Final Report:
Contamination of Groundwater in Fishermans Bend Due to the Impacts of Legacy Landfills

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Key Terms

Term	**Definition**
BPEM	Best practise environmental management
CIS	Coode Island Silt
CUTEP	Clean up to extent practicable – a policy used by EPA Victoria
Emerging Contaminants	Artificial or naturally occurring chemicals that aren't monitored in the environment but have the potential to enter the environment and cause adverse ecological and/or human health effects.
EPA	Environmental Protection Authority Victoria
GenX™	Replacement PFAA compound
GME	Groundwater monitoring event
Leachate	Water that has percolated through the solid waste of a landfill and leached constituents
Legacy Landfill	Landfills with or without engineered procedures that have accumulated a significant amount of age
LOR	Limit of reporting
mbGL	Meters below ground level
Natural Attenuation	A variety of natural processes that without any interference act to diminish the mass or concentration of a chemical within the environment
NEPM	National Environment Protection Measures
PFAA	Perfluoroalkyl acids
PFAS	Per- and Polyfluoroalkyl substances
PFCA	Perfluoroalkyl carboxylic acids
PFSA	Perfluoroalkyl sulfonic acids
PMS	Port Melbourne Sands
PMS	Port Melbourne Sands
QAQC	Quality Assurance and Quality Control
Unlined Landfill	A landfill in which no effort has been made to restrict the leaching of waste contents into the adjacent environment

Executive Summary

As the world’s population increases, the demand for housing and residential areas close to economic and metropolitan centres are anticipated to rise. Fishermans Bend, Australia’s largest urban renewal project and current brownfields site, faces several environmental challenges. Groundwater contamination can be a pervasive problem, which can negatively affect not only the environment, but the credibility and reputation of planned redevelopments. This report will investigate the contributions legacy landfills have on groundwater contamination in Fishermans Bend, with a particular focus on emerging contaminants PFAS and 1.4 dioxane. A detailed desktop study was completed, which entailed an investigation of Fishermans Bend legacy landfills, the mechanisms of contaminant fate and transport and current legislation surrounding emerging contaminants.

Due to Covid-19 related restrictions, a sampling event could not be undertaken as per the original Project Proposal. Research utilised previous sampling events which provided several insights into groundwater conditions. This historic data has provided the opportunity to develop pathway receptor models, estimate contaminant concentration at receptors and evaluate potential risks. While this report extensively details legacy landfills of Fishermans Bend and their associated contamination, there are still several data gaps which have been identified, with follow up field programs and investigations recommended in section 6.0.

This study acknowledges the people of the Kulin nation, the Traditional Owners of the land that Fishermans Bend resides in and whose sovereignty has never been ceded. The sand flats of the Yarra Delta were important meeting places and held spiritual significance for First Nation Peoples (Biosis 2013).

1.0 – Introduction

Fishermans Bend is located directly south west of Melbourne CBD and occupies an area of 480 hectares (Victoria State Government 2020). In 2012, Fishermans Bend became a Capital City Zone and is currently Australia's largest urban renewal project (Victoria State Government 2020). The area will accommodate approximately 80,000 residents by 2050 and will include employment districts, residential areas, schools, universities and parklands (Victoria State Government 2020). The planned redevelopment currently consists of the following precincts of Employment, Lorimer, Montague, Sandridge and Wirraway as seen on figure 1 below (Victoria State Government 2020).

Fishermans Bend has been associated with many noxious trades including chemical manufacturing, tanneries, abattoirs and landfills since the mid-1800s (Biosis 2013). In the early 1900s, the area underwent an industrial boom with aviation and vehicle manufacturers drawn to the site (Biosis 2013). Many of these industries could have contributed to landfilling, due in part to numerous by products associated with manufacturing processes (Biosis 2013; Lack 1985).

This project entails an extensive investigation of legacy landfills in Fishermans Bend and their potential to contaminate groundwater. Previous studies completed by Hepburn et al. (2016-2019) have indicated that legacy landfills may contribute to groundwater contamination. These landfills may potentially pose a risk to the environment and human health, further exacerbated by the fact that the exact waste type is unknown and the presumption that they are un-engineered (e.g. no basal lining system). The targeted contaminants from this investigation are primarily emerging contaminants PFAS and 1. 4 dioxane.

Figure 1 – Fishermans Bend site location (Source: SGS Economics & Planning)

1.0 – Statement of Problem

As the world is becoming more urbanised to accommodate increasing populations, the demand for more liveable space within urban centres is increasing (Kotval 2016). Governments worldwide are revitalising, and redeveloping brownfield sites located near city centres (Kotval 2016). However, many of these sites have a history of contamination which can provide both challenges and opportunities (Kotval 2016). While converting industrial land to residential can offer economic and community growth, the redevelopment of these areas may introduce new receptors and pathways for contamination (Kotval 2016; Syms 2004).

Groundwater is a precious resource, with numerous beneficial uses. Its protection is paramount, given its extensive connection with surface water, extractive uses and cultural significance. Leachate, a prolific by product of landfills has been known to migrate extensively in groundwater (Kjeldsen et al. 2002). Leachate can contain several toxic chemicals, potentially impacting its beneficial uses. Landfills can contain several decades worth of waste, particularly in an industrial setting. In these settings, landfills may contain by-products and chemicals which an ordinary municipal landfill may not, potentially increasing risk. Due to this, landfills have the potential to emit recalled chemical compounds into the groundwater for many years after closure.

Emerging contaminants such as PFAS and 1.4 dioxane have applications in many industrial and commercial products. As a result, they may accumulate in relevantly high concentrations within landfill leachate. Delineating leachate plumes, and analysing movement through groundwater is an important task in evaluating any potential risk to receptors. Sites with long industrial histories, often have heavily contaminated groundwater and soil which may be linked to decades of industrial and landfill related pollution. While groundwater has the potential to be extremely beneficial, it also has the potential to mobilise and proliferate contamination (Kotval 2016)

Fishermans Bend is a complex brownfield site and is known to contain four distinct areas of landfilling as indicated in Figure 2.

Figure 2 – Location of legacy landfills (Source: Nearmap 2020)

Identification of receptors is an important task in understanding the extent of the problem. Leachate may impact groundwater and receptors in the following ways.

- Contamination of potable and domestic water supplies
    - Human exposure to the contaminants via direct contact or ingestion

- Discharge of contaminated groundwater into receiving surface waters
    - Human exposure to the contaminants via direct contact or possible ingestion
    - Impacts to the ecosystems within surface water at groundwater discharge regions (e.g. Yarra River and Hobson Bay)
    - Damage to groundwater dependent ecosystems within the groundwater environment (e.g. stygofauna)

- Uptake by groundwater dependant terrestrial ecosystems
    - Uptake by vegetation resulting in increased availability of the contaminant in the environment and food chain.

- Groundwater contacting construction and utility workers
    - Human exposure due to accidental ingestion or inhalation

- Volatilisation of groundwater and intrusion into buildings
    - Human exposure via indirect contact such as inhalation

Detailed literature reviews and desktop studies were completed to investigate impacts of leachate contaminated groundwater and their potential receptors. This included investigating hydrogeology, emerging contaminant properties including their respective fate and transport as well as landfill site history.

Having a detailed site characterisation is imperative to understanding the potential risks posed to the beneficial uses of groundwater (Syms 2004). Landfills can act as point sources of groundwater contamination for many years, thus quantifying the impacts they have on groundwater quality can aid in the development of future risk assessments and management plans.

Through collaboration with EPA Victoria and Australian Contaminated Land Consultants Association (ACLCA), this study may be used to inform future research regarding the contribution legacy landfills have in proliferating emerging contaminants in groundwater and surrounding environments. New data can allow for further site characterisation and risk assessment by EPA Victoria, including awareness of emerging contaminants which may inform future regulatory action by the agency.

2.0 – Methodology

The following is altered to accustom the changes in scope which were made in response to Covid-19 related restrictions. All previous reports have detailed the scope as being based around the data received from the sampling event suggested in this report under Future Works (Section 6.1.3). This sampling event was not completed due to Government and University Covid-19 related restrictions which were implemented during 2020.

2.1 – Research and design questions

Research and design questions where established based on data gaps in previous research as well as preliminary findings from Engineering Capstone B.

These questions consist of the following:

General

- Who are the beneficial users of groundwater in Fishermans Bend?
- Who are the potential receptors of leachate impacted groundwater?
- Can potential risks to receptors, be quantified or estimated?
- What sampling plan or field works could be employed to investigate potential impacts further?

Further delineation of leachate plumes

- Utilising historical data, can the extent of landfill leachate in groundwater be better delineated? Is so, what techniques would be most applicable for Fishermans Bend?
- To what extend does the delineation of impacted groundwater, influence pathway receptor models?

PFAS

- Does PFAS originating from legacy landfills pose a risk to receptors?
- Is there evidence of PFAS precursor degradation? if so, can this be impactful?
- Is there any correlation with the PFAS found, waste type and age of landfill?

1.4 dioxane

- Is emerging contaminant, 1.4 dioxane present at landfills sites? What kind of future field works will be needed to determine or establish this?

2.2 – Process steps

1. **Background and Desktop Research**

Throughout this project, a very detailed desktop study, otherwise known as literature review, was completed to grasp a more thorough understanding of the problem at hand and all its counterparts.

This entails investigating a wider history of the site and researching contaminants in question, including PFAS and 1. 4 dioxane. With these contaminants it is important to note their toxicity and ecological and human health guideline values. This involves researching international guidelines for some contaminants due to a lack of current Australian guidelines. The research also entails a detailed historical and hydrogeological investigation which will be used to create a better conceptual understanding of the site.

2. **Delineation of landfill leachate plumes**

Data from previous sampling events will be analysed to delineate potential leachate impacted regions, in conjunction with findings from historical investigations. This includes the creation of Piper Plots to analyse groundwater geochemistry and the mapping of groundwater alkalinity. This will aid in assigning potential receptors and developing more comprehensive pathway models.

3. **Analysis of PFAS results**

With the aid of literature, historical results will be analysed to determine if any correlations with age, waste type and PFAS exist. From this analysis, comparisons against other landfills can be made, potentially increasing understanding and conceptualisation of sites in Fishermans Bend.

4. **Receptor identification**

A receptor is defined as any entity which may contact to leachate impacted groundwater. These receptors will be identified by desktop research and interpretation of data, such as leachate plume delineation. Identification will aid in evaluating how the presence of contaminated groundwater effects its beneficial uses.

5. **Estimation of PFAS concentration at receptor**

Using Darcy Flux equations, the concentration of PFAS at receptors will be estimated at applicable locations. This will help in quantifying and understanding potential risks.

6. **Pathway receptor model and assessment against trigger levels**

The pathway receptor model combines all literature findings and data analysis, to create a comprehensive model of the source and pathways of groundwater contamination. This model will be used in conjunction with contaminant guidelines and trigger levels and will form the basis of future recommendations.

7. **Recommendations**

Recommendations will be made using multiple lines of evidence from findings in the above process steps. Recommendations are primarily intended for EPA Victoria, to aid in better understanding of risk and to support any future regulatory actions

3.0 – Background and Desktop Research

3.1 – Previous studies of Fishermans Bend legacy landfills

- **Hepburn et. al (2016 – 2019)**

Hepburn et. al (2016) identified legacy landfills through desktop research. In July 2017, 38 EPA Victoria bores were sampled for a broad range of contaminants including PFAS. Hepburn et. al (2019) identified research gaps in the global literature with regards to PFAS in groundwater and legacy landfills. Some key findings include the delineation of leachate impacted regions and comparisons of PFAS results against literature.

- **Aecom (2015-2017)**

Aecom conducted baseline groundwater studies on behalf of EPA Victoria from 2015 to 2017 (Aecom 2017). Included in the studies were desktop research regarding the locations of historic landfilling. 75 monitoring bores where installed from 2015 to 2017 by Aecom. Aecom conducted several monitoring events on these bores with PFAS sampled in some in May and July 2017. The investigations also included the sampling of some private bores. Analysis of contamination originating from legacy landfills was not attempted with the scope of the study being a baseline investigation (Aecom 2017). Several bores that are known to be leachate impacted where sampled, with this data being publicly available.

- **Environmental audits**

Sinclair Knight Merz – Report of Environmental Audit: Todd Road, Port Melbourne (1999)

This audit was completed on the southern section of the former Port Melbourne Tip. The audit included historical and hydrogeological investigations as well as groundwater sampling of several bores. Key findings include information regarding waste composition, time of filling, groundwater flow direction and depth of waste.

Lane Consulting - Environmental Auditor’s Report Lot Lb, 69-119 Salmon Street, Port Melbourne, Vic (1999)

This audit was completed on the former Salmon St. Tip. Included in the audit was information regarding waste type, time of filling and groundwater flow direction. Groundwater was also sampled in several bores.

Dames & Moore Group – Environmental Audit – Melbourne City Link Western Link Area 9: Elevated Roads Melbourne, Victoria (1999)

This audit was completed as part of the City Link Freeway project and was located in the area of the former Graham St. Tip. The audit included information on site history, waste type, time of filling and groundwater flow direction.

3.2 – Landfills and the environment

Landfills are an essential structure in society but without utilising appropriate engineering methods, landfill by-products such as leachate and gas can have negative effects on adjacent environments. Landfill leachate is formed when water from the surrounding environment enters the landfill cell and percolates through the waste resulting in a contaminated liquid (Cheremisinoff 1997). The level of contamination and production of leachate can be influenced by external factors such as temperature, depth of landfill, waste composition and landfill age (Cheremisinoff 1997). Leachate composition largely contains organic carbon based compounds and ammonia, and it can be observed that as landfill age increases the concentration of organics decreases, however the ammonia and nitrogen concentration may increase (Cheremisinoff 1997). Phosphorus, chlorides, calcium, magnesium, sulphate, dissolved solids, heavy metals and BTEX also contribute to the composition of landfill leachate. These levels may fluctuate over time, with factors such as seasonal variations influencing this (Cheremisinoff 1997).

After leachate is produced it may infiltrate the groundwater through the landfill base which can lead to contamination of aquifer systems. Leachate mobility is influenced by the permeability of the soil and the concentration of contaminants within the leachate (EPA SA 2019). Several recommendations have been made in EPA Victoria's guidance document, '*Victoria Siting, design, operation and rehabilitation of landfills BPEM 2015*' to limit leachate production. This includes recommendations that landfills be constructed above the regional water table, at minimum of 2 m above the long term average groundwater elevation. (EPA Victoria 2015).

Groundwater is a fragile resource with many recharge and discharge points throughout the environment, specific to each aquifer. If a plume of contamination infiltrates into groundwater it may have adverse effects on the environment and humans who benefit from it. Leachate impacted groundwater has the potential to damage ecosystems within the environment, through discharge to surface water.

Contaminated groundwater can come into direct contact with construction workers during excavation and earthworks of an urban renewable project, such as the excavation of basements and underground carparks. Depending on the composition, contaminated groundwater can potentially volatilise, and the gas produced by landfills may ingress into buildings presenting possible health risks to inside receptors (Mumford, Mustafa & Gerhard 2016).

3.2.1 – Legislation surrounding closed landfills

Legislation regarding closed landfills has changed significantly over the past 50 years. At present closed landfills are required to be rehabilitated, with a final impervious layer known as a cap being an essential requirement. Current closed landfills are also required to provide financial assurance for 30 years for aftercare management (EPA Victoria 2018).

EPA Victoria has provided a guidance document titled '*Best Practice Environmental Practice – Siting, design, operation and rehabilitation of landfills*' (2015) in which they provide guidance on the construction, management and rehabilitation of landfills in Victoria.

The following is paraphrased from the guidance document (EPA Victoria 2015).

An essential part of closing an operational landfill is designing a cap which acts as the final impervious layer. The purpose of the capping is to:

- Reduce infiltration of water into the landfill cell and reduce the expulsion of landfill gas
- Provide a physical barrier between the environment and the waste, which can be utilised for rehabilitating the area for an alternate use

The reduction of surface water infiltration reduces the subsequent production of leachate. Close landfill legislation is currently an important tool in reducing impacts to the environment. For legacy landfills that where filled decades before any legislation, there may be an added risk caused by the lack of engineering controls and aftercare management.

3.4.1.1 – Low-Permeability Liner Cap

The landfill cap can have a low-permeability layer such as clay and/or a flexible membrane liner to reduce seepage. It is acknowledged that the installation and maintenance of a clay layer for the cap is difficult due to the consistency of the waste, due to its heterogenous nature. Uneven settling of waste may lead to this layer cracking. Due to this it is suggested that a drainage layer be placed between the soil layer and the low-permeability cap. The drainage layer is typically sandy soil or gravel and will reduce excess moisture that has seeped through the soil layer that has not been indifferent via evapotranspiration. As a result of desiccation of the low-permeability layer, the drainage layer is often only used in high rainfall areas or on a cap with a shallow gradient.

3.3 – Legacy Landfills of Fishermans Bend

3.3.1 – The importance of site history

An understanding of site history is an important aspect of any site conceptualisation. The National Environmental Protection Measures (NEPM Schedule B2) explicitly mentions site history as an important foundation for a successful preliminary site investigation. Increased knowledge of site history can aid in the analysis and interpretation of data.

Landfills can be complex and largely undocumented. The risk that a landfill poses varies upon several subjective conditions such as location, waste type, construction, time of filling and level of interaction with the environment (Christensen et al. 2001). Many of these conditions can only be accurately known with a detailed understanding of site history.

The Victorian Landfill Register indicates that no closed landfills are in Fishermans Bend, including both industrial and residential areas (EPA Victoria 2020). A somewhat contradictory statement, this supports the fact that landfilling in Fishermans Bend was highly informal with little information existing on official channels.

3.3.2 – Development of landfilling in Fishermans Bend

- **Early history**

Landfilling has a long history in Fishermans Bend though it is not well documented. Prior to European settlement, Fishermans Bend comprised of vast sand ridges and wetlands, hence the original name of the area 'Sandridge' (Biosis 2017).

Albert Park Lake is the only natural remnants left of a vast network of costal estuaries that once comprised present-day Port Melbourne, South Melbourne, and South Bank (Biosis 2017). These wetlands, lagoons and sand ridges posed a nuisance to early European settlers who intended to develop the land (Biosis 2017). From mid to late 1800s to the early 1900s wetlands and sand ridges where progressively removed, with large amounts of fill used for levelling (Biosis 2017). A layer of fill up to five meters deep across Fishermans Bend can be partly attributed to the levelling of the once undulating landscape (Biosis 2017).

- **Sand quarrying and landfills**

Quarrying and landfilling have an intertwined history in Melbourne, which continues to the present day. Fishermans Bend once contained numerous sand quarries which helped supply Melbourne's demand for construction sand. From the 1800s to mid-1900s sand quarries were found throughout, with many created to aid in the construction of the Commonwealth Aircraft Corporation airfield located in the west of Fishermans Bend (Cooney 1984). Due to the shallow water table within the Port Melbourne Sands, several artificial lagoons where created by quarrying. Saltwater Lake located in West Gate Park is the only visible remnants of sand quarrying in Fishermans Bend (Cooney 1984).

Figure 3 – Saltwater Lake (Source: Wikiwand)

3.2.2 – Previously identified landfills

Legacy landfills where previously identified by Hepburn et. al (2017) (see figure 4). These landfills where identified as areas where possible historic sand quarrying and landfilling may have taken place (Hepburn et. al 2019)

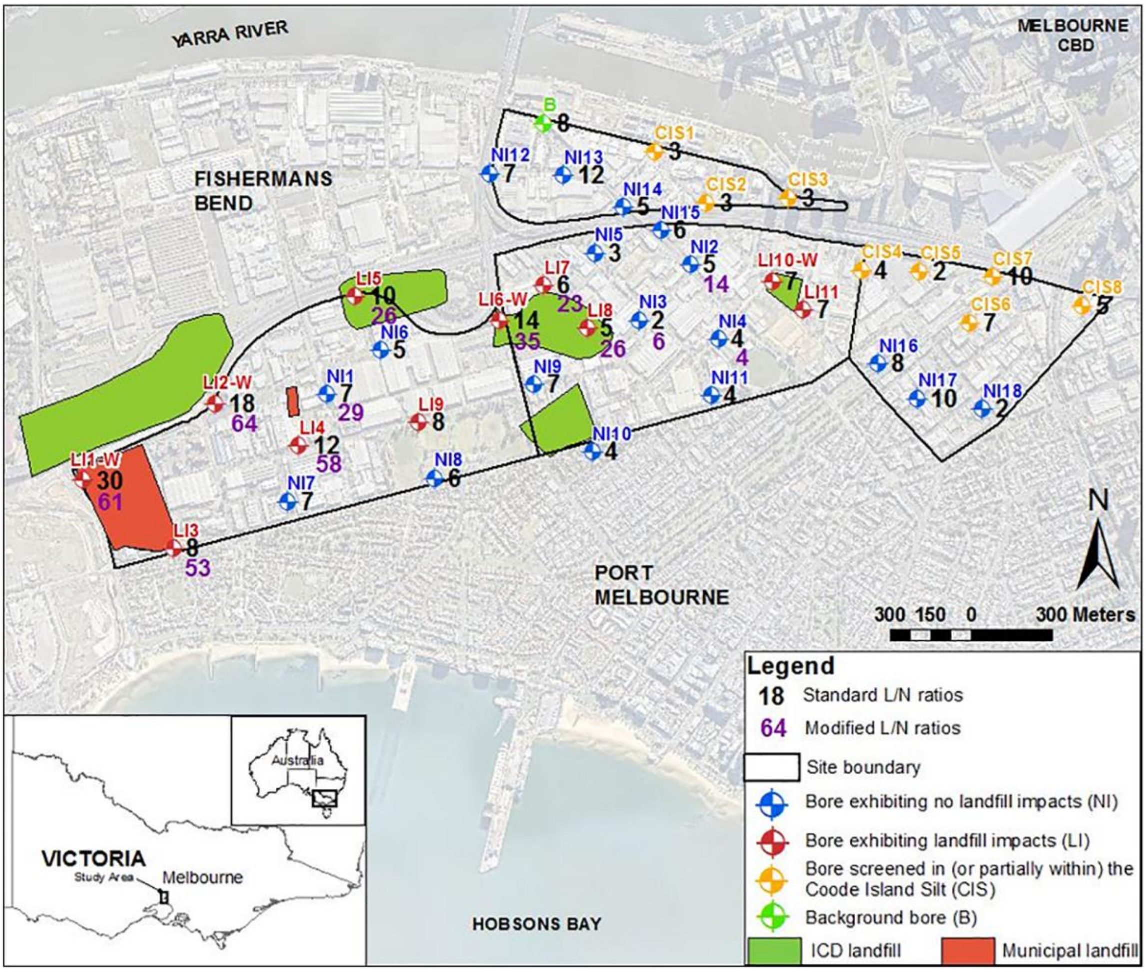


Figure 4 – Previously identified legacy landfill areas (Hepburn et. al 2019)

3.2.3 – Reclassification of previously presumed landfills

This project examined detailed historical evidence, including photographs, eyewitness testimonies and historical reports. On this basis a re-classification of legacy landfills of Fishermans Bend was possible, thereby improving understanding of their extent, waste type and site histories.

Findings from this investigation, indicate that landfilling in Fishermans Bend can be divided into four distinct areas. This is a reclassification from previous studies which have suggested up to seven individual landfills may be present. See figure 5 below for updated legacy landfill locations.

Figure 5 – Updated legacy landfill locations (Source: Nearmap

3.2.3.1 – East Murphy Reserve (East)

Located in the east of present-day Murphy Reserve, this site has previously been classified as an area of potential landfilling (Aecom 2015). An Environmental Audit completed by Senversa in 2019, concluded that the area was likely 'disturbed land' associated with a former runway built in the 1930s (Beveridge Williams 2019). This was further supported with groundwater in the vicinity not found to contain characteristic landfill leachate indicators (Hepburn et. al 2019). The approximate location of this site can be found at bore N110 in figure 4.

3.2.3.1 – Corner of Boundary Street and White Street

This area was considered a potential legacy landfill by Hepburn et. al. (2017). Aecom (2015) conducted a historical investigation of the area and concluded that the site was used as a waste destructor in the early 1900s (Aecom 2015). The land was then used briefly as a timber yard before being used as a council depot from around the 1950s to present (Port Places 2020).

As a council depot the site was used as a waste transfer station and was sometimes referred to as a 'tip' by locals in the area (Port Places 2020). A transfer station is where waste from a municipality is transported to a central location, before being recycled or forwarded to a landfill.

Groundwater results in the area suggest that the site is impacted by characteristic landfill leachate indicators, such as ammonia and potassium (Hepburn et. al 2019). This may from leaching of waste from stockpiles in the transfer station or from surface water runoff. There is no indication that the site has been used as a landfill, however the site has had a long history associated with waste management. The approximate location of this site can be found at L10-W and LI11 in figure 4.

3.2.4 – Former Graham St. Tip

Figure 6 – Approximate extent (orange) (Source: nearmap 2020)

Information regarding the former Graham St. Tip has been found through historic photographs, eyewitness testimony and a 1999 environmental audit by Dames & Moore Group.

On 11/08/20 a questionnaire was completed by Port Melbourne local Mr. Allan Marshall who has been familiar with the area since the late 1950s. The questionnaire can be found in appendix C. Mr. Marshall's insights into the area's history are highly valuable in better understanding the extent and nature of the landfilling.

According to historical photographs, the site was operational from the 1940s to 1974, when construction of the West Gate freeway was beginning (Dames & Moore Group 1999). In the 1940s the site consisted of two separate quarries. In previous studies these two quarries were considered two separate landfills. However, from aerial photographs the two quarries appear to be combined into one in the 1950s, therefore they will be considered as one for the purpose of this investigation. The quarry extended below the shallow water table and produced artificial lagoons as can be clearly seen in historical photographs (See figure 7 below). Mr. Marshall described the water quality of these lagoons as 'visually ok' with many frogs and reeds.

Figure 7 – Graham St. Tip [ca. 1950-ca. 1960] with lagoons visible (source: Pratt 1950)

According to Mr. Marshall, the area was referred to as a quarry not a landfill. Even though referred to as a quarry, landfilling activities were taking place at the site. According to Mr. Marshall, house demolition material, furniture, and rubble from factories were discarded (Marshall 2020). Mr. Marshall describes an abundance of scrap metals such as copper and brass and thousands of discarded 'neon lighting tubes'. Mr. Marshall explains that the site was not used for disposing 'household garbage' sometimes referred as municipal or putrescible waste. Mr. Marshall mentions dumping taking place in the south east corner of the site with trucks entering from Salmon Street. This is consistent with what can be seen in historic photographs with an unmade road leading to Salmon Street from an area that appears to be highly trafficked in the southeast, a possible location where dumping from trucks was taking place. Mr. Marshall also describes occasional strong acid or chemical smells in locations of recent dumping, which suggest that liquid waste may have been deposited at the site.

Mr. Marshall describes 'normal dumping' in the east side of the quarry taking place until the new freeway was built, with this occurring around the year 1974. The entire quarry was than filled with 'dirt, rock, bricks, broken concrete, demolition material, furniture, and rubble from factories' within a year (Marshall 2020).

A 1999 environmental audit by Dames & Moore Group was completed as part of the City Link Project in the area of the site. The waste material was encountered at almost 7 meters in some locations and described as containing; bricks, concrete, wood, glass, rubber, domestic garbage, pockets of ash, coke, scrap metal, foundry sand, slag and other waste (Dames & Moore Group 1999)

3.2.4.1 – Key Findings

- The bulk of the filling occurred in the early 1970s just prior to the construction of the West Gate Freeway.
- The east of the site contains older waste from approximately the 1950s to 1960s
- Most of the waste can be described as construction and demolition (C&D) and commercial and industrial (C&I)
- Disposal of liquid wastes may have occurred
- Putrescible waste is not assumed to be found at the site.
- Some filling occurred below the groundwater table.
- Landfilling was likely informal and ad-hoc in nature

Figure 8 – Leachate impacted water being sampled with waste clearly visible.
(Source: Baulderstone Horibrook Engineering 1996)

3.2.5 – Former Salmon St. Tip

Figure 9 – Approximate extent (orange) (Source: nearmap 2020)

Information regarding this site has been obtained from a 1999 Environmental Audit by Lane Consulting.

The site was a former sand quarry and landfill with operations ending by 1971 (Lane Consulting 1999). Findings from geotechnical investigations indicated that a significant proportion of the landfill contained industrial solid waste, with sections of up to 20% putrescible waste, concentrated in thin layers (Lane Consulting 1999). A Cross section of the landfill (Figure 10) indicates that it has maximum depth of 9 meters, with some waste deposited below the water table (Lane Consulting 1999).

From 1968 aerial photographs, the site still comprises of a sand quarry (Connelly Environmental 1996). In 1971 the site was fully filled which may indicate that the bulk of filling occurred in a relatively short period.

3.2.5.1 – Key Findings

- The time filling ended is known
- Waste can be described mostly as municipal (putrescible), commercial and industrial.
- Waste in known to be below the water table.
- Bulk of filling may have occurred in the early 1970s.

