/kg), followed by PFHxS.
- ∴ No samples were above the FSANZ human health trigger level for investigation for PFOS and the sum of PFOS+ PFHxS.

Table 22: Offal Mammalian Sampling Results Summary – Off-Site					
Number of samples	Compound	Concentration Range ¹	No. of Sample > LOR	Median Concentration of Detects ^{1,2}	Exceeds Trigger Value ³
2	PFOA	< LOR	0	NC	0
2	PFOS	4.8 – 7.9	2	NC	0
2	PFHxS	< LOR – 0.92	1	NC	NA
2	PFOS + PFHxS	5.7 – 7.9	2	NC	0

Notes:

- All values in µg/kg.
- Only samples above the Limit of Reporting (LOR) were included in the calculations. Median concentration was not calculated when there were less than three samples above LOR.
- Exceeds FSANZ Trigger Value for Further Investigation. Assessment of potential dietary exposure to perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS) occurring in foods sampled from contaminated sites – Table 8, Supporting Document 2. Food Standards Australia New Zealand (FSANZ), April 2017.

'NA' – Not Applicable.
'NC' – Not Calculated.

5.4.5.6 Milk

Two samples of goat’s milk were collected from a nearby farm. No PFAS compounds were detected in either sample.

5.4.6 NEMP 2.0 Draft Guidelines

The draft update of the PFAS National Environmental Management Plan 2.0 (NEMP 2.0) by HEPA includes a new indirect exposure ecological guideline for soil (HEPA, 2019). The indirect exposure guideline values are intended to account for various pathways and bioaccumulation that can occur for organisms that are not in direct contact with PFAS contaminated soil. The guideline is based on exposure of a secondary consumer (e.g. animals that consume organism which have been primarily exposed to PFAS compounds in soils i.e. earthworms or other macroinvertebrates). At Ohakea the secondary consumer is most likely to be birds. However, birds are controlled on site to limit the potential effects on air traffic on the base which may limit their exposure. Additionally, knowledge of the area of contaminated soil is also limited. Therefore, the draft guideline was not applied to the samples collected from the base at Ohakea because the assumptions have not been verified due to incomplete knowledge of exposure pathways.

The draft terrestrial biota guideline for bird eggs for ecological exposure protective of birds was derived to protect the survival and development of bird eggs and chicks. The guideline for the sum of PFOS + PFHxS is 0.2 µg/kg. The draft guideline was developed for the lowest observed adverse effects level with

a safety factor of 10. However, due to limited bird toxicological data and recent studies indicating birds can be affected at lower concentration; the new guideline was adjusted by an additional uncertainty factor of 10. The new draft guideline is an indication of the level at which adverse effects may start to occur.

Unfertilised poultry eggs were sampled for this investigation (Section 5.4.5), and several samples exceeded the ecological exposure protective of birds' guideline. These results indicate that raising of chickens may not be appropriate at the location where the unfertilised eggs were collected.

5.4.7 Groundwater Transect

Evidence of transformation of PFAS was examined by comparing the molar concentration of PFAS from several groundwater wells extending south-west from the base. To determine if molar concentrations are increasing or decreasing in concentration with distance from the base.

The molar concentration⁸ for seven PFAS compounds (PFOS, PFOA, PFHxS, PFHxA, PFPeA, PFBA, and 6:2 FTS) were calculated along a transect extending from the base towards the edge of the plume to assess the behaviour of PFAS in groundwater (Figure 4).

The molar concentrations of samples from one on-site well (FTA_MW4) and four off-site wells (GW45, GW29, GW2 and GW30) are shown in Appendix C. The following was observed:

- ✦ All measurable PFAS had higher concentrations on-site and generally decreased with distance from the base with the exception of PFHxS (Chart 1, Figure 4).
- ✦ The ratio of PFHxS to PFOS increased with distance from the base (Chart 2, Figure 4).
- ✦ The ratio of 6:2 FTS and its terminal breakdown products PFHxA, PFPeA, PFBA stayed the same off-site regardless of distance from the base, however, there was higher ratio of 6:2FTS on-site (Chart 3, Figure 4).
- ✦ In the wells examined along the transect, PFPeA generally had the highest molar concentration both on and off-site, followed by PFOS.
- ✦ PFOA generally had the lowest molar concentrations.

⁸ Molar concentrations are related to the number of moles of a solute. When looking at chemical and biological transformation, the weight of a compound may be affected but not the number of mols present. Comparing molar concentrations allows for the differences in atomic weight between molecules.

5.4.8 Surface Water Transect (Makowhai Stream)

The results of surface water samples collected along the length of the Makowhai Stream from Ohakea towards the edge of the plume were compared to understand the behaviour of PFAS in surface water, in particular how the concentration of PFAS varies with increasing distance from Ohakea.

The concentration of PFOS in samples collected from the Makowhai Stream in February 2018 are shown on Chart 4. The results show that the lowest concentrations of PFOS were observed closest to the site. PFOS concentration peaked in SW20 approximately 1.5 km downstream from the base. Thereafter, PFOS decreased with distance from the base.

Over four rounds, lower concentrations were observed during the winter months for all sampling locations on the Makowhai Stream, with a peak during summer months (Chart 5).

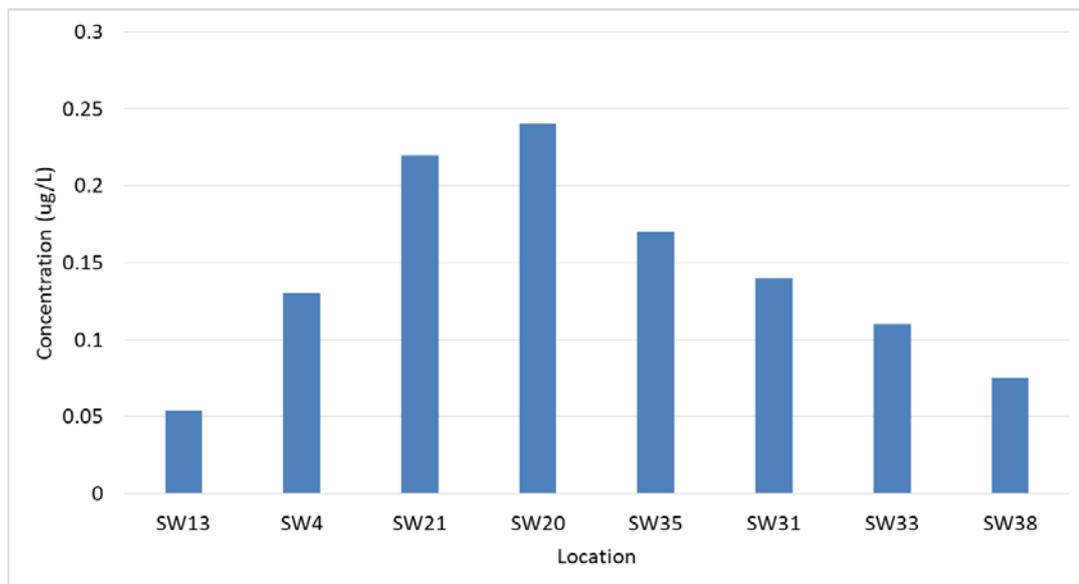


Chart 4. Concentration of PFOS in the Makowhai Stream with increasing distance from the base from left to right.

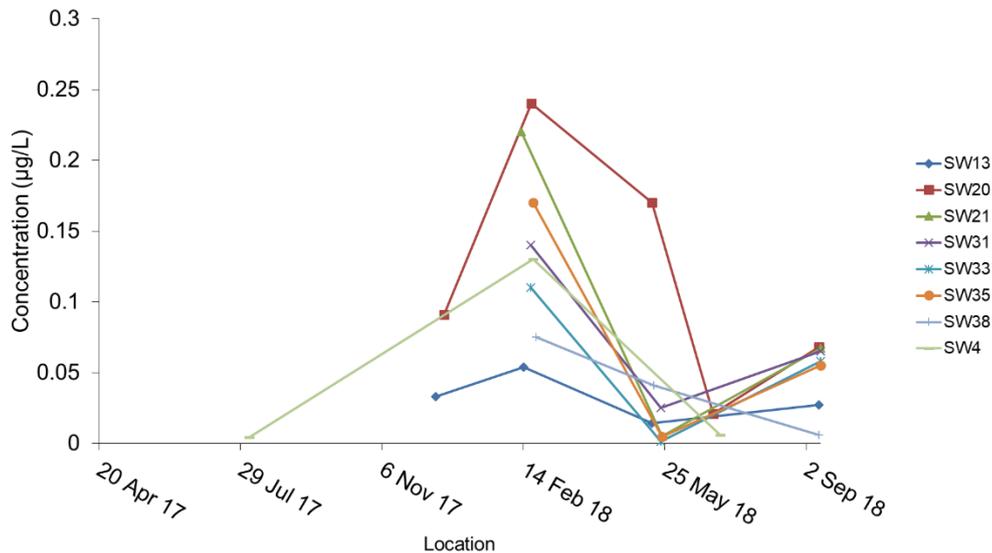


Chart 5. PFOS concentrations in surface water in the Makowhai Stream between April 2017 and September 2018.

