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Dear Sir/Madam

Albion Park Training Facility
PFAS Management Options Assessment

1 Introduction

Fire and Rescue NSW (FRNSW) engaged GHD Pty Ltd (GHD) to undertake a management options assessment (MOA) for the FRNSW Albion site, located at Airport Road, Albion Park, NSW 2527 (the site). The MOA was required to provide a discussion document for a remediation workshop to be held in Sydney in 2018.

The MOA was in response to identified contamination from per- and poly-fluorinated alkyl substances (PFAS) which were derived from the former use of specific aqueous film forming foams (AFFF) at the site.

2 Purpose

The purpose of this report is to provide FRNSW with an understanding of the potential management options to address onsite and offsite contamination of soil, groundwater and surface water.

The document first summarises the site setting and constraints, potential remedial/management options and then some suggested management scenarios for discussion. Approximate, ball park costs for aspects of the remediation are included for the purpose of preliminary budget planning. Owing to the nature of this emerging issue, management options and remedial technologies are continually under review and the costs provided in this report should be treated as provisional items for the purpose of budget estimates only.

3 Approach

The approach used to develop the MOA comprised:

- Assessment of the results of previous investigations at the site;
- A data gap analysis to identify where further data might be needed;
- A qualitative risk assessment to inform the level of remediation required;
- Assessment of the volumes and extents of contamination;

- A remediation options assessment to select the most suitable remedial and/or management technology to address the contamination issues;
- Selection of remediation and or management options for discussion.

3.1 Previous analytical results

A preliminary site investigation (PSI) was undertaken by GHD in 2016 to identify potential sources of contamination and areas of potential concern and develop a sampling and analytical plan for further intrusive investigations on the site. The findings of the PSI are reported in:

- GHD (2016) *Albion Park PFAS Investigation, Preliminary Site Investigation and Sampling and Analysis Quality Plan*, August 2016 (the PSI).

Following the PSI, an environmental site assessment (ESA) was undertaken by GHD in 2016. The aim of the investigation was to characterised impacts from PFAS on the site and the surrounding environment. The findings of the ESA are reported in:

- GHD (2017a) *Fire & Rescue NSW, Albion Park Training Facility, Environmental Site Assessment*. April 2017.

A further ESA was undertaken in May 2017. The findings of the May 2017 ESA are reported in:

- GHD (2017b) *Fire & Rescue NSW, Albion Park Training Facility, Phase 2 Environmental Site Assessment*. October 2017.

The results of the two ESAs included:

- Standing water levels in on-site wells were recorded to be between 2.61 mTOC (GW04) and 3.35 mTOC (GW02). The general groundwater flow direction was inferred to be towards the north-east.
- Analysis of the soil and sediment samples **on-site** indicated the following:
  - Only one onsite soil sample (SB09_0.0_0.1) reported PFAS above the residential human health screening criteria. It was, however, below the industrial/commercial criteria.
  - Sediment sample SS05 had the highest PFAS concentrations in sediment across the site. This was taken from the retention pond.
- Analysis of the soil and sediment samples **off-site** indicated the following:
  - Four soil samples had concentrations of PFHxS and PFOS (sum of total) above the nominated human health screening criteria at GW03, SB12, SB14 and SB15 collected during the December 2016 ESA. The screening criteria is highly conservative for residential when the area is open space. These samples were taken from the adjacent commercial property and the gum tree plantation east of the site indicating soil access by the public may be limited.
  - Two samples report concentrations of PFOS above the nominated ecological screening criteria at GW03 and SB15 collected during the December 2016 ESA.
  - All off-site sediment samples reported detects of PFAS with the exception of SS02 and SS06. This indicates that PFAS is likely to be migrating off-site via the surface water drainage pathways.