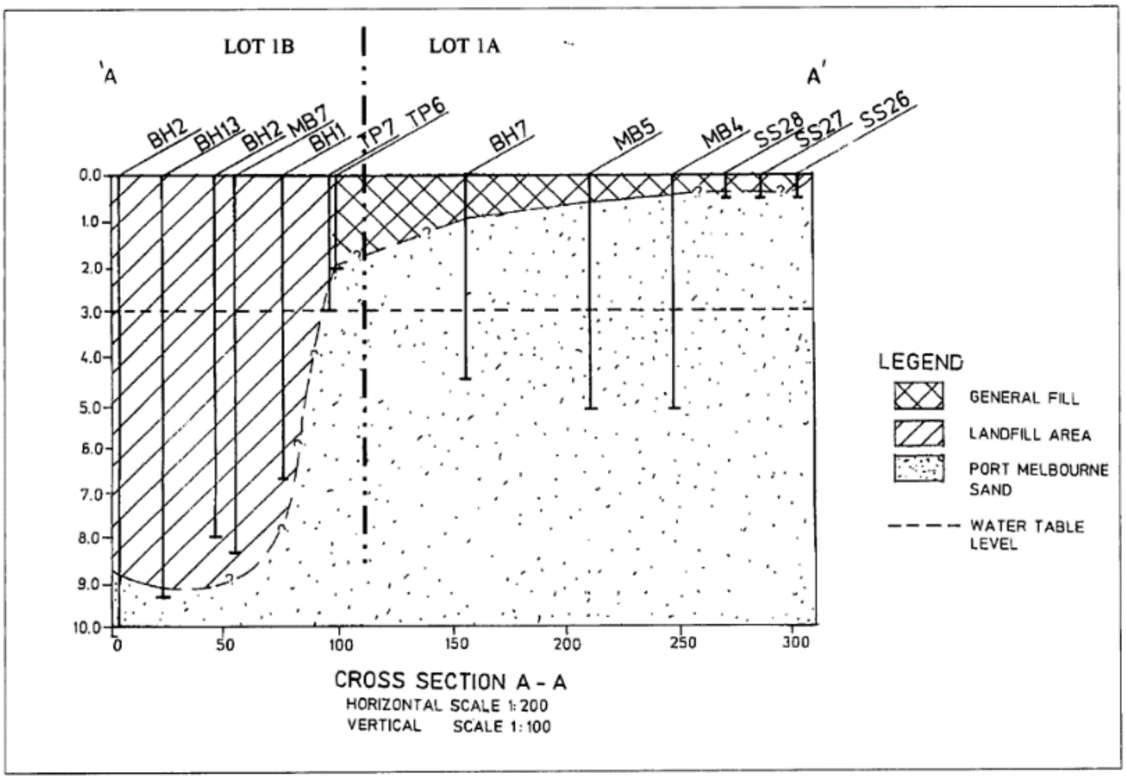


Figure 10 – Landfill cross section of the Former Salmon St. Tip
(Source: Lane Consulting 1999)

3.2.6 – The Port Melbourne Tip

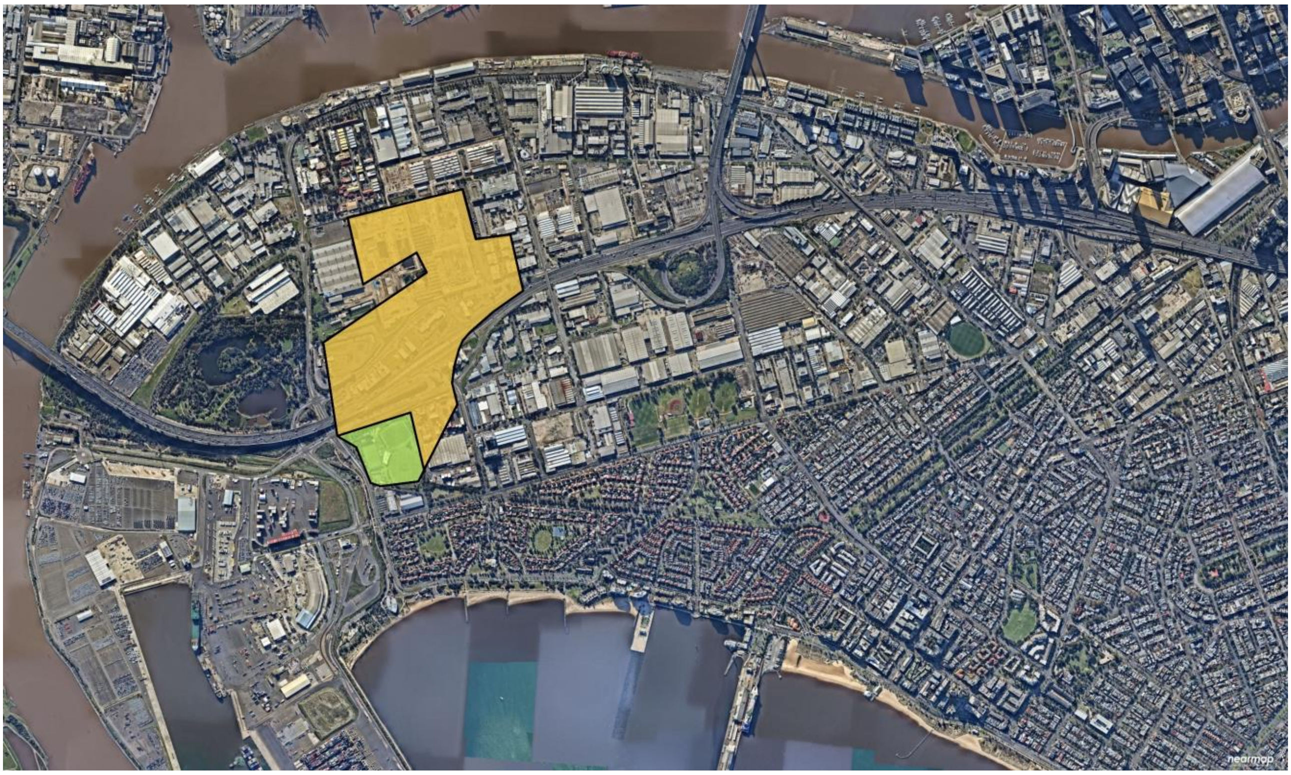


Figure 11 – Approximate extent (orange - filled before 1975, Green – filled 1975-1991)
(Source: nearmap 2020)

Information regarding this site has been obtained from historic photographs, municipal plans, and a 1999 Environmental Audit by Sinclair Knights Merz (SKM).

The Port Melbourne Tip is the largest and most documented landfill in Fishermans Bend. Council records indicate the site was used as a quarry and landfill from the 1930s, with sandmining and filling occurring concurrently until the 1950s (Golder Associates 2001).

From Historical photographs, the northern section was the first to be fully filled with this occurring in the late 1950s. When West Gate Freeway construction started in the early 1970s, most of the site had already been filled. The Orange shaded region in the figure 11 above, depicts areas that were filled prior to 1975.

In the south of the landfill, a renewed stage of sandmining took place in the late 1960s, where fill material was supposedly removed (Golder Associates 1991). The new sand mine was filled between 1974 and 1978 with tipping continuing into the early 1990s (Golder Associates 1991).

Figure 12 – Port Melbourne Tip – North [ca. 1950-ca. 1960] (source: Pratt 1950)

Records from the Port Phillip Council indicate that the site was used for all types of waste up till 1971 (Golder Associates 1991). After 1971, the tipping of industrial waste ceased, with household garbage (municipal waste) being discarded till approximately 1979 (Golder Associates 1991). From 1979 to its closure in the early 1990s, the site was used for various waste material originating from council works such as street sweepings, with refuse being disposed on rare occasions (Golder Associates 1991).

In the area subject to the environmental audit, which is bounded by the Westgate Freeway to the north, Todd Rd. to the west and Williamstown Rd. to the south, the area consists of two distinct sections of waste type (GHD 1999). The south of the site contained a quantity of solid inert waste, with the north and central of the site subject to the filling of municipal and domestic wastes. In the southern section, fill is expected to be at a maximum depth of 8 meters (GHD 1999).

An engineered cap was constructed on the central and northern section of the site in the mid-1990s (SKM 1999). The cap was designed to reduce surface water infiltration into the waste mass, a technique used to reduce leachate production.

3.2.6.1 - Key findings

- Sections where filled at different times
- Waste can generally be described as municipal (putrescible), commercial and industrial.
- The landfill is the youngest in Fishermans Bend
- Waste is known to be deposited below the groundwater table
- Landfilling was council operated and formal

Figure 13 – Exposed waste during 2001 caping works at Port Melbourne Tip - South (Source: Australian Turfgrass Management 2005)

3.2.7 – Landfilling in the vicinity of present day West Gate Park

Figure 14 – Approximate extent (orange) (Source: nearmap 2020)

Information regarding this site has been obtained from a 1984 West Gate Park G roundwater Study by A M Cooney. The present-day Saltwater Lake was once a sand mine, and was quarried between 1942 and 1945, likely to aid in the construction of an airport runway extension (Cooney 1984).

- **Early filling**

Early filling occurred between the 1940s and early 1970s, before the West Gate Freeway was constructed. The northern edge of present day Saltwater Lake was likely an area of waste disposal, with historical photographs showing distinct tracks leading to it, possibly from trucks dumping waste from factories (Cooney 1984).

Metal shavings as well as discharges of oily material were known be deposited on the northern boundary of Saltwater Lake (Cooney 1984). In the north west of Saltwater Lake, fire bricks and crucibles fragments where found, indicating possible foundry waste material (Cooney 1984). In the north east bitumen waste was found, likely associated with the construction of the airfield (Cooney 1984).

- **West Gate Bridge related filling**

Much of the southern lagoon to the west was filled during the construction of the West Gate Bridge in the 1970s (Cooney 1984). A description of the fill material includes, demolition rubble, foundation excavation material and concrete test cylinders (Cooney 1984). As a result, a layer of fill of between 2 to 10 meters covers much of the West Gate Park area (Cooney 1984).

- **Filling related to West Gate Park Construction**

During the construction of West Gate Park which began in 1984, vast quantities of rubble and soil of all kinds where trucked in from across Melbourne, with a tipping fee helping aid in the construction of the Park (West Gate Park Biodiversity 2020). The exact placement of this material and type is unknown.

3.7.2.1 – Key findings

- Disposal was highly informal, with vast amounts of construction related fill
- The waste that has been disposed can be largely be classified as industrial
- Some construction fill has been deposited below the water table, as evident with the filling of the lagoon.

Figure 15 – Partially filled lagoon of present day Salt Water Lake [1945]
(Source: The University of Melbourne 2005)

3.4 – Geology

Fishermans Bend is situated within the Yarra River estuary and consists of quaternary aged river-delta sediments (Hepburn et. al 2019).

The following geological units (from youngest to oldest) are described in Holdgate and Norvick (2017) as follows.

- **Anthropogenic Fill**

Fill covers most of Fishermans Bend and is highly variable (Holdgate & Norvick 2017) Fill has been found to contain; demolition and building waste, clay, sands, dredge spoil and other waste (Holdgate & Norvick 2017). Fill varies in thickness, from the shallow subsurface to approximately 5 metres depth. (Holdgate & Norvick 2017). Fill can be found in greater thicknesses in infilled quarries.

- **Port Melbourne Sands**

The Port Melbourne Sands (PMS) is the youngest unit found in the Yarra Delta, consisting of yellow-brown medium-to fine-grained sands (Holdgate & Norvick 2017). The PMS was deposited in the form of sand ridges also known as sand dunes (Cooney 1984). The original surface landform was destroyed by industrial activity with the last natural remnants of sand ridges seen in the 1940s (Cooney 1984). The PMS has low cohesivity with shell beds being more common in the lower extents (Holdgate & Norvick 2017). Across Fishermans Bend, the unit ranges in thickness from 5 to 10 metres.

- **Coode Island Silt**

The Coode Island Silt (CIS) consists of dark grey brown, silty clays (Holdgate & Norvick 2017). The unit was formed from infilling of river cut valleys of the Maribyrnong and Yarra Rivers delta's (Holdgate & Norvick 2017). The unit can be highly carbonaceous and can include plant matter and woody material (Holdgate & Norvick 2017). The CIS has an average thickness of between 20 and 25 m (Holdgate & Norvick 2017). The unit is a potential acid sulphate soil due to its high pyrite content (Cooney 1984). The contact between the overlying PMS is generally sharp however gradation can occur (Holdgate and Norvick 2017). The transitional material between the layers typically consists of clayey sand (Hepburn et. al 2019).

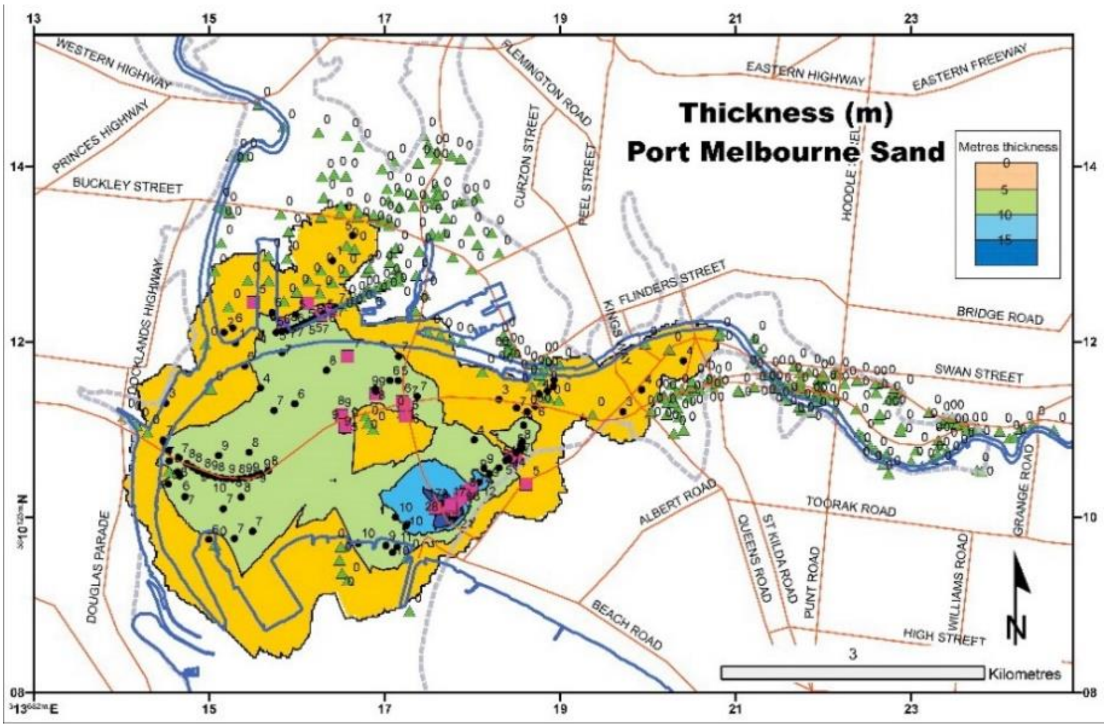


Figure 16 - Thickness of the Port Melbourne Sands (Source: Holgate & Norvick 2017)

3.5 – Hydrogeology

Having a detailed understanding of site hydrogeology will aid in the delineation of landfill leachate plumes and help predict possible pathways for contaminants. Geochemistry of groundwater can have a significant influence on contaminant fate and transport. Its knowledge can aid in the development of a well-defined pathway receptor model.

Groundwater of Fishermans Bend has been the subject of numerous investigation and studies in recent years. Recent hydrogeological investigations have utilised a network of 75 monitoring bores, installed by EPA Victoria between 2015 and 2017. Several environmental audits have also been completed in the past 25 years which can provide useful site-specific groundwater information.

3.5.1 – Groundwater in Fishermans Bend

The PMS acts as a shallow unconfined high yielding aquifer (Hepburn et. al 2019). Anthropogenic fill can also be an aquifer when found below the groundwater table. CIS is considered an aquitard due to its very low permeability.

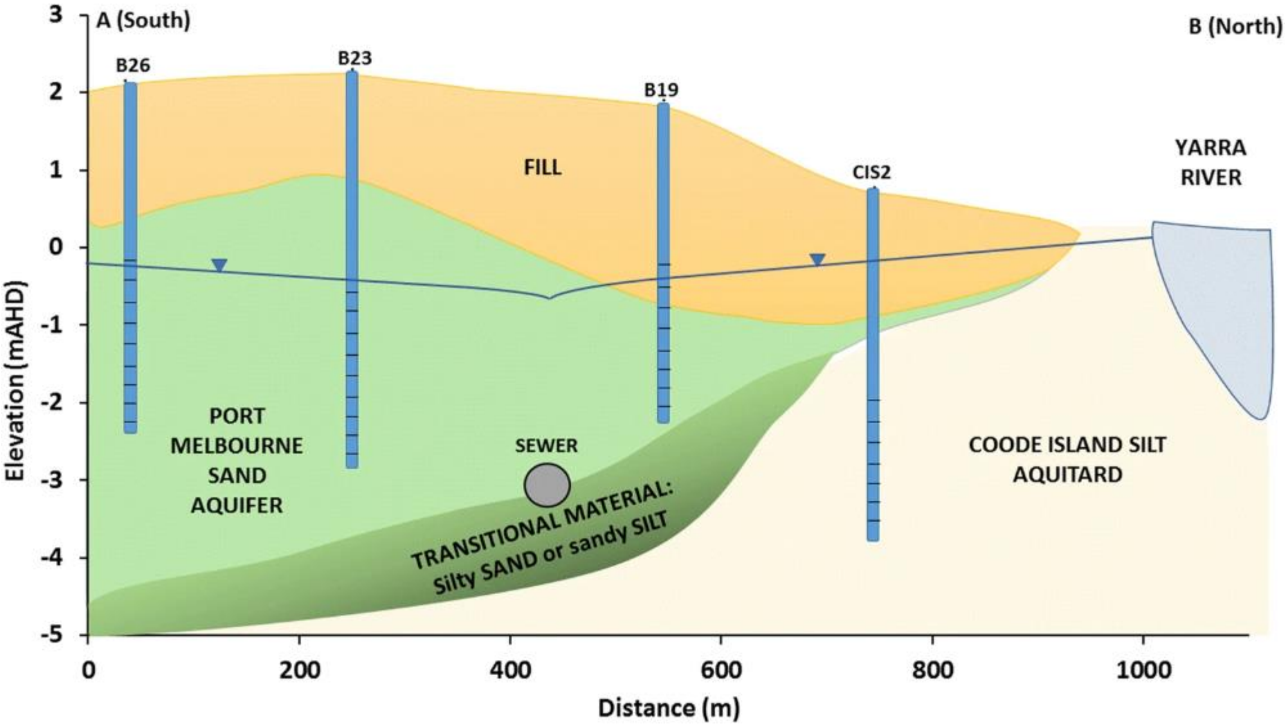


Figure 17 – Cross section of Fishermans Bend (Hepburn et. al 2019)

3.5.2 – Recharge of groundwater

3.5.2.1 – PMS aquifer

Groundwater in the PMS is predominantly recharged by rainfall (Hepburn et. al 2019). This has been indicated by a positive correlation between rainfall and head levels in hydrographs (Hepburn et. al 2019). Relatively high tritium values in the PMS are also an indicator of modern recharge in the groundwater (Hepburn et. al 2019). Recharge is likely influenced by seasonal changes of evapotranspiration (Hepburn et. al 2019). Groundwater within 300 metres of the Yarra River has a similar composition to ocean water, with a saline wedge being present (Hepburn et. al 2019)

3.5.2.2 – CIS aquitard

The modern source of water into the CIS is mostly from ingress from the adjacent Yarra River (Hepburn et. al 2019). This is indicated by a fluctuation in salinity at the times of peak river level (Hepburn et. al 2019). The environmental tracer tritium has been found to be present in the CIS groundwater, indicating a component of modern recharge (Hepburn et. al 2019). As rainfall recharge is considered unlikely, the modern water component is possibly from inter-aquifer leakage via transitional material from the overlining PMS aquifer (Hepburn et. al 2019).

3.5.3 – Aquifer physical properties.

Port Melbourne Sands		**Source**
Hydraulic conductivity	1.7 to 23 m/day	Hepburn et. al 2019
Hydraulic gradient	0.0012 and 0.0014 (mean =0.0013)	Hepburn et. al 2019

Coode Island Silt		**Source**
Hydraulic conductivity	0.0005–0.003 m/day	Hepburn et. al 2019

Table 1 – Groundwater physical properties.

3.5.4 – Aquifer geochemistry

The PMS groundwater has total dissolved solids (TDS) ranging between 189 to 3,680 mg/L (Hepburn et. al 2019). For reference, ocean water generally has a TDS of > 35,000 mg/L. Water found in the aquifer is $Ca\text{-}HCO_3^-$ dominant, however in localised areas impacted by industrial activities and legacy landfilling the water may become $Ca\text{-}SO_4^{2-}$ and $Na\text{-}HCO_3^-$ dominate (Hepburn et. al 2019). In contrast, groundwater in the CIS aquitard is Na-Cl dominate and saline with TDS ranging between 19,600 and 23,900 mg/L. Groundwater geochemistry can be highly heterogeneous, with added complexities from the inputs of industrial activities.

3.5.4 – Potential geochemical controls on contaminants and transport

- **Dissolved oxygen**

The dissolved oxygen can be highly variable ranging from 0.1 to 5.72 mg/L (Aecom 2016). The amount of dissolved oxygen may influence biochemical reactions and the composition of microbes within groundwater. This may influence degradation pathways for certain contaminants.

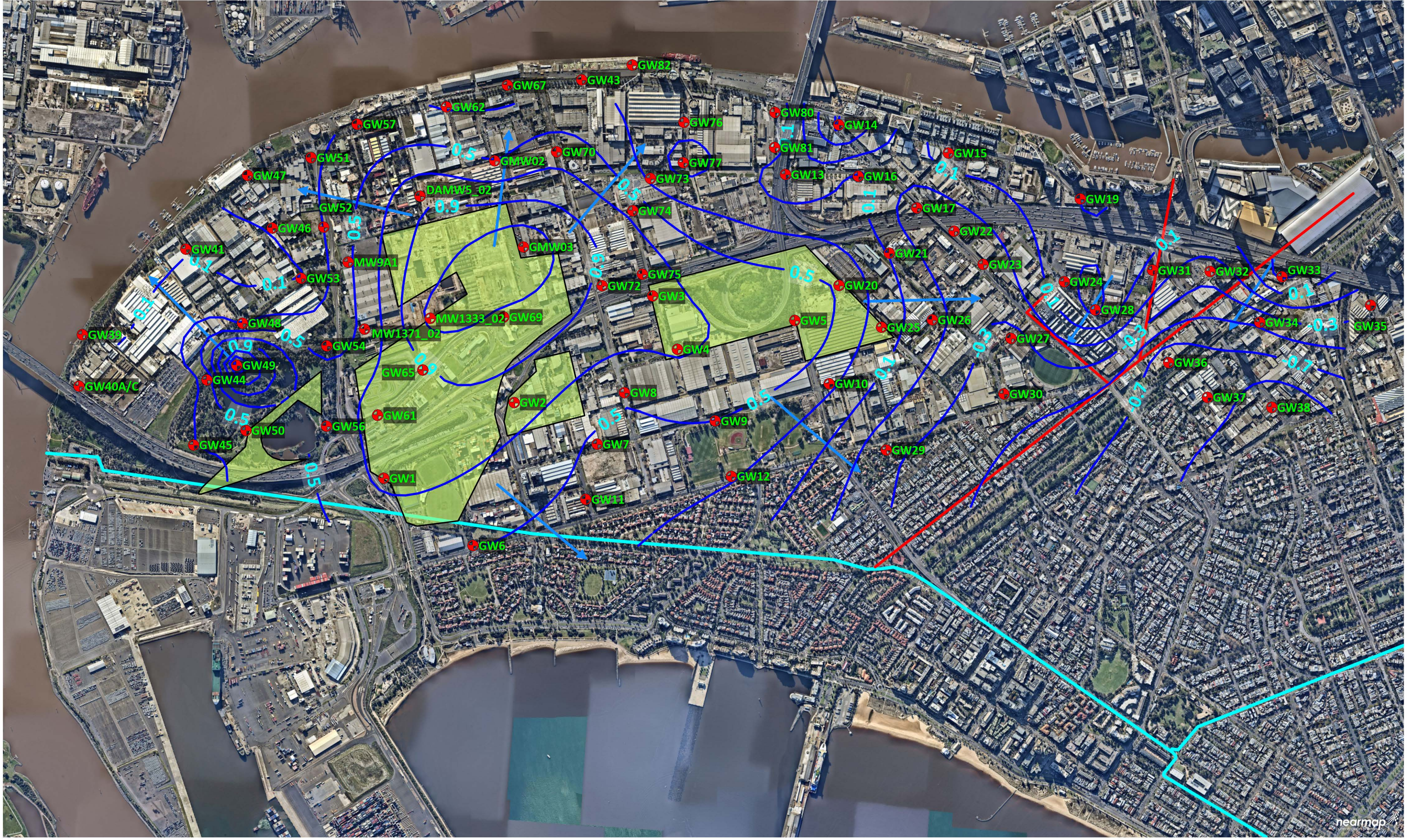
- **Reduction-Oxidation (Redox) Potential and pH**

The redox potential varies across the site from -56 to >500 mV (Aecom 2016). Redox potential can aid in determining if groundwater is in an aerobic or anaerobic condition. The generally high redox potential indicates that groundwater is found mostly in an aerobic (oxygen present) environment. Redox potential can also aid in determining the type of contaminant found and their speciation, with some contaminants in groundwater having differing concentration depending on redox state (United States Geological Survey 2020).

pH is typically neutral with a median of 6.56 (Aecom 2016). In areas associated with industrial contamination the pH can be as low as 3 (Aecom 2016). The pH can influence the speciation of some contaminants, microbial activity and sorption mechanisms which can affect contaminant mobility and fate and transport.

3.5.5 – Groundwater Flow direction

Inferred Groundwater Flow Direction - July 2017 (Aecom)



LEGEND

🟩 Legacy Landfill

━ Redundant Melbourne Main Sewer

━ Operational Sewer

━ Inferred groundwater contour **m AHD**

━ Inferred flow direction

● Groundwater monitoring bore

Figure 18

0 1000 2000 m

Drawn: Nathan Northby
Basemap: Nearmap

Contours created using
Kriging gridding method

3.5.5.1 – Discussion

Groundwater flow within approximately 500-800m of the northern boundary appears to flow towards the Yarra River. The redundant Melbourne Main Sewer as depicted in red in the figure 18 above, acts as a groundwater drain and influences the flow considerably. This is particularly evident at a branch of the redundant Melbourne Main Sewer at Ingles Street with groundwater flow appearing to diverge on that location. The sewer was constructed in 1890s and is located at a depth of – 3.4 m AHD and consists of a 300 mm diameter open cracked ceramic conduit (Aecom 2015). The sewer is not used however it is still connected to the operational Hobson Bay Main sewer, which provides a pathway for groundwater to discharge and flow from the site. The Hobson Bay Main Sewer which runs parallel to Hobson Bay at an offset of approximately 400-500 m may also act as a preferential pathway for groundwater flow (Aecom 2015). The sewer was constructed in the 1890s and given its age may be compromised allowing infiltration of groundwater. The flow towards Hobson Bay appears to be in a south easterly direction. Groundwater in the vicinity of Westgate Park appears to be affected by mounding at GW49, with groundwater flowing in a radial direction.

3.5.6 – Landfill impacts on groundwater flow

Specific groundwater investigations conducted as part of environmental audits have suggested that local groundwater flow can be affected by landfills. Groundwater mounding has been noted on the Salmon St. Tip and Port Melbourne Tip sites (Egis Consulting 1999; Sinclair Knight Merz 1999) Mounding occurs when water infiltrates the porous medium within the landfill, artificially raising the water table relative to the natural geology causing groundwater to flow radially. Mounding can be reduced by capping, an engineering control which reduces groundwater infiltration.

Information obtained from historical investigations, combined with hydraulic flow lines indicate that groundwater mounding is likely occurring on the northern section of the former Port Melbourne Tip. This section of landfill was filled in the late 1950s with groundwater appearing to flow in a radial direction from the presumed waste mound.

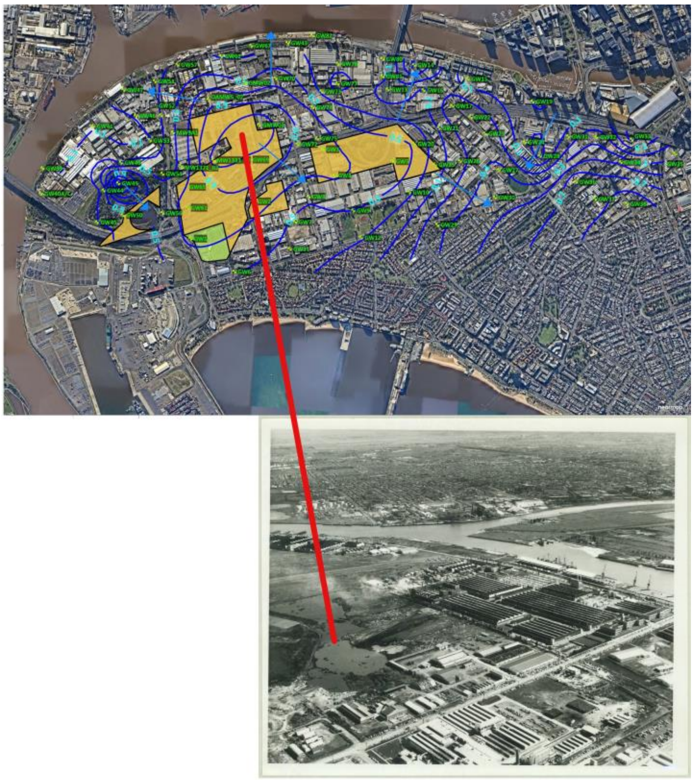


Figure 19 – Port Melbourne Tip during operation and present-day area of groundwater mounding (source: nearmap;Pratt 1950)

3.5.7 – Potential changes to groundwater flow

- **Scenario - Rehabilitation of Hobson Bay Main Sewer**

The redundant Melbourne Main Sewer has a significant effect on groundwater flow in Fishermans Bend. Due to this, if the sewer becomes disconnected from the operational Hobson Bay Main Sewer the flow direction may change significantly. Rehabilitation works have been completed on Brighton Main Sewer (Upper Hobson Bay Main) in 2018-2019, which relined the original 130-year-old sewer with fibreglass (Interflow 2019).