5.5 Discussion

5.5.1 Results Summary

PFAS was detected in all media sampled with the exception of goat's milk.

Exceedances of applicable guidelines and trigger values were observed for groundwater (drinking water), surface water, eggs, fish tissue and watercress.

In all media tested on-site PFOS was the most commonly detected and present in the highest concentration of all compounds that were analysed for.

In biota and sediment sampled off-site, PFOS was present in greater concentrations than other PFAS compounds. However, in groundwater and surface water sampled off-site PFHxS concentrations were generally higher than PFOS concentrations.

Comparatively, PFOA was observed in relatively low concentrations across all media both on-site and off-site.

Based on comparison of the on-site and off-site sample results, the majority of PFAS mass in groundwater remains on-site. Median sum of PFOS + PFHxS is an order of magnitude higher than the median of off-site samples.

In addition, there is potentially significantly greater mass of PFAS in the unsaturated soil (i.e. soil above the water table) than in the groundwater.

5.5.2 PFAS Mass Distribution Estimate

To estimate the distribution of PFAS mass that might be expected in the unsaturated soil versus the amount that might be expected in the groundwater, a comparison of shallow soil samples and shallow groundwater samples collected from the same locations on base was undertaken. This involved comparing the concentration of soil samples collected from the same location to the concentration of groundwater samples from the same area. Where possible, groundwater samples collected at approximately the same time as the soil samples were used. Three locations on base were investigated, and these are listed below (Figure 2):

- ✧ FTA (MW1 and MW2) – 6 soil samples
- ✧ MW5 – 4 soil samples
- ✧ MW9 – 6 soil samples

To estimate the mass of PFAS in the unsaturated soil versus the mass in the underlying groundwater water at each of the 3 sites, the ratio of PFAS in soil versus groundwater was calculated by dividing the geometric mean of PFOS and PFHxS in soil samples (in µg/kg) by the corresponding concentration PFOS and PFHxS in groundwater (in µg/L)⁹.

The results are presented in Table 23 and show a wide range in ratios. At the Fire Training Area, the amount of mass in the soil is approximately 10 times that present in the groundwater. At MW5, the amount of mass in the soil is approximately 200 times that present in the groundwater. At MW9, the amount of mass in the soil is approximately 100 times that present in the groundwater.

Table 23: Ratio of PFAS in Soil to Groundwater - Unsaturated Zone ¹				
Site	Matrix	Relative Amount of PFOS	Relative Amount of PFHxS	Relative Amount of PFOS + PFHxS
FTA	Silt	10.9	0.5	7.0
MW5	Unknown	199	9.5	106
MW9	Silt	107	0.6	45
Geometric mean		62	1	32

1. Units soil ug/kg; water ug/L

⁹ This is similar to calculating the K_d . K_d is the calculation of water/soil mixture which is in equilibrium with each other. The calculation of groundwater/soil values in Table 23 are not in direct contact with other.

Although there are only three sites, it can be seen that PFOS concentrations are significantly higher in the unsaturated soil relative to the groundwater when compared to PFHxS. This is in agreement with the findings of other investigations, undertaken overseas, into the partitioning of PFAS compounds (e.g. CONCAWE, 2016; AECOM, 2017). The geometric mean for PFOS and PFHxS (although not directly comparable with K_d) is within the range of the K_d values presented in Table 1.

The results also indicate that, at these locations, there is a significantly greater mass of PFAS (particularly PFOS, less so for PFHxS) in the unsaturated soil than in the groundwater. This finding is significant for the future prediction of the plume, as the mass of PFAS in unsaturated soil may continue to be a source of PFAS to groundwater for many years. Meaning that, even though fire training with AFFF ceased at Ohakea in 2015 it will be many years before the mass of PFAS in soils at Ohakea is depleted.

5.5.3 Groundwater

5.5.3.1 Plume Composition

Due to the mobility and persistence of PFAS in the environment, PFAS can form large plumes depending on the hydrological and geological setting (ITRC, 2018b). In the case of Ohakea, the known PFAS plume extends approximately 3 km and is approximately 5 km wide. However, the southern extent of the plume has not been determined.

A significant portion of the PFAS mass in groundwater has been retained on the base, where it is likely to leach to groundwater slowly, over time (predicted mass in groundwater illustrated in Diagram 3, model predictions are discussed further in Section 7). PFAS concentrations in groundwater were higher on-site than off-site.

PFAS concentrations off Base generally decreased with distance with the exception of PFHxS. PFHxS can form due to the breakdown of other PFAS compounds but is also a component of the legacy AFFF used by NZDF. It is difficult to know whether the recorded concentration of PFHxS is primarily from direct application or from transformation.

These patterns are consistent with several international studies which also estimate that a significant mass is retained in the source area (i.e. unsaturated zone and saturated zones) and generally decrease with distance from the source (Dauchy *et al.*, 2017, Weber *et al.*, 2017). In some cases, 80-90% of PFOS is known to be retained in the source area (AECOM, 2017). Old fire-fighting training areas can be long term sources of PFAS for many decades, if not hundreds of years (Badel *et al.*, 2015).