- Leachability testing confirmed that PFAS impacted soils and sediments have the potential to release PFAS to the environment at concentrations exceeding the nominated screening levels.
- Analysis of the groundwater and surface water samples indicated the following:
  - The highest concentration of PFAS contamination in groundwater was GW03 located adjacent to the retention pond.
  - GW01 to GW05 exceed drinking water criteria with GW01, GW02 and GW03 exceeding the recreation criteria and GW01, GW02. GW03 and GW04 exceeded the ecological screening criteria.
  - The highest value of PFAS contamination on-site is from the surface water retention pond in the north-eastern corner of the fire training ground.
  - PFAS was detected in all the surface water drainage lines leading from the retention pond.
  - PFAS is detected down gradient in Albion Creek and its unnamed tributary adjacent Poplar Avenue.
  - Levels of PFAS in surface water decrease with increasing distance from site.
  - Concentrations of PFAS in a surface water sample near the discharge point of Albion Creek to Lake Illawarra exceeded ecological guidelines.
  - PFAS was detected in surface water in all the surface water drainage lines leading from the retention pond.
  - Levels of PFAS in surface water decrease with increasing distance from site.
  - Concentrations of PFAS in a surface water sample near the discharge point of Albion Creek to Lake Illawarra exceeded ecological guidelines in December 2016. However, was below the laboratory LOR in May 2017.
  - SW08 and SW09 surface water samples collected in Koona Bay, Lake Illawarra were below the nominated ecological guidelines.
  - PFOS was detected close to the laboratory LOR in sediment from SS07. This location is a tributary to the north of Albion Creek suggesting potentially another unconfirmed source of PFAS.

3.2 Site setting and constraints

The main features of the Albion site setting and their relevance to determining appropriate management options are provided in Table 1

Table 1 Site setting and contaminant issues

Aspect	Summary	Issues
Site location	In close proximity to Lake Illawarra.	Located near a significant recreational area and ecosystem. Humans consume edible biota from the Lake.

Aspect	Summary	Issues
Geology and hydrogeology	Quaternary porous sediment aquifer over deeper fractured rock aquifer. Groundwater is likely to flow towards the Lake to the east. No extractive use of groundwater downgradient of the site. Groundwater is generally brackish to saline. Salinity likely to increase towards the Lake.	Shallow aquifer may be more transmissive than the deeper one and is likely to discharge into the Lake. Salinity is a significant controller of PFAS solubility and therefore, fate and transport.
Hydrology	The site has a surface water retention pond located in the north-eastern corner of the site, receiving onsite surface water drained through a variety of constructed drains. Onsite drains take water offsite to Albion Creek which flows into Lake Illawarra.	Surface drains may be a significant migration pathway offsite and into Albion Creek and thence to the Lake.
Contaminants of concern	PFAS – notably PFOS, PFHxS, PFOA. Identified in soil, sediment, groundwater and surface water onsite and offsite. Water soluble, can sorb to soil and sediments, leachable, resistant to degradation, possibly toxic to animals and humans, bioaccumulate in the food chain, long half-lives in humans and high adverse profile in the media.	The physico-chemical characteristics of PFAS make these chemicals very hard to remove from the environment and to destroy. PFAS has been released to the environment and therefore plants, animals and human have the potential to become exposed to PFAS. PFOS_PFHXS exceed screening criteria in surface water and groundwater. PFAS have received very negative reporting in the media and have a high perception of risk to the community.
Contaminant sources	AFFF products containing PFAS are no longer used on the site so no primary sources exist. Significant secondary sources of PFAS contamination include the retention pond and site soils/sediments. The highest PFAS in groundwater was found in a well adjacent to the pond. The retention pond contains elevated PFAS and PFAS is widespread in soils and drains.	The site, therefore, remains a potential source of PFAS contamination to offsite receptors.

Aspect	Summary	Issues
Contaminant fate and transport	PFAS can leach from soil into groundwater and migrate offsite. PFAS can migrate offsite in drains. PFAS may partition to sediments upon contact with more saline surface water. Dissolved PFAS can be taken up by plants. Smaller PFAS molecules are more soluble and less able to sorb to organic material than larger molecules.	PFAS can migrate considerable distances and discharge into Lake Illawarra. There it may partition into sediments near the mouth and potentially expose benthic organisms to PFAS, which in turn can be predated by more migratory species. Concentration of PFAS in the lake water are likely to be highly diluted and may not be detectable. A gum tree plantation adjacent to the site, may extract PFAS from groundwater.
Regulatory constraints	Currently no accepted waste disposal criteria for PFAS Screening criteria for ecological receptors tend to be very low. The criteria protective of human consumption of impacted biota is generally below laboratory LORs. Based on the EnRisk[1] (2016) decision tree process for prioritisation, the site is currently classified as a priority 1 site	Offsite disposal to a landfill is not a currently available option. Offsite disposal to a treatment facility is a potential option
Remedial constraints	PFAS can be destroyed thermally but at very high temperatures i.e. >1400ºC. Many other technologies have been tested at bench scale but not full scale. There are methods that can remove PFAS from water including filtration methods and reverse osmosis.	Remedial methods are not well established and may be cost-prohibitive if volumes of water and/or soil are large. Options are discussed further in Section **Error! Reference source not found.**.