Rehabilitation works have not been planned for the junction of the redundant Melbourne Main Sewer and operational Hobson Bay Main Sewer (Melbourne Water 2020). However, given the age of the sewer, future works may need to be completed. Hypothetically, if the junction between the Hobson Bay Main Sewer and the redundant Melbourne Main Sewer were hydraulically separated by installation of a fibreglass barrier for example, then the redundant sewer will eventually be fill by groundwater. This will render its status as a groundwater drain and preferential pathway for flow. As a result, groundwater may flow towards the natural topographic direction of the Yarra River and Hobson Bay, which may have implications for contaminant migration to receptors.

Figure 20 – Rehabilitation works on the 130 year old Upper Hobson Bay main sewer. (Source: Interflow 2019)

3.6 – Landfills and emerging contaminants

A contaminant may be labelled ‘emerging’ when new discoveries indicate that it has a potential, perceived or real risk to the environment or human health (US EPA 2010).

New detection methods may also reveal an emerging contaminant if it is increasingly evident at significant levels (Foronda 2019). Below are some steps that can be taken to classify a contaminant as emerging.

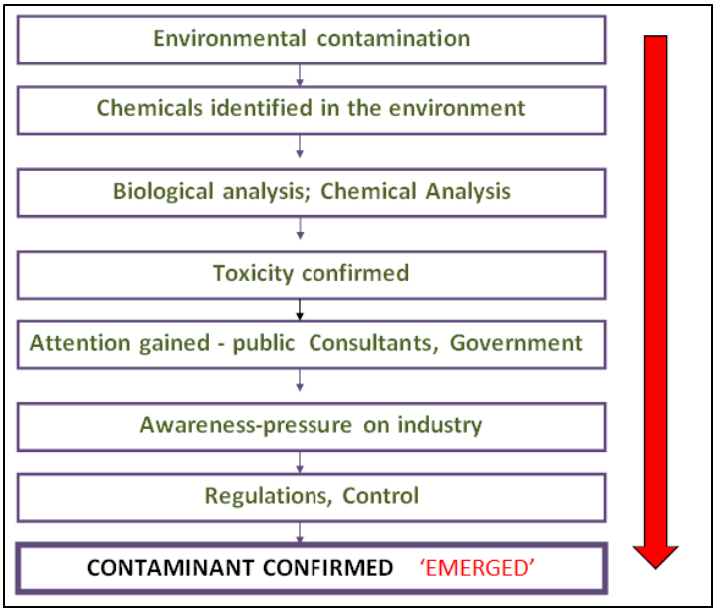


Figure 21 – Emerging contaminates (Source: Foronda 2019)

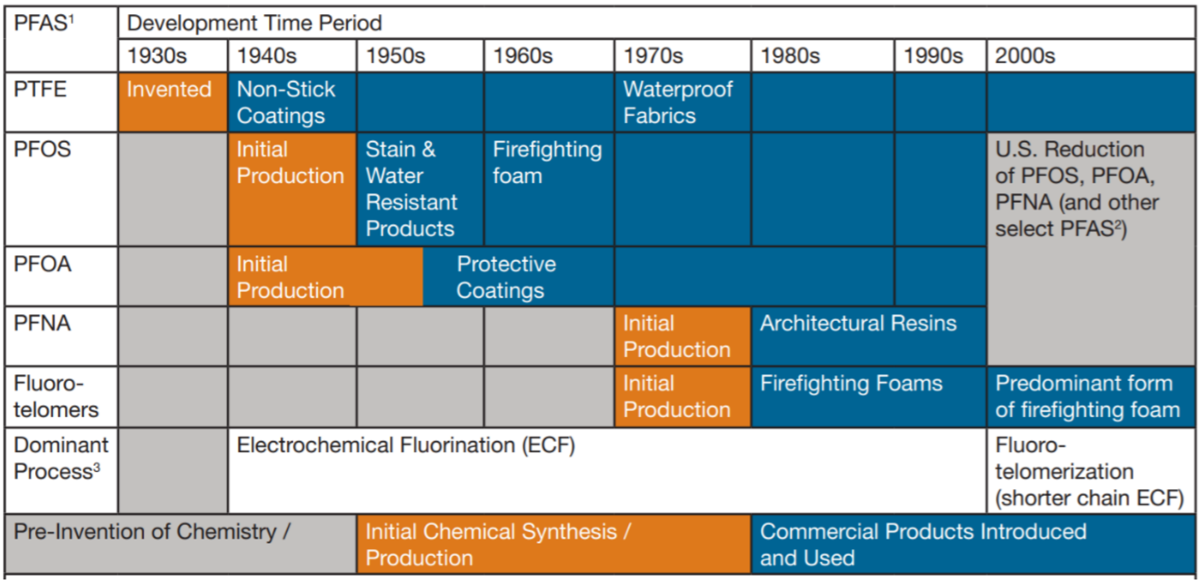
Many consumer and industrial products are created using unregulated chemicals and are readily discarded into landfill once their product life has expired.

The extent of unregulated chemicals can be seen on US EPA’s chemical substance inventory which indicates that only 1% of all chemicals on the US market are tested for toxicity (Royal Society of Chemistry 2015). An example of this is PFOS & PFOA which were once unregulated and extensively used before they were exposed to be toxic and phased out (3M 1999). Due to thousands of unregulated chemicals entering landfills, they may act as a long-term source of emerging contaminates.

3.7 – Per and polyfluoroalkyl substances (PFAS)

3.7.1 – History, use & potential danger

Per and polyfluoroalkyl substances (PFAS) are a group of over 4000 chemicals which have been manufactured since the early 1940s (US EPA 2018). Some PFAS properties include, oil and water repellence, friction reduction and temperature resistance. Due to these useful properties PFAS is often found in coatings for textiles, cookware and firefighting foams (ITRC 2020).



PFAS[1]	Development Time Period						
	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s
PTFE	Invented	Non-Stick Coatings			Waterproof Fabrics			
PFOS		Initial Production	Stain & Water Resistant Products	Firefighting foam				U.S. Reduction of PFOS, PFOA, PFNA (and other select PFAS[2])
PFOA		Initial Production	Protective Coatings					
PFNA					Initial Production	Architectural Resins		
Fluoro-telomers					Initial Production	Firefighting Foams		Predominant form of firefighting foam
Dominant Process[3]		Electrochemical Fluorination (ECF)						Fluoro-telomerization (shorter chain ECF)
Pre-Invention of Chemistry /			Initial Chemical Synthesis / Production			Commercial Products Introduced and Used		

Figure 22 – Timeline & history of PFAS (Source: ITRC 2020)

3.7.2 – Physical and chemical properties

PFAS can be categorized into two groups, polymers and non-polymers. The carbon-fluorine covalent bond of PFAS presents high binding energy rendering it from breakdown under natural environmental conditions. This makes PFAS highly persistent in the environment (ITRC 2020).

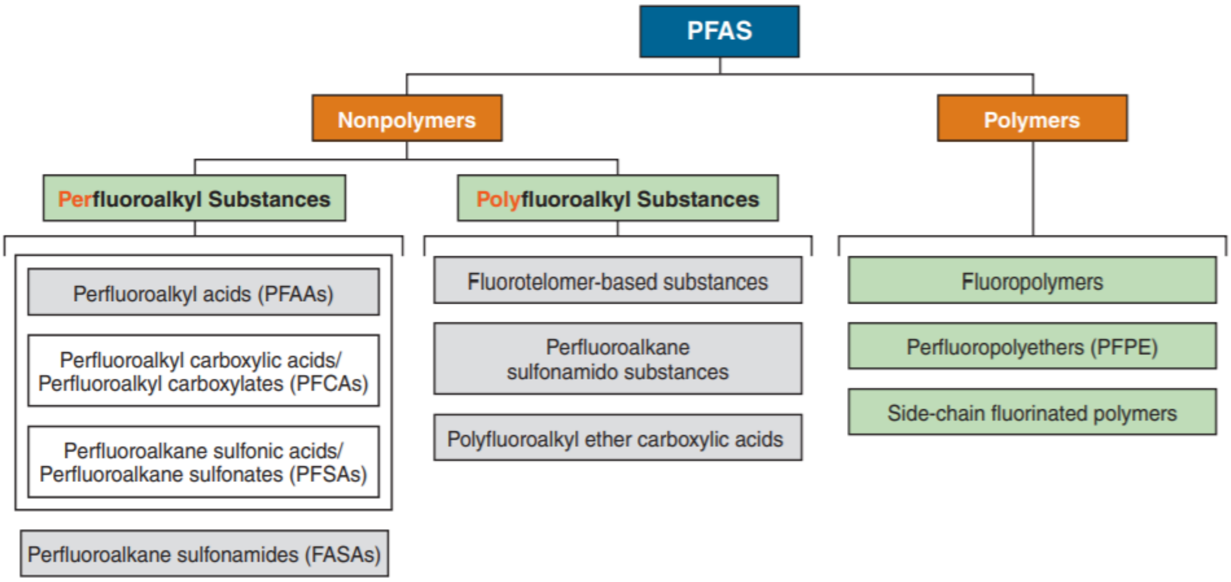


Figure 23 – PFAS family (Source: ITRC 2020)

3.7.2.1 – Perfluoroalkyl Substances

Perfluoroalkyl substances have a carbon tail which comprises of at least two carbon atoms which is attached to a charged functional group (head) of primarily carboxylates or sulfonates (ITRC 2020). The naming convention ‘perfluoro’ indicates that all bonding sites within the carbon tail are fluorinated, except the binding to the functional group (ITRC 2020). The carbon tail is also assigned a name from organic chemistry nomenclature such as octane and the functional group is identified by sulfonates (S) and carboxylates (A). These compounds cannot be physically degraded in the environment and are therefore known as ‘terminal PFAS’ (ITRC 2020).

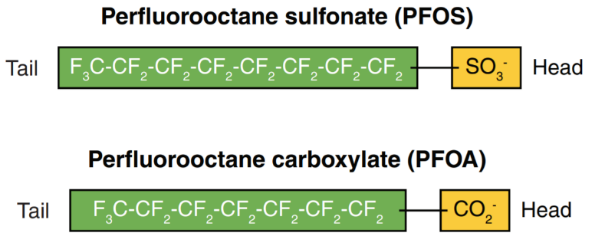
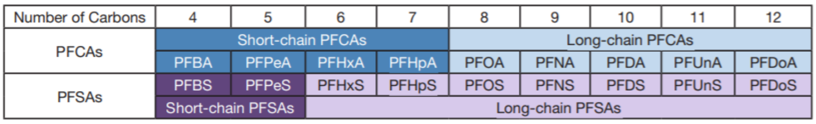


Figure 24 – PFOS & PFOA
(Source: ITRC 2020)

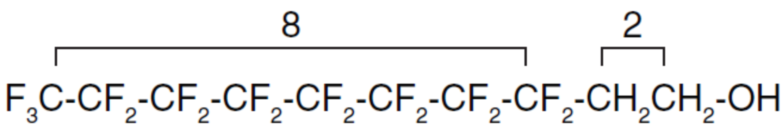


Number of Carbons	4	5	6	7	8	9	10	11	12
PFCAs	Short-chain PFCAs				Long-chain PFCAs				
	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA
PFSAs	PFBS	PFPeS	PFHxS	PFHpS	PFOS	PFNS	PFDS	PFUnS	PFDoS
	Short-chain PFSAs		Long-chain PFSAs						

Figure 25 – Short chain and long chain PFAS
(Source: ITRC 2020)

3.7.2.3 – Polyfluoroalkyl Substances

When the carbon chain is not fully fluorinated but has at least two sites which are the compound is referred to as ‘polyfluorinated’ (ITRC 2020).



$$\overbrace{F_3C\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2\text{-}CF_2}^{8}\text{-}\overbrace{CH_2CH_2}^{2}\text{-}OH$$

8:2 FTOH (8:2 fluorotelomer alcohol)

Figure 26 – Polyfluoroalkyl Substance (Source: ITRC 2020)

When discussing a compound such as 8:2 fluorotelomer alcohol, the first number indicates the number of fluorinated sites within the carbon tail and the second indicates how many sites are not (ITRC 2020). To better distinguish polyfluoroalkyl substances their name incorporates the way it was synthesised, for example fluorotelomers are created by telomerisation and given the prefix FT (Fluro telomerisation) (ITRC 2020).

3.7.2.2 – PFAS precursors

A PFAS precursor is a PFAS that has the potential to degrade into terminal PFAA (ITRC 2020). A wider knowledge of PFAS precursors may help better anticipate concentrations downgradient of a source (ITRC 2020). It is important to include PFAS precursors as part of a testing suite as terminal PFAS concentration can increase due to the precursor degradation (ITRC 2020). This may have implications for site characterisation, conceptual models and risk assessments. The PFAS National Environmental Protection measures, also known as PFAS NEPM 2.0 is the current best practice in Australia and recommends testing for precursors (Department of Agriculture, Water and the Environment 2020).

A research paper by Hamid et. al (2020) indicates that bacteria found in landfill leachate may biodegraded 6:2 FTS under aerobic conditions, resulting in a transformation to PFPeA, PFHxA and PFBA (Hamid, Li & Grace 2020). These transformation products will then not degrade further under ordinary environmental conditions (Hamid, Li & Grace 2020; ITRC 2020). Precursors can also degrade under abiotic conditions by processes such as hydrolysis and photolysis (Martin et al. 2010).

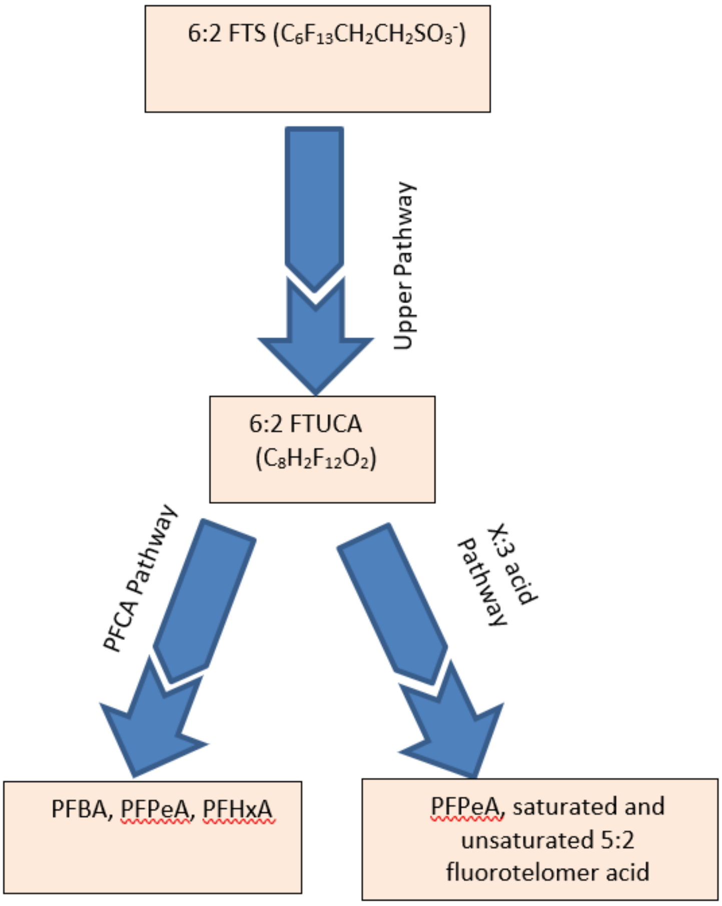


Figure 27 – 6:2 FTS biotransformation
(Source: Hamid, Li & Grace 2020)

3.7.3 – PFAS Fate and transport

Fate and transport refer to a chemicals behaviour in the environment which can include biological, chemical and physical process that influence its dispersal and migration. The fate and transport of PFAS can be very complex as it comprises of thousands of different compounds that exhibit a range of properties (ITRC 2020). This echoes the significance of not making wide assumptions in site characterisation, based on assumptions of the fate and transport of a few well-studied PFAS.

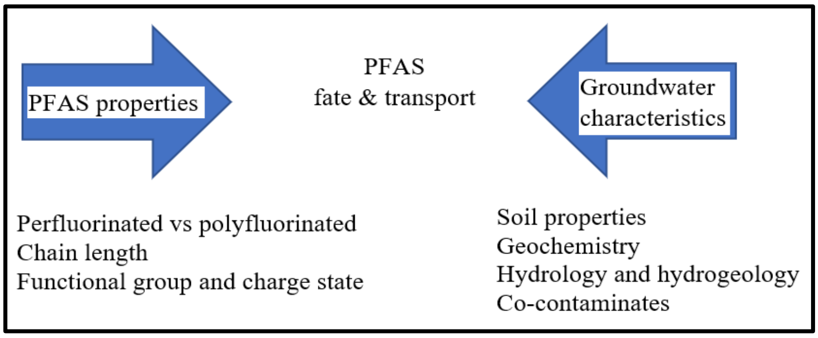


Figure 28 – PFAS fate and transport considerations (Adopted form: ITRC 2020)

3.7.3.1 – Movement in groundwater

As PFAS typically have high aqueous solubility, their mobility in ground water may be high (ITRC 2020). When PFAS migrates into groundwater the main factors that influence its mobility include, partitioning to soil and the air-water interface, transformation both biotic and abiotic and matrix diffusion (ITRC 2020). The geochemistry and biogeochemistry of an aquifer can significantly influence the transport of PFAS (ITRC 2020). Knowledge of aquifer properties and geochemistry is therefore crucial in predicting movement of PFAS in groundwater.

3.7.3.2 – Phase Partitioning

When PFAS migrates into the groundwater, it may leach through the vadose zone (partially saturated) to the fully saturated zone which allows for an air -water interface to exist. As PFAS typically behave like surfactants, it is common for the chemicals to accumulate at the air-water interface as it lowers the surface tension between the two mediums (Costanza et al. 2019). This accumulation between mediums occurs due to the fluorinated carbon chain having both hydrophobic and lipophobic properties (Brusseau 2018). When collecting at the interface the hydrophobic PFAS head positions away from the water while the hydrophilic head is attracted towards it (ITRC 2020). This mechanism may potentially retard the migration of PFAS through the vadose zone and may result in the air-water interface acting as a long term store of PFAS (Costanza et al. 2019). In the context of Fishermans Bend, this mechanism is not expected to be the primary driver of movement and migration, with a significant amount of waste located below the vadose zone.

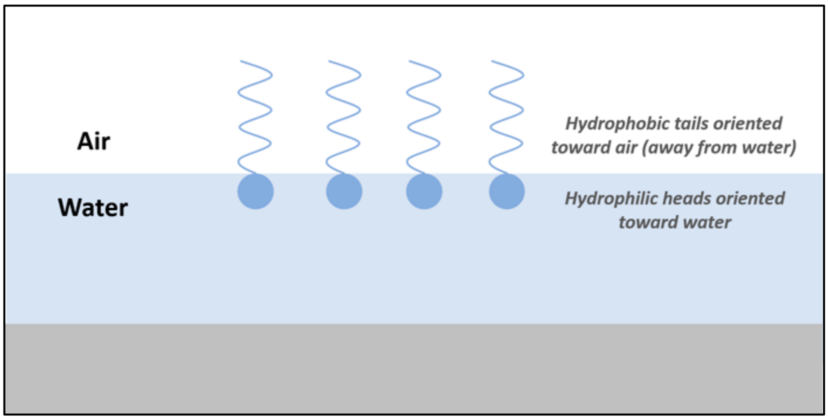


Figure 29- Air water Interface PFAS interaction (Source:ITRC 2020)

3.7.3.3 – Partitioning to soil

Due to the influence of clay content and organic matter, particles within soil and groundwater are often anionic (Efretuei 2016). PFAS can be found in the environment as anions (negatively charged), cations (positively charged) and as zwitterions (both positively and negatively charged) (IRTC 2020). PFAA under normal environmental conditions will present as anions however, in rare conditions when the pH is below 3, PFAA will be found in cationic form (IRTC 2020).

PFAS can be found to have anions, cations and zwitterions under normal environmental conditions. PFAS that are cations and zwitterions may be attracted to the negatively charged soil, potentially retarding its movement within groundwater (IRTC 2020). PFAA which include PFOS and PFOA are negatively charged under ordinary environmental conditions (IRTC 2020). It is assumed that there will be no absorption onto soils due to electrostatic attraction as both PFAS and the soil have a negative charge (IRTC 2020).

PFAS can also sorb to organic carbon within soil, making it a potential retardation mechanism (ITRC 2020). The organic carbon partitioning (K_{OC}) is used to help predict soil adsorption, with PFAS of a longer chain length generally having a higher K_{OC} (IRTC 2020). The most extensively researched PFAS (PFCA and PFSA) are assumed to associate with organic carbon fractions in the soil due to hydrophobic partitioning (IRTC 2020). Soils that contain high organic content such as Coode Island Silt may retain higher amounts of PFAS relative to soils with less organic material. This finding may have potential implications for site characterisation and conceptual models.

Predicting sorption of PFAS to soil in groundwater is complex. Accurately predicting, requires an extensive knowledge of geochemistry (IRTC 2020). Bulk partitioning coefficients (Kd) is the grouping of all soil partitioning factors with each PFAS having a unique (Kd) value (IRTC 2020).

3.7.3.4 – Biotic and abiotic transformations

The transformations of precursors to terminal PFAA can occur through biotic and abiotic pathways, hence the fate and transport of precursor compounds can be significantly influenced (ITRC 2020). When a precursor transforms into a terminal PFAA, their physical and chemical properties may also change (ITRC 2020). For example, PFAS precursors that exhibits a cationic charge may degrade into a PFAA with a negative charge, thus increasing its movement through groundwater, due to relative absence of electrostatic attraction.

It is assumed that when the point source (e.g. landfill) is older, a higher percentage of terminal PFAS may be found due in part to the degradation of precursors (IRTC 2020). If this pathway is not taken into consideration, PFAA concentrations at legacy landfills may be underestimated. To better predict this fate and transport mechanism, when analysing for PFAS, a total oxidisable precursors (TOP) test can be performed to assess degree of precursor degradation activity (ITRC 2020).

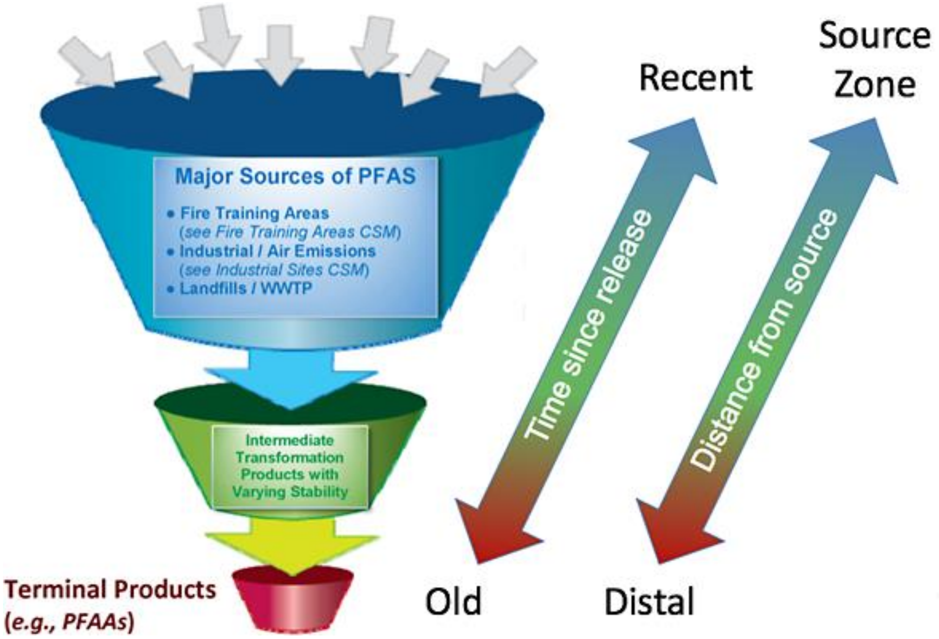


Figure 30 – Change in PFAS composition with time (Source: ITRC 2020)

3.7.3.5 – Matrix Diffusion

Relative to advection, the diffusion rate of PFAS in groundwater is considered slow (ITRC 2020). Quantifying the diffusion rate of PFAS in soil is an area of ongoing research, with it being theorised that diffusion of PFAS plays an integral part of movement throughout the groundwater system (ITRC 2020). The PFAS that has absorbed into the soil within the groundwater system has the potential to back-diffuse, which occurs when a contaminant diffuses from a low permeable area to a high permeable one (ITRC 2020; Halloran & Hunkeler 2020).

As terminal PFAS will not degrade in the environment, they may have a higher likelihood of experiencing back-diffusion which may be more significant relative to other degradable solvents (ITRC 2020). Diffusion has been recognised as a factor that enabled PFAS to penetrate concrete in firefighting training facilities (Baduel, Paxman & Mueller 2015). Studies like this highlight the potential of diffusion mechanisms and the importance of further research (Baduel, Paxman & Mueller 2015).

3.7.3.6 – Advection and hydraulic dispersion

The mechanical transport of water influences the fate and transport of contaminants within the groundwater system. Factors such as hydraulic gradient, permeability and effective porosity of an aquifer influence its mechanical transport (ITRC 2011). Differing velocities and flow paths of contaminants causes hydraulic dispersion (ITRC 2011).

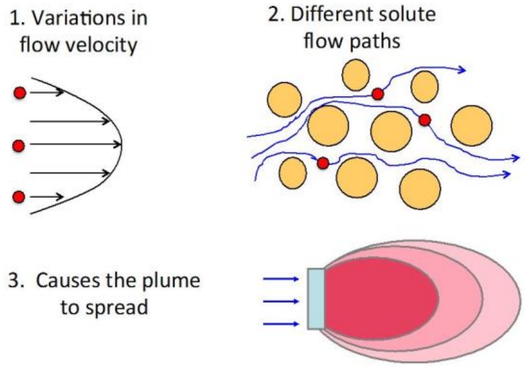


Figure 31– Hydraulic Dispersion (Source ITRC 2011)

3.7.4 – Toxicity

PFAS consist of thousands of compounds with many of their toxicities still unknown (ITRC 2020). PFOS and PFOA are the most widely research compounds in terms of toxicity (ITRC 2020). PFOS and PFOA are known persistent organic pollutants, with these contaminants added to the Stockholm Convention in 2009 (Australian Government 2017).

PFAS have been shown to be highly mobile within the environment, with a potential for bioaccumulation and toxicity within plants and animals (Department of Agriculture, Water and the Environment 2020). It is noted in PFAS NEMP 2.0 that when evaluating risks to human health it is important to sample edible sizes (e.g. a fish fillet), whereas when assessing ecological risks, entire prey organisms should be targeted (Department of Agriculture, Water and the Environment 2020).

When assessing the overall environmental risk, bioaccumulation is a critical factor. The bioconcentration factor is dependent on PFAS structure, with increasing fluorocarbon chain lengths resulting in higher bioconcentration (Hekster et al. 2003). To aquatic and more specifically marine organisms, PFOS has been shown to be “moderately acutely toxic and slightly chronically toxic” (Hekster et al. 2003).

When PFOS and PFOA enter the human body, they have half-lives of 8.67 years and 1-3.5 years, respectively. PFCAs that have a longer chain length are likely to remain in the body longer then their shorter chain counterparts (Kudo et al. 2001). When in the body, these chemicals are distributed to the liver, kidney and plasma with excretion occurring via urine and feces (Hekster et al. 2003). Scientists have tested rodents and primates with PFOS, PFOA, 6:2 FTOH, 8:2 FTOH, 10:2 FTOH and 12:2 FTOH in which some compounds were found to be carcinogenic and induced “chromosomal aberrations and polyploidy” to the test subjects ovaries (Hekster et al. 2003; OECD 2002; US EPA 2002). According to the US EPA, if humans or animals consume PFAS for extended period of time, bioaccumulation may occur leading to adverse health problems such as low infant birth weights, effects on the immune system, cancer and thyroid hormone disruption (US EPA 2018).

Current Australian ecological and human health guidelines surrounding PFAS can be found in Appendix A of this report.

3.8 – 1.4 dioxane

1.4 dioxane ($C_4H_8O_2$) is a clear artificial industrial chemical which is entirely miscible in water (US EPA 2017). This clear liquid is often used within the chemical industry to stabilise chlorinated solvents and is an ingredient in many household products, thus making it evident in many municipal waste landfills (California Office of Environmental Health Hazard Assessment 1998). 1.4 dioxane has been found in sites contaminated with volatile chlorinated hydrocarbons and landfill leachate (Karges et. al 2018).

1.4 dioxane is likely to be a contaminant at industrial sites, as a by-product of the manufacturing process of polyethylene terephthalate (PET), 1, 1, 1-trichloroethane (TCA) and trichloroethylene (TCE) (US EPA 2017). At elevated temperatures, this chemical is extremely unstable and under certain moisture conditions can produce explosive peroxides (California Office of Environmental Health Hazard Assessment 1998; US EPA 2017). Photooxidation can degrade the polymer surface of 1.4 dioxane via exposure to oxygen or ozone which is facilitated by radiant energy such as UV light which can result in a half-life of 1 to 3 days (US EPA 2017).

3.8.1 – Health and Environmental Effects

Food will often contain traces of 1.4 dioxane because even though it does not bioaccumulate, biomagnify or bioconcentrate in the food, adhesives on packaging's or on crops that are treated with pesticides containing 1.4 dioxane can be a source of contamination (US EPA 2017). The US EPA has classed this chemical as a B2 probable human carcinogen as it is readily absorbed via lung and gastrointestinal tract and has been shown to cause cancers in animals after exposure (US EPA 2017; US EPA 2006; Jackson & Lemke 2019; California Office of Environmental Health Hazard Assessment 1998).

3.8.2 – Toxicity

Any person may be exposed to the contaminant 1.4 dioxane via inhalation, oral or dermal routes. The U.S. Department of Health and Human Services has reported that the adverse effects of this chemical may increase with longer exposure (United States Department of Human Health and Services 2012).