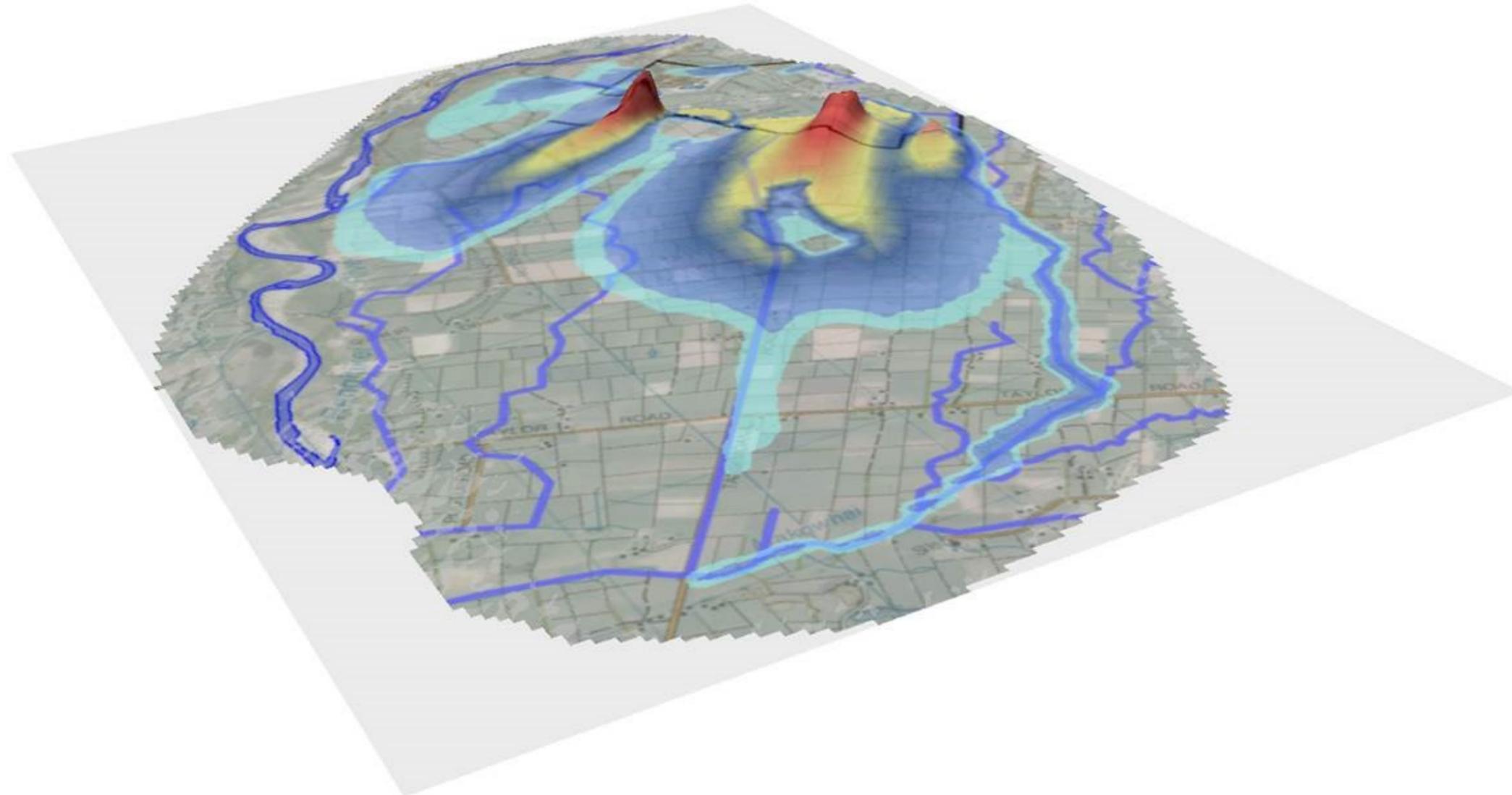


Diagram 3: Predicted mass of PFOS + PFHxS in groundwater > 0.06 ug/L

5.5.3.2 Transformation

There is some limited evidence that transformation of polyfluorinated compounds is occurring based on the molar concentration of wells in the plume transect. Possible evidence for transformation of PFAS is occurring is:

1. Increase in the relative ratio of molar concentration of PFHxS/PFOS with distance from the source. This may be due to unknown longer chain precursors compounds are degrading to PFHxS and/or the fact that PFHxS is more mobile in groundwater which is causing the relative ratio of these two compounds to change.
2. The decrease of 6:2 FTS between on-site and off-site monitoring wells. However, it is possible that this decrease may be due to changes in the formulation used within the AFFF and/or 6:2 FTS being strongly absorbed to soils.
3. The presence of short chain PFCA such as PFPeA, PFHxA and PFBA may be an indicator of transformation. However, we cannot rule out the presence of short chain PFCAs in the parent foams. However, PDP analysis of modern foams indicates that's that there are no to very low concentrations of short chain PFCAs in raw AFFF product.

Polyfluorinated compounds such as 6:2 FTS are known to transform into terminal short chain PFCAs such as PFHxA, PFPeA and PFBA (Weber *et al.*, 2017). When considering the plume transect, there was little evidence of transformation of 6:2 FTS into terminal PFCAs in the plume. PDP expected that ratio would change with distance as 6:2 FTS concentrations decrease (due to degradation) and the concentration of the terminal products increased. However, 6:2 FTS and its breakdown products showed constant ratios regardless of distance from the base.

Conversely, PFPeA was a major component of the plume composition despite not being known as a component of AFFF foams commonly used by NZDF (3M, Ansul and Chemguard). This indicates that some transformation of unmeasurable precursor compounds is occurring within the plume.

Based on the data above and TOPA analysis of a variety of AFFF concentrate there is currently no evidence that abiotic or biotic transformation are increasing the concentration of PFOS (C8) but there is limited evidence that these processes maybe increasing the concentration of PFHxS (C6). It is possible over time that the relative ratio of PFHxS to PFOS may continue to increase.

5.5.3.3 Seasonal Changes

The short sampling period was not sufficient for seasonal trends to be observed in groundwater. Some fluctuations are expected over the seasons, however, no discernible seasonal patterns were found.

5.5.4 Surface Water and Sediment

PFAS has been observed in surface water, and to a lesser extent sediment, in the Makowhai Stream and its tributaries but not in the Rangitikei River. Concentrations of PFAS in the Makowhai Stream are low immediately adjacent to the base, peaking approximately 1.5 km from the base. One potential mechanism for this is the influence of groundwater recharge where PFOS concentrations in the stream are highest.

In general, lower concentrations of PFOS were observed in surface water with increasing distance from the base. Lower concentrations reflect diluting inflows of surface water from the wider catchment as the water moves away from the source of PFOS.

During the short sampling period, higher concentrations of PFOS were observed in the Makowhai Stream in summer months and lower concentrations in the wetter winter months. Further sampling would be necessary to establish if this is a consistent pattern.

These results illustrate that complex interaction between groundwater and surface water at Ohakea is occurring and the potential for groundwater and surface water to be both a source, pathway and a sink of PFAS.

5.5.5 Biota

Of the limited sampling conducted, the highest concentrations were observed in fish, the highest of those were from fish in the Makowhai Stream. Fish which contained PFAS were located between 1.5 and 6 km from the Ohakea base.

This was followed by poultry eggs. Seven eggs, collected from a single property, were above the trigger point for further investigation for the sum of PFOS + PFHxS. The chickens on the property were kept for domestic use and not for commercial food supply. The Ministry of Primary Industries reviewed the sample results and provided advice to the owner of the chickens with respect to consumption of eggs from chickens raised on that property.

There were low concentrations of PFAS in farmed animal meat and offal, and no PFAS was detected above the LOR in milk.

5.5.6 Comparison of Fish, Surface Water and Sediment Results

Despite comparatively high PFAS concentrations in fish, PFAS concentrations were very low in sediment (Table 24). All surface water samples adjacent to fish sample locations were also low, except for SW20, which exceeded the ANZECC 95% ecological protection guideline for PFOS on two occasions. This may be attributed to bioaccumulation of PFAS in fish tissue.

Table 24: Fish samples and associated surface water and sediment results ¹

Fish Sample	PFOS (µg/kg)	Surface water sample	PFOS (µg/L)	Sediment Sample	PFOS (µg/kg)
FS1	11 - 13	SW14	0.004 – 0.018	SD1	0.11
FS1B	15	SW17	0.024 -0.026	-	-
FS2	24 -80	SW44	0.003 – 0.0099	SD6	< LOR
FS3	23	SW56	< LOR	SD7	0.0019
FS4	31	SW20	0.0021 - 0.240 ¹	SD5	< LOR

1. ANZECC 95% Species Protection - Technical Draft Default Guideline Value for PFOS is 0.13 µg/L.

6.0 Updated Conceptual Site Model

Based on the findings reported above, the conceptual site model (CSM) developed during the DSI has been updated. In general, CSM remains little changed in terms of sources, pathways and receptors.

The main finding from this investigation is the importance of surface water which acts a pathway for PFAS to migrate a significant distance from the original source. In addition, the interaction between surface water and groundwater means that, in certain conditions, surface water acts as a secondary source of PFAS to groundwater and vice versa.

A pictorial representation of the CSM is provided in Appendix D.

7.0 Groundwater Plume Modelling and Evolution Predictions

7.1 Approach to Plume Evolution Assessment

Groundwater flow and solute transport modelling (plume modelling), was employed to assist interpretations of how the existing sum of PFOS + PFHxS groundwater plume (the plume) may evolve into the future. A future prediction timeframe of 125-years (into the future) was adopted e.g. predictions from year

2019 to approximately year 2144. The timeframe was selected to provide high-level interpretations of potential plume evolution scenarios through the short, medium and long-term future.

The sum of PFOS + PFHxS was modelled because of its applicability to the interim drinking water guideline.

The questions this assessment sought to address are outlined below:

- ∴ How much contaminant mass (PFOS + PFHxS) may be present in the existing plume?
- ∴ What is the likely shape of the existing plume?
- ∴ What size is the likely area at or above the current drinking water guideline (≥ 0.06 ug/L PFOS + PFHxS with Uncertainty of Measurement (UOM))?
- ∴ What is the likely size of the plume in 125 years?
- ∴ How long before the plume may decay to be below drinking water guideline?
- ∴ What and where are the likely key receptors of the plume?
- ∴ How long may the plume take to deplete in area and mass, e.g. how long may it take to halve the current area and mass?

For all the above questions, it was agreed that 'best estimate' responses/commentary/diagrams would be provided. Please note that unless otherwise stated, all associated information within this section is considered to represent 'best estimate' only.

Predictions were set up within a 3D numerical groundwater flow and solute transport model. Model simulations were 'calibrated' to reasonably match the available observation data and conceptual hydrogeological understanding of the region and the plume at present day (present-day simulation). All relevant, available observation data collected from the NZDF sampling investigations and HRC borehole database were incorporated.