3.3 Summary

The information presented above indicated that the site is a likely source of offsite PFAS contamination.

4 Management drivers

Based on the limited data set, there appears to be a risk to offsite ecological receptors and potentially human recreational users of Albion Creek and Lake Illawarra. The presence of PFAS in offsite media also poses a potential reputational risk for FRNSW.

[1] EnRisk (2016) Proposed decision tree for prioritising sites potentially contaminated with PFAS. 25 February 2016

GHD concludes that:

- Impacted PFAS sources include the retention pond water and sediment and site soils. The extent of soil contamination may be relatively limited. Groundwater contamination appears limited in extent and largely retained onsite. Offsite groundwater maybe impacted through infiltration of PFAS from drains rather than large scale migration.
- The main driver for management is the immediate prevention of any further migration of PFAS from onsite sources to the offsite environment.
- Addressing the main source of PFAS contamination onsite (the retention pond) should be a priority to achieve this outcome.
- Soil and groundwater contamination remediation need not be addressed at this stage as their impacts to offsite receptors is considered negligible. However, a more systematic soil assessment across the site is recommended. In case the regulatory authority require more active remediation of these media, a contingency approach has been included in Section 5.4.

5 Management options approach

The options discussed below do not necessarily address all contamination but rather provide a means of mitigating further impact through a combination of source reduction and isolation of the contamination.

Management options discussed below are subject to further site investigations.

The main approaches are:

- PFAS mass reduction through destruction, isolation or removal; or
- Control of migration through interception or isolation; or
- A combination of the two.

5.1 Soil

It is likely that PFAS contamination is present over most of the site, albeit a low concentrations. The PFAS onsite does not represent a significant risk to human health based on a commercial/industrial setting. Therefore, physical removal of all this soil is not considered a practicable immediate response or commensurate with the risks posed by the soil.

Potential management options for the site’s soils include:

- Maintenance of any hardstand area to restrict rainwater access to the subsoil and to prevent runoff from impacted hardstand. This might involve resealing or further capping with concrete of asphalt. This would reduce the impact risk of mass migration to the groundwater.
- Targeted excavation of the soils with the highest PFAS concentrations followed by either:
  - Offsite disposal to an appropriately facility for destruction
  - Onsite encapsulation in an engineered facility
  - Onsite treatment with a stabilising agent.

5.2 Groundwater

Groundwater PFAS extent is largely confined to the site and immediate surrounds. GW05 contains low concentrations of PFAS but this may have infiltrated from the nearby drain. Wells downgradient from the site and between the site and receptor (Lake Illawarra) do not contain detectable levels of PFAS.

Remediation of groundwater impacted by PFAS is considered impractical due to the lack of proven, economically viable methods, the relatively limited extent of the PFAS plume, the lack of groundwater use in the area and the relatively low risk posed by groundwater to the ecosystem of Lake Illawarra. The risks posed by the groundwater PFAS concentrations are considered lower than that from the surface water. Consequently, an immediate management response to groundwater contamination is considered a lower priority than the management of surface waters.

Other options for dealing with the risks of groundwater contamination include:

- Institutional restrictions of groundwater extraction e.g. groundwater extraction prohibitions. Such approaches would require approval and implementation by the relevant authorities and may not be greeted favourably by local community. However, these approaches have been successfully implemented in other areas subject to groundwater contamination from a range of sources and would require community consultation and active stakeholder engagement
- Source migration reduction through capping of soils and isolation/removal of surface water and sediment sources.
- Groundwater monitoring plan to include triggers that indicate when the risk profile changes and contingencies should triggers be exceeded.

5.3 Surface water and sediments

The surface water and associated sediments in the retention pond and site drains appear to represent the main potential sources of offsite PFAS impact. A significant mass of PFAS was identified in the surface retention pond water and sediment and PFAS was identified in offsite sediment and surface water.

The mass in the retention pond has probably the most potential to migrate offsite and impact onsite drainage lines and groundwater and offsite drains and surface water bodies. These are readily accessible at the surface onsite and therefore, are amenable to removal or treatment.

Consideration should be given to decommissioning of existing onsite drains and replacement with lined drains and sediment traps in conjunction with hardstand maintenance discussed in Section 5.1.

5.3.1 Surface water

Options for management of surface water include:

- Removal and replacement of the existing retention pond. The replacement pond should be engineered to prevent infiltration into the groundwater e.g. concrete or other impermeable lining. This would require the initial removal and treatment of the existing water and sediment and associated contaminated soils. This might impinge on the operational capacity of the site temporarily whilst the works are completed.