The US EPA notes that even with minimal exposure to 1.4 dioxane via any route your risk of developing cancer may increase (US EPA 2017). Barber (1934) has documented 5 deaths of factory workers that worked primarily with 1.4 dioxane vapours with possible dermal exposure occurring within a 2-week period (Barber 1934). The majority of the victims suffered abdominal pains and vomiting prior to passing (Barber 1934). Autopsy's performed on the deceased showed lesions ranging in degree on both the liver and kidneys as well as edema on the brain, which was linked to the 1.4 dioxane exposure (Barber 1934; Johnstone 1959). As stated in the Johnstone (1959) report the workers were exposed to an average of 470 ppm of 1.4 dioxane for 1 week before passing away (Johnstone 1959). After performing tests on volunteer subjects there were a range of respiratory affects observed after exposure to 1. 4 dioxane increased.

These ranged from no adverse respiratory affects to nose, throat and mucous membrane irritation (Ernstgard et al. 2006; Fairley et al. 1934; Wirth and Klimmer 1936). 1.4 dioxane exposure to rats has also shown "nuclear enlargement of the respiratory epithelium of the nasal cavity" (Kaisai et al. 2008). According to the report by Kaisai et al. 2008, after exposure the rats exhibited elevations in red blood cell count, hemoglobin, hematocrit and in mean corpuscular volume (Kaisai et al. 2008). 1. 4 dioxane has also been linked to loss of body weight up to 32%, an increase of miscarriages, still births and low birth weights (NICNAS 1998; Stott et al. 1981).

The current international health guidelines are given in Appendix A of this report.

3.9 – Remediation techniques

3.9.1 – PFAS

As fate and transport of PFAS plays a major role in contamination, the first step of remediation is to create a detailed site characterisation (ITRC 2020). The utilisation of sorption technologies is the most widely used techniques in remediation of PFAS impacted groundwater (McGregor 2018).

- **Pump and treat (ex situ treatment)**

Currently the pump and treat method is the most common form of remediation (ITRC 2020). Contaminated groundwater can be extracted from an aquifer where is than treated and reinstated within the aquifer or discharged as surface water (ITRC 2020). This is currently the most common form of PFAS remediation in groundwater (ITRC 2020). Sorption technologies are utilised to remove PFAS from contaminated water and can be utilised as part of a pump and treat system. Granular Activated Carbon (GAC) is used to remediate PFAS contaminated water and has been proven to remove PFOA, PFOS and PFNA from contaminated groundwater (ITRC 2020). The GAC utilises physical mass transfer, which absorbs PFAS. Once the pumped groundwater has been treated by GAC, the filament is removed and thermally treated, a process which destroys the remaining PFAS (ITRC 2020).

- **Injection of colloidal activated carbon (CAC) into groundwater (In-situ treatment)**

Colloidal activated carbon (CAC) is a proven in-situ treatment of PFAS contaminated groundwater (McGregor 2018). CAC can be injected into aquifers and utilises physical mass transfer processes to absorb PFAS (McGregor 2018). It is important to note that this technology is still emerging, and its effectiveness is the subject of ongoing research (ITRC 2020).

3.9.2 – 1.4 dioxane

- **Pump and treat (ex situ treatment)**

For sites contaminated with 1.4 dioxane a common treatment is the ex-situ pump-and-treat remediation method (Jackson & Lemke 2019). This method involves extracting 1.4 dioxane contaminated water and adding hydrogen peroxide and ozone or exposing the extracted water to UV light. Both methods utilise the oxidation of carbon bonds on the chemical to facilitate degradation, however the process is not 100% effective (Jackson & Lemke 2019; Stefan & Bolton 1998). When 1.4 dioxane is in low to warm temperatures it has been shown to degrade in bio-stimulated and bioaugmented microcosms.

Experimentation with 1.4 dioxane and wastewater sludge enriched with iron III, has been shown to facilitate degradation (Jackson & Lemke 2019; Li et al. 2015; Shen et al. 2008). These experiments have indicated that there is possibility for both aerobic and anaerobic biodegradation of 1.4 dioxane. As 1.4 dioxane is unaffected by sorption into soil particles, its migration from the atmosphere to the groundwater may be rapid, with this movement rendering it relatively unaffected by photooxidation in the atmosphere (Jackson & Lemke 2019; US EPA 2017). Once within the soil and groundwater 1. 4 dioxane is impervious to biodegradation due to its molecular structure (Jackson & Lemke 2019).

4.0 – Findings

4.1 – Delineation of landfill leachate impacted regions

Previous investigations by Hepburn et. al (2017-2019) sampled a network of 38 groundwater bores in the precincts of Lorimer, Wirraway, Sandridge and Montague (See Figure 32). An additional 27 bores where drilled in May 2017 in the Employment District located in the north west of Fishermans Bend (Aecom 2017). These additional bores have yet to be investigated for potential landfill leachate impacts.

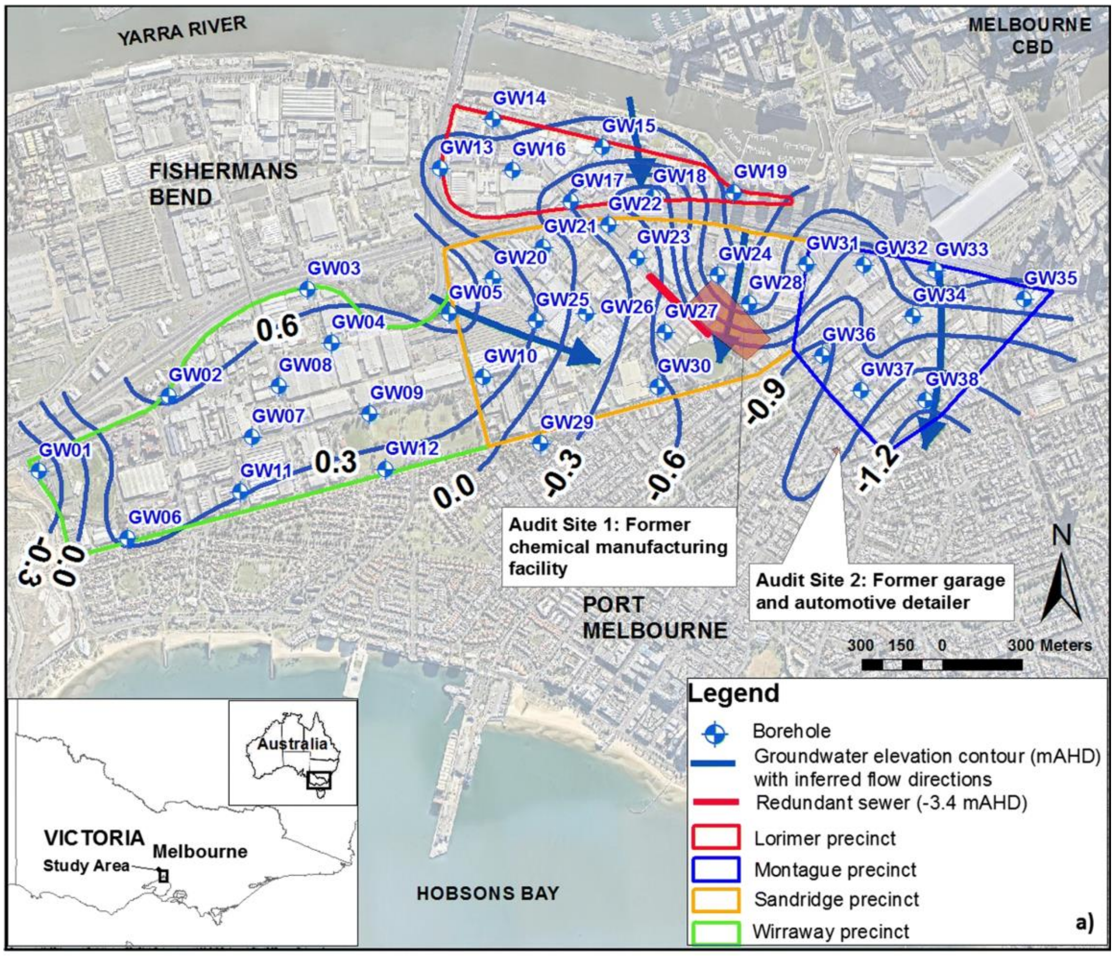


Figure 32 – Original bores included in the delineation of landfill impacts (Hepburn et. al 2019)

4.1.1 – Methodology

To delineate potential leachate impacted regions, data from Aecom's Groundwater Monitoring Event in July 2017 was first extracted. This Data was then assessed using multiple techniques, including the standard L/N ratio, alkalinity as $CaCO_3$ and Piper Plots. Findings where then compared against each other to delineate potential leachate impacted regions. Results were also interpreted against findings from the historical investigation as well as literature. Bores which will be utilised in this new delineation of leachate impacts can be seen in figure 33 below. Data that has been used in calculations can be found in appendix D.

Figure 33 – Bores included in the new delineation of landfill impacts
(Source nearmap 2020)

4.1.2 – L/N ratio

Identification of leachate impacted regions was completed by Hepburn et. al (2019) from analysis of the 38 initial bores using the standard and modified L/N ratios. See figure 34 below for previously identified leachate impacted regions.

The L/N ratio is a method used to distinguish between leachate impacted and non-impacted regions (Mulvey 1999). The method uses dominant indicators of leachate such as potassium and ammonia compared to characteristic non dominant ones of, magnesium, calcium, and sodium (Hepburn et. al 2019).

Standard L/N = $(K + NH_3) / (Mg + Ca + Na) \times 100$ (Mulvey, 1999)

Hepburn et. al (2019) identified limitations with the method, given the reliance on potassium and ammonia as leachate indicators, the possible oxidisation of ammonia to nitrate, and the variability of ammonia concentration in different waste types. The additional environmental tracer, the ratio of PFOA/PFAA was suggested as an addition to the standard L/N ratio, as it had a strong to positive correlation with conventional leachate indicators (Hepburn et. al 2019).

Modified L/N = $(K + NH_3) / (Mg + Ca + Na) + (PFOA/PFAA) \times 100$ (Hepburn et. al 2019).

There are limitations with using the modified L/N ratio in all areas of Fishermans Bend, due to limited PFAS results. Moreover, the relatively high limit of reporting (LOR) of the PFAA results (10 to 100 ng/L) by Aecom (2017) increases uncertainty when compared to results by Hepburn et. al (2017) with a LOR of 0.2 ng/L. Given the limited data available, the standard L/N ratio was chosen as the most suitable option for the delineation of leachate impacted regions.

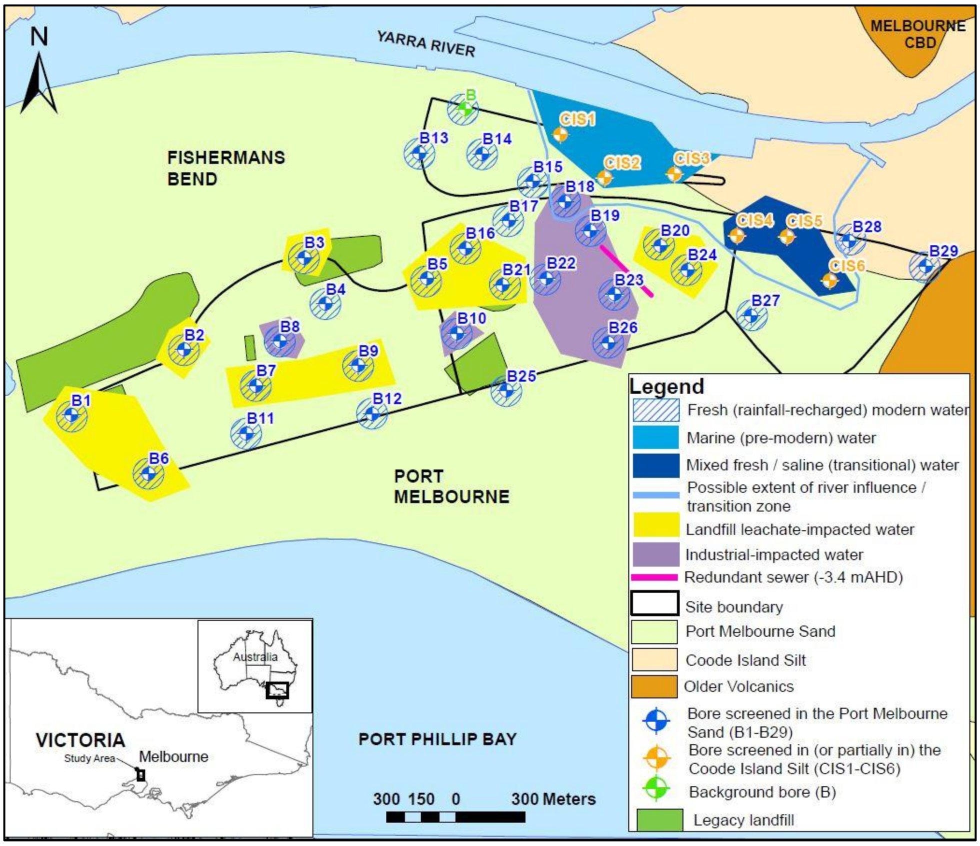


Figure 34 – Previously identified landfill impacted region in yellow (Source: Hepburn et. al 2019)

4.1.3 – Updated Standard L/N ratio

The standard L/N ratio was calculated from data from 75 monitoring bores, sampled by Aecom in July 2017. Computer software, Surfer was used to produce the figure 35 below, with contours calculated from a radial base function.

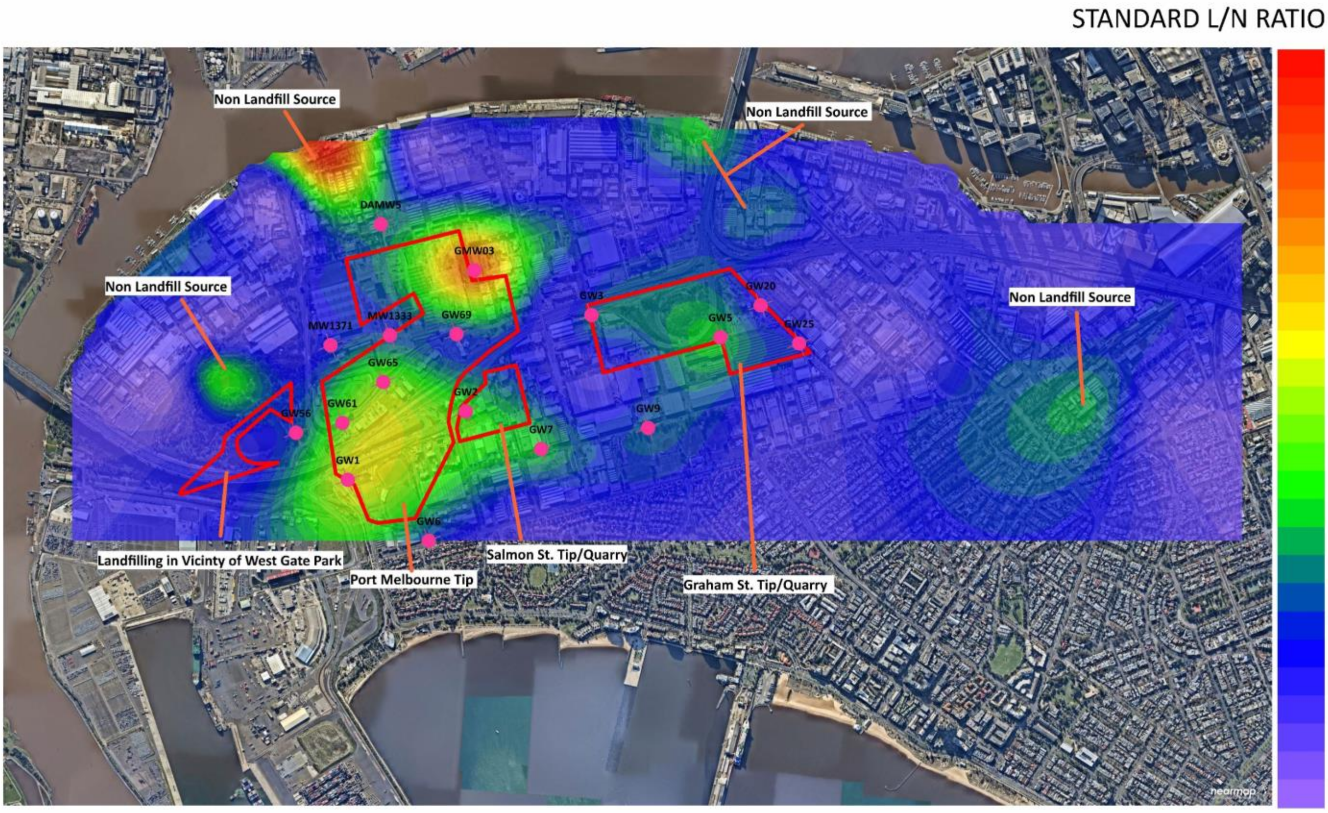


Figure 35 – Standard L/N ratio - predicted leachate impacted bores in pink (Source: nearmap 2020)

4.1.4 – Discussion

4.1.4.1 – Distinguishing between landfill and non-landfill sources

Identification of landfill boundaries was well established through the historical investigation. Only areas that are in the vicinity of a landfill as depicted in figure 35 above were considered leachate impacted. All other areas were interpreted to be from non-landfill sources. The accuracy of the standard L/N ratio is limited when there are multiple sources of contamination (Hepburn et. al 2019).

An increase in standard L/N ratio was detected in the north of West Gate Park but this is considered an outliner and non-landfill related. For reference, two bores GW49 and GW02 have similar standard L/N ratios however the concentrations of analytes are different by many orders of magnitude. GW49 low concentrations of ammonia and potassium are not representative of landfill leachate.

mg/L	Ammonia	Potassium	Sodium	Calcium	Magnesium	Standard L/N ratio
GW49	0.2	3	6	8	6	15.9
GW02	71	45	523	57	70	16.0

Table 2 – Comparison of GW49 and GW02

4.1.5 – Correlation between waste type and standard L/N Ratio

4.1.5.1 – Port Melbourne Tip & Salmon St. Tip

Both sites where known to contain putrescible waste with ammonia being a known breakdown product (Kjeldsen et al. 2002). The highest L/N ratios and ammonia concentration were found in the vicinity of these two landfills, which is expected given the waste type.

4.1.5.2 – Graham St. Tip

From the questionnaire completed by Mr Marshall, this site was not known to contain putrescible waste. The site was mainly used for demolition and construction wastes, furniture, and rubble from factories (Marshall 2020). These types of waste can be considered solid and inert. As the site did not contain putrescible waste the amount of ammonia produced is predicted to be less. The standard L/N ratio of bores in the vicinity of the site were less than the Port Melbourne Tip, which is expected given the absence of putrescible waste. Both areas where filled at approximately the same time (early 1970s) as such, the difference in L/N ratio is hypothesised to be caused by a difference in waste type.

	Waste Type	Time filled	Ammonia	Standard L/N ratio
GW02	Putrescible	Late 1960s	72 mg/L	16.0
GW05	solid/construction	Late 1960s	7.5 mg/L	13.7

Table 3 – Comparison of L/N ratio and waste type

According to Mr. Marshall on few occasions a ‘very bad chemical or acid smell’ was noticeable in areas of recent dumping. This may be related to industrial liquid waste disposal. liquid waste may potentially be a source of ammonia (Syed 2006). The decomposition of materials containing nitrogenous organic matter, such as wood products originating from furniture or demolition waste may also contribute to the production of ammonia.

4.1.5.3 – Landfilling in the vicinity of West Gate Park

A distinct high standard L/N ratio was not seen in this area. However, the L/N ratio is skewed by high sodium concentrations. It is hypothesised that the hyper saline Saltwater Lake is contributing to these elevated concentrations. It is considered that the use of the standard L/N ratio for this area is limited. It is recommended that these bores are sampled for PFAS with the modified L/N ratio applied or another leachate indicator method be used.

4.1.6 – Alkalinity as a leachate indicator

4.1.6.1 – Background

The acid neutralising capability of a solution is known as alkalinity (Devlin 1990). Any strong or weak bases dissolved in a sample contribute to its total alkalinity, as it buffers acidity (Devlin 1990). Examples of strong bases include OH^- and weak bases CO_3^{2-} and HCO_3^- , NH3 and fatty acids anions (Devlin 1990). At near to neutral pH, weak bases can be present at high concentrations thus significantly increasing alkalinity (Devlin 1990).

Alkalinity is commonly reported as “mg/L as CaCO3”. This unit equates the alkalinity to that of a solution containing CaCO3 dissolved in water (Kennesaw State University 2017). CaCO3 when dissolved in water produces the neutralising base OH^-. Total Alkalinity as CaCO3, is the sum of bicarbonate, carbonate and hydroxide alkalinity (McDonald 2006). The type of alkalinity found is dependent on the pH (McDonald 2006). Below 4.3 pH, no alkalinity is present, between 4.3 and 8.3 pH only bicarbonate is found (McDonald 2006). Above pH 8.3, carbonate and hydroxide alkalinity are detected (McDonald 2006). Alkalinity as CaCO3 in Fishermans Bend is found in its bicarbonate form. Alkalinity is found naturally in groundwater and is mainly formed from rain and surface water containing dissolved carbon dioxide and the dissolution of carbonate minerals in the geology (Kentucky Geological Survey 2020).

4.1.6.2 – Alkalinity and landfill leachate

Alkalinity is a parameter often routinely monitored at landfill sites, however often very little interpretation of the values is attempted (Devlin 1990). Alkalinity in landfill leachate is known to consist of bicarbonate and volatile fatty acid alkalinity (Leite et al. 2014). In landfills, bicarbonate alkalinity can be formed by dissolution of the carbonate materials present in waste (Devlin 1990). In landfills containing putrescible waste, the acidification stage in anaerobic decomposition may also contribute substantially to total alkalinity (Devlin 1990).

During the decomposition process, waste in a landfill first undergoes initial aerobic decomposition followed by anaerobic (Devlin 1990). In anaerobic conditions, acidification occurs producing organic acids, CO2 and hydrogen. This process can last for several years in a landfill environment (Devlin 1990). During this stage short chain aliphatic acid anions are produced (Devlin 1990). These ions buffer the acidity generated and contribute to a significant amount of alkalinity (Devlin 1990). It has been suggested that up 11% to 52% of landfill leachate alkalinity can be attributed to this process (Baedecker & Back 1979). In the final stage of the anaerobic process, methanogenic bacteria consume organic acids and produce methane and carbon dioxide, commonly referred to as landfill gas (Devlin 1990).

4.1.6.3 – Application for Fishermans Bend legacy landfills

Fishermans Bend contains landfills where putrescible waste was deposited. As such the mapping of regional alkalinity may assist in identifying leachate impacted regions. This can be achieved by comparing background alkalinity with areas of landfilling to assess if a positive correlation exists. An added benefit is that alkalinity may help delineate the type of waste found (e.g. high or low amount of putrescible waste) and the level of decomposition activity.

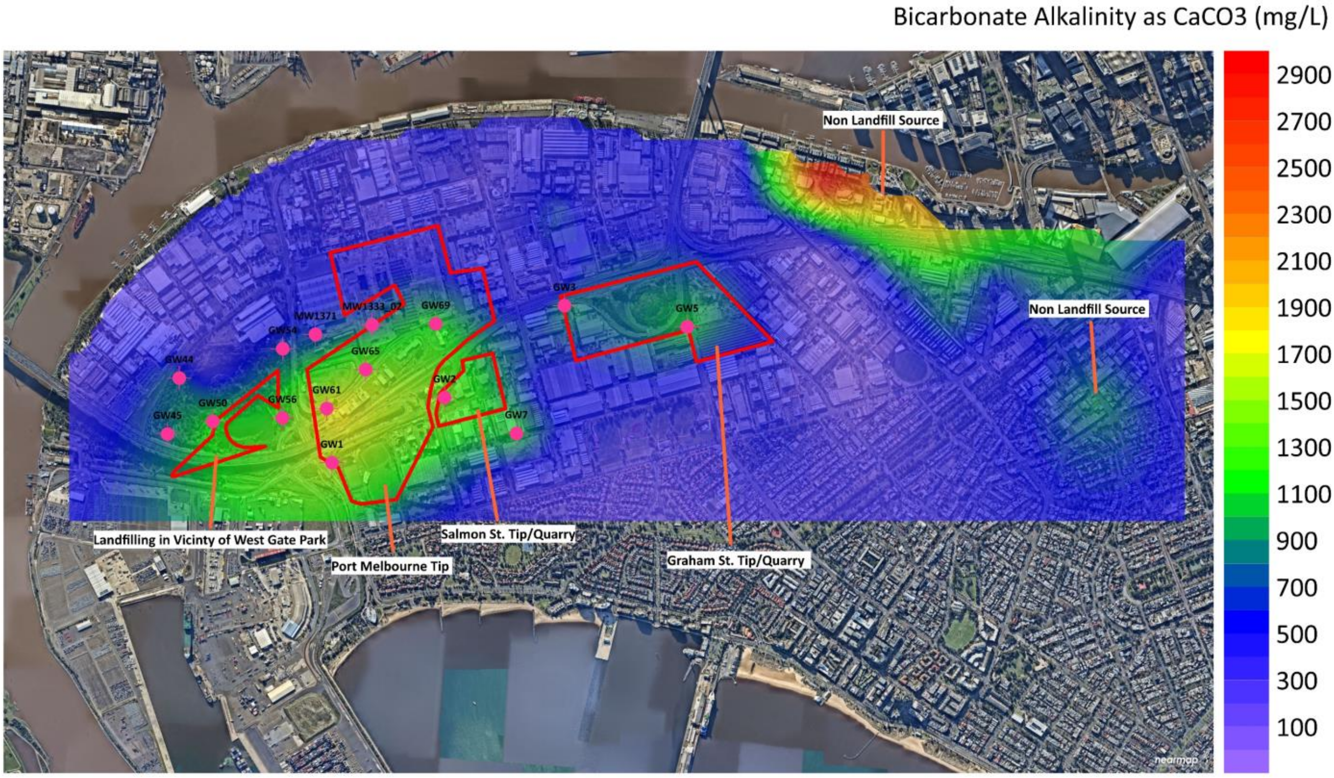


Figure 36 – Regional Alkalinity as CaCO3 (Source: Nearmap 2020)

Figure 36 was produced from the bicarbonate alkalinity results in Aecom's July 2017 sampling round and consists of data from 75 monitoring bores. Computer software, Surfer was used to produce the figure above, with contours calculated from a radial base function.

4.1.7 – Discussion

A correlation exists for higher concentrations of bicarbonate alkalinity as CaCO3 to be found where legacy landfills are located. Given the correlation, the use of alkalinity may be a useful tool in delineating leachate impacted regions in Fishermans Bend.

High detects are also found in non-legacy landfill areas, with these assumed to be caused by non-landfill related industrial activities. Higher detects of alkalinity near the river may be associated with dissolution of carbonate containing shells naturally present in the Coode Island Silt aquitard (Holdgate and Norvick 2017).

4.1.7.1 – Port Melbourne Tip & Salmon St. Tip

Alkalinity is found at relatively high concentrations and is assumed to be associated with the anaerobic decomposition of putrescible waste, resulting in the production of volatile fatty acid alkalinity. Carbonate containing materials found in the waste may also contribute to the total alkalinity.

Both environmental audits conducted on these sites in the late 1990s, concluded that the landfills where producing gas, with methane detected at non- hazardous levels (Lane Consulting 1999; Sinclair Knight Merz 1999). The production of methane indicates that anaerobic decomposition of waste is taking place, further evidence of the production of volatile fatty acid alkalinity.

Interestingly, alkalinity was not detected at elevated concentration at the north of the Port Melbourne Tip. From historical photographs, the north of Port Melbourne Tip was the first area to be filled with complete filling in the 1950s (Pratt 1950). The older age of this section may be a reason why alkalinity is less, with decomposition activity expected to decrease with age (Lane Consulting 1999).

Another possible explanation is that this section of the landfill was used for a different kind of waste disposal and contains less putrescible waste. Images taken in the 1950s prior to filling indicate that the landfill was receiving liquid waste from factories.

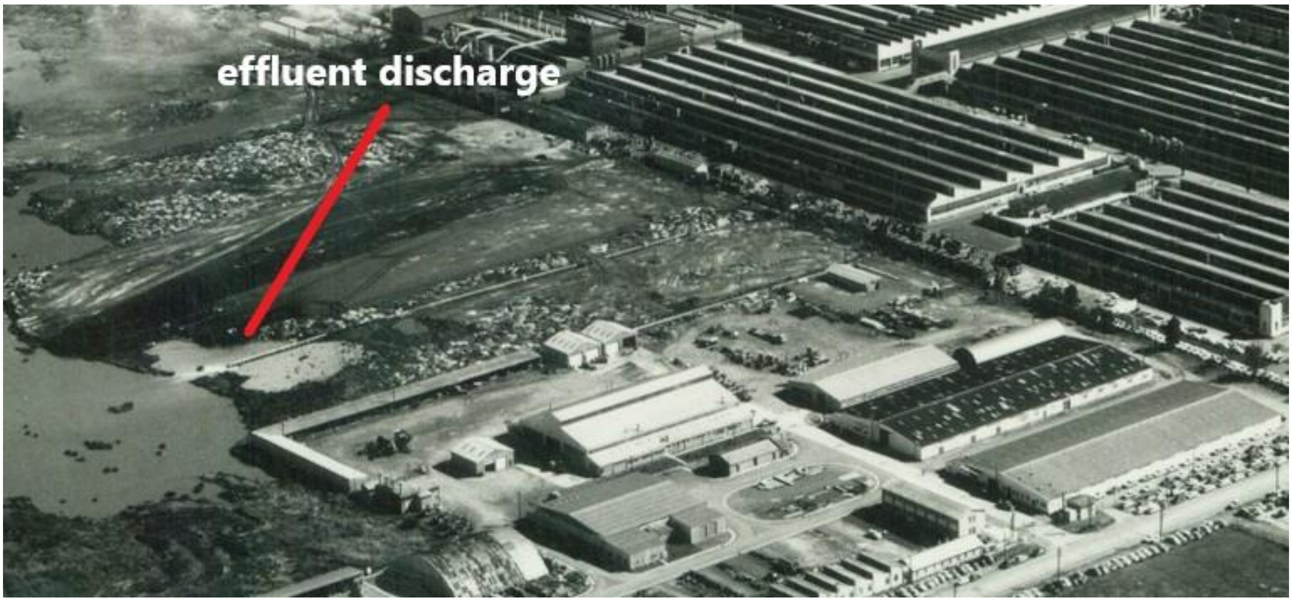


Figure 37 – Liquid waste disposal at the Port Melbourne Tip
[ca. 1950-ca. 1960] (source: Pratt 1950)

Hypothetically, the liquid waste deposited in this area may have had little effect on alkalinity or overall production may have been less than that produced by putrescible or solid waste. The standard L/N ratio indicated that the area may be leachate impacted. Therefore, it may be interpreted that the area contains a waste type that is not common with other landfills in Fishermans Bend.