7.2 Key Assumptions

As with any type of prediction modelling, and particularly cases where long-term predictions are required, numerous assumptions and uncertainties are inherent. These assumptions and uncertainties must be realised and taken into consideration when making technical interpretations and/or communicating the interpretations to stakeholders.

From the present-day simulation, a 'best estimate' prediction scenario was run for 125 years into the future. Key assumptions adopted for this prediction are outlined below:

- ∴ Existing, known soil source zones (PFAS related HAIL areas shown in Figure 3) were set to input as a combined PFOS + PFHxS source (e.g. as a single species) into the shallow groundwater system at a selected concentration. Input concentration for each source zone was assigned based on available data and/or comparative estimate of product use/exposure for each area. As PFOS + PFHxS based AFFF products are no longer used onsite, the adoption of depleting sources¹⁰ was deemed a reasonable approach.
- ∴ Selected surface water drains that originate on-site and drain off-site were also set as input sources to the plume. These have been incorporated in attempt to simulate the effect of PFOS + PFHxS transported from base via the surface water route, and then discharging from surface water into the adjacent shallow groundwater/aquifer.
- ∴ Both the soil source and surface water source contaminant inputs were set to 'deplete' (or leach into groundwater) at a rate that decreased by 50% every 25-years (e.g. equivalent to a first-order decay rate with a 25-year half-life)¹¹. This has been adopted arbitrarily as a 'best estimate', and based on case work undertaken by Baduel *et al.* (2015) in Queensland. PDP undertook a limited literature review to identify potential leaching rates in soils and did not identify any other suitable estimate (see Section 2.3.2).
- ∴ Within the model, the combined PFOS + PFHxS contaminant species was assumed as completely conservative e.g. the contaminant is not allowed to 'breakdown' by any type of chemical or biological decay process. This assumption is based on the persistence of PFOS and PFHxS in particular. The literature indicates that breakdown of these particular contaminants is likely to be many decades and hence it was not considered an important factor for the predictions; and was excluded from the modelling for simplicity.
- ∴ Contaminant migration within the groundwater system was modelled using two approaches:
 - a) without effective 'contaminant retardation' – to simulate a highly mobile and dispersive groundwater system e.g. acts to create a larger and faster moving/expanding/contracting plume; and

¹⁰ 'Depleting Source' = the mass flux of contaminant entering the groundwater system from a source is assumed to be reducing over time.

¹¹ Half-life in this instance refers to the time that it takes for 50% of mass of PFOS absorbed onto soils to be leached out. It does not refer to degradation/break down of PFOS into other compounds

- b) with an estimated effective 'retardation factor' – to simulate the influence of contaminant sorption to aquifer material (such as silt, clay, sand particles) e.g. act to create a smaller but slower moving/expanding/contracting plume.

The detailed hydrogeological conceptual model, geological model, numerical model set-up, calibration, and prediction settings for the groundwater model are described in detail in the Supplementary Report Groundwater Modelling (PDP, 2019).

7.3 Existing Plume Interpretation

A general description of the existing plume (present-day simulation) is provided below, and an interpreted extent is displayed graphically on Diagram 4. The interpreted existing plume extent (both with and without retardation) together with groundwater sample locations is shown on Figure 5.

- ∴ The majority of the existing PFOS + PFHxS groundwater plume is likely to have formed from contaminant which has leached through the soil profile and into the groundwater system.
- ∴ Area of the plume (PFOS + PFHxS ≥ 0.06 ug/L) is estimated at 1100 ha to 1600 ha.
- ∴ Total PFOS + PFHxS mass of the existing plume (in solution) is estimated between 50 kg to 70 kg. This is considered a best estimate but contains significant uncertainty.
- ∴ Even though PFOS + PFHxS containing product is no longer used on site, a significant mass of contaminant is still likely to be contained within the surface soils/unsaturated zone from historic use. These areas are termed 'Soil Source Zones' (refer to HAIL areas in Figure 3) and their presence is expected to provide continued leaching of contaminant to groundwater.
- ∴ At least 13 individual onsite Soil Source Zones are either known or suspected and are contributing to the overall plume (the model assumes these are the only sources of PFAS). In theory, each Soil Source Zone is likely to be producing an individual plume, but due to the geographical spread and nature of the groundwater flow system beneath the wider Ohakea site, these individual plumes have coalesced into essentially a single plume e.g. a greater plume comprised of a number of smaller plumes. The contour plot on Diagram 4 enables some differentiation of the individual plumes within the greater plume.
- ∴ Additional Soil Source Zones may also be present that are yet to be identified. If present, these may be producing additional plumes.

- ∴ Surface water has been identified as another key route pathway for PFOS + PFHxS contaminant to migrate from site and into groundwater. Surface water flow can move contaminants much faster than groundwater flow, and due to the strong connection between groundwater-surface water within the region, contaminant transport via surface water is a key influencing factor for the groundwater plume. There are three key conceptual methods for this:
 - Run-off containing PFOS + PFHxS that flows into streams/drains which exit the Ohakea Site e.g. run-off from the Soil Source Areas, or from contaminated concrete, etc. Further along the streams/drains, contaminant may discharge into the adjacent shallow groundwater system; where the stream is losing flow and/or during losing conditions.
 - Some areas of the groundwater plume are likely to discharge groundwater into streams/drains which are connected to groundwater e.g. are cut below the water table. This moves contaminant from the groundwater system into the surface water system, which can then re-discharge back into the shallow groundwater system.
 - Sediments within the streams/drains may adsorb PFOS + PFHxS (from either of the abovementioned methods), and then these sediments can effectively become off-site Soil Source Zones. These sediments may continue to leach contaminant to both the groundwater and surface water system.
- ∴ From the more southern Soil Source Zones e.g. FTA – the plume migrates in a generally SSE direction, and is interpreted to extend approximately 3 km from the site boundary in this direction (to the 0.06 ug/L limit).
- ∴ From the remaining western and northern Soil Source Zones– the plume migrates in a generally SW to W direction, and is interpreted to extend to the Rangitikei River (which is up to approximately 3 km).
- ∴ The thickness (e.g. the depth) of the groundwater plume to the 0.06 ug/L limit is generally not expected to extend greater than approximately 50 m below ground surface. This is primarily due to the interpretation that on a regional scale, deeper groundwater is generally upwelling e.g. deeper groundwater is moving upwards and into the shallow portion of the groundwater system. It is stressed that PFOS + PFHxS sampling from a range of depths has been limited, which to date, has prevented further validation of this concept.
- ∴ In locations where significant groundwater abstraction is occurring from deep boreholes, the action of pumping may pull the plume deeper than it would otherwise have migrated.

Graphical interpretation of the existing plume (PFOS + PFHxS ≥ 0.06 ug/L) is provided in Diagram 4 below, which contains both the non-retarded and retarded estimates. Both of these present-day estimates are considered equally likely; from a conceptual probability and statistical calibration standpoint. Hence the 'best estimate' of the existing plume is interpreted to lie within the range displayed on Diagram 4.

In addition to the extent of the plume above 0.06 ug/L displayed on Diagram 4, the maximum extent of the existing plume (as defined by 'above detection' or ≥ 0.001 ug/L (PFOS + PFHxS)), estimated at approximately 3600 ha, is displayed on Figure 5. The boundary of this area has been developed by consideration of known hydrogeological factors that will act to constrain the plume (geological unit boundaries, flow divides, fluvial depositional characteristics, contaminant transport processes etc.). While reference is made to the model predictions, its configuration is reliant more on separate assessment of the known hydrogeological features at the extremities to bound the domain in which the plume can move. However, it is still subject to some uncertainty dependent on the state of knowledge of the hydrogeology in the boundary areas. Hence, it should be considered a probability extent e.g. PFOS + PFHxS detection outside of this extent is considered unlikely, but not impossible.