- Construction of alternative storage e.g. ponds or tanks. This would allow for the site to become operational in a shorter timeframe and allow for the concurrent decommissioning of the existing retention pond and its contaminated media. The remediation of the existing retention pond could be achieved in a controlled manner and in a timeframe more suitable to budgetary constraints.
- Treatment of the water by a remediation contractor.
- Tanking of water to an offsite waste treatment facility.

Of these, only water treatment and disposal was considered for costing as the other options are not considered practical or necessarily available. GHD has obtained quotes from a remediation contractor for the onsite treatment of surface water for the purpose of budget estimates. These are discussed in Section 6.1.

5.3.2 Sediment

Addressing of the sediments in the dams and onsite retention basin require the initial removal and treatment of the surface water (see above). The main options for sediment include:

- Offsite disposal. The NSW EPA waste guidelines provide classification criteria for PFAS-impacted soils. However, this option would require agreement from the receiving landfill.
- Onsite retention of the sediment, either by:
  - encapsulation in an engineered facility. The facility would be designed to resist erosion, direct rainwater away and prevent leaching of water through the sediment; or
  - treatment and reuse. The sediment would need to be assessed for acid sulphate potential and its engineering properties if it is to be reused on site.

An indicative cost estimate is provided for offsite disposal and onsite encapsulation. Treatment and reuse wold be subject to approval by the EPA, the engineering characteristics of the soil and suitable reuse areas being available. However, this does not remove the mass from the site and would not remove the potential for leaching of PFAS from the reused soils. Therefore a cost estimate is not provided.

5.4 Contingencies

While GHD recommends the remediation of the site surface water and sediments, it is possible that the regulatory authority may require more intrusive approach to other contaminated media. For this reason, GHD has conducted a remediation options assessment (ROA) for soil and groundwater.

The ROA considers broad general response actions which are categories of actions for accomplishing remedial objectives and can be combined to form remedial alternatives. These are:

- No Action (rejected).
- Institutional controls.
- Containment.
- Removal.
- In-situ treatment.

- Ex-situ Treatment.

The assessment first considered a large number of remedial options and reviewed them in terms of their likely or proven efficacy for addressing PFAS. This results is a short list of methods for further consideration. The options retained for further consideration and discussion in the workshop are listed in Table 2 and 3.

Table 2 Soil management options

General Response Actions	Remedial Technology	Process Options	Descriptions	Treated compounds	Limitations	Effectiveness	Implementability
Containment	Capping	Clay Cap	Compacted clay placed over the impacted area. Clay should be covered by at least 0.5m of silty sand or sandy soil to maintain the integrity of the clay cap (i.e., to protect it from root penetration).	Prevents mobilisation of PFAS compounds by infiltration of surface waters	May require a large volume of imported soil in excess of the volume of contaminated soil. This may be sourced from on-site. Would require an Environmental Management Plan (EMP) to ensure ongoing effectiveness. Legacy issue retained.	The compacted clay liners are effective if they retain a certain moisture content but are susceptible to cracking if the clay material is desiccated. They do not prevent rising groundwater levels from contacting the impacted soils and dissolving contaminants.	Good
		Asphalt or Concrete Cap	Paving grade asphalt or concrete placed over the prepared impacted area. Fill settlement must be evaluated in considering a concrete cap design. Sprayed asphalt needs to be covered with soil or opaque reflective paint to protect the asphalt from ultraviolet light and retard oxidation.	Prevents mobilization of PFAS compounds by infiltration of surface waters	May require a large area of asphalt or concrete. Would not prevent rising groundwater levels from contacting the impacted soils. Would require an EMP to ensure ongoing effectiveness. Legacy issue retained.	Effective if maintained well. Susceptible to deformation in constant wetting and drying conditions. They do not prevent rising groundwater levels from contacting the impacted soils. Would require an EMP to ensure ongoing effectiveness.	Good
Removal	Excavation (to the extent practicable)	Excavation with on-site treatment	Excavation of impacted solids using standard construction equipment (i.e. backhoes, bulldozers, and front-end loaders). Soils are treated to reduce contaminant concentrations or to stabilise compounds against future leaching. Soil are analysed for suitability for re-use on site.	Excavation is applicable to the PFAS compounds. Treatment methods require further assessment	Treatment methods may be expensive and many are unproven. Disposal of treatment end products may be problematic.	Dependent on the technology used. Mixing with binding agents has been shown to be effective in full scale operations. Refer to insitu and Ex situ treatment methods below.	Could be implemented assuming there is sufficient suitable area for treatment and an effective method for treatment is provided. Treatment can be conducted over a timeframe suitable to F&RNSW
		Excavation with on-site encapsulation	Excavated soils are placed in a purpose-built engineered retention facility to prevent access to the soils from human activity and the elements, notably infiltration, leaching and run-off.	Excavation is applicable to the PFAS compounds	Potential significant regulatory and technical problems with implementation. The regulatory process could be lengthy and involved. Legacy issue retained.	Effectiveness is dependent on the design and maintenance of the facility. It does not remove the liability from the site but should break the source-receptor pathway.	Could be implemented assuming there is sufficient suitable area for treatment and there is regulatory acceptance. Volumes of soil cannot be predicted at this stage.
		Excavation with temporary on-site stockpiling	Excavated soils are placed in purpose-built stockpiles to prevent access to the soils from human activity and the elements, notably infiltration, leaching and run-off. Storage would be temporary to allow for removal of source and planning for treatment at a later date.	Excavation is applicable to the PFAS compounds	Fugitive emissions such as dust and particulates are often a problem during operations. Stockpile facility would need to be weather-proof and allow no leaching to soils and groundwater.	Effective in removing PFAS mass from the environment and from potentially contributing more PFAS to groundwater and surface water. Effectiveness is dependent on the design and maintenance of the stockpiles. It does not remove the liability from the site but allows F&RNSW more time to consider budgetary requirements in their remediation planning i.e. spreading the cost of remediation over a longer time period.	Could be implemented assuming there is sufficient suitable area for stockpiling.