4.1.7.2 – Graham St. Tip

Alkalinity is present at slightly elevated concentration at the site. With the landfill not known to contain putrescible waste, alkalinity produced may be from carbonate containing materials found in solid waste and not from fatty acid alkalinity. The fact that alkalinity concentration is less in sites known to contain putrescible waste, and which were filled at similar times, is further evidence of the contribution of volatile fatty acid alkalinity. According to Mr. Marshall, demolition and construction waste were deposited at the site. Concrete products such as cement are known to produce alkalinity when in contact with water and is one possible explanation for its increase (Björk & Eriksson 2002). Foundry waste, including slag have also been found within the waste which may be contributing to alkalinity production (Dames & Moore Group 1999; Mayes, Younger & Aumônier 2008).

4.1.7.3 – Landfilling in the vicinity of West Gate Park

A significant finding of the mapping of alkalinity is its elevated concentration at this site. Leachate migrating from the Port Melbourne Tip may be an obvious source, however from the comparisons of alkalinity directly down gradient of bores in waste as well as groundwater flow direction the amount of contribution is considered low. The historical investigation uncovered that the area was used for the ad-hoc deposal of foundry waste (Cooney 1984).

Foundry waste is largely comprised of silicates and alumino-silcates and can include materials such as slag, and fragments of firebricks and crucibles. (Cooney 1984; Mayes, Younger & Aumônier 2008). When weathered, these waste products can undergo hydrolysis and dissociate in solution producing the hydroxyl ion (OH-) (e.g. Alkalinity) (Mayes, Younger & Aumônier 2008). Foundry waste has been known to produce leachate with a pH as high as 13 (Mayes, Younger & Aumônier 2008). Given the relatively high alkalinity and the absence of putrescible waste, this may be a possible explanation for the alkaline groundwater.

Demolition waste related to the construction of the West Gate Bridge is also found in the area (Cooney 1984). This waste is known to comprise of demolition rubble, foundation excavation material and concrete test cylinders (Cooney 1984). Like the Graham St. Tip, carbonate containing materials like concrete may be contributing to alkalinity production.

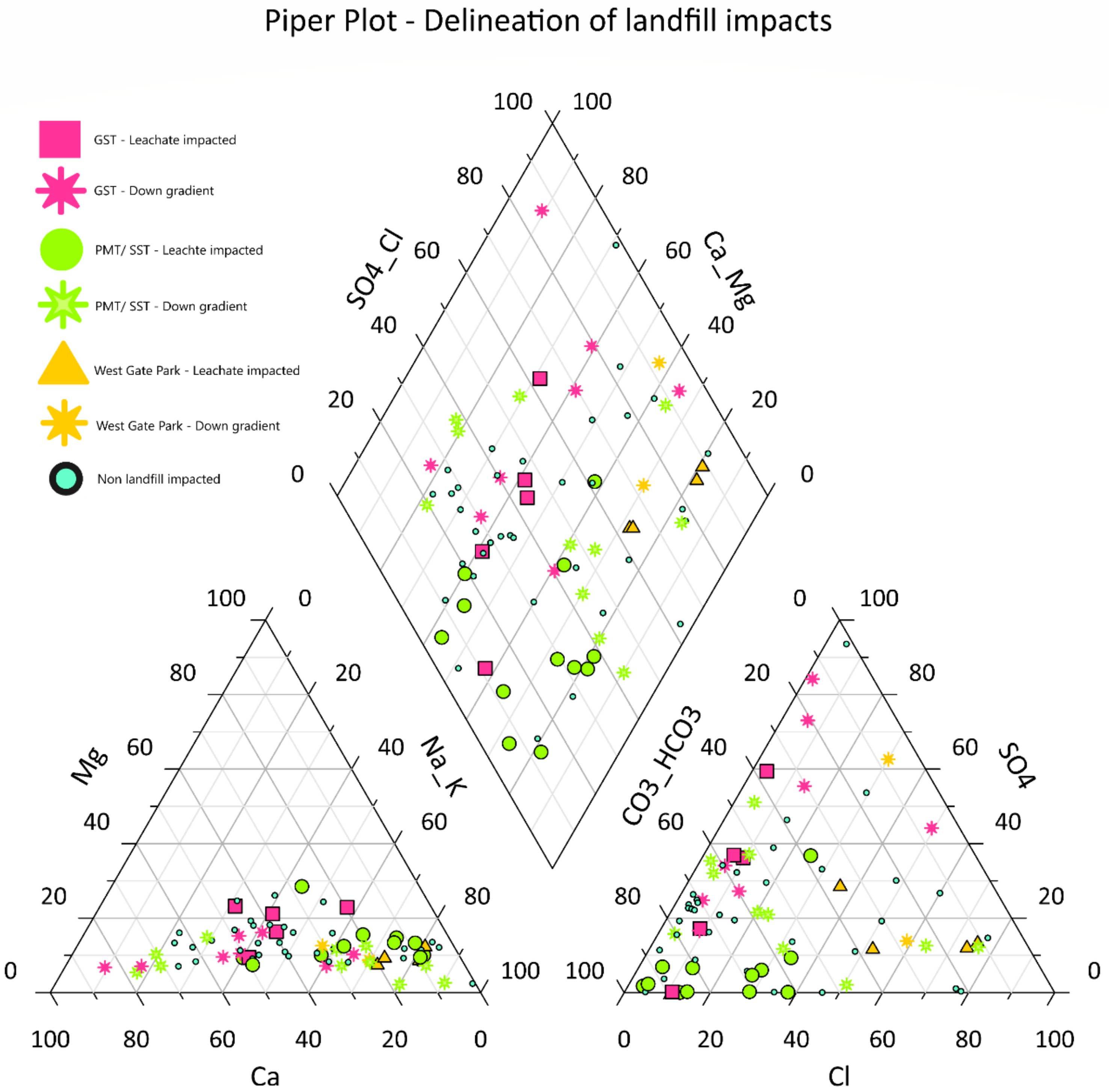
4.1.7.4 – Summary and key findings

The use of the L/N ratio in conjunction with alkalinity may be a useful tool in delineating leachate impacts. Results from both methods have a correlation with each other in several landfilling areas. The results support the use of these methods in conjunction and may have future application for other sites where legacy landfills are found.

- All areas that were identified by the historical investigation where found to have evidence of leachate impacts
- Waste types identified from the historical investigation are supported by some results.

4.1.8 – Groundwater geochemistry and landfill impacted regions

A piper plot was created from the results of 78 groundwater bores sampled in July 2017 by Aecom. Results from the Piper Plot are used to determine the makeup and dominate fraction of the groundwater geochemistry. The bottom left triangle represents the cations and the bottom right anions. The top diamond represents a mixture of both cations and anions.



GST = Graham S. Tip

PMT/SST = Port Melbourne Tip / Salmon St. Tip

Figure 38 – Combined Piper Plot

Figure 39 – Piper Plot dominate fractions (Source: Hatari Labs)

4.1.8.1 – Graham St. Tip

In the close vicinity of the waste mass, groundwater in the anions is dominate by bicarbonate and magnesium-bicarbonate type groundwater. Moving away from the waste mass (GW25, GW26, GW30, GW22) the groundwater becomes dominated by sulphate and calcium chloride type water. This change in groundwater geochemistry may indicate attenuation of the plume or that dilution is taking place.

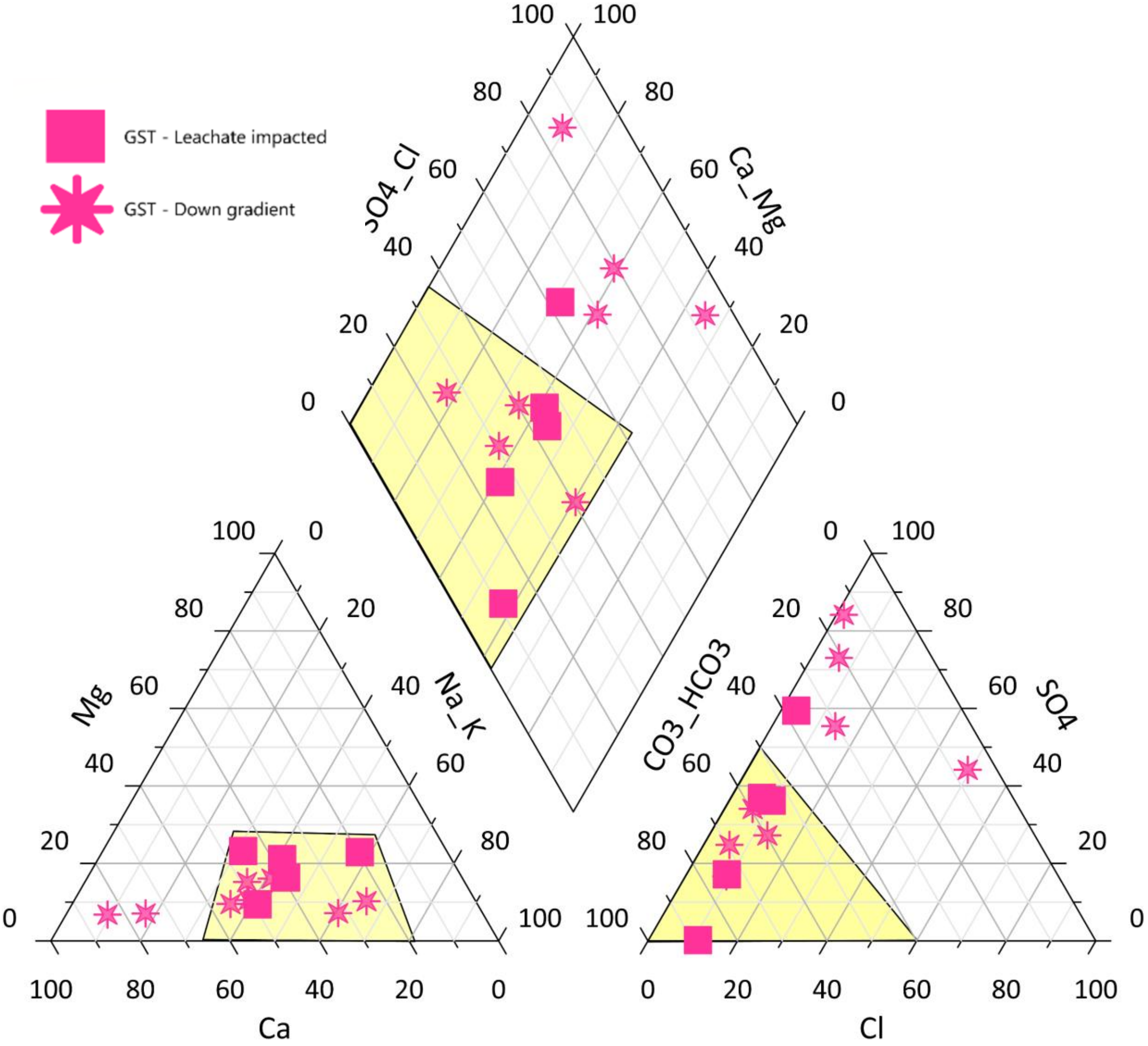


Figure 40 – Graham St. Tip Piper Plot – (yellow shade near/on waste)

4.1.8.2 – Port Melbourne Tip and Salmon St. Tip

Groundwater in the vicinity of the waste mass is dominated by bicarbonate type groundwater in the anion fraction and sodium-potassium in the cation fraction.

Groundwater within 300 m of the Yarra River is influence by a saline wedge, making distinctions between landfill impacted and non-impacted groundwater difficult. Heading downgradient from the northern extant of the Port Melbourne Tip, groundwater quality may be influenced by leachate impacts. This has been suggested as the groundwater geochemistry found at GW57, GW67 and GW43 have similarities to leachate impacted bores on the Piper Plot. Bore GW47 GW51, also located along the Yarra River and close to GW57 appears to be different than bores directly to the east. The geochemistry of these bores is a more sodium-chloride type, with the Yarra River being the likely source. This may indicate that groundwater discharging between, GW57 and GW43 may be influenced by the former Port Melbourne Tip. It should be noted that this area may also be influenced by other industrial sources, such as the former General Motors Holden factory.

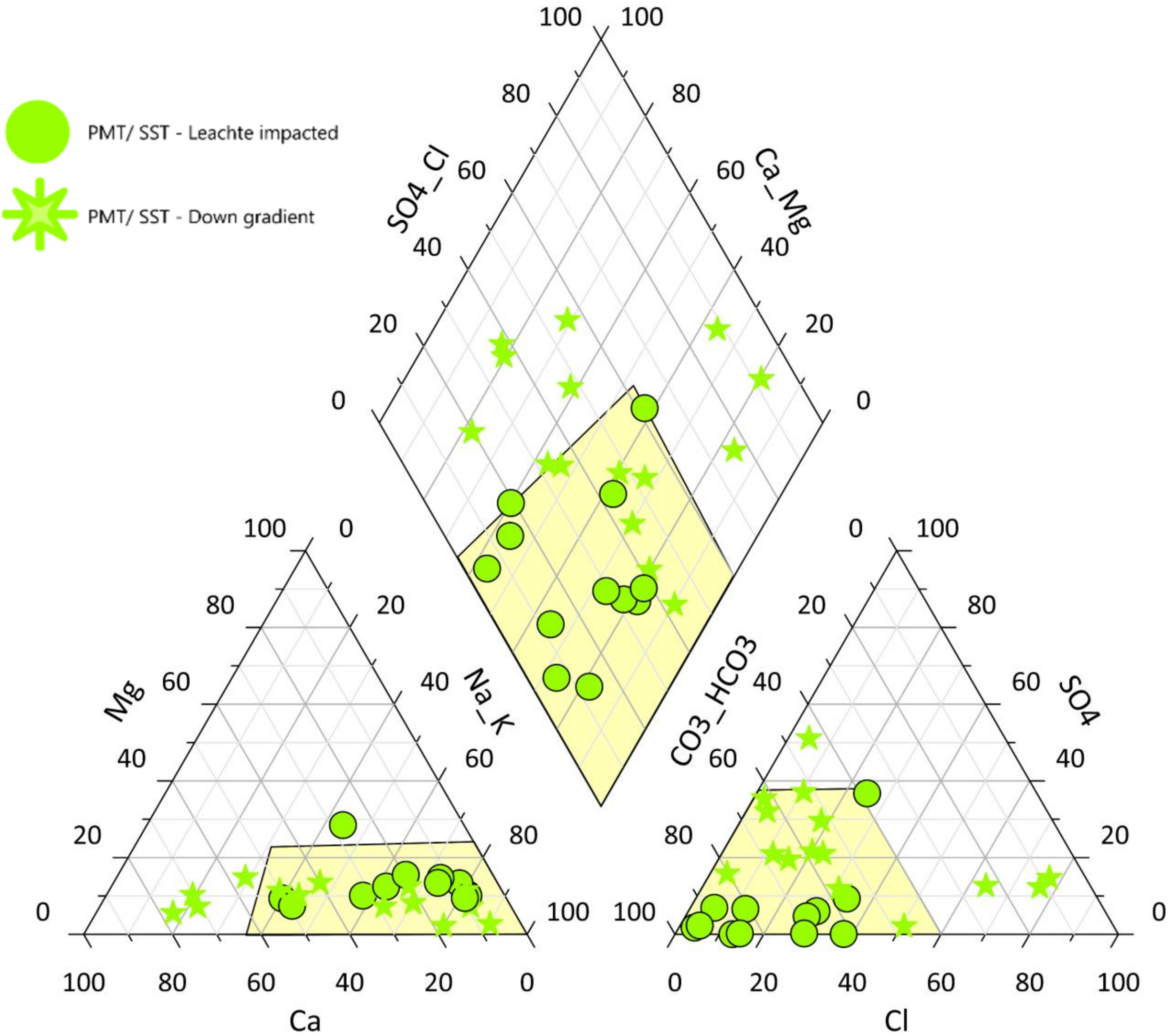


Figure 41 – PMT/SST Piper Plot – (yellow shade near/on waste)

4.1.8.3 – Landfilling in the vicinity of West Gate Park

Groundwater in this vicinity is dominated by sodium chloride. This is likely caused by baseflow from the hyper saline Saltwater Lake and influence from the Yarra River (Cooney 1984). Given the dominance of sodium- chloride type groundwater, assessing leachate impacts is difficult. GW45 and GW56 have the closest to a non-dominate and mixed type groundwater which may indicate an input from an anthropogenic source, possibly landfill related.

GW40 has a different anionic make up with sulphate type groundwater found. This is an outliner when compared to bores upgradient. GW40 is a private bore with the construction details unknown (Aecom 2017). If the bore is partly screened in the Coode Island Silt, this may explain the higher composition of sulphate. A point source from industrial activity in the vicinity may also be a reason for elevated sulphate concentrations.

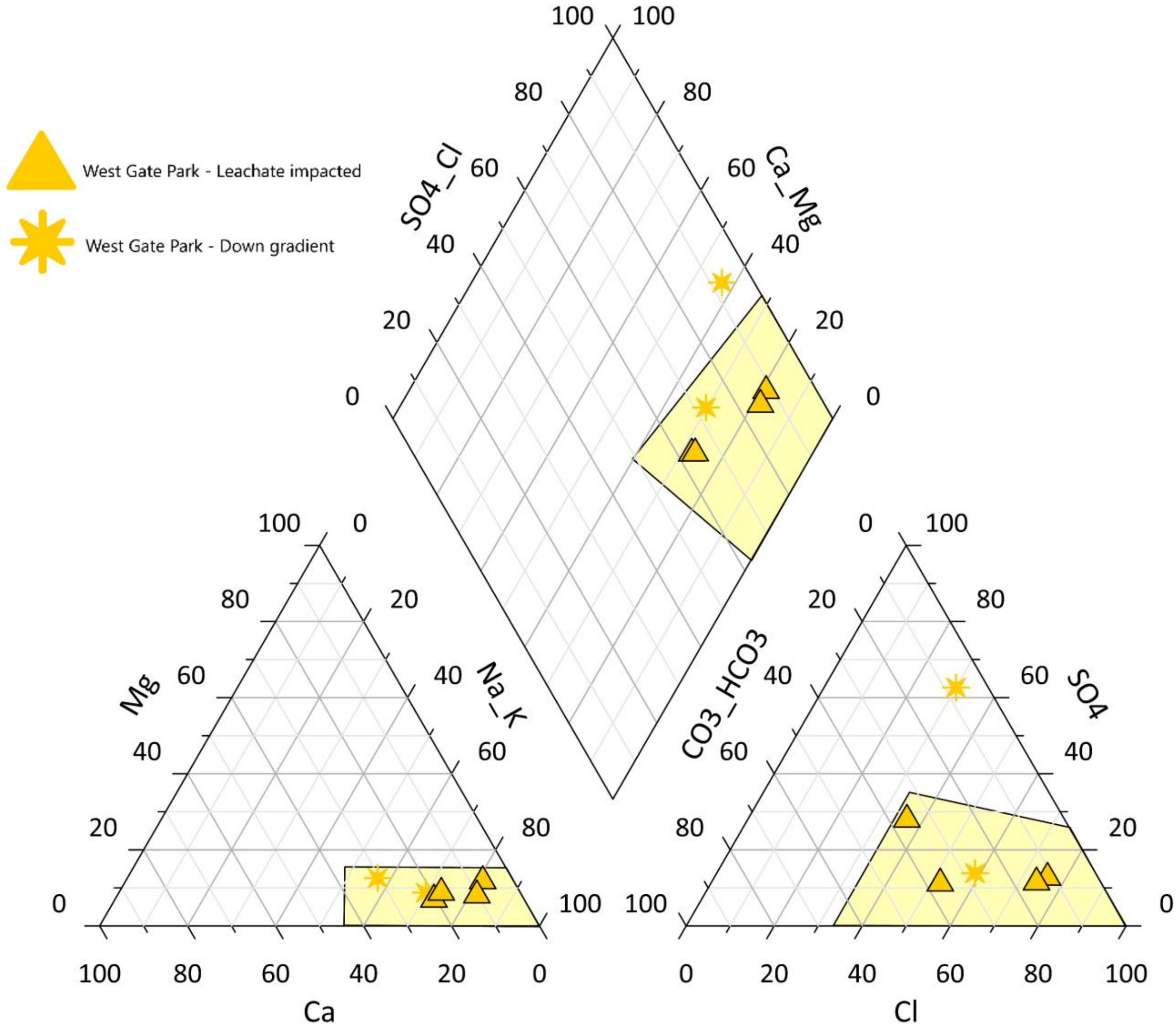
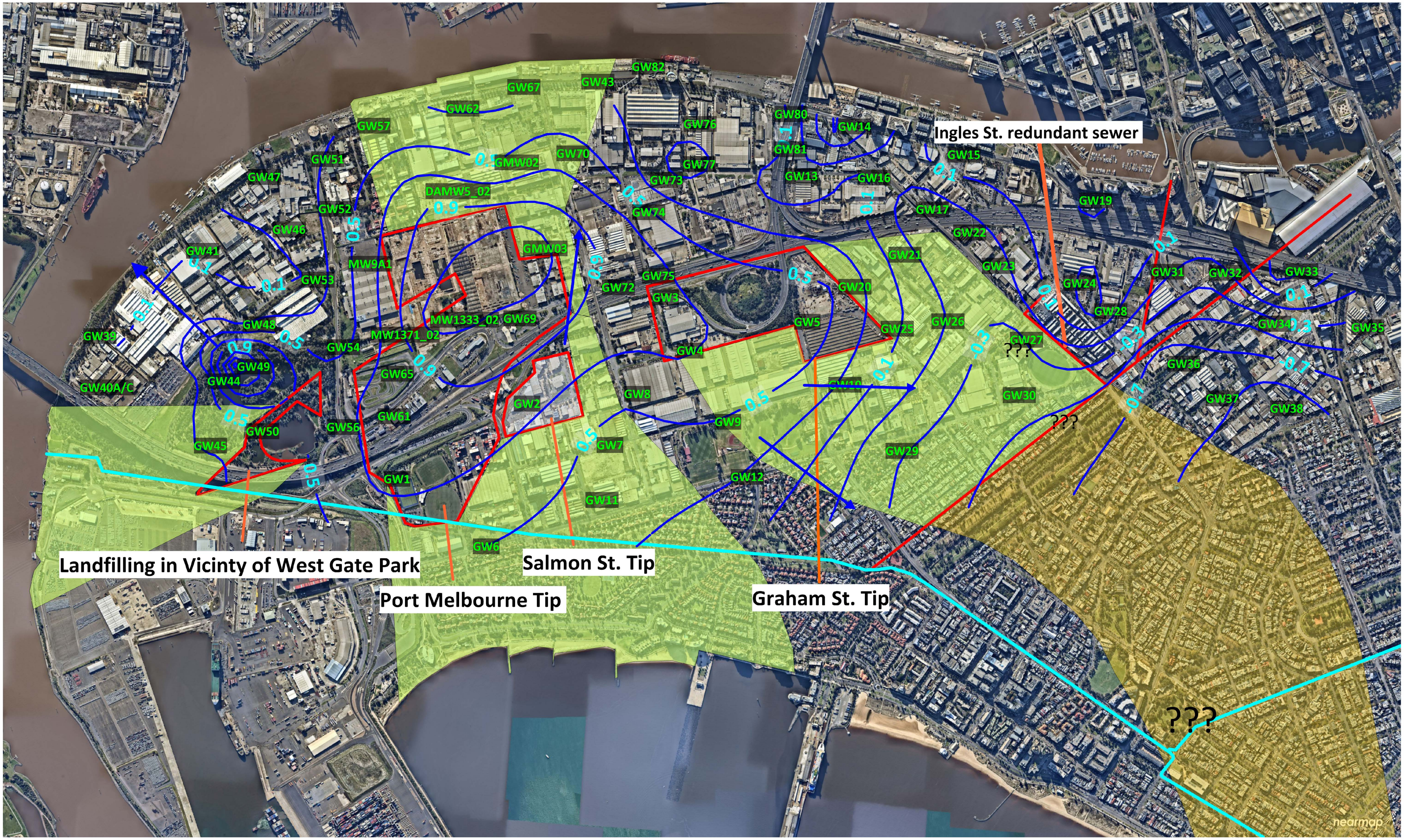


Figure 42 – Landfilling in vicinity of West Gate Park - (yellow shade near/on waste)

4.1.9 – Summary and findings

Utilising multiple lines of evidence from the L/N ratio, alkalinity, Piper Plots and groundwater flow direction, a figure was produced to estimate potential leachate impacted regions. This figure has a high degree of uncertainty, and its intended use is to assign general discharge areas and to aid in the identification of potential receptors.



🟩 Potential Leachate Impacted Region

🟧 Inferred Leachate Impacted Region (No Data)

Figure 43

Drawn: Nathan Northby
Basemap: Nearmap

Contours created using
Kriging gridding method

4.2 – Analysis of PFAS Data

4.2.1 – Methodology

PFAS results from Hepburn et. al (2017) and Aecom (2017) will be analysed and compared against literature. The aim is to assess if there are any correlations between Fishermans Bend landfills and other Australian sites. This will aid in a better understanding of the possible factors which may influence PFAS makeup and concentration.

4.2.2 – Landfills and PFAS

PFAS is present in many consumer and industrial products. With landfills being the ‘end of life’ for many of these products, there leaching and migration into the environment may continue for many decades.

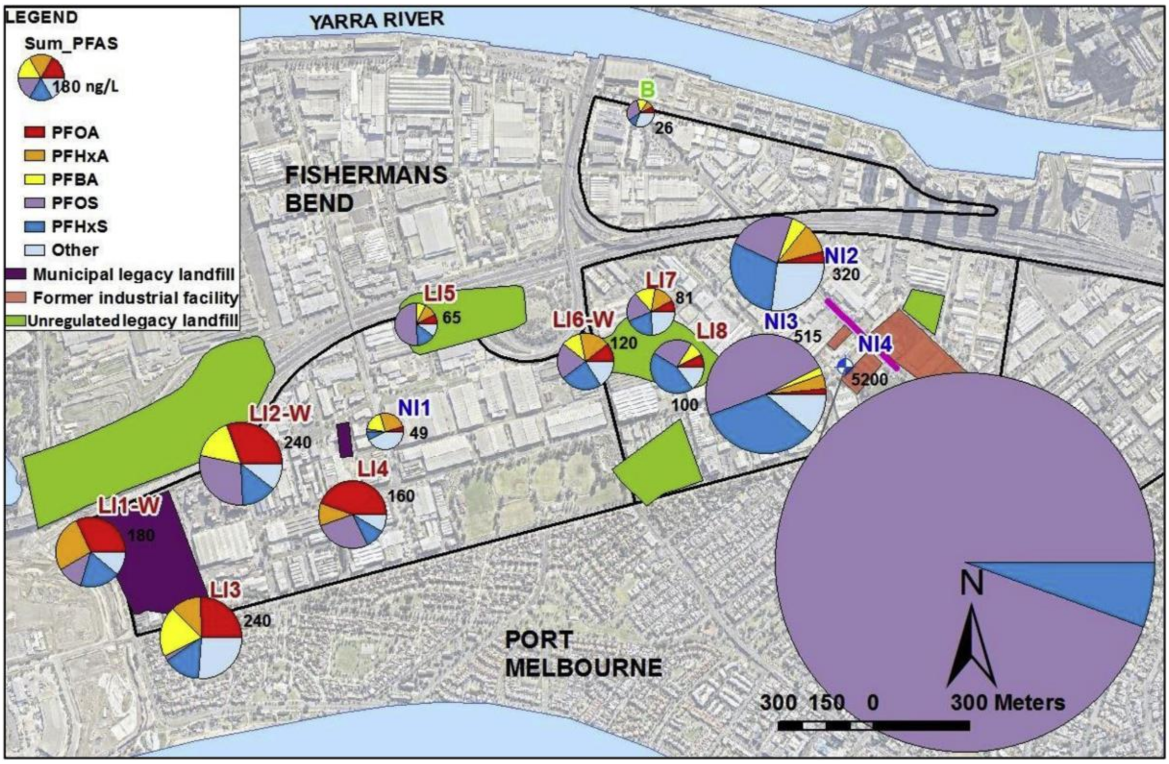


Figure 44 – PFAS results Hepburn et al 2019

Fishermans Bend landfills can be divided into three main categories of:

- Municipal solid waste (MSW) (primarily organics)
- Commercial and industrial (C&I) (timber glass, cardboard, paper, and plastics)
- Construction and demolition (C&D) (concrete, timber, metals, plastic, soil)

As identified from the historical investigation, liquid and industrial waste may also be found. It should be noted that prior to 1987 there was no regulations against the disposal of liquid waste at landfill (EPA Victoria 2010). The composition of PFAS in landfills can be influenced by several factors. Some of which can include landfill age, waste type and operational status (Gallen et. al 2017). Investigating the type of PFAS found in landfills can be an important step in developing a pathway receptor model and can aid in the assessment of risk.