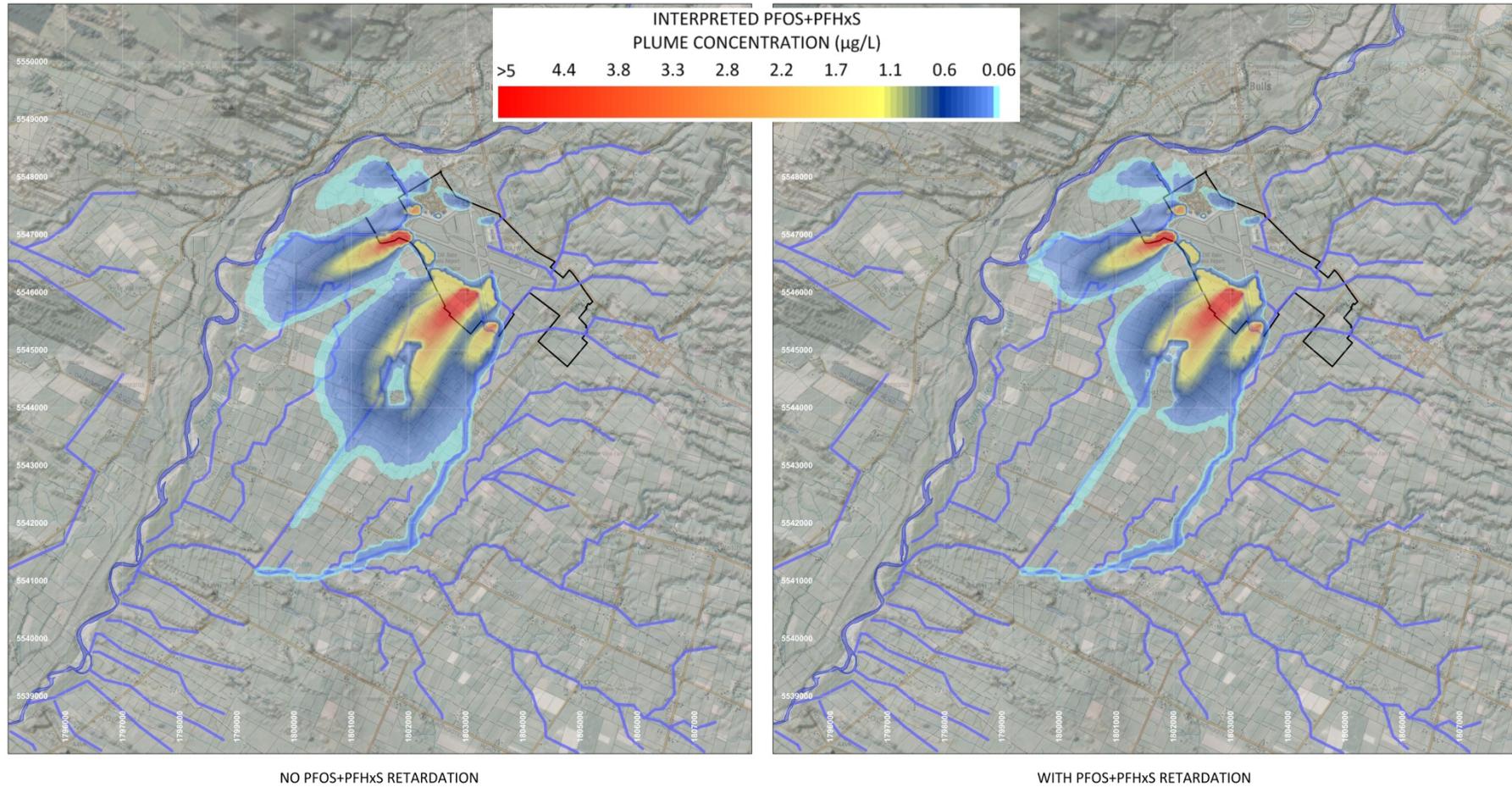


Diagram 4: Estimated Range of the Existing Plume

7.4 Best Estimate Future Plume Predictions and Interpretations

Key processes which influence the evolution of the plume are identified as:

- ∴ Groundwater flow direction and gradients. In general, the plume is predicted to evolve and migrate in agreement with groundwater flow.
- ∴ Groundwater flow boundaries. The plume is generally halted at groundwater flow boundaries e.g. major surface water features, groundwater flow divides, geological and topographical controls.
- ∴ Rate of contaminant input (from source zones to groundwater) vs rate of contaminant outflow (from groundwater to sinks). These assumptions, particularly the rate of source input, are influential to how large the plume evolves within the adopted timeframe e.g. if a greater rate of source input is adopted, a larger plume prediction would eventuate within the same time period, vice versa for a lesser rate.

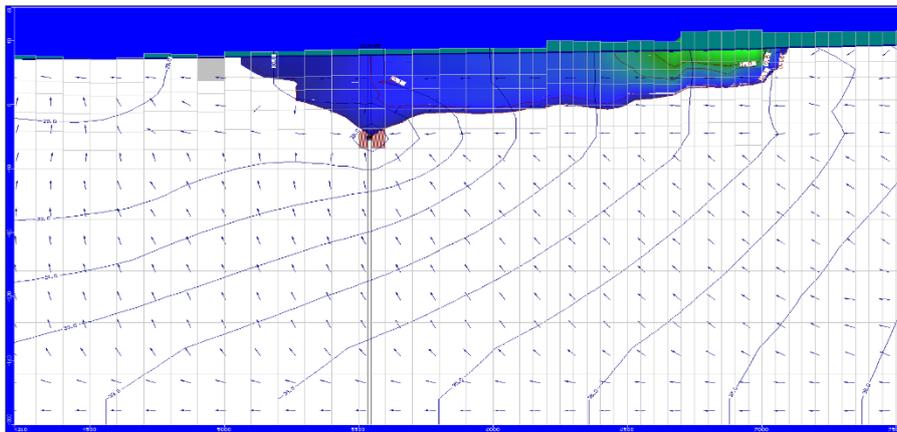
A general description of the 'best estimate' future plume predictions and interpretations is provided below. The predicted plume evolution over the adopted 125-year time period¹² is displayed graphically on Diagram 5, (no retardation) and Diagram 6, (with retardation). These represent the 'best estimate' range of plume evolution. The predicted maximum future plume extent (both with and without retardation) together with groundwater sample locations is shown on Figure 6.

- ∴ Plume is expected to continue migrating and expanding before beginning a slow process of depletion.
- ∴ The individual 'arms' of the plume are generally expected to continue advancing in their current direction of travel until they encounter a major groundwater discharge boundary (i.e. Rangitikei River or Makowhai Stream).
- ∴ The leading edge of the plume (e.g. the PFOS + PFHxS 0.06 ug/L contour), is expected to advance at a maximum velocity of approximately 50 m/year to 100 m/year in the primary direction of travel (e.g. longitudinal axis).
- ∴ The width of 'flanks' of the plume (PFOS + PFHxS >0.06 ug/L) are generally expected to remain similar to that of the present day prediction and into the medium term e.g. overall minimal expansion of plume width (transverse axis). Into the long-term (50 years +), the width of the plume

¹² A 125 year time period was chosen based on it being five times the depletion half-life used in the model. After five times the half-life the leaching rate of PFAS from the soil to the groundwater plume will be less than 3.2% of the initial leaching rate.

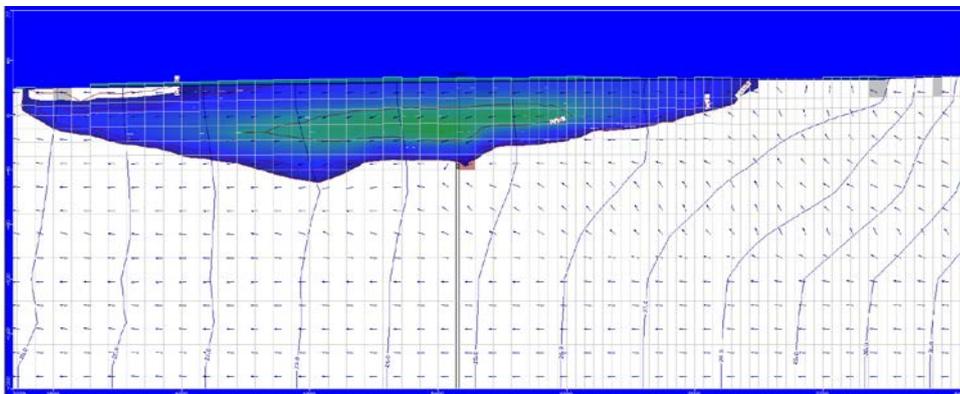
is expected to contract e.g. plume evolves into a longer but narrower shape.

- ∴ Within approximately 2 km from base Ohakea, the maximum vertical thickness of the plume is generally expected to remain at approximately 40 m or less. This can however be influenced by groundwater abstraction, which can locally 'drag' the plume downwards. An example is shown below from a borehole approximately 55 m depth with a 1200 m³/day take (annualised).