General Response Actions	Remedial Technology	Process Options	Descriptions	Treated compounds	Limitations	Effectiveness	Implementability
Ex Situ Treatment (assumes excavation)	Biological	Phytoremediation	Use of plants and their associated rhizospheric microorganisms to remove, transfer, stabilise, and/or destroy contaminants in soil or groundwater.	There is currently no literature on the effectiveness of Phytoremediation on PFAS compounds however uptake by plants in dissolved form is feasible and this may be effective in removing PFAS from excavated soils.	A treatment area would be required for this process which might impinge on site activities. Plant material would then have to be harvested and require disposal.	Unknown but theoretically possible based on PFAS solubility. With excavated soils, the access by plant roots could potentially be achieved. The presence of a gum plantation next to the site and the lack of PFAS in groundwater downgradient from this plantation may mean the trees have taken PFAS up from the groundwater. This needs further assessment and research to confirm this observation and assess its effectiveness.	While there is insufficient information to prove its effectiveness, theoretically it may be a viable option to address soils on site.
	Physical-Chemical Treatment	Soil Washing	Water-based process for washing soils to remove contaminants. The process involves either dissolving or suspending the contaminants in solution. The contaminated water from the washing is then treated and treated soil replaced in the excavation	PFAS compounds likely to be amenable to flushing/washing	May require several washing events. Water treatment system would be required.	Effectiveness would need to be assessed by pilot testing to assess the concentration of treated soil against remediation criteria.	Requires a custom-built plant unless a suitable hire plant is available. May be costly and would depend on the volume of soil requiring treatment. Likely to be more economical with larger soil volumes.
		Solidification/Stabilisation/Sorption	Contaminants are immobilised by sorption, precipitation or incorporation into crystal lattices or physically encapsulation by the addition of suitable reagent or concrete. The process is designed to reduce leaching potential and to improve soil condition.	Sorption of PFAS compounds on to various substrates have been assessed in the literature and been shown to have some benefit. Some proprietary products have been tested in the lab and at full scale. Soils may be encapsulated in cement.	Mixtures of contaminants may make formulation of a single process difficult. Doesn't destroy or remove contaminants. Long term effects are difficult to predict and long-term management may be required.	Full scale stabilisation projects has been documented in Australia. Site-specific testing of the material would be required to assess effectiveness.	Requires some bench testing or pilot trials to optimise mixtures and pre-treatments requirements. Relatively short remedial timeframe.
		Effluent treatment (assumes soil washing)	The process may be modified to treat effluent from soil washing to more effectively remove PFAS from the soil rather than simply immobilising it.	PFAS compounds specifically.	Would depend on the ability of the soil washing process to remove PFAS from the soil. This might be limited by the soil properties i.e. grain size, pH. There is little information of throughputs of large scale processes required.	CRC-Care literature indicated two successful waste water treatment projects involving treatment of 200,000L of waste water.	Likely to be implementable. Commercial organisations and CRC Care have developed treatment systems. Would likely require removal of colloidal material from the waste water stream to be effective.