4.2.3 – Factors effecting composition

4.2.3.1 – Waste type

Landfills containing greater than 50 % C&D waste are suggested to contain higher levels of PFAS in comparison with landfills containing > 50 % MSW (Gallen et. al 2017). This trend is not seen in landfills in Fishermans Bend with PFAS concentration in MSW landfills generally being higher.

This reason may be attributed the fact that landfills containing higher percentages of C&D waste like the Graham St. Tip where more informal and ad-hoc, when compared to organised community landfills such as the Port Melbourne Tip (Marshall 2020). This may decrease waste density, resulting in a reduction in overall PFAS concentration. The makeup of PFAS in landfills can also be influenced by impurities in commercial formulation of commonly used PFAA (Gallen et. al 2017). PFOS for example has major impurities of (∼10%) PFHxA, PFHpA with PFOA formulations commonly found contaminated with (∼3%) PFOS (Jiang et al. 2015).

The predominate PFAS in leachate can be highly variable (Gallen et. al 2016). In Fishermans Bend, PFOA is the dominate PFAA in MSW landfills, such as the Port Melbourne Tip and Salmon St. Tip. PFOS, PFHxS, PFHxA where also detected at elevated concentrations which is consistent with studies of closed MSW Landfills in Australia (Gallen et. al 2017; Gallen et. al 2016).

4.2.3.2 – Age and lag time

Lag time can exist between the time PFAS containing products enter the market to when they are landfilled (Gallen et. al 2017). This lag time can be different depending on the service life of products. For example, carpets may take longer to enter landfills when compare to products with a shorter service life (Gallen et. al 2017). Due to this lag time, younger landfills may be found with elevated PFAS concentrations (Gallen et. al 2017). This lag time may also be a reason for a decrease in PFAS in Fishermans Bend landfills containing C&D waste, with these materials generally having a higher service life in comparison with products from an MSW stream.

From studies of MSW leachate, a statistically evident ($p < 0.05$) exponential decrease has been seen in concentration of PFOA, PFOS, PFHxA, PFHpA, PFHxS with increasing age (Gallen et. al 2017). This may be caused by older landfills potentially having less stockpiles of PFAS containing waste and from multiple decades of leaching activity (Gallen et. al 2017). Studies from Germany have also found a positive correlation with decreasing PFAS concentration and age (Busch et al. 2010). In Australian landfills accepting >50% C&D waste a statistically significant relationship was observed for an increase of PFHxA and PFHpA with age (Gallen et. al 2017). Gallen et. al (2017), commented that the increase may be attributed to the transformation of PFAA precursors.

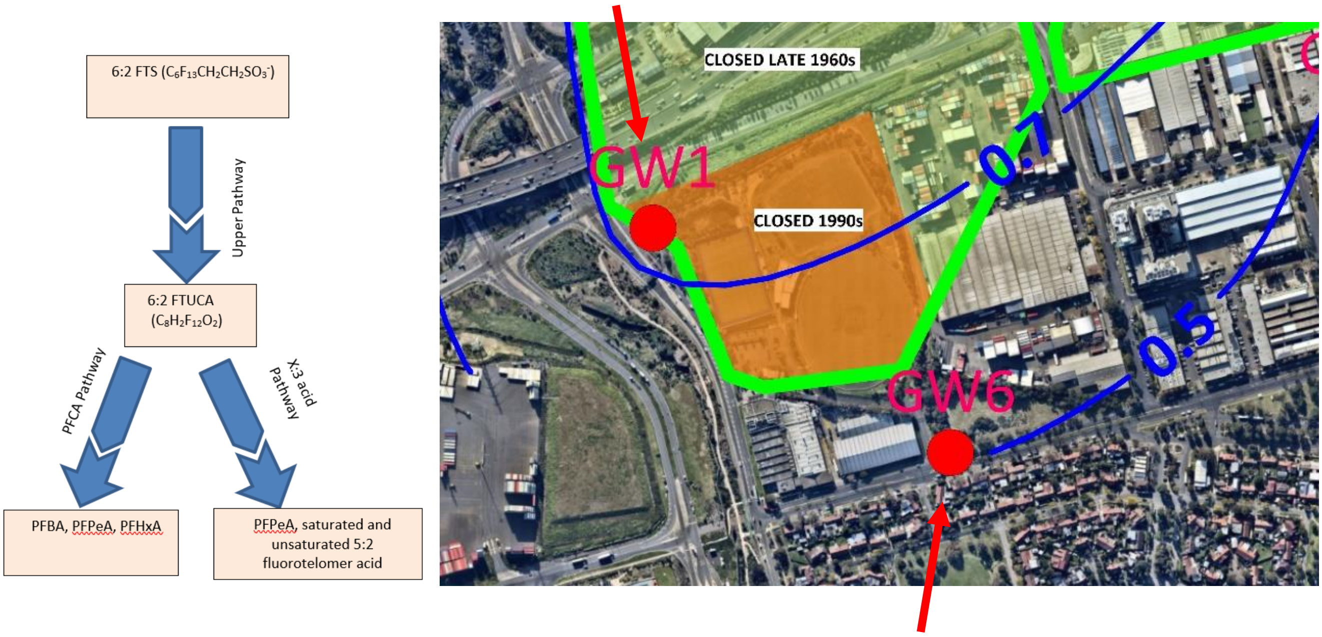
This trend is not seen in Fishermans Bend, with PFHpA undetected in landfills containing large amounts of C&D waste. With C&D containing landfills closing in the early 1970s, the effect of product lag time may be a reason why this trend is not observed, with the production of PFAS precursors only beginning in the 1970s (ITRC 2020).

4.2.3.3 – Potential evidence of PFAS precursor breakdown

With the times of landfilling well established through the detailed historical investigation and with production times of PFAS precursors known through literature, the study of precursor degradation in Fishermans Bend is possible. Hepburn et al. (2017) sampled for PFAS precursor 6:2 Fluorotelomersulfonate (6:2 FTS). 6:2 FTS was only detected in GW01, a bore screened within the waste mass of the former Port Melbourne Tip. Some sections of this site where operational until to the early 1990s (Sinclair Knights Merzs 1999). This bore had a 6:2 FTS concentration of 3.2 ng/L.

Fluorotelomer production began in the 1970s and is likely the reason why 6:2 FTS is only detected at the Port Melbourne Tip, with all other landfill sites closing in the early 1970s (ITRC 2020).

ng/L	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUDA	PFBS	PFPeS	PFHxS	PFHpS	PFOS	6:2 FTS
GW01	<0.2	<0.2	46	<0.2	56	<0.2	<0.2	<0.2	14	<0.2	34	1	20	3.2



ng/L	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUDA	PFBS	PFPeS	PFHxS	PFHpS	PFOS	6:2 FTS
GW06	49	15	29	22	61	<0.2	<0.2	<0.2	16	8.8	35	<0.2	4.5	<0.2

Figure 45 – Potential evidence of PFAS precursor degradation
(Source: Hamid, Li & Grace 2020; nearmap 2020)

4.2.3.3 – Discussion

Under aerobic conditions and with bacteria found in MSW landfills, 6:2 FTS can transform into PFPeA, PFHxA and PFBA (Hamid Li & Grace 2020). 6:2 FTS was detected in GW01, with its signature breakdown products of PFBA, PFPeA, PFHxA found in downgradient bore GW06. Out of all the bores that where leachate impacted, PFPeA is only found in GW06. Gallen et. al (2017) suggested that PFPeA, may increase in concentration with age in some landfills, with this potentially attributed to precursor degradation (Gallen et. al 2017). Relatively high alkalinity result at GW01, may suggest that microbial activity is occurring, with this attributed to the production of fatty acid alkalinity. Dissolved oxygen found within the shallow PMS aquifer may be providing the needed aerobic conditions. These findings may suggest that there is precursor degradation occurring in Fishermans Bend, however it is likely to only effects landfills that where filled after the 1970s.

4.2.3.4 – Total organic carbon (TOC)

Hepburn et. al (2019) found no significant negative correlation (decrease in concentration) with groundwater TOC and PFAS. A study of 27 landfill sites in Australia showed a strong positive relationship with TOC and PFAS concentrations (Gallen et. al 2017). It has been suggested that higher TOC increases PFAS sorption processes, subsequently decreasing concentration in groundwater (Gallen et. al 2017; ITRC 2020).

In the Gallen et. al (2017) studies, leachate was sampled from central leachate ponds, a relatively undiluted sample. Fishermans Bend leachate impacted bores are diluted by the ingress of groundwater, resulting in a considerably lower TOC concentration. As is seen in figure 46 below, at low TOC concentrations the relationship is more variable. The variability at low TOC concentrations may be a reason why this trend is not seen in Fishermans Bend Landfills.

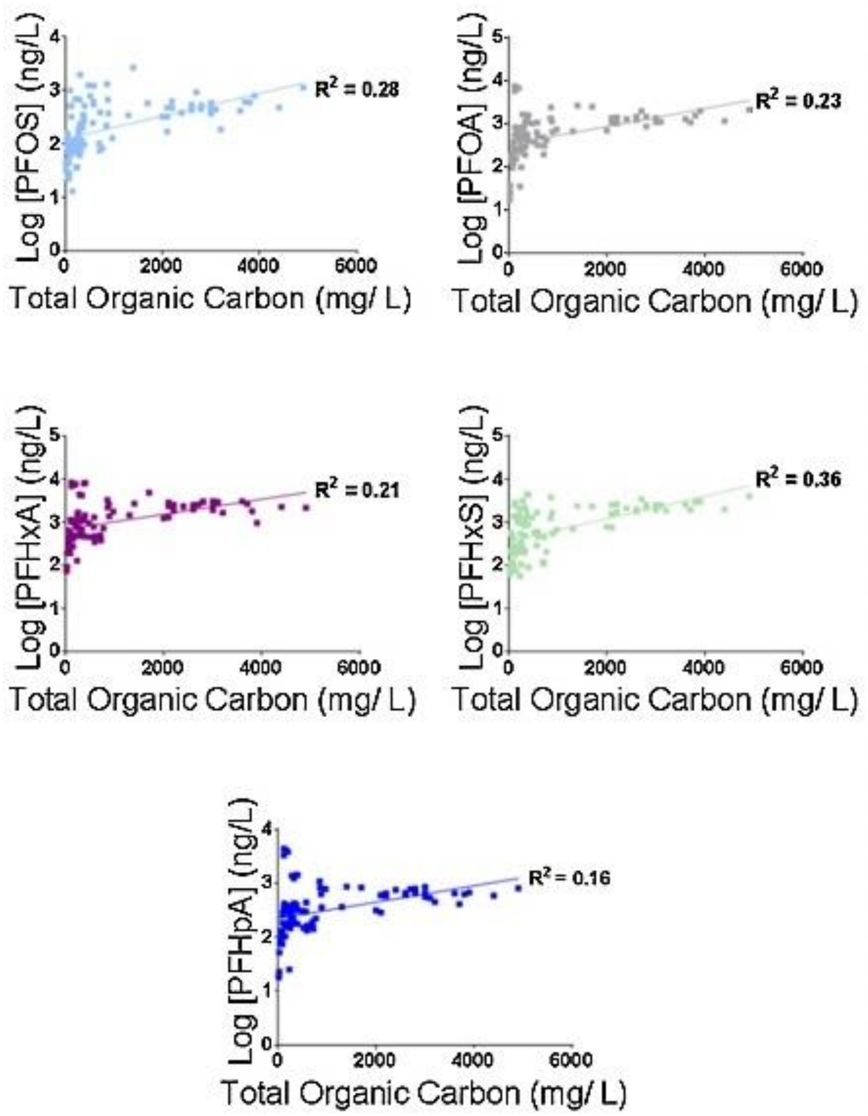


Figure 46 – TOC – log(PFAA) relationship (Source: Gallen et. al 2017)

5.0 – Discussion and results

5.1 – Receptor identification

For this context, a receptor is defined as an entity which may contact landfill impacted groundwater.

5.1.1 – Beneficial users of groundwater

In Victoria, the beneficial users of groundwater are subject to the State Environment Protection Policy (Waters) (SEPP 2018). In the legislation, total dissolved solids (TDS) are used to classify its segment ranging from A1 to F. The higher the TDS the less beneficial users there are.

TDS in Fishermans Bend ranges from 189 to 3,680 mg/L (Hepburn et. al 2019). This places groundwater in Fishermans Bend between Segment A1 to A2.

The following possible beneficial users of groundwater is as follows:

- Water dependant ecosystems and species
- Potable water supply
- Potable mineral water supply
- Agriculture and irrigation
- Industrial and commercial
- Water-based recreation
- Buildings and structures
- Traditional Owner cultural values
- Cultural and spiritual values

In Victoria, 'groundwater quality restricted use zones' (GQRUZs) are used to designate areas where one or more beneficial use is restricted (DELWP 2019). GQRUZs can be set when an environmental audit finds evidence of groundwater contamination which evokes restrictions to its beneficial use (DELWP 2019). When a GQRUZs is established groundwater is required to be contained within a set restricted zone (DELWP 2019). Once a GQRUZs is set, the groundwater must be cleaned up to the extent practicable (CUTEP) (DELWP 2019).

As the entire Fishermans Bend region is subject to an Environmental Audit overlay, and with multiple sources of potential groundwater contamination, the amount of GQRUZs is expected to increase with future redevelopments.

Figure 47 – Location of GQRUZs (blue shade) in Fishermans Bend region (Source: Victoria Unearthed 2020)

Table 4 – Receptor identification

Beneficial Use	**Potential groundwater receptor**
Water dependant ecosystems and species	Groundwater discharge to surface water Hobson Bay (marine), Yarra River (estuarine), West Gate Park lakes (wetlands) - Terrestrial groundwater dependent ecosystems These ecosystems have been identified from the BOM Groundwater Dependent Ecosystems Atlas (BOM 2020). - West Gate Park - Damp Sands Herb-rich Woodland - Port Melbourne Beach foreshore - Coast Banksia Woodland/Coastal Dune Scrub Mosaic
Potable water supply Agriculture and irrigation	As Fishermans Bend is connected to a reticulated water supply, the likelihood that groundwater is used for potable use is very low. However due to the low TDS in some areas this beneficial use is still technically applicable. Due to the high unlikeliness of potable use, it has been neglected as a potential receptor.
Potable mineral water supply	As Fishermans Bend is not located in a designated mineral water zone, this beneficial use is not applicable (Victoria Unearthed 2020).
Agriculture and irrigation	As the area is within reticulated water supply, the likelihood of this beneficial use being applicable is low. An environmental audit overlay and an expected increase in GQRUZs in the area, decreases the likelihood of this beneficial use. However due to low TDS this beneficial use cannot be ignored.
Industrial and commercial	This beneficial use is not considered to be applicable for Fishermans Bend. The proposed redevelopment will limit the application, with a decrease in industrial and commercial dwellings. Reticulated water is currently used for industrial and commercial use, making it highly unlikely that groundwater will be used.
Water-based recreation	Hobson Bay, Yarra River and lakes of the West Gate Park are receptors for this beneficial use. It is illegal to swim in the Yarra River adjacent to Fishermans Bend, limiting primary contact recreation in that area (Aecom 2016).
Building and structures	Groundwater in the study area is shallow. As a result, contaminated groundwater may contact basement structures, building foundations and subsurface utilities. Groundwater contacting construction and utility workers may also be a possibility at the site. Contaminated ground water may also volatilise and ingress into buildings and structures.
Traditional Owner cultural values & Cultural and spiritual values	Groundwater and surface water can be culturally significant for Traditional Owners. Protecting this beneficial use can be achieved by protecting other beneficial uses, such as water dependant ecosystems and species (SEPP Waters 2018). Traditional Owner consultation should be sought after if water management plans are proposed (SEPP Waters 2018).

5.2 – Estimation of PFAS concentration at receptor

Given the large amount of PFAS compounds, only PFAS with trigger levels in PFAS NEPM 2.0 will be assessed. This includes PFOS, PFOA, PFHxS.

5.2.1 – Graham St. Tip

The discharge location of groundwater is predicted to be the redundant Ingles St. Sewer. Hobson Bay is also a potential receptor and is located approximately 1.3 kms away. Given the strong influence of the sewers and limited PFAS data near the shoreline of Hobson Bay, it has been deemed that quantifying PFAS concentration with current information available is not feasible nor appropriate.

5.2.1.1 – PFNA as a tracer

PFAS variability between different sources can make the analysis of specific compounds and their proportions and ratios a possible tracer in some applications, as suggested by Hepburn et al (2019). In areas with long industrial history and with many potential PFAS sources this technique may also be beneficial to ascertain the contribution from a particular source.

GW20, GW26, GW27 have been chosen as there is a connected flow path towards the redundant Ingles St. sewer (receptor) from the Graham St. Tip.

	PFBA	**PFPeA**	**PFHxA**	**PFHpA**	**PFOA**	**PFNA**	**PFDA**	**PFUDA**	**PFBS**	**PFPeS**	**PFHxS**	**PFHpS**	**PFOS**	**6:2 FTS**
GW20	11	<0.2	12	<0.2	6	8.6	<0.2	<0.2	7.3	3.7	16	<0.2	16	<0.2
GW26	11	12	19	<0.2	7.7	0.69	<0.2	<0.2	24	15	170	7.1	250	<0.2
GW27	24	6.3	29	3.8	18	0.73	1.3	<0.2	8.5	5.1	280	5.3	4800	<0.2

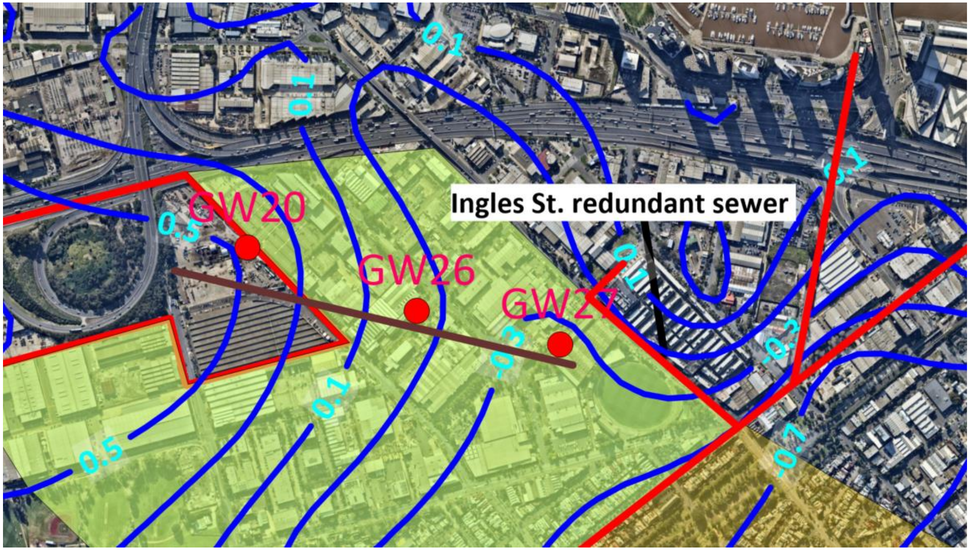


Figure 48 – PFNA concentration deceasing towards receptor
(Source: Hepburn et. al 2019; nearmap 2020)

At leachate impacted bore GW20, Perfluorononanoic acid (PFNA) is detected at a concentration of 8.6 ng/L. This bore had the highest detect of PFNA when sampled by Hepburn et. al (2017).

In up gradient bores sampled for PFAS, (GW5 and GW20) PFNA is less than LOR. Therefore, the source of PNFA is likely from a point source within the waste mass. Following the flow of groundwater from GW20 to GW27 all PFAS except for PFNA and 6:2 FTS increase in concentration relative to GW20. This is an indication that other sources of PFAS are entering the system between GW20 and the receptor (Ingles St. sewer).

As PFNA is the only compound above LOR that does not follow this same trend the source of PFNA is likely coming from the landfill. As PFNA will not biodegrade or transform under ordinary environmental conditions, it may be a useful tracer for this application (ITRC 2020).

Assuming fate and transport mechanism such as dispersion, diffusion and dilution are constant between all PFAA compounds, the sorption to organic carbon would likely be a controlling factor for migration (IRTC 2020). PFNA has a Koc value of (2.36 – 3.69), compared with PFOA of (1.89- 2.63), PFOS of (2.4 – 3.7) and PFHxS of (2.4 – 3.1) (ITRC 2020). PFNA has a similar Koc range as PFOS and PFHxS with PFOA slightly less. This may suggest that PFOA will travel further in comparison to PFOS and PFHxS. Over the approximate 600 m between GW20 to GW27, PFNA concentration reduced by approximately 90 %. As the plume concentrations downgradient likely do not follow a linear trend, applying this factor may have a high degree of uncertainty.

At GW05 and GW20, PFOS, PFOA and PFHxS concentrations are similar to PFNA at GW20. Given that PFNA reduces in concentration by 90%, 300 metres away from the assumed source, a higher source concentration would theoretically increase concentrations down gradient if following the same trend.

Therefore, it has been conservatively estimated that PFOS, PFHxS, PFOA having similar Koc values to PFNA may have a concentration of <0.5-2 ng/L at the redundant Ingles St. sewer, which is directly related to the landfill. With PFOA having a lower Koc, the concentration at the receptor may be on the higher range of this estimate.GW27 had PFAS composition that was very different to other bores in the proximity to landfills, with a disproportionate amount of PFOS (4800 ng/L). This bore was suggested to be impacted by a non-landfill point source, potentially attributed to a nearby paper or manufacturing process facility (Hepburn et. al 2019).

Given the high amounts of PFHxS, PFOA and PFOS originating from non-landfill point sources, the amount of PFAS arriving at the receptor that is directly attributed to the landfill is considered very low.

5.2.1.2 – Estimation of mass discharge to redundant ingles street sewer (landfill only)

An estimate of contaminant concentration discharging into the receptor was calculated using Darcy's Law. The movement of PFNA from GW20, GW26 & GW27 was used to estimate the concentration of PFOS, PFOA, PFHxS at the redundant sewer.

Full calculations can be found in appendix B.

$$Q = K \times A\ (h_1 - h_2)/L \qquad \text{(Darcy's Law)}$$

Q = flow rate m^3/day

K = hydraulic conductivity m/day

($h_1 - h_2$) = hydraulic gradient

Key Assumptions

- The system is in a theoretical steady state.
- The sewer simulates a drain and is 300 mm in diameter (Aecom 2015).
- A constant concentration of contaminant contacts the sewer.
- The hydraulic conductivity is obtained from slug test results at GW26 (Hepburn et. al 2017).
- An average hydraulic gradient calculated between GW27 and the sewer will be applied.
- Groundwater only discharges into one side of the sewer pipe. (e.g. ½ of total surface area).

5.2.1.3 – Results

Estimated concentration of PFOS, PFOA, PFHxS at redundant sewer

= < 0.5 – 2 ng/L

Estimated PFOS, PFOA, PFHxS discharge to sewer per day

=1 – 5 µg/day

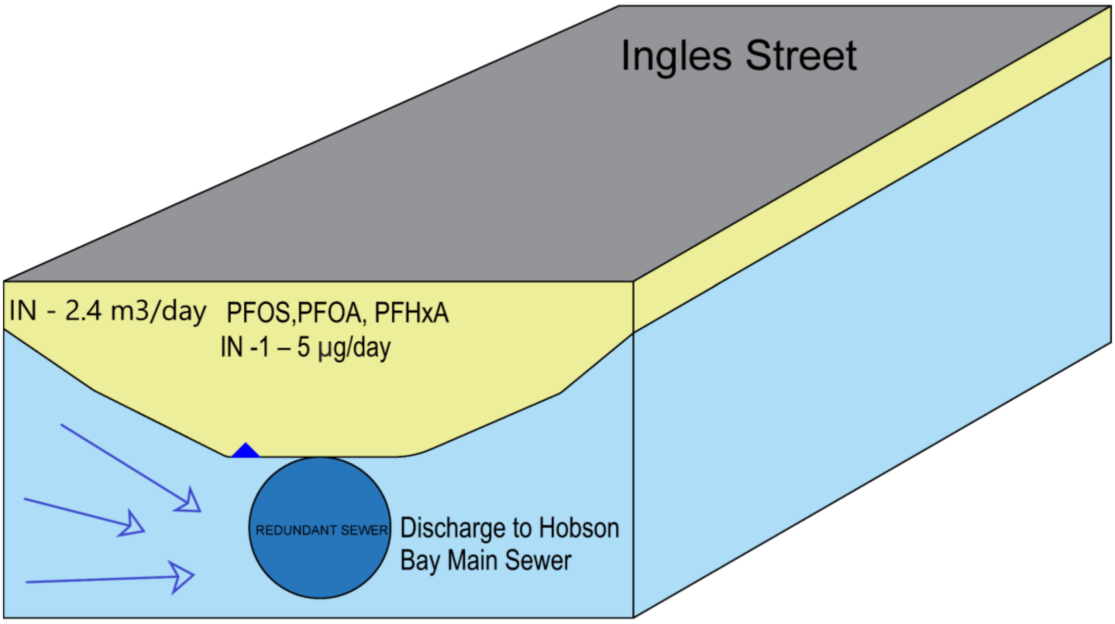


Figure 49 – Ingles St. sewer conceptual diagram

5.2.1.3 – Assessing discharge to other receptors

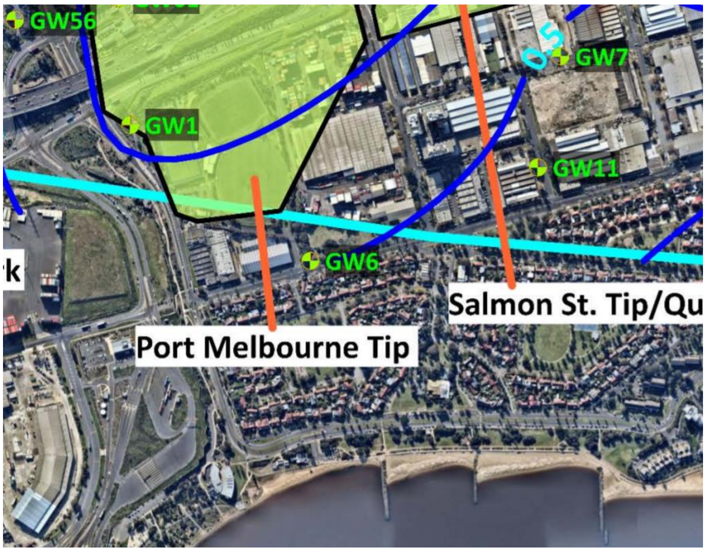
Hobson Bay located approximately 1.3 km away may also be a receptor. Given its increase distance in comparison to the redundant Ingles St. sewer, the concentration is expected to be considerably less. An estimation of concentration is not possible due to limited PFAS data available at the present time.

5.2.2 – Port Melbourne Tip

The receptors of groundwater at this location have been determined to be Hobson Bay, located approximately 450 m south, Yarra River approximately 500 m north and potentially the lakes of West Gate Park. The operational Hobson Bay Main Sewer may also be receiving contaminated groundwater.

5.2.2.1– Port Melbourne Tip South

At GW06, located 450 m north of Hobson Bay the following concentrations of PFOS, PFHxS and PFOA are observed.



ng/L	PFHxA	PFOA	PFOS
GW1	46	56	20
GW6	29	61	4.5

Figure 50 – PFAS Concentration at GW01 & GW06
(Source: Hepburn et. al 2019; nearmap 2020)

At GW06, PFHxS and PFOS decreased relative to GW01, with the increase in PFOA possibly related to precursor breakdown, as discussed in section 4.2.3.3. As precursors often need a bacterial source to facilitate breakdown, once PFAS precursors are clear from leachate areas transformations may reduce considerably. Due to high complexity and limited data available, for this discussion it is assumed that past GW06 no degradation of precursors is taking place.

Concentrations at Hobson Bay are expected to be less than concentrations at GW06, due to natural attenuation processes. However, given the lack of down gradient bores any estimation will have a high degree of uncertainty. Being highly conservative, the concentration at the closest bore can be used as a maximum possible concentration. PFOS being less than 5 ng/L, and assuming its movement mechanisms are like PFNA traveling from the Graham St. Tip site to the Ingles St. sewer, concentrations may be estimated to be between <0.5 and 2 ng/L at the receptor. This has been assumed due to similarities in travel distances. PFOA and PFHxS have higher concentrations at GW06, as such modelling its movement based on PFNA has a higher degree of uncertainty. Another possibility is that the plume is still in its early stages of movement and may advance towards the receptor further in the future. If fate and transport mechanisms such as degradation and dilution are minimal, then a higher concentration could potentially reach the receptor. At the receptor, PFHxS and PFOA concentrations are expected to be higher than PFOS however due to high uncertainties an estimation has not been attempted.

5.2.2.1 – Port Melbourne Tip – North

Limited PFAS data is available for this section of landfill located approximately 500 m away from the Yarra River. DAMW5, the closest bore to the site (north) and GW67 situated close to the shoreline of the Yarra River where both sampled for PFAS. High limits of reporting in comparison to Hepburn et. al (2017) limits the degree of interpretation possible. Factories that have been constructed over the waste may also be a contributing source of PFAS. Piper Plots showed evidence that between, GW57 and GW43 groundwater geochemistry is different to other areas, possibly indicative of an anthropogenic source. GW67 is assumed to be within the saline wedge of the Yarra River therefore PFAS detected may be partly sourced from the river. The General Motors Holden factory is also located on the northern section of the landfill and may also be impacting, with automotive factories known to be a source of PFAS (ITRC 2020).