(Note: displayed prediction is an E-W long-section generally along the plume from the Run-Up pit, and is 25 years into future. Shaded area is PFOS + PFHxS ≥ 0.06 ug/L, blue lines are groundwater head contours, blue arrows are groundwater flow direction, shaded red square is the borehole pumping zone).

- ∴ As the plume migrates further from the Soil Source Zones, parts of the plume are predicted to encounter areas where vertical groundwater gradients (of the shallow system) are weaker or even slightly downwards. In these areas, vertical thickness of the plume (PFOS + PFHxS ≥ 0.06) is predicted to increase up to approximately 60 m.



(Note: displayed prediction is an E-W cross-section, across the plume width at approximately 3400 m downgradient from FTA, and is 75 years into future. Shaded area is PFOS + PFHxS ≥ 0.06 ug/L, blue lines are groundwater head contours, blue arrows are groundwater flow direction, shaded red square is the borehole pumping zone.)

- ∴ Understanding and predictions of plume evolution in the vertical direction is considered significantly more uncertain than for the longitudinal and transverse directions. This is primarily due to a paucity of data in the vertical direction, leading to a higher degree of uncertainty.
- ∴ The plume area (PFOS + PFHxS >0.06 ug/L) is expected to increase by approximately 30% to 60% before eventually depleting.
- ∴ The 'best estimate' of the likely time period for the existing plume (PFOS + PFHxS >0.06 ug/L) to decrease below its current area is estimated to be in the order of 75 years (no retardation) to 100 years (with retardation).
- ∴ The time to halve the existing plume area (PFOS + PFHxS >0.06 ug/L) is estimated to be greater than 100 years; best estimate 95 years (no retardation) to 125 years (with retardation).
- ∴ A maximum future extent of the plume (as defined by 'above detection' or $\geq 0.001 \text{ug/L}$ (PFOS + PFHxS) is estimated at approximately 4300 ha. As for the existing plume prediction, the boundary of this area has been developed by consideration of known hydrogeological factors that will act to constrain the onward movement of the plume (geological unit boundaries, flow divides, fluvial depositional characteristics, contaminant transport processes etc.). While reference is made to the model predictions, its configuration is reliant more on separate assessment of the known hydrogeological features at the extremities to bound the domain in which the plume can move. However, it is still subject to some uncertainty dependent on the state of knowledge of the hydrogeology in the boundary areas. Hence, it should be considered a probability extent e.g. PFOS + PFHxS detection outside of this extent is considered unlikely, but not impossible. The timing of when this maximum extent could be reached is likely to be in the long-term future i.e. >50 years.
- ∴ The overall mass of PFOS + PFHxS within the plume is expected to increase by approximately 20% to 30% before eventually depleting.
- ∴ It is estimated at 50 to 75 years for the plume to have decreased in mass below the present day mass. The time to halve the existing plume mass (PFOS + PFHxS) is estimated to be greater than 100 years (best estimate 110 to greater than 150 years).
- ∴ A summary table of the generalised plume evolution predictions over the short, medium, and long-term is provided in Table 25.

Table 25: Summary of Generalised 'Best Estimate' Plume Evolution Predictions and Interpretations			
Question	Present Day to Short Term (0 yrs to approx. 10 yrs)	Medium Term (approx. 10 yrs to 50 yrs)	Long Term (approx. 50 yrs to 125 yrs)
How much contaminant mass (PFOS + PFHxS) may be present in the plume?	50 to 70 kg (generally increasing)	65 k to 85 kg (likely contains peak)	85 kg to 20 kg (generally decreasing)
What is the likely area of the plume?	Max area generally increasing	Max area generally increasing (likely contains peak)	Max area generally decreasing
What size is the likely area at or above the current drinking water guideline (≥ 0.06 ug/L PFOS + PFHxS with UOM)?	1100 ha to 1400 ha (generally increasing)	1400 ha to 2200 ha (likely contains peak)	2000 ha to 100 ha (generally decreasing)
What and where are the likely key receptors of the plume?	Generally, all of the: Surface water bodies NW through SSW of the base, within 2 km to 3 km. Shallow wells/boreholes NW through SSW of the base, within 2 to 3 km.	Generally, all of the: Surface water bodies W through SSW of the base, within 6 km. Shallow wells/boreholes W through SSW of the base, within 6 km.	Some of the: Surface water bodies W through SSW of the base, within 6 km. Shallow wells/boreholes W through SSW of the base, within 6 km.
How fast is the leading edge of the plume advancing?	Maximum estimated at approximately 50 m/year to 100 m/year (likely contains peak advance rate)	Maximum estimated at approximately 50 m/year or less (advance of plume is generally slowing)	Plume edge has generally halted at the Rangitikei River and Makowhai Stream. (plume is no longer advancing)
What is the likely shape of the plume?	Three primary plume 'arms'. Shape remaining generally similar to the present day prediction but beginning to elongate.	Evolving from three primary 'arms' towards only 'two' primary arms. The smaller northern arm is depleting, while the remaining southern and western arms continue to elongate.	Continued elongation of the two primary arms, until a maximum length is reached. Width of the plume arms begins to significantly decrease, and plume begins to break apart from the primary onsite source areas.
Comments on the expected level of uncertainty associated with the prediction	Likely to contain greater certainty.	Contains significant uncertainty.	Likely to contain the greatest level of uncertainty

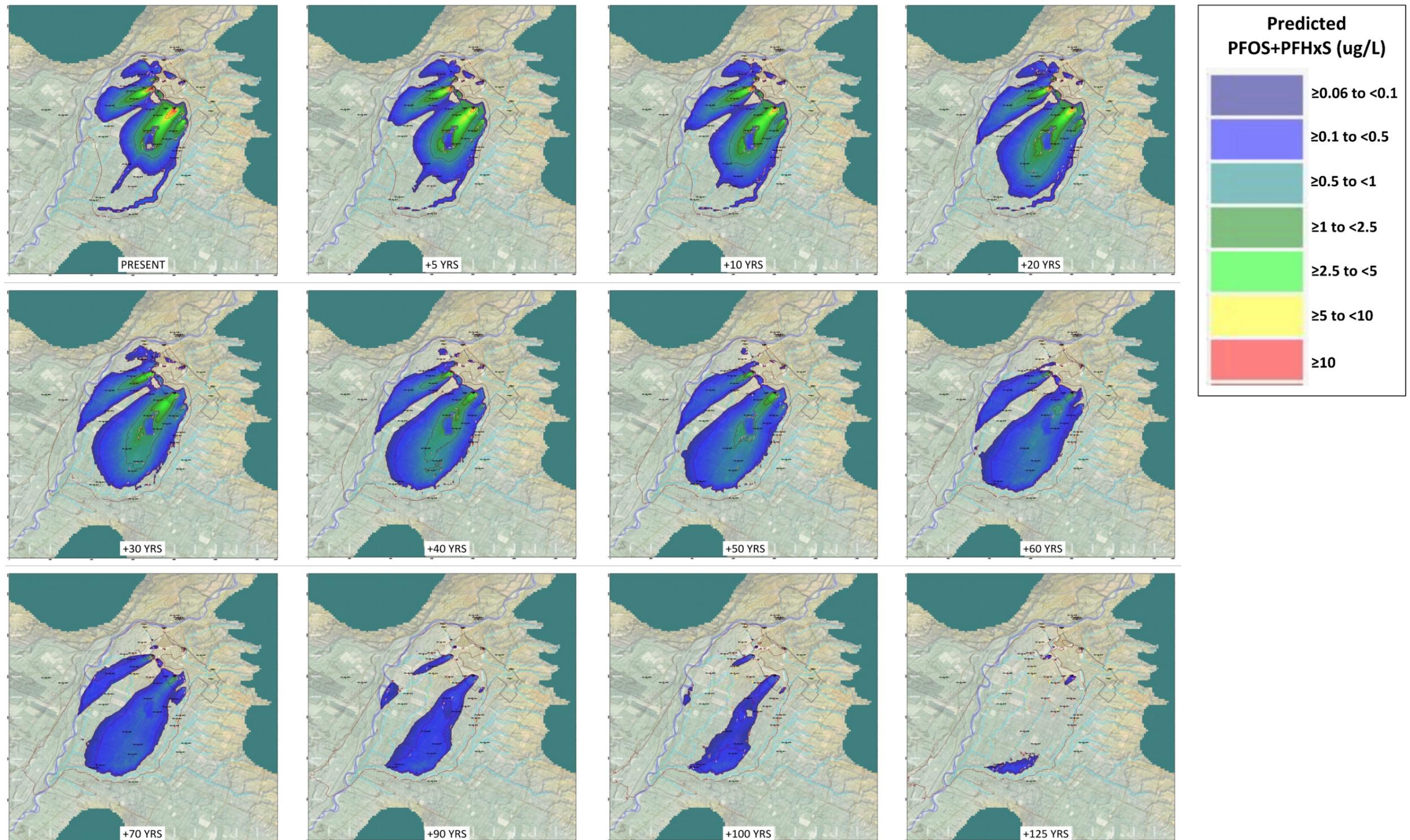


Diagram 5: 'Best Estimate' Decaying Source Future Plume Prediction (no retardation)