General Response Actions	Remedial Technology	Process Options	Descriptions	Treated compounds	Limitations	Effectiveness	Implementability
		Incineration	High temperatures, 1,200 °C+, are used to combust (in the presence of oxygen) organic constituents in hazardous wastes. Plasma arc technology can also create sufficient heat to destroy PFAS	Literature indicates high temperature incineration is beneficial for PFAS destruction.	Significant energy requirements and potential to generate GHGs. Incomplete combustion may create additional contaminants of concern e.g fluorine. Disposal of solid residues may be problematic as they may concentrate other inorganic compounds. Probably not a mobile option and soils would need to be delivered to a licenced facility.	Effective. Literature indicated PFAS compounds can be incinerated at temperatures of 1200ºC. ToxFree facility in Queensland has conducted such work and achieve over 99% destruction.	Good - Would require off site disposal of soils to a licenced facility but these do exist.

Table 3 Groundwater management options

General Response Actions	Remedial Technology	Process Options	Descriptions	Treated compounds	Limitations	Effectiveness	Implementability
Containment	Hydraulic Barriers	Vertical Wells	Conventional groundwater extraction is pumping in vertical wells. Other extraction device include vacuum enhanced recovery, jet-pumping systems, etc.	Well technology is applicable to the PFAS	Limited by the effective capture zone of each well. Careful hydrogeological assessment and pilot trials would be needed to assess effective radius of influence and pumping rates. Volumes of water produced requiring treatment might be excessive and need treatment - the rate of treatment would need to match or exceed the rate of extraction.	Widely used and demonstrated effectiveness. Generally effective for hydraulic containment (i.e. horizontal migration) and ineffective for groundwater restoration.	Good. Common technology; often combined with other treatment technologies applied to the extracted groundwater in an integrated system.
		Interception Trenching	Trenches backfilled with granular material provide preferred flow path for collection in pipe or sump. Groundwater collection technique to increase production rate from low permeability areas.	Method allows for capture of impacted groundwater rather than actual treatment. The treatment would occur ex-situ. (However, should the technology exists, reactive material could be included in the trench to treat the groundwater in situ).	Depth of PFAS impact not well known. Large volumes of water likely to be produced which requires treatment.	Widely used and demonstrated effectiveness.	Good. Groundwater is shallow.
In Situ Treatment	Chemical	Chemical Oxidation	Aqueous injection of oxidizing agents (activated persulphate, Fentons) to promote abiotic in situ oxidation of PFAS	Some literature suggests this might be an effective method of PFAS destruction assuming site-specific trials are conducted.	Unproductive oxidant consumption by natural media. Application involves injection of aqueous phase reagents will be significantly constrained in low permeability media. OH&S issues associated with handling oxidants.	Theoretically effective, but requires good contact between contaminant and reagent. Aquifer heterogeneity not clearly understood but could make uniform distribution difficult and would limit effectiveness.	Relatively easy to implement. Deployment could be through wells, trenches or infiltration basins.
	Biological	Phytoremediation	Phytoremediation is a set of processes that uses plants to remove, transfer, stabilise and destroy organic/inorganic contamination in ground water, surface water, and leachate. These mechanisms include enhanced rhizosphere biodegradation, hydraulic control, phyto-degradation and phyto-volatilization.	No literature on this process and its effectiveness on treating AFFF.	Toxicity and bioavailability of biodegradation products is not always known. Degradation by-products may be mobilised in groundwater or bio-accumulated in animals. More research is needed to determine the fate of various compounds in the plant metabolic cycle. Disposal of harvested plants can be a problem if they contain high levels of heavy metals. Climatic or seasonal conditions may interfere or inhibit plant growth, slow remediation efforts, or increase the length of the treatment period. It can transfer contamination across media, e.g., from soil to air. Phytoremediation will likely require a large surface area of land for remediation. Phytoremediation for extraction or degradation is generally limited to relatively shallow depths of root penetration.	PFAS has been shown to be present in plants and therefore, uptake of dissolved PFAS by plants may be effective as long as the root systems are deep enough. This might require larger plant species (e.g. eucalypts)	Most applicable for control of shallow groundwater plumes. High concentrations of hazardous materials can be toxic to plants but this may not be the case with PFAS. It is still in the demonstration stage. Pumping the water out of the ground and using it to irrigate plantations of trees may treat contaminated groundwater that is too deep to be reached by plant roots however this may only serve to increase the area of impact. High rainfall may flush the contaminants back into groundwater.

