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ENVIRONMENTAL ASSESSMENT WORKS

South Australian Environment Protection Authority

Hendon Broader Assessment Area - Stage 3 Works

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Environmental Assessment Works

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EXECUTIVE SUMMARY

Greencap was commissioned by the South Australian Environment Protection Authority to conduct Stage 3 Environmental Assessment Works within the Hendon Broader Assessment Area, Hendon, South Australia. The purpose of the work was to obtain additional seasonal data with respect to the distribution of volatile chlorinated hydrocarbon compounds in groundwater and soil vapour. In addition, the work has included groundwater fate and transport modelling to inform the boundaries of a potential groundwater prohibition area and an update of a previously developed human health / vapour intrusion risk assessment.

As requested by the EPA, the additional works did not consider the Laugh'n'Learn Child Care / Early Learning Centre west of the Tapleys Hill Road / West Lakes Boulevard intersection or the northern portion of the Hendon Industrial Area as these areas are subject to separate environmental assessment works.

Groundwater and Soil Vapour Monitoring

The investigations comprised the sampling and analysis of 31 groundwater monitoring wells and 28 soil vapour points across the Hendon Broader Assessment Area. All groundwater and soil vapour samples were analysed for volatile chlorinated hydrocarbons (the main contaminants of concern), with ten selected groundwater samples per monitoring round also analysed for natural attenuation parameters and major cations and anions.

Groundwater analytical results were compared to potable, recreational and irrigation criteria to maintain consistency with previous assessment work completed across the Hendon Broader Assessment Area, while soil vapour results were compared to interim soil vapour Health Investigation Levels as presented in the NEPM.

A number of elevated chlorinated hydrocarbon concentrations were reported in groundwater above the adopted groundwater criteria with the most significant concentrations reported from monitoring wells GW09, MW02, MW04, MW05, MW07 and MW08. The elevated trichloroethene concentrations ranged from 32µg/L (MW02) to 780µg/L (MW07) while the elevated tetrachloroethene concentrations ranged from 52µg/L (MW02) to 78µg/L (MW05). Elevated 1,2-dichloroethene concentrations ranged from 62µg/L (MW07) to 252µg/L (GW09). A Trend analysis was undertaken for a number of groundwater wells, with the majority of concentration trends displaying stable or decreasing trends. Increasing trends were identified in monitoring wells MW04, MW06, MW07 and MW08, suggesting that the chlorinated hydrocarbon plumes have not reached steady state conditions and may still be migrating from up hydraulic gradient sources.

A number of elevated concentrations of chlorinated hydrocarbons were reported in soil vapour above the adopted criteria, particularly for trichloroethene where elevated concentrations were elevated at the majority of locations tested (ranging from 29µg/m^3 (SV30) to 19,000µg/m^3 (SV22)). The elevated concentrations in soil vapour generally coincided with elevated concentrations in nearby groundwater monitoring wells. A trend analysis was undertaken, with decreasing trends evident at all soil vapour point locations assessed. This suggests that the volatile chlorinated hydrocarbons in soil vapour may be undergoing natural degradation or volatalisation processes.

Conceptual Site Model

A conceptual site model has been developed to characterise site conditions within the Hendon Broader Assessment Area and to form a basis for the construction of a 3D numerical model. The main considerations in the conceptual site model include:

- *The geological setting of the Hendon Broader Assessment Area is complex. Significant variations in the subsurface material does not enable the boundaries of geological units to be confidently determined.*
- *The regional groundwater flow within the Hendon Broader Assessment Area is in a north westerly direction in the eastern portion and a south westerly direction in the western portion.*

- *The groundwater contour pattern is influenced by low groundwater levels measured in MW07 and MW25. Previous assessments (AECOM, 2016) appear to indicate that these areas may be influenced by groundwater discharge to the deep sewer main located in the vicinity.*
- *A shallow (possibly perched) aquifer was identified by Coffey in 2011 during investigations conducted within the vicinity of a former service station in Royal Park (north western portion of the Hendon Broader Assessment Area). The groundwater flow direction in the perched aquifer was assessed to be to the south west, while groundwater in the deeper regional uppermost aquifer was assessed to be to the north west.*
- *Hydraulic conductivity estimates during previous investigations (Coffey, 1992 and PB, 2013a) were only conducted for a limited number of wells located to the south-east of Tapleys Hill Road. The coverage of these locations was not sufficient to enable confident delineation of different hydraulic conductivity zones for the model.*
- *The exact location(s) of the potential sources of groundwater impacts and their dimensions have not been defined sufficiently to enable accurate replication within the numerical model.*
- *The chlorinated hydrocarbons identified as the primary chemicals of concern are unlikely to undergo significant degradation/de-chlorination and the overall distribution of the parent and daughter products in groundwater is further complicated by the presence of multiple suspected sources/plumes.*

Groundwater Fate and Transport Modelling

The primary objective of the numerical modelling is to assist in defining a proposed groundwater prohibition area 'to ensure that the pathway of direct exposure to contaminated groundwater is not realised' between the contaminated plumes and local residents. A summary of the numerical 3D modelling and its findings follows:

- *Initially a groundwater flow model was constructed. Key components of the flow model included constant head boundaries positioned along the eastern and western extents of the model domain, default 'no-flow' boundaries along the northern and southern edges of the model and drain boundary conditions positioned at the locations of the deep sewer mains identified in previous reports (PB, 2014a; URS, 2015a; URS, 2015d; AECOM, 2016).*
- *The flow model was calibrated and used as the basis for the transport model. The transport model was constructed based on a number of assumptions including constant sources of contamination (assigned with maximum concentrations reported in the groundwater wells since 1992) as well as no chemical sorption and no degradation of the contaminants.*
- *During the transport model calibration, the source locations/dimensions and dispersivity values were varied to achieve a reasonable match between the mapped and simulated plume configuration, extensions and concentrations.*
- *After calibration, the transport model was run until the simulated chlorinated hydrocarbon concentrations in groundwater reached steady state conditions (i.e. the plumes reached their maximum extents and concentrations under the modelled conditions).*
- *The modelling results indicate that the groundwater contamination may have occurred at or around 1950 and also that there are multiple plumes emerging from different sources. The modelling results also indicate that the deep sewer mains appear to be influencing the plume migration by acting as a hydraulic 'sink'