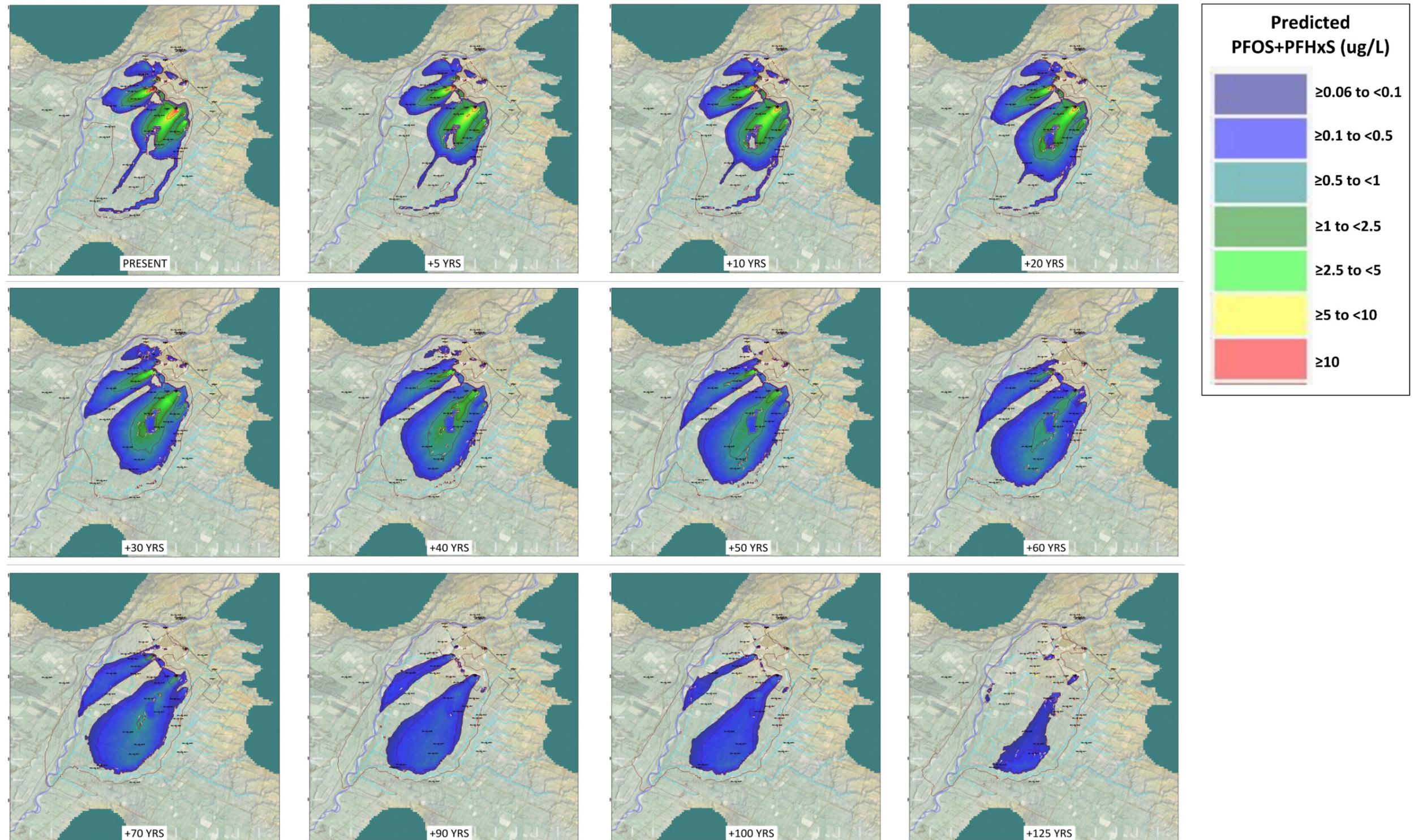


Diagram 6: 'Best Estimate' Decaying Source Future Plume Prediction (with retardation)

7.5 Source Zone Removal Scenario

As discussed in Section 7.4, the assumption of a slowly depleting source was considered as the 'best estimate' for future plume predictions. A prediction was also completed whereby the existing Soil Source Zones and Surface Water Source Zones were assumed to have already completely depleted e.g. prediction starts with the existing plume prediction, the modelled source zones are instantaneously removed, and then model is run into the future for 125 years. This scenario is considered analogous to a 'Best Possible Case' estimate and its purpose is to provide a prediction which tends towards the fastest perceivable (but unlikely) plume depletion.

General description of the 'source removed' future plume predictions and interpretations are outlined below. The predicted plume evolution over the adopted 125-year time period is displayed graphically on Diagram 7 (no retardation) and Diagram 8 (with retardation).

- ∴ Plume is expected to continue migration, but the plume is likely to 'disconnect' from source zones e.g. the three primary 'arms' of the existing plume break off from their respective source zone areas.
- ∴ Plume depletion is likely to be significantly more rapid than for the 'best estimate' scenario, however plume depletion is still on the multiple decade scale. It is estimated at approximately 20 to 50 years for the plume (PFOS + PFHxS >0.06 ug/L) to have decreased in area from the present day prediction, and estimated at approximately 55 to 80 years for the plume area to halve.
- ∴ The individual 'arms' of the plume are generally expected to continue advancing in their current direction of travel until they encounter a major groundwater discharge boundary (i.e. Rangitikei River or Makowhai Stream).
- ∴ The leading edge of the plume (e.g. the PFOS + PFHxS 0.06 ug/L contour), is expected to advance at a similar velocity to that of the 'best estimate' prediction e.g. maximum advance velocity of approximately 50 m/year to 100 m/year in the primary direction of travel (e.g. longitudinal axis).
- ∴ The trailing edge of the plume is predicted to move away from the onsite source areas at varying rates, which are primarily controlled by the interpreted geology immediately beneath or downgradient of the source areas i.e. onsite source areas dominated by shallow gravels are likely to experience rapid plume disconnect, and then the trailing edge migrating off-base at a similar velocity to the respective leading edge advance. Areas containing silt/clay dominated geology are likely require much longer timeframes before the plume disconnects, and slower trailing edge migration.

- ∴ The maximum width of 'flanks' of the plume (PFOS + PFHxS >0.06 ug/L) are generally expected to remain similar to the 'best estimate' prediction. However, due to the plume disconnect and more rapid depletion in this scenario, the plume is not predicted to elongate into the medium- and longer-term future.
- ∴ The behaviour of the plume in the vertical direction is generally similar to that described in Section 7.4 for the 'best estimate' scenario.
- ∴ The overall mass of PFOS + PFHxS within the plume is expected to decrease at approximately twice the rate (faster) than for the 'best estimate' scenario. The time to halve the existing plume mass (PFOS + PFHxS) is estimated to be in the order of 50 to 70 years+.