General Response Actions	Remedial Technology	Process Options	Descriptions	Treated compounds	Limitations	Effectiveness	Implementability
Ex Situ Treatment (assumes extraction)	Chemical	Chemical Oxidation	Oxidizing agents are used to destroy organic contaminants in an ex situ storage area Potential oxidizing agents are activated persulphate and Fentons Reagent.	Some literature information on the potential effectiveness of this method on PFAS.	Lack of full scale examples. Would require site-specific trials. Heterogeneity of the aquifer is not understood.	Lack of full scale examples. Would require site-specific trials.	Lack of full scale examples. Would require site-specific trials.
		Precipitation	This process transforms dissolved compounds into an insoluble solid, facilitating the compound's subsequent removal from the liquid phase by sedimentation or filtration. The process usually uses pH adjustment, addition of a chemical precipitant and flocculation. It is used as a pre-treatment process with other technologies (such as chemical oxidation or air stripping), where the presence of metals would interfere with treatment.	No literature on this method applied to PFAS. However PFOS has a tendency to partition to sediments in waters with high salinity. Increasing the salinity of the water may remove it from the water stream allowing for marine disposal of the effluent water. Impacted sediments would then need treatment and disposal.	Untested method.	Unproven effectiveness but theoretically could be an effective method of removing PFOS from a waste water stream.	Unproven
	Physical Treatment	Granular activated Carbon (GAC) Adsorption	GAC adsorption is a full-scale technology in which ground water is pumped through one or more vessels containing activated carbon to which dissolved organic contaminants adsorb. GAC is incinerated at the end of its life.	Applicable to PFAS	Streams with high suspended solids (> 50 mg/L) and oil and grease (> 10 mg/L) may cause fouling of the carbon and may require frequent treatment. Unknown sorption capacity or site-specific data. GAC becomes a waste source that needs destruction.	The technology has some efficacy for addressing PFAS according to literature although not every one agrees. Work conducted by GHD has shown it to be effective in achieving guideline criteria for drinking water and trade waste disposal for low turbidity waters. Contaminant removal efficiencies need to be further assessed.	Carbon adsorption systems can be deployed rapidly. Would need a site-specific design
		CRC Care Method	Uses modified clay as an adsorption media for PFAS. Water is initially stripped of colloidal content and then passed through a number of chambers to remove the PFAS from the water. Clay media is collected by CRC for disposal.	PFAS specifically	May be limited by required throughput. CRC quote 4L per hour which may not be adequate for groundwater remediation. However this rate may be increased if water is colloid free.	Apparently successful in treating waste water according to CRC literature	Apparently implementable according to CRC literature
		Reverse osmosis	Impacted water is forced through a membrane or series of membranes to remove water from dissolved phases	Has been demonstrated in Queensland to be effective on removing PFAS from waste	Expensive technology and high energy consumer.	Experience from Queensland water treatment facility showed it removed 100% of PFAS from impacted water.	RO systems can be deployed rapidly. Would need a site-specific design
Disposal	Extraction	Reinjection	Reinjection of groundwater to the aquifer upgradient or side-gradient to the impacted area.	PFAS	Limited by the capacity of the aquifer to receive the groundwater.	Could create enhanced gradients which would mobilise contamination	Relatively easy to implement

6 Indicative cost estimates

The available contamination data provided a certain level of understanding of the site, however, there are a number of uncertainties or data gaps remaining. The uncertainty can only be further reduced by further assessment work. Consequently, a number of assumptions have to be made which utilise information gained from comparable sites where some data is available and based on our experience with similar sites. In addition, some inputs for developing the indicative cost estimates are from Rawlinsons, *Australian Construction Handbook, Edition 35, 2017.*

Recognising that there is risk of cost exceedance, suitably robust contingencies have been to be applied to these costs for any budgeting or other financial purposes. The costs, contingencies and sundries should be ratified by a suitably qualified cost estimator and preferably market tested, should greater certainty be required.

GHD has provided indicative surface water and sediment volumes based on the surface area of the dams.

- The estimated surface water volume for the onsite retention pond is approximately **570,000 L**.
- Sediment within the retention pond is estimated to be in the order of 290 m^3 based on pond surface area of 570 m^2 and an assumed thickness of 0.5 m.