It has been assumed that PFOS (10 ng/L) and PFHxS (20 ng/L) at DAMW3 may be sourced partially from the landfill. As GW67 has a higher concentration it is assumed that an additional source of PFAS is entering between the landfill and the shoreline.

ng/L	PFHxA	PFOA	PFOS
DAMW5	<10	20	10
GW67	<10	<20	80

Figure 51 – PFAS Concentration at DAMW5 & GW67
(Source: Hepburn et. al 2019; nearmap 2020)

- **Assumption of concentration based on previous data.**

Given that PFOS of 10 ng/L is close to PFNA concentration found at the Graham St. Tip (8.6 ng/L) its movement may be alike, assuming geology and other physical processes are similar. Bores in vicinity of the Graham St. Tip and DAMW5 are both screened in the Port Melbourne Sands aquifer (Aecom 2017). Using this estimate it can be assumed that PFOS and PFHxS at the receptor, directly related to the landfill may be between <0.5 and 2 ng/L. This estimate has a high degree of uncertainty as it is modelled on non-site specific data. As PFOA concentrations are below LOR, making predictions can only be hypothetical, with half the LOR taken as the concentrations. Therefore, the concentration at DAMW5 for PFOA is 5 ng/L and PFHxS 10 ng/L. A concentration at the receptor of PFOS, PFHxS, PFOA is estimated to between <0.5 – 2 ng/L. It should be noted that the plume may be in an early stage of movement and may advance towards the Yarra River further in the future.

5.2.2.2 – Estimation of mass discharge to Yarra River

An estimate of contaminant discharging into the receptor was calculated using Darcy's Law.

The movement of PFNA from GW20, GW26 & GW27 was used to estimate the concentration of PFOS, PFOA, PFHxS towards the Yarra River.

Full calculations can be found in appendix B.

$Q = K \times A\ (h_1 - h_2)/L$ (Darcy's Law)

Q = flow rate m^3/day

K = hydraulic conductivity m/day

$(h_1 - h_2)$ = hydraulic gradient

Key assumptions

- System is in steady state.
- A representative hydraulic gradient between the Yarra river and the landfill will be used.
- A range of hydraulic conductivities (K) will be use from literature, due to the absence of field K results.
- A single transect will be used along the river from GW57 and GW43 to calculate discharge amounts.
- The aquifer properties are homogenous.
- Possible attenuation processes at the groundwater surface water interface will not be quantified.
- Thickness of the Port Melbourne Sands aquifer at the Yarra River has been inferred form Aecom (2017) bore logs.

5.2.2.3 – Results

Estimated concentration of PFOS, PFOA, PFHxS at Yarra River

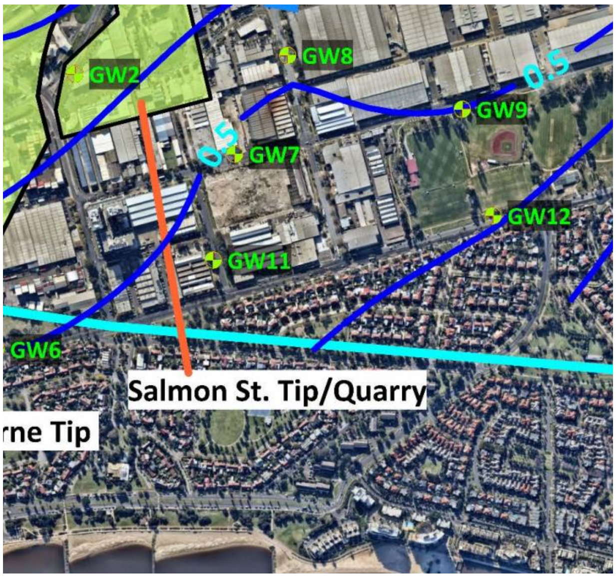
= <0.5 – 2 ng/L

Estimated PFOS, PFOA, PFHxS discharge to Yarra River per day

= 0.0005 - 0.28 mg/day

5.2.3 - Salmon St. Tip

PFAS has not been sampled in bore GW11. If sampled the bore will be beneficial in ascertaining down gradient PFAS concentrations. At GW07, PFOS and PFHxS concentrations have reduced considerably from upgradient bore GW02, whilst PFOA concentrations did not.



ng/L	PFHxA	PFOA	PFOS
GW2	<0.2	74	71
GW7	17	73	44

Figure 52 – PFAS Concentration at GW02 & GW07
(Source: Hepburn et. al 2019; nearmap 2020)

GW07 is located at a similar distance away from Hobson Bay as GW01. Given its increased distance to the receptor, PFAS is expected to attenuate more than in comparison to GW06. Again, conservative estimates will have to be used given the lack of sampled and available down gradient bores. Taking a conservative approach, it should be assumed that PFAS may be present at the receptor. The concentration of this is highly variable. Based on groundwater flow paths the distance to receptor is greater than groundwater from GW06. Due to this added uncertainty, the concentration at GW06 will be used conservatively across the predicted impacted region of both areas. Given lake of geological data on PMS thickness on the shoreline of Hobson Bay, an estimate of discharge amount has not been attempted.

5.2.4 - Landfilling in the vicinity of West Gate Park

No bores where sampled for PFAS in the vicinity of Westgate Park, with evaluation at the present time not possible. The major receptors of groundwater are expected to be the Yarra River and the lakes of West Gate Park. Given distances to receptor (Yarra River) of approximately 500 metres and based on findings, such as PFNA migration from the Graham St. Tip, it is possible that PFAS may be impacting the receptor. Lake sediments are also known to absorb PFAS (Mussabek et al. 2019). If leachate impacted groundwater is entering the lake, PFAS may accumulate within these sediments possibly presenting a risk to the ecology (Mussabek et al. 2019).

5.2.5 - Discussion on coastal aquifers and surface water interaction

Given high uncertainties in assumptions and lack of field data, a discussion on the interaction at the groundwater surface water interface may aid in a better understanding of possible attenuation processes. The interaction between coastal aquifers, oceans and rivers can have complex hydrodynamic features which complicate the direct application of flux and contaminant concentration estimates (Duque et al. 2019)

5.2.5.1 – PFAA in estuarine environments and salting–out effects

Salinity is a known controlling factor of the sorption of organic compounds onto suspended solids (Hong et al. 2013). Water that has high salinity is more ordered and compressible, which reduces aqueous cavity formation and the solubility of many organic compounds (Turner 2003). As salt concentrations increase, solubility of PFAA is known to decrease (Hong et al. 2013). Solubility of PFOS in freshwater is approximately 370 mg/L compared to 12.4 mg/L in saline water (Hong et al. 2013). This reduction in solubility is known as the 'salting out effect'(Turner 2003). Due to 'salting effects' PFAA in higher saline environments absorb to suspended solids at a greater rate (Hong et al. 2013). For PFAA greater than ($C \geq 8$), binding affinity (Kd) has been known to increased exponentially with increasing salinity (Hong et al. 2013). Studies of the Youngsan and Nakdong river estuaries determined the salinity was the most important factor in controlling the adsorption of PFAA (Hong et al. 2013).

When fresh groundwater and high salinity sea water meet at an interface, the change in binding affinity (Kd) of PFAA can result in an increase of absorption to sediments and suspended solids (Hong et al. 2013). This could create areas where PFAS accumulates, possibly at higher concentration than others, potentially increasing risks to ecological and human receptors.

Given that an interface between fresh groundwater and saline surface water exists through a wedge, theoretically this area may absorb PFAS more readily. GW67 located within this saline wedge has a high PFOS concentration, with the increased absorption of PFOS in saline water being a possible influence.

In terms of risk to the receptor, absorption at the saline wedge may retard movement into receiving surface water reducing total contaminant discharge. In Fisherman Bend this saline wedge is known to extend approximately 300 metres inland of the shoreline (Hepburn et. al 2019). Conversely, this interface may hypothetically increase PFAS in an area close to the shoreline, where it can than accumulate in sediments. Given the ecosystems present in marine estuarine sediments and use of water close to the shoreline for recreational purposes, this phenomenon may increase PFAS exposure.

5.3 – Pathway receptor model and assessment against trigger levels

Identifying the pathway of groundwater contamination to receptors is important in developing models and understanding possible risks. For this evaluation, only PFAS contamination will be assessed.

5.3.1 – Levels of protection

The level of protection depends on the type of surface water and level of urbanisation. Levels of protection influences trigger levels set for certain contaminants. As PFAS bioaccumulates, the next highest level should be used (PFAS NEPM 2.0).

Receptor	**Water Segment (SEPP Waters 2018)**	**Level of Protection (SEPP Waters 2018)**
Yarra River	Central Foothills and Coastal Plains	Slightly to moderately modified 95% protection
Hobson Bay	Marine and Estuarine - Hobsons Bay	Slightly to moderately modified 95% protection
Lakes of Westgate Park	Wetland – Lakes	Slightly to moderately modified 95% protection

Table 5 – Levels of protection

5.3.2 – Correct application of trigger levels

In an Australian context, trigger levels are used to inform further investigation and do not necessarily indicate harm to the environment. Given the uncertainties in assessing discharge concentration and volumes, any trigger level exceedances are only intended to inform future investigations. This uncertainty may also extend to results under trigger levels with further investigation possibly needed for confirmation.

Given the bioaccumulative nature of PFAS, protection levels have been changed in accordance with PFAS NEPM 2.0. A species protection of 99% is suggested for slightly to moderately modified waters. As PFAS is bioaccumulative, dilution factors are not applied to the trigger levels.

5.3.3 – Surface water receptors of legacy landfills

- Yarra River & Lakes of West Gate Park – Slightly to moderately modified

Level of protection	Guideline	PFOS	PFOA
99%	Ecological Water Quality Guideline Values (marine)	0.00023 µg/L	19 µg/L

- Hobson bay – Slightly to moderately modified

Level of protection	Guideline	PFOS	PFOA	Sum PFOS and PFHxS
99%	Ecological Water Quality Guideline Values (marine)	0.00023 µg/L	19 µg/L	–
–	Human Health Guideline Values - Recreational water quality guideline value	–	10 µg/L	2 µg/L

Table 6 – Applicable guideline values

5.3.3.1 – Graham St. Tip

- Receptor – Redundant Ingles St. Sewer

PFOS, PFOA, PFHxS contaminated groundwater originating from the landfill is estimated to discharge at the sewer at a rate of approximately 1 – 5 µg/day. Once in the sewer, water is expected to flow through the operational network, where it is ultimately discharged into the Southern Ocean via the Western Treatment Plant (Melbourne Water 2020). As there is not currently a tertiary treatment stage for PFAS removal at the Western Treatment Plant, all PFAS is expected to discharge into the Southern Ocean (Melbourne Water 2020). Interpretation of potential impacts is considered beyond the scope of this project, with the contribution of this individual site being extremely minimal in comparison to other sources of PFAS in wastewater. At present the sewer may be considered beneficial as it captures contaminated groundwater and diverts it away from surface water receptors such as the Yarra River and Hobson Bay. Future upgrades to wastewater treatment facilities may include removal of PFAS, subsequently reducing discharge to the environment.

5.3.3.2 – Port Melbourne Tip South and Salmon St. Tip

- Receptor – Hobson bay and Lakes of West Gate Park

Ecological protection

Hobson Bay is classified as slightly to moderately modified (SEPP Waters 2018). As such a conservative species protection of 99% is applied due to the bioaccumulative nature of PFAS.

Given the low PFOS trigger level of 0.23 ng/L and with the estimated concentration of <0.5 – 2 ng/L of PFOS entering Hobson Bay this trigger may be exceeded. Due to this, future investigational works may be recommended. High levels of uncertainty make any ecological risk assessment unfeasible at the present time. The concentration of PFOA potentially discharging to the receptor is expected to be well below the trigger level of 19 µg/L. With the interface of saline and fresh water known to increase sorption of PFAS, accumulation of PFAS at the shoreline may theoretically occur, potentially impacting marine ecosystems close to it.

The lakes of West Gate Park are considered a slightly to moderately modified with a species protection of 99 %. No groundwater bores have been tested for PFAS in the vicinity of Westgate

Park, therefore detailed assessment is not possible at the present time. Given the low trigger level of PFOS (0.23 ng/L) the impacts of the Port Melbourne Tip cannot be excluded, with future investigational works needed before any assessment is possible.

Contact recreation.

Contact recreation guidelines are not triggered with estimated levels entering Hobson Bay. With PFAS know to absorb more readily to suspended solids in saline environments, there may be a potential for PFAS to accumulate in sediments near the shoreline close to recreational users, increasing the potential for accidental ingestion. This is only hypothetical and would require a detailed investigation before any assessment is possible.

Figure 53 – Sandridge Beach - located south of the former Port Melbourne Tip (Source: TripAdvisor 2020)

5.3.3.3 – Port Melbourne Tip North

Receptor – Yarra River

Ecological protection

As the Yarra River north of Fishermans Bend is considered slightly to moderately modified, a species protection of 99 % is used. The estimated PFOS, PFOA, and PFHxS concentrations potentially discharging to the receptors has been estimated at <0.5 – 2 ng/L. At these concentrations only the PFOS trigger level of 0.23 ng/L is applicable. Given the potential for PFOS to exceed the trigger level at the receptor, future investigational works may be recommended. PFAS may sorb to sediments near the shoreline of the Yarra River potentially increasing concentration at that specific location. A detailed investigation would be required before any assessment is possible.

As swimming is illegal in the Yarra River adjacent to Fishermans Bend only assessment against ecological water quality guidelines is considered necessary.

5.3.4 – Non surface water receptors

5.3.4.1 – Terrestrial groundwater dependent ecosystems

The ‘Port Melbourne Beach foreshore - Coast Banksia Woodland/Coastal Dune Scrub Mosaic’ is found between the south of the former Port Melbourne Tip and Sandridge Beach. As these plants are partly dependent on groundwater, uptake of PFAS may be possible. Given PFAS is bioaccumulative, uptake by plants may be a mechanism for PFAS to enter the food chain. Likewise, ‘West Gate Park - Damp Sands Herb-rich Woodland’ may also be subject to a similar process. Due to lack of data, assessment is not possible at the present time.

5.3.4.2 –Buildings and structures

With shallow groundwater found in Fishermans Bend, construction and utility workers may contact contaminated groundwater. The redevelopment of the area may increase the frequency of this contact. Examples include the creation of underground carparks and the installation and maintenance of underground utility services. Accidental ingestion of groundwater will be the most likely exposure route for this case. Contact water recreation guidelines may be suitable for this scenario, as accidental ingestion is taken into consideration. Generally, it is expected that risk of PFAS exposure to construction and utility workers is very low.

6.0 - Recommendations and future works

6.1 - Recommendations

Recommendations were based on multiple lines of evidence, drawn from research on the extent of legacy landfill impacts on groundwater, including potentially impacted receptors and beneficial users. Recommendations are primarily intended for EPA Victoria to aid in better understanding of risk and to support any future regulatory actions.

- **Creation of a groundwater restricted zone**

Given Fishermans Bend is subject to widespread groundwater contamination originating from numerous sources, it is recommended that EPA Victoria create a groundwater restrictive zone on the entirety of Fishermans Bend. This will eliminate the extractive beneficial uses of potable water supply, agriculture and irrigation, and industrial and commercial. Even though their use is considered highly unlikely, a restrictive zone will be a simple way to eliminate the risk, as these beneficial uses are technically still applicable at the present time. Recommendations where based on groundwater quality results from Hepburn et al. (2017) and Aecom (2015 - 2017) which detail the extent of groundwater contamination at the site.

- **Future works to Hobson Bay Main Sewer**

Recommendations are based on hydrogeological investigations from this report. Given the redundant Melbourne Main Sewer's ability to capture potentially contaminated groundwater and divert it away from key receptors, any future works that impact the junction between the redundant sewer and the operational Hobson Bay Main Sewer, should take this factor into consideration. It is recommended that the relevant authorities such as, EPA Victoria, DELWP and Melbourne City Council are notified, and appropriate action be taken to ensure that any future replacement or rehabilitation works do not impede discharge from the redundant Melbourne Main Sewer.

- **Further investigation of 1.4 dioxane**

Given the lack of information surrounding this contaminant, it is suggested that further research by universities or government corporations such as EPA Victoria be conducted to fully understand the repercussions this chemical may have in the environment. From these studies, guidelines for drinking water and ecological and recreational water quality can be solidified. Based on these findings guidelines can be implemented across Victoria, with potential for use in other jurisdictions.

- **A prolonged sampling of sites contaminated with PFAS**

As noted in section 3.7.3.5 of this report, back diffusion of PFAS is a possibility for contaminated sites. This effect may prevent the return of groundwater to its background levels and has the possibility to be a long term issue even if the site is classed as 'remediated'. To prevent this issue, it is recommended that EPA Victoria research the possibility and risks this effect may pose and to sample site consistently even after they are deemed 'remediated' to ensure no back-diffusion is observed.

6.1 – Future investigational works (using existing EPA wells)

6.1.1 – Groundwater monitoring event (GME) – 2020

The network of 75 EPA owned groundwater bores will be used in this GME. Originally these works where planned for July 2020, however due to Covid-19 related restrictions completion has not been possible.

Groundwater bores that were delineated by this investigation to be potentially leachate impacted will form the basis of this GME. The figure below depicts the bores that are intended to be sampled.

Figure 54 – Planed sampling locations (Source: nearmap)

6.1.2 – Purpose of the GME

6.1.2.1 – Landfills and PFAS precursors

The age of the landfill will be compared to the results received from the total oxidisable precursors (TOP) assay. It is known that when a precursor is in the environment for a longer period of time it is more likely to break down into a terminal PFAA. With knowledge of when particular PFAS were invented and the age of the landfill known, a correlation between the two could be made (ITRC 2020).

The former Port Melbourne Tip has shown indication of precursor degradation along its flow path. To examine this further, it is suggested that testing is undergone for precursor compounds and their relative by-products as obtained by literature. Across a connected flow path, if there is a decrease in precursor product and an increase in terminal PFAS, this could be evidence of PFAS transformations.

- **Significance**

Future site characterisations and risk assessments could be established if a correlation between landfill age and PFAS precursors is established. Older landfills may leach terminal PFAS into the environment for longer than expected due to the slow degradation of PFAS precursors. These terminal PFAA may have the potential to present a greater risk to the environment than there previous PFAS precursors.

6.1.2.2 – PFAS

PFAS that have not been previously tested, will be tested to create a broader baseline of data. Resampling of previously sampled PFAS will aid in the interpretation and analysis of data including potential fate and transport mechanisms and natural attenuation.

- **Significance**

As the toxicity of PFAS is continually being researched, the discovery of new PFAS can alter future risk assessments (ITRC 2020). A change in PFAS between sampling events may indicate potential precursor degradation, however it could also indicate that some PFAS has been leached out over time. Groundwater may undergo seasonal change, resulting in changes in PFAS concentrations. Multiple sampling events can be useful in evaluating and assessing this.

6.1.2.3 – 1:4 dioxane

Testing for 1.4 dioxane would be a first in Fishermans Bend history and will establish a baseline level of contamination. Much like the case study of 6:2 FTS in the Port Melbourne Tip, the contaminant can be analysed between bores of a connected flow path, which may yield information relating to its fate and transport. There is also potential to make correlations between landfill age and the introduction of 1.4 dioxane.

- **Significance**

Due to 1.4 dioxane being an emerging contaminant, its detection and concentration level has the potential to impact future risk assessments.

6.1.2.4 – Leachate characteristic compounds and change over time

Leachate composition is known to change over time and a comparison of sampling events may indicate to what degree this is occurring. This may aid in assessing natural attenuation of compounds. Changing leachate composition has the potential to alter future risk assessments and site characterisations.

6.1.3 – Sampling Plan

Over two or three days 23 groundwater bores will be sampled using a peristaltic pump. Samples will be delivered to a selected laboratory and to be tested for the following analytes:

- **Leachate characteristic compounds**

  TDS, TOC, dissolved methane, ammonia, metals, alkalinity, sulfate, anions & cations.

- **General groundwater parameters (obtained during low flow purge)**

  Dissolved oxygen, redox, EC, pH

- **1:4 dioxane**

- **PFAS**
  Suite of 40 PFAS
  Total oxidisable precursors assay (TOP)

The 38-compound suit will include.

PFAS Type	**Significance**
perfluoroalkyl carboxylic acids & perfluoroalkyl sulfonic acids	'Terminal' PFAS (Precursor products)
HFPO-DA (GenX) & ADONA	PFAA replacement compounds
perfluoroalkane sulphonamides	PFSA precursors
fluorotelomer sulfonic acids	PFCA precursors
polyfluoroalkyl ether acids	PFAA precursors

Table 7 – PFAS types sampled

6.1.3.1 – QC/QA

To safeguard the laboratory results and to ensure there are no errors in the laboratory work, QAQC samples will be required. All appropriate sampling and testing guidelines as per EPA Victoria specifications outlined in Publication 669 (Groundwater Sampling Guidelines 2000) and SESD Operating Procedure for Groundwater Sampling from the US EPA are to be followed. (US EPA 2013; EPA Victoria 2000)

The following is paraphrased from Publication 669 from EPA Victoria (Groundwater Sampling Guidelines 2000) and details the low flow purging technique that will be utilised.

- Bore details, location, depth and diameter needs to be recorded and all equipment to be disinfected and have evidence of calibration. Results from past events are collected and owner of the bores will be informed of the sampling event.

- Groundwater level should be measured before disturbance with all bores measured in the same day to a common datum.
- The low flow pump inlet is placed in the middle of the screened interval
- Begin purging at a rate of 0.1 to 0.5 L/min, this rate can be increased given the drawdown is kept to an appropriate standard
- During purging groundwater parameters are to be documented at regular intervals until said parameters have stabilised in which sampling will begin.

The following is paraphrased from the SESD Operating Procedure for Groundwater Sampling from the US EPA and details the peristaltic pumping technique that will be utilised (US EPA 2013).

- Ensure tubing is attached to a secure object or the protective casing
- Tubing is inserted into the ferrule nut fitting of a vacuum container transfer cap
- A suitable length of tubing is to be placed between the remaining transfer cap assembly ferrule nut fitting and the vacuum side of the flexible tubing within the peristaltic pump head and secure fittings
- Turn the pump on and within a few minutes water should collect into the transfer container. If water doesn't start to collect tighten the ferrule nuts to ensure vacuum system
- When the transfer container is full, turn the pump off and remove the transfer cap assembly. Decanter into the appropriate sample bottles.
- Once sampling of the bore is complete, all tubing is discarded

Quality assurance will be conducted in accordance with NEPM (2013) Schedule B2 and EPA Victoria PFAS National Environmental Management Plan (2018)

Quality assurance will be obtained by the following

- Sampling preparation – All equipment will be disinfected (bladders, tubes, interface meters etc..) with a solution of verified PFAS free Liquinox™ solution prior to sampling each bore. Cross contamination will be limited by using Nitrile gloves while sampling.
- Field quality Assurance (QA) – In accordance with PFAS National Environmental Management Plan (2018) a QA sample will be conducted every 10 samples. The QA will include a laboratory duplicate and an interlaboratory triplicate with a rinsate sample at an occurrence of 1 in 10 also taken.
- Sample handling – Samples will be place in a chilled esky immediately after sampling for transportation to the laboratory with suitable security seals in place.
- Documentation – Field notes and chain of custody are to be documented.
- Laboratory QA – In line with NEPM (2013) Schedule B3 the laboratory will be NATA accredited and will contain at a minimum: Process batch, analysis blank, duplicate analysis, laboratory control sample, matrix spikes and surrogate spikes (NEPM 2013).

6.2 – Additional field works

6.2.1 – Installation of new wells

The pathway receptor model identified the area between the south of the former Port Melbourne Tip and Hobson Bay as a region where PFOS may be entering the receptor at concentrations above ecological trigger levels. For further investigation, it is recommended that a network of monitoring wells screened in the PMS aquifer be installed along the foreshore as depicted in the figure 55 below.

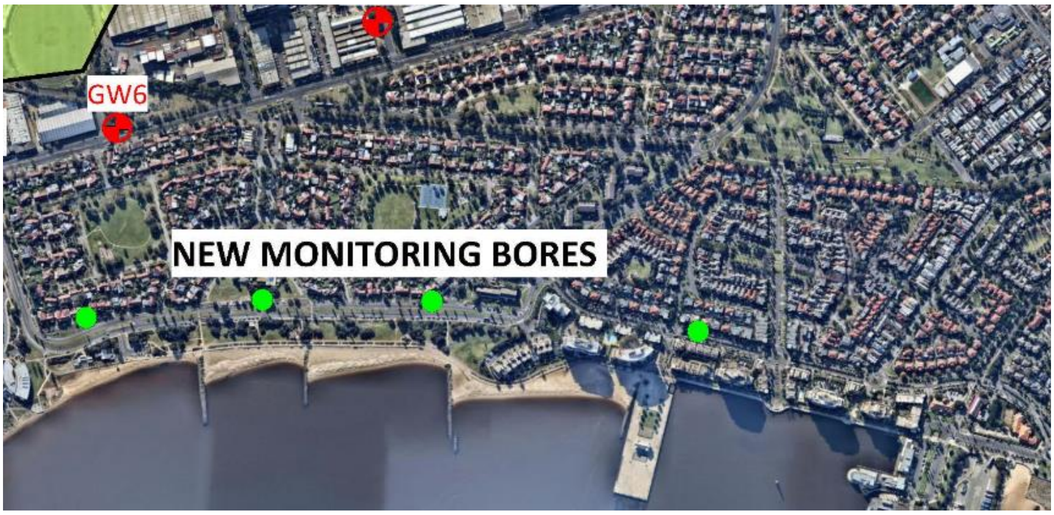


Figure 55 – Installation of new monitoring wells

Once developed, the bores should be sampled for the same analytes as in the planned 2020 GME. Results from this will provide further lines of evidence and aid in the further quantifying of risk. When sampling for PFAS the lowest LOR should be used.

Existing bores north of the Port Melbourne Tip and on the shoreline of the Yarra River including, GW51, GW57, GW62 and GW67 should be sampled with the same analytes as in the planned 2020 GME. These bores should be sampled with the lowest LOR. These results can be compared against bores DAMW5 and GMW02 to assess if any PFAS can be directly correlated with the landfill, similar to PFNA in the Graham St. Tip. This may aid in delineating between a landfill and non-landfill source and provide more lines of evidence which may inform future investigations and risk assessments.

6.3.2 – Sediment sampling

Sediments ideally close to the shoreline of Sandridge Beach and the Yarra River north of the Port Melbourne Tip should be sampled for PFAS. Sediments in the lakes of West Gate Park should also be sampled. This may help in understanding potential sorption processes to sediments at the groundwater/seawater interface and within lakes. Results from this can aid in development of future risk assessments and pathway receptor models.

6.3.4 – Biota sampling of terrestrial groundwater dependent ecosystems

Potential impacted terrestrial groundwater dependent ecosystems such as the ‘Port Melbourne Beach foreshore – Coast Banksia Woodlands’ and ‘West Gate Park - Damp Sands Herb-rich Woodland’ can have biota sampled for PFAS to assess if plants and vegetation are up taking PFAS from the groundwater. Data from this sampling can be used in future ecological risk assessments.

7.0 - Acknowledgments

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8.0 – Group work member contribution table

Section	**Person(s) responsible and percentage**
Executive summary	Nathan 50%, Jorja 50%
Introduction/Statement of Problem	Jorja 100%
Background & Statement of Problem	Jorja 100%
Lit Review – Geology & Hydrogeology	Nathan 100%
Lit review – Landfills in Fishermans Bend	Nathan 100%
Lit Review - Previous studies of landfills	Nathan 100%
Lit review - Landfills and the environment	Jorja 100%
Lit review - Landfills and emerging contaminants	Jorja 100%
Lit Review - PFAS & 1:4 Dioxane	Jorja 100%
Lit review – Toxicity	Jorja 100 %
Lit review - Remediation techniques	Jorja 100 %
Lit review – Guideline	Jorja 100 %
Methodology	Nathan 50%, Jorja 50%
Delineation of landfill leachate impacted regions	Nathan 100%
Analysis of PFAS Data	Nathan 100%
Receptor identification	Nathan 100%
Estimation of PFAS concentration at receptor	Nathan 100%
Pathway receptor model	Nathan 100%
Recommendations and future works	Nathan 50%, Jorja 50%
Acknowledgments	Nathan 50%, Jorja 50%
Appendices	Nathan 50% Jorja 50%

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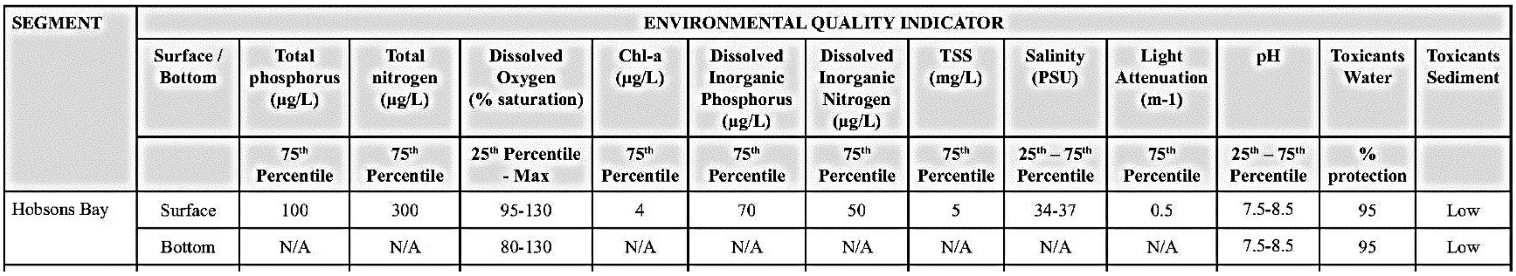
9.0 – Appendices

9.1 - Appendix A – Guidelines

Guideline values for contaminants, often put in place by governments, are used to reduce risks to human and ecological health. The guidelines are based on the best scientific evidence with the guideline values designed to minimised effects received by sensitive aspects of the surrounding environments, this could include humans or aquatic life. Below is a figure that outlines broad contamination guidelines for Hobsons Bay near Fishermans Bend.