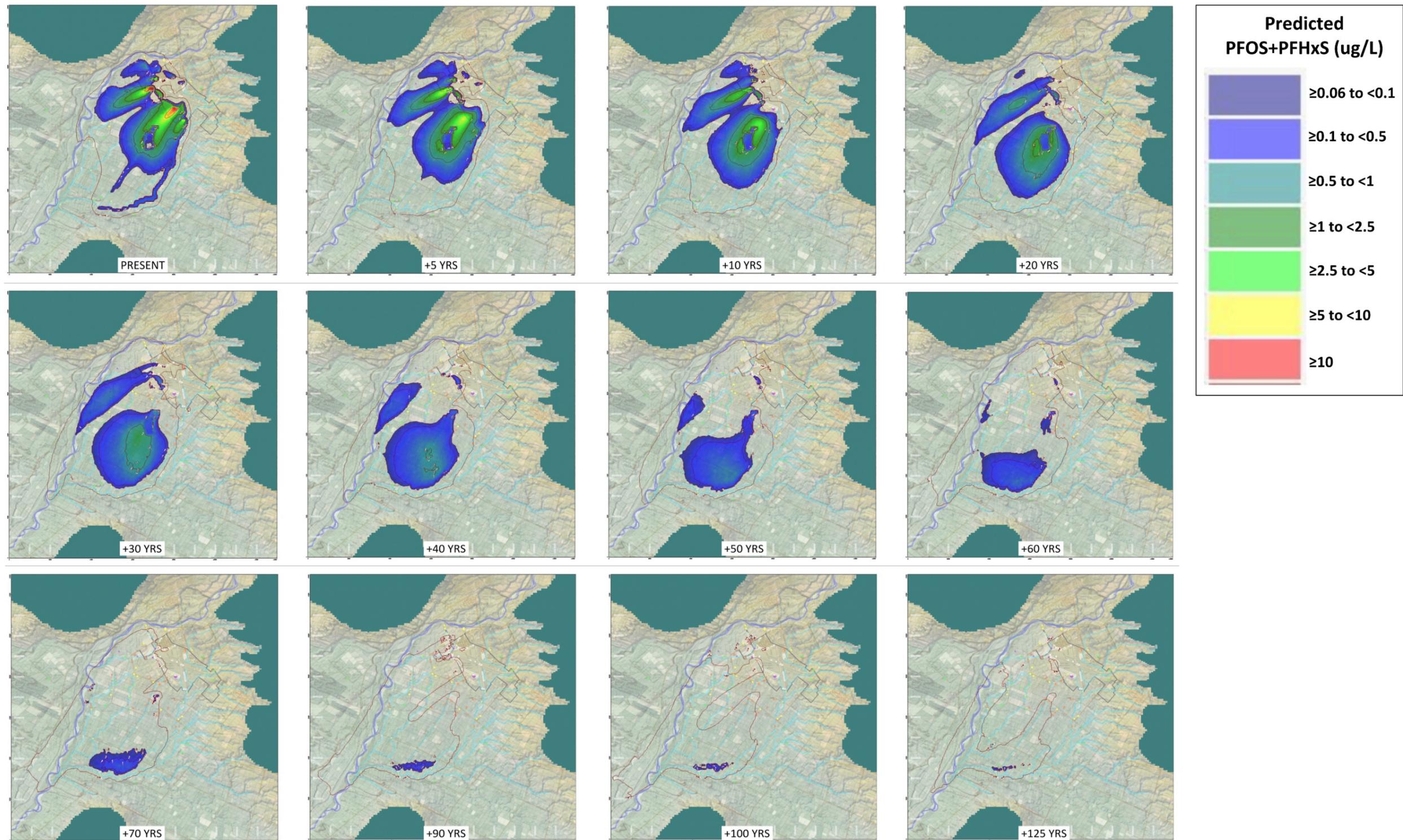


Diagram 7: Remove Source Future Plume Prediction (no retardation)

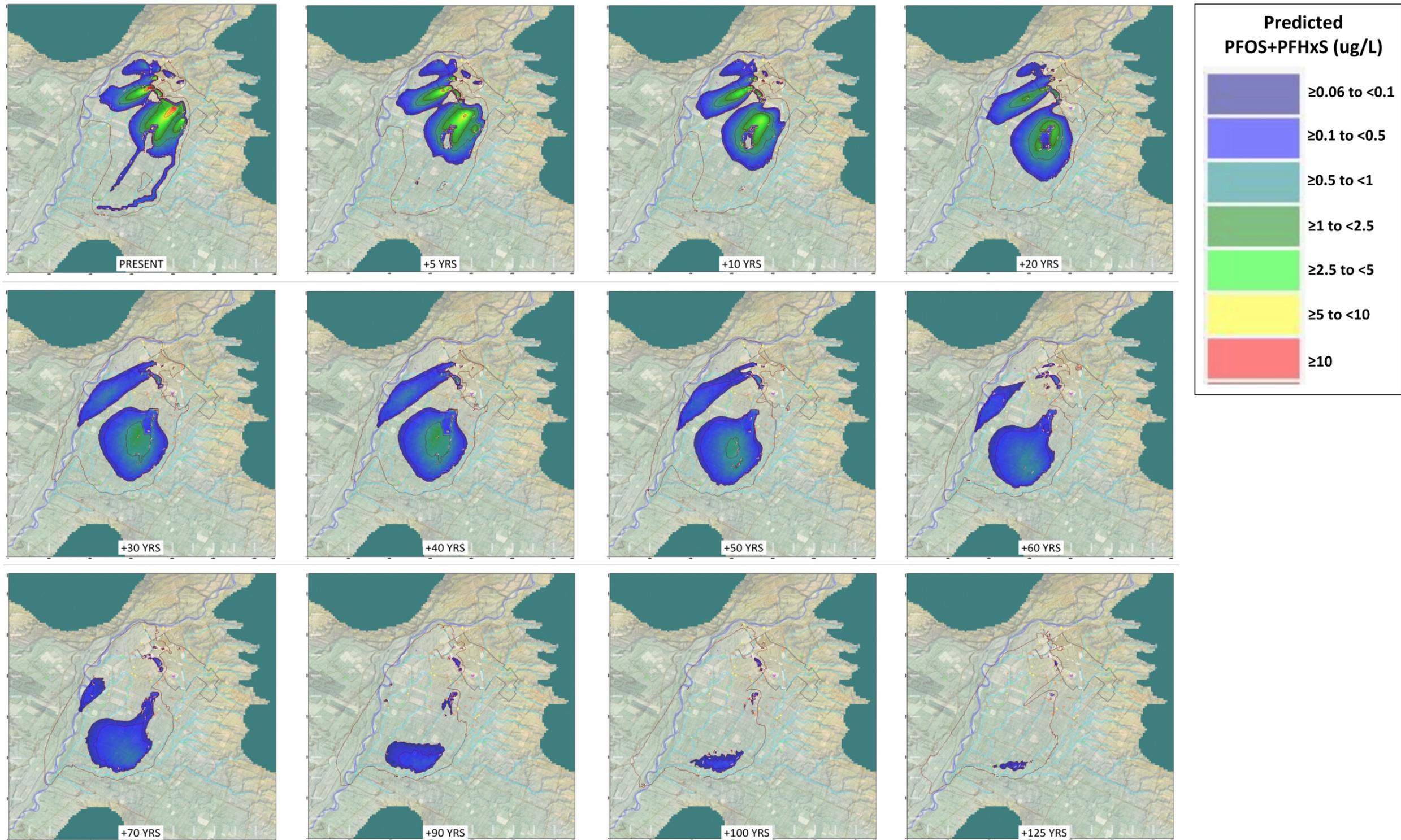


Diagram 8: Remove Source Future Plume Prediction (with retardation)

7.6 Longer Source Depletion Scenario

An alternative scenario which adopts an even longer source depletion was completed. Under this scenario, the soil source zones and surface water source zones were set at a depletion rate which took twice as long than that adopted for the 'Best Estimate' scenario. This equates to a depletion which halves the concentration every 50-years rather than 25-years.

The purpose of this scenario is to provide a prediction which tends towards the slower end of possible source zone depletion, and to evaluate what effect this could have on the predicted plume. Inherently, the assumptions of this scenario require that a greater source mass to be available for leaching e.g. more mass in the soil zone to supply contaminant leaching over a longer time period.

A general description of the 'longer source depletion' future plume predictions and interpretations are outlined below. The predicted plume evolution was run out to a 250-year time period and is displayed graphically on Diagram 9 (no retardation) and Diagram 10 (with retardation). Comparisons are made below to the 'Best Estimate' plume predictions:

- ∴ The plume is generally predicted to take on a similar overall shape and aerial extent however the depletion of the plume is likely to be significantly slower.
- ∴ The maximum width or 'flanks' of the plume (PFOS + PFHxS >0.06 µg/L) are generally expected to be similar. The width of the plume is expected to start contracting near the 80-year time mark. Contraction is expected to be slow and to gradually reduce over the subsequent 80-100 years.
- ∴ It is estimated at 80 to 140 years for the plume to have decreased in mass to below the present-day mass estimate. The time to halve the existing plume mass (PFOS + PFHxS) is estimated to be 170 years to greater than 230 years.
- ∴ The PFOS + PFHxS >0.06 µg/L extent is predicted to have largely depleted by approximately 200-years future, however, detectable concentrations are predicted to remain.