6.1 Water

GHD has obtained quotes from a remedial contractor for the treatment of the surface water based on rate per litre basis. Based on the assumed volume, the indicative cost estimate to treat the water in the retention pond is in the order of **$.** This figure excludes discharge and sediment management.

The price included:

- Removal of waters from the primary dam;
- Process the waters through the mobile PFAS treatment system
- Discharge treated water into temporary storage tanks
- Sampled, analyse, and validated the waters to satisfy the discharge criteria (at present the discharge criteria has not been established)

According to the contractor, the end result of the treatment would be discharge of the treated water or use for irrigation. It is not clear from the contractor's quote what criteria this is based on or whether this is a valid assumption. GHD makes no assertion that their methodology will achieve regulatory approval for discharge or irrigation, but provide the quote for indicative costing purposes. This would need to be further assessed.

6.2 Sediment

6.2.1 Offsite disposal

This option is subject to landfill acceptance of the sediment. It is likely that they would not receive sludge and the sediment is therefore likely to require dewatering.

The indicative cost estimate to dispose of **290 m^3** of dry sediment offsite is in the order of **$.**

This estimate includes allowances for excavation, transport, plant hire and landfill waste levy.

The benefits of this method (assuming landfill acceptance) is that it permanently removes PFAS mass from the site.

6.2.2 Onsite encapsulation

GHD have used a proprietary spreadsheet to calculate the cost for construction of an engineered soil repository to contain the sediments, indefinitely. The indicative cost estimate to construct the facility for 290 m^3 of sediment is in the order of **$**.

Additional costs would be incurred for excavation and haulage of the sediment to the facility and compaction. Such costs may be in the order of **$**.

This indicative cost estimate is based on:

- Design
- Cell construction with geosynthetic lining, clay capping, leachate collection and sump, set out, stormwater management.
- 20% contingency.

Such a facility would require ongoing maintenance and monitoring and the PFAS mass will remain on site indefinitely. This would incur additional costs. However, if the landfill will not receive the sediment, this may be the only response to PFAS mass isolation.

6.2.3 Exclusions

The indicative cost estimates provided above excludes a number of items including:

- Planning approval
- Auditing
- Validation sampling
- Quality control or verification inspections
- Gas venting systems
- Dewatering of sediments

7 Summary

Indicative cost estimates for the water and sediment management are summarised in **Error! Reference source not found.**

Table 4 Indicative management cost estimates

Media	Method	Indicative cost estimate
Onsite Water	Treatment and discharge	$
Onsite Sediment	Offsite disposal	$
	Onsite encapsulation	$

8 Limitations

This report has been prepared by GHD for FRNSW and may only be used and relied on by FRNSW for the purpose agreed between GHD and the FRNSW as set out in Section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than FRNSW arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described throughout this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report on the basis of information provided by FRNSW and others who provided information to GHD, which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

GHD has prepared the indicative management cost estimates set out in Section 6 of this report ("Indicative Cost Estimate") using information reasonably available to the GHD employee(s) who prepared this report; and based on assumptions and judgments made by GHD.

The Indicative Cost Estimate has been prepared for the purpose of providing FRNSW with estimates for internal FRNSW use only and must not be used for any other purpose.

The Indicative Cost Estimate is a preliminary estimate only. Actual prices, costs and other variables may be different to those used to prepare the Indicative Cost Estimate and may change. Unless as otherwise specified in this report, no detailed quotation has been obtained for actions identified in this report. GHD does not represent, warrant or guarantee that the works can or will be undertaken at a cost which is the same or less than the Indicative Cost Estimate.

Where estimates of potential costs are provided with an indicated level of confidence, notwithstanding the conservatism of the level of confidence selected as the planning level, there remains a chance that *the cost will be greater than the planning estimate, and any funding would not be adequate. The confidence level considered to be most appropriate for planning purposes will vary depending on the conservatism of the user and the nature of the project. The user should therefore select appropriate confidence levels to suit their particular risk profile.*

The opinions, conclusions and any recommendations in this report are based on information obtained from, and testing undertaken at or in connection with, specific sample points. Site conditions at other parts of the site may be different from the site conditions found at the specific sample points.

Site conditions (including the presence of hazardous substances and/or site contamination) may change after the date of this Report. GHD does not accept responsibility arising from, or in connection with, any change to the site conditions. GHD is also not responsible for updating this report if the site conditions change.

Sincerely

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