TABLE 6: ENVIRONMENTAL QUALITY INDICATORS AND OBJECTIVES FOR PORT PHILLIP BAY



SEGMENT	**ENVIRONMENTAL QUALITY INDICATOR**												
	Surface / Bottom	**Total phosphorus (µg/L)**	**Total nitrogen (µg/L)**	**Dissolved Oxygen (% saturation)**	**Chl-a (µg/L)**	**Dissolved Inorganic Phosphorus (µg/L)**	**Dissolved Inorganic Nitrogen (µg/L)**	**TSS (mg/L)**	**Salinity (PSU)**	**Light Attenuation (m-1)**	**pH**	**Toxicants Water**	**Toxicants Sediment**
		75th Percentile	**75th Percentile**	**25th Percentile - Max**	**75th Percentile**	**75th Percentile**	**75th Percentile**	**75th Percentile**	**25th – 75th Percentile**	**75th Percentile**	**25th – 75th Percentile**	**% protection**	
Hobsons Bay	Surface	100	300	95-130	4	70	50	5	34-37	0.5	7.5-8.5	95	Low
	Bottom	N/A	N/A	80-130	N/A	N/A	N/A	N/A	N/A	N/A	7.5-8.5	95	Low

Source: (Victorian Government Gazette, 2018)

The following table is an extract from the Department of Agriculture, Water and the Environment Report, NEMP 2.0 (Department of Agriculture, Water and the Environment 2020), it outlines human health guideline values for PFOS, PFHxS and PFOA as developed by health regulators.

Human Health Guideline Values- NEMP 2.0 (Department of Agriculture, Water and the Environment 2020**)**			
Sum of PFOS and PFHxS	**PFOA**	**Description**	**Comments and source**
0.02 µg/kg bw /day	0.16 µg/kg bw /day	Tolerable daily intake (TDI)	FSANZ 2017
0.07 µg/L	0.56 µg/L	Drinking water quality guideline value	Australian Government Department of Health 2019
2 µg/L	10 µg/L	Recreational water quality guideline value*	NHMRC 2019

The following table is an extract from the Department of Agriculture, Water and the Environment Report, NEMP 2.0 (Department of Agriculture, Water and the Environment 2020), it outlines ecological water quality guideline values for PFOS, PFHxS and PFOA as developed by water regulators.

Ecological Water Quality Guideline Values - NEMP 2.0 **(**Department of Agriculture, Water and the Environment 2020**)**				
Exposure scenario	**PFOS**	**PFOA**	**Exposure scenario**	**Comments and source**
Freshwater	0.00023 µg/L	19 µg/L	99% species protection - high conservation value systems	Australian and New Zealand Guidelines for Fresh and Marine Water Quality - technical draft default guideline values for PFOS and PFOA. Note 1: The 99% species protection level for PFOS is close to the level of detection. Agencies may wish to apply a 'detect' threshold in such circumstances rather than a quantified measurement. Note 2: The draft guidelines do not account for effects which result from the biomagnification of toxicants in air- breathing animals or in animals which prey on aquatic organisms. Note 3: The WQGs advise[41] that the 99% level of protection be used for slightly to moderately disturbed systems. This approach is generally adopted for chemicals that bioaccumulate and biomagnify in wildlife. Regulators may specify or environmental legislation may prescribe the level of species protection required, rather than allowing for case-by-case assessments.
	0.13 µg/L	220 µg/L	95% species protection - slightly to moderately disturbed systems	
	2 µg/L	632 µg/L	90% species protection - highly disturbed systems	
	31 µg/L	1824 µg/L	80% species protection - highly disturbed systems	
Interim marine	0.00023 µg/L	19 µg/L	99% species protection - high conservation value systems	As above. Freshwater values are to be used on an interim basis until final marine guideline values can be set using the nationally-agreed process under the Australian and New Zealand

	0.13 µg/L	220 µg/L	95% species protection - slightly to moderately disturbed systems	Guidelines for Fresh and Marine Water Quality. Note 1: The WQG advise that in the case of estuaries, the most stringent of freshwater and marine criteria apply, taking account of any available salinity correction. Note 2: Marine guideline values developed by CRC CARE are under consideration through the nationally- agreed water quality guideline development process.
	2 µg/L	632 µg/L	90% species protection - highly disturbed systems	
	31 µg/L	1824 µg/L	80% species protection - highly disturbed systems	

The following table is a summarized extract from Department of Health and Human Services Report on 1, 4 Dioxane (US Department of Health and Human Services, 2006) and outlines regulations and guidelines internationally for 1, 4 Dioxane. There are also guidelines detailed in the table that outline the NHMRC advise on 1.4 Dioxane (NHMRC 2008; NRMMC 2011)

Regulations, Advisories, and Guidelines Applicable to 1,4-Dioxane

Agency	Description	Information	Reference
EPA	Drinking water standards and health advisories		EPA 2004b
	1-day HA for a 10kg child	4.0mg/L	
	10-day HA for a 10kg child	0.4 mg/L	
	10^4 cancer risk	0.3 mg/L	
California	Drinking water guidelines	3µg/L	HSDB 2010
Florida		5 µg/L	
Maine		32 µg/L	
Massachusetts		50 µg/L	
NHMRC 2008, NRMMC 2011/2018	Regarding Primary contact recreation and drinking water	0.05 mg/L	World Health Organisation (WHO) (2017) Guidelines for Drinking Water Quality

9.2 – Appendix B – Concentration of PFAS at receptor

Mass discharged to redundant ingles street sewer (landfill only)

Key Assumptions:

- The system is in a theoretical steady state.
- The sewer simulates a drain and is 300 mm in diameter (Aecom 2015).
- A constant concentration of contaminate is at the sewer.
- The hydraulic conductivity is obtained from slug test results at GW26 (Hepburn et. al 2017).
- An average hydraulic gradient calculated between GW27 and the sewer will be applied.
- Groundwater only discharges into one side of the sewer pipe. (e.g. ½ of total surface area).

Hydraulic gradient

Distance to Ingles St. Sewer from GW27, following a flow perpendicular to inferred groundwater contours equals 110 meters. (Source: Aecom July 2017)

Head level at GW27 = -0.3 mAHD

Head level at sewer = -0.1 mAHD

Hydraulic gradient (i) = dh/dl

(i) = (0.3-0.1) m/ 110 m =0.0018

Hydraulic conductivity (K) (obtained from GW26).

Average of two slug test performed by Hepburn et. al.

Test 1 = 5.3 m/day

Test 2 = 9.7 m/day

Average = 7.5 m/day

Dimensions at discharge point.

Dimensions of length are obtained from historical plans.

Length of sewer = 380 m

Dimeter = 300mm

Surface area of discharge = ½ of surface area of sewer pipe = $0.5\times h\times(2\times\pi\times r) = 0.5\times380\times(2\times\pi\times0.15)$

$= 179\ m^2$

Darcy flux and contaminate discharge amount.

The Darcy Flux is defined as the flow per unit cross sectional area.

Darcy's Law

Q (flow rate) = Hydraulic conductivity (K) × cross sectional area × hydraulic gradient

$= 7.5\ m/day \times 179\ m^2 \times 0.0018$

$= 2.4\ m^3/day$

Approximately 2.4 m^3/day is discharging to the sewer.

Contaminate discharge per day.

PFOS, PFOA, PSHxS = <0.5 – 2 ng/L

= 500 – 2000 ng/m^3

= 2.4 m^3/day × 500 ng/m^3 = 1200 ng/day

= 2.4 m^3/day × 2000 ng/m^3 = 4800 ng/day

= 1 – 5 µg/day

Port Melbourne Tip – North

Estimation of hydraulic gradient.

Hydraulic gradient (i) = dh/dl

(i) = (0.9-0.3) m/ 380 m =0.0015

Figure 56 – (Source: nearmap 2020)

Hydraulic conductivity (K) (obtained from GW26).

As no field data relating to hydraulic conductivity in the area has been completed, a literature value of between (1.7 to 23) m/day will be used.

Cross sectional area

Data obtained from Aecom Bore logs from GW67 and GW43 will be used to estimate a representative PMS thickness at the river.

ID	Thickness of PMS
GW43	5.5 m
GW67	4.2 m

Source (Aecom 2017).

An average PMS thickness of 5 meters will be used in calculations.

The distance between GW57 and GW43 following the shoreline is approximately 800 meters.

Therefore, discharge cross sectional area (Q) = 5m × 800m = 4000 m^2

Contaminate concentration (assumed landfill origin)

PFOS, PFOA, PSHxA = 0.5 – 2 ng/L

Darcy flux and contaminate discharge amount.

The Darcy Flux is defined as the flow per unit cross sectional area.

<u>Darcy’s Law</u>

Q (flow rate) = Hydraulic conductivity (K) × cross sectional area × hydraulic gradient

1.7 m/day × 4000 m^2 × 0.0015

10 m^3/day

23 m/day × 4000 m^2 × 0.0015

= 140 m^3/day

(10 to 140) m^3/day discharges to the Yarra River.

Contaminate discharge per day.

PFOS, PFOA, PSHxA = <0.5 – 2 ng/L

= 500 – 2000 ng/m^3

10 m^3/day × 500 ng/m^3 = 5000 ng/day

10 m^3/day × 2000 ng/m^3 = 20000 ng/day

140 m^3/day × 500 ng/m^3 = 70000 ng/day

140 m^3/day × 2000 ng/m^3 = 280000 ng/day

A conservative estimate of between (0.0005 to 0.28) mg/day of landfill related, PFOS, PFHxS and PFOA may be discharging into the Yarra River.

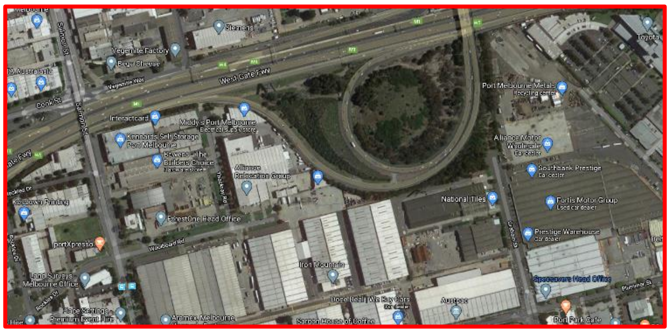
9.3 – Appendix C – Graham St. Tip questionnaire

RMIT Research Project – landfills in Fishermans bend.

Questionnaire – Graham Street Quarry/Tip

Name of participate: Allan Marshall

Approximate location: 522-516 Graham St



Current site

Date: 11/08/20

Site - 1950-1960

Question	Answer
How long have you known the area around the north of Graham street for?	Since 1957, till they filled in about half the quarry. Not sure of that date, but you can find out when the Westgate Freeway and Graham Street over-pass started construction there.
Prior to development, what was the area commonly referred to as by the locals? (e.g. quarry/tip/dump etc...)	For my friends and I, Quarry. Reason being that there was a separate tip/dump off Todd Road, where the school oval is now.
Have you had any direct interaction/contact with the former quarry/tip site while in was in operation? (e.g. have walk near or through etc...)	Again, since 1957. It was a beautiful long walk around it, but you had to get over old cyclone fence topped with barbed-wire, easy; but that meant only a few locals would do it. The west side of the quarry was high, but the land slopped down gently to the water and there were a few islands just off shore. There was a 44 gallon drum raft and a long narrow wooden boat that we used to sail to the islands. Some times we swam in the water, but never put our heads under in-case we swallowed some.

Did you witness or know of any tipping of waste at the site? If yes, do you know what kind of waste was disposed there? (e.g household garbage, factory waste etc…)	A lot of house demolition material and furniture and rubble from factories were dumped there and it was great to go through it for scrap metals like copper and brass that we sold at a local scrap merchant. Lots of treasures to be found when we were younger. House-hold garbage and similar were "not" dumped here, but the Port Tip. In my time thousands of "neon" light tubes were dumped there, some-times dozens together still in their cardboard covering. Of course we threw them in the water and broke them with our shanghais' or had sword fights with them; and yes, the inside white powder got on us and we breathed it in. So bad waste would be, the tubes, lead and even asbestos sheeting. No old tyre dumping, but an occasional one. NOTE: - dumping was only on the east (Williamstown Road) side of the quarry.
Was the tip organised and formal, like that of the Port Melbourne Tip?	Trucks usually only entered by the Salmon Street entrance; I do remember a small hut for a gate-keeper but never really saw one around.
How would you describe the water lagoons at the site?	Just one big lake; never knew how deep, with a few small shallow bays.Water quality visually looked okay. Many frogs in the reeds and hundreds of tad-poles.The western end was covered in fennel (liquorice weed) up to three metres tall and half the north side had a lot of reeds.
Did the site have a noticeable odour?	The air smelt good, but on a few occasions there was a very bad chemical/acid smell from an area of recent dumping.
Do you know the approximate time the quarry/tip was fully filled? Was the quarry filled progressively over time or was it filled in a relatively short period?	A peninsula in the middle of the east side was forming from normal dumping, but when the freeway was announced, truck loads filled with dirt, rock, bricks and broken concrete were dumped starting from the east side.It was a quick operation, officials would know more, but to me it took a least a year to fill. It was a big quarry. A lot of house demolition material and furniture and rubble from factories were dumped there and it was great to go through it for scrap metals like copper and brass that we sold at a local scrap merchant. Lots of treasures to be found when we were younger. House-hold garbage and similar were "not" dumped here, but the Port Tip.

9.4 – Appendix D – Tabulated data

PFAS Results

Hepburn et. al (2017)

		PFBA	**PFPeA**	**PFHxA**	**PFHpA**	**PFOA**	**PFNA**	**PFDA**	**PFUDA**	**∑PFCA**	**PFBS**	**PFPeS**	**PFHxS**	**PFHpS**	**PFOS**	**∑PFSA**	**6:2 FTS**	**∑PFAS**
		ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L
DATE	**LOR**	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Jul-17	**GW1**	<0.2	<0.2	46	<0.2	56	<0.2	<0.2	<0.2	100	14	<0.2	34	1	20	69	3.2	180
Jul-17	**GW2**	39	<0.2	<0.2	<0.2	74	<0.2	<0.2	5.3	120	8.9	6.8	34	4.4	71	130	<0.2	240
Jul-17	**GW6**	49	15	29	22	61	<0.2	<0.2	<0.2	180	16	8.8	35	<0.2	4.5	64	<0.2	240
Jul-17	**GW7**	<0.2	<0.2	17	<0.2	73	<0.2	<0.2	<0.2	90	10	3.5	14	<0.2	44	72	<0.2	160
Jul-17	**GW3**	5.1	<0.2	6	<0.2	5.1	<0.2	<0.2	<0.2	16	4.2	2.1	9.3	<0.2	33	49	<0.2	65
Jul-17	**GW5**	13	<0.2	20	<0.2	12	<0.2	<0.2	<0.2	45	12	6.2	28	<0.2	24	70	<0.2	120
Jul-17	**GW20**	11	<0.2	12	<0.2	6	8.6	<0.2	<0.2	38	7.3	3.7	16	<0.2	16	43	<0.2	81
Jul-17	**GW25**	9.1	<0.2	<0.2	<0.2	7.5	<0.2	<0.2	<0.2	17	9	6.4	45	<0.2	26	86	<0.2	100
Jul-17	**GW8**	8.8	14	13	4.8	2.1	<0.2	<0.2	<0.2	43	2.1	<0.2	3.6	<0.2	1.3	7	<0.2	49
Jul-17	**GW23**	17	13	34	12	12	0.76	<0.2	<0.2	89	31	16	96	3.9	75	220	10	320
Jul-17	**GW26**	11	12	19	<0.2	7.7	0.69	<0.2	<0.2	50	24	15	170	7.1	250	470	<0.2	520
Jul-17	**GW27**	24	6.3	29	3.8	18	0.73	1.3	<0.2	83	8.5	5.1	280	5.3	4800	5100	<0.2	5200
Jul-17	**GW14**	3.3	3	2.4	<0.2	1.7	0.67	2.2	<0.2	13	2	<0.2	2.6	<0.2	7.7	12	<0.2	26

PFAS Results

Aecom (2017)

		6:2 FTS	PFOA	PFOS	4:2 FTS	PFBA	PFPeA	8:2 FTS	N-Me-FOSA	N-Me-FOSE	FOSA	PFBS	PFDS	PFTeDA	PFTrDA	N-Et-FOSA	PFDcA	PFHpA	PFHxA	N-Et-FOSE	PFDoA	PFNA	PFUnA	Sum of PFAS	Sum of PFAS (WA DER List)	Sum of PFHxS and PFOS	10:2 FTS	N-Methyl perfluorooctane sulfonamidoacetic acid	PFPeS	PFHpS	PFHxS	N-Ethyl perfluorooctane sulfonamidoacetic acid
		0.05	0.01	0.01	50	0.0001	20	0.05	0.05	0.05	0.02	0.02	0.02	0.05	0.02	0.05	0.02	0.02	0.02	0.05	0.02	0.02	0.02	0.01	0.01	0.01	0.05	0.02	0.02	0.02	0.02	0.02
DATE	**LOR**	µg/L	µg/L	µg/L	ng/L	MG/L	ng/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
10/07/2017	**GW01**	<0.05	0.08	0.04	<50	0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	0.05	<0.05	<0.02	<0.02	<0.02	0.3	0.3	0.07	<0.05	<0.02	<0.02	<0.02	0.03	<0.02
11/07/2017	**GW04**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
10/07/2017	**GW07**	<0.05	0.1	0.08	<50	0.002	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	0.02	<0.05	<0.02	<0.02	<0.02	2.2	2.2	0.08	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
17/07/2017	**GW10**	<0.05	<0.01	0.04	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	0.07	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.15	0.15	0.08	<0.05	<0.02	<0.02	<0.02	0.04	<0.02
12/07/2017	**GW12**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/07/2017	**GW13**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/07/2017	**GW19**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/07/2017	**GW21**	<0.05	0.05	0.28	<50	<0.0001	80	<0.05	<0.05	<0.05	<0.02	0.02	<0.02	<0.05	<0.02	<0.05	<0.02	0.04	0.05	<0.05	<0.02	<0.02	<0.02	0.63	0.63	0.39	<0.05	<0.02	<0.02	<0.02	0.11	<0.02
12/07/2017	**GW27**	<0.05	0.01	4.62	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	4.9	4.9	4.89	<0.05	<0.02	<0.02	<0.02	0.27	<0.02
10/07/2017	**GW31**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	0.05	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.05	0.05	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
10/07/2017	**GW34**	0.07	0.03	0.06	<50	0.0001	120	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	0.02	0.09	<0.05	<0.02	<0.02	<0.02	0.49	0.49	0.06	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
11/07/2017	**GW38**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/05/2017	**GW40A/C**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	0.05	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.16	0.16	0.11	<0.05	<0.02	<0.02	<0.02	0.11	<0.02
11/05/2017	**GW41**	<0.05	<0.01	0.02	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.06	0.06	0.06	<0.05	<0.02	<0.02	<0.02	0.04	<0.02
14/07/2017	**GW41**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
13/07/2017	**GW42AC**	<0.05	<0.01	0.68	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.68	0.68	0.68	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
16/05/2017	**GW49**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
11/07/2017	**GW49**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
11/05/2017	**GW51**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.08	0.08	0.08	<0.05	<0.02	<0.02	<0.02	0.08	<0.02
17/07/2017	**GW51**	<0.05	<0.01	0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.06	0.06	0.06	<0.05	<0.02	<0.02	<0.02	0.05	<0.02
16/05/2017	**GW61**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	0.03	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	0.05	<0.05	<0.02	<0.02	<0.02	0.1	0.1	0.02	<0.05	<0.02	<0.02	<0.02	0.02	<0.02
14/07/2017	**GW61**	<0.05	0.02	0.04	<50	<0.0001	90	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	0.07	<0.05	<0.02	<0.02	<0.02	0.25	0.25	0.07	<0.05	<0.02	<0.02	<0.02	0.03	<0.02
9/05/2017	**GW67**	<0.05	<0.01	0.03	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.03	0.03	0.03	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
13/07/2017	**GW67**	<0.05	<0.01	0.08	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.08	0.08	0.08	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/05/2017	**GW72**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
14/07/2017	**GW72**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
11/05/2017	**GW73**	<0.05	0.01	0.07	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.12	0.12	0.11	<0.05	<0.02	<0.02	<0.02	0.04	<0.02
13/07/2017	**GW73**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
8/05/2017	**GW81**	<0.05	0.31	0.26	<50	<0.0001	590	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	0.33	0.46	<0.05	<0.02	<0.02	<0.02	2.34	2.31	0.62	<0.05	<0.02	0.03	<0.02	0.36	<0.02
14/07/2017	**GW81**	<0.05	0.41	0.27	<50	0.0002	1000	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	0.63	0.68	<0.05	<0.02	<0.02	<0.02	3.53	3.51	0.59	<0.05	<0.02	0.02	<0.02	0.32	<0.02
12/05/2017	**MW1333**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/07/2017	**MW1333**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
11/05/2017	**DAMW5**	<0.05	<0.01	<0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	<0.01	<0.01	<0.01	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02
12/07/2017	**DAMW5**	<0.05	<0.01	0.01	<50	<0.0001	<20	<0.05	<0.05	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.05	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.03	0.03	0.03	<0.05	<0.02	<0.02	<0.02	0.02	<0.02

Standard L/N ratio and Alkalinity data

Aecom (2017)

		Bicarbonate Alkalinity as CaCO3	Carbonate Alkalinity as CaCO3	Hydroxide Alkalinity as CaCO3	Total Alkalinity as CaCO3	Ammonia (as N)	Chloride	Calcium (Filtered)	Magnesium (Filtered)	Potassium (Filtered)	Sodium (Filtered)
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
DATE	LOR	1	1	1	1	0.1	1	1	1	1	1
10/07/2017	**GW01**	1600	<1	<1	1600	68.8	866	94	119	157	776
14/07/2017	**GW02**	1400	<1	<1	1400	58.8	254	57	70	45	523
11/07/2017	**GW03**	912	<1	<1	912	0.78	136	202	113	47	173
11/07/2017	**GW04**	601	<1	<1	601	0.02	30	189	49	13	54
11/07/2017	**GW05**	1070	<1	<1	1070	6.14	163	100	117	56	238
11/07/2017	**GW06**	621	<1	<1	621	8.49	494	263	83	54	422
10/07/2017	**GW07**	1080	<1	<1	1080	32	205	286	53	38	189
14/07/2017	**GW08**	424	<1	<1	424	2.37	39	206	30	14	43
11/07/2017	**GW09**	391	<1	<1	391	5.13	84	167	32	24	117
17/07/2017	**GW10**	234	<1	<1	234	0.07	24	67	21	8	42
11/07/2017	**GW11**	272	<1	<1	272	0.37	13	155	11	9	26
12/07/2017	**GW12**	132	<1	<1	132	0.04	28	67	9	7	25
12/07/2017	**GW13**	358	<1	<1	358	0.07	19	111	28	14	47
17/07/2017	**GW14**	59	<1	<1	59	0.02	11	16	3	2	12
12/07/2017	**GW15**	2930	<1	<1	2930	36	12200	322	1090	231	7330
12/07/2017	**GW16**	394	<1	<1	394	0.18	23	105	31	21	76
12/07/2017	**GW17**	294	<1	<1	294	0.63	119	126	31	14	146
12/07/2017	**GW19**	2000	<1	<1	2000	36.6	8830	290	881	160	5170
12/07/2017	**GW20**	735	<1	<1	735	4.29	112	238	99	27	242
12/07/2017	**GW21**	338	<1	<1	338	0.77	44	90	20	8	161
11/07/2017	**GW22**	90	<1	<1	90	0.42	51	61	23	7	52
11/07/2017	**GW23**	82	<1	<1	82	1.71	762	181	76	26	459
12/07/2017	**GW24**	732	<1	<1	732	10.4	761	102	71	39	555
12/07/2017	**GW25**	533	<1	<1	533	4.97	60	284	145	35	161
17/07/2017	**GW26**	105	<1	<1	105	0.21	15	298	24	7	26
12/07/2017	**GW27**	73	<1	<1	73	0.05	11	32	3	<1	7
11/07/2017	**GW28**	819	<1	<1	819	8.2	160	61	46	33	444
11/07/2017	**GW29**	408	<1	<1	408	0.02	109	162	28	8	96
14/07/2017	**GW30**	39	<1	<1	39	0.54	14	48	10	5	32
10/07/2017	**GW31**	546	<1	<1	546	0.32	3010	787	210	53	1480
17/07/2017	**GW32**	868	<1	<1	868	11.6	1740	613	168	36	716
11/07/2017	**GW33**	828	<1	<1	828	7.86	539	205	98	29	224
10/07/2017	**GW34**	565	<1	<1	565	8.2	812	92	92	46	548
12/07/2017	**GW35**	35	<1	<1	35	7.24	130	454	253	40	279

		Bicarbonate Alkalinity as CaCO3	**Carbonate Alkalinity as CaCO3**	**Hydroxide Alkalinity as CaCO3**	**Total Alkalinity as CaCO3**	**Ammonia (as N)**	**Chloride**	**Calcium (Filtered)**	**Magnesium (Filtered)**	**Potassium (Filtered)**	**Sodium (Filtered)**
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
DATE	LOR	1	1	1	1	0.1	1	1	1	1	1
11/07/2017	**GW36**	370	<1	<1	370	2.83	169	70	29	20	128
11/07/2017	**GW37**	586	<1	<1	586	0.48	21	25	37	31	204
11/07/2017	**GW38**	900	<1	<1	900	0.02	860	9	32	25	1260
11/07/2017	**GW39**	227	<1	<1	227	1.41	594	93	38	19	283
11/07/2017	**GW40**	142	<1	<1	142	3.99	710	286	118	16	518
14/07/2017	**GW41**	176	<1	<1	176	0.07	13	66	7	8	18
13/07/2017	**GW42AC**	8	<1	<1	8	0.1	17	11	5	2	13
13/07/2017	**GW43**	284	<1	<1	284	0.92	121	133	30	18	84
11/07/2017	**GW44**	790	<1	<1	790	12.2	6580	293	575	129	3500
14/07/2017	**GW45**	780	<1	<1	780	5.57	1360	263	104	38	907
13/07/2017	**GW46**	308	<1	<1	308	1.7	40	174	46	14	76
14/07/2017	**GW47**	447	<1	<1	447	2.96	5140	283	400	138	2670
17/07/2017	**GW48**	271	<1	<1	271	0.91	124	86	52	7	180
11/07/2017	**GW49**	59	<1	<1	59	0.17	6	8	6	3	6
11/07/2017	**GW50**	1170	<1	<1	1170	13.4	7410	477	444	148	3830
17/07/2017	**GW51**	327	<1	<1	327	0.33	1080	78	62	25	692
10/07/2017	**GW52**	397	<1	<1	397	0.97	198	85	32	11	265
17/07/2017	**GW53**	371	<1	<1	371	1.23	91	90	38	10	188
11/07/2017	**GW54**	680	<1	<1	680	6.9	500	158	77	21	362
10/07/2017	**GW56**	1250	<1	<1	1250	1.48	1540	369	207	171	1370
13/07/2017	**GW57**	343	<1	<1	343	1.88	145	57	7	84	173
14/07/2017	**GW61**	1780	<1	<1	1780	66.4	875	112	174	142	877
17/07/2017	**GW62**	188	<1	<1	188	0.26	1510	299	75	30	638
14/07/2017	**GW65**	1450	<1	<1	1450	59.1	725	116	140	101	594
13/07/2017	**GW67**	490	<1	<1	490	1.24	147	146	49	16	154
14/07/2017	**GW69**	1120	<1	<1	1120	13.8	838	95	97	61	768
13/07/2017	**GW70**	156	<1	<1	156	0.31	33	46	10	3	40
14/07/2017	**GW72**	376	<1	<1	376	2.43	22	128	13	6	34
13/07/2017	**GW73**	633	<1	<1	633	2.82	43	141	58	13	110
14/07/2017	**GW74**	610	<1	<1	610	9.98	47	160	73	22	146
14/07/2017	**GW75**	328	<1	<1	328	0.6	16	115	23	10	41
13/07/2017	**GW76**	442	<1	<1	442	2.51	321	105	32	21	235
13/07/2017	**GW77**	243	<1	<1	243	0.14	21	87	18	4	26
14/07/2017	**GW80**	454	<1	<1	454	2.51	40	109	48	26	66

		Bicarbonate Alkalinity as CaCO3	**Carbonate Alkalinity as CaCO3**	**Hydroxide Alkalinity as CaCO3**	**Total Alkalinity as CaCO3**	**Ammonia (as N)**	**Chloride**	**Calcium (Filtered)**	**Magnesium (Filtered)**	**Potassium (Filtered)**	**Sodium (Filtered)**
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
DATE	LOR	1	1	1	1	0.1	1	1	1	1	1
14/07/2017	**GW81**	478	<1	<1	478	1.46	56	174	60	24	99
13/07/2017	**GW82**	267	<1	<1	267	0.49	720	243	79	29	392
12/07/2017	**MW1333_02**	727	<1	<1	727	8.44	151	92	96	19	130
12/07/2017	**MW1371**	611	<1	<1	611	6.69	46	58	46	13	179
12/07/2017	**DAMW5**	308	<1	<1	308	1.02	14	66	10	12	46
12/07/2017	**F3**	210	<1	<1	210	1.62	13	19	19	12	28
13/07/2017	**GMW02**	376	<1	<1	376	5.05	491	80	49	18	245
12/07/2017	**GMW03**	398	<1	<1	398	13.2	23	24	24	33	98
12/07/2017	**MW9AI**	505	<1	<1	505	13.4	335	32	12	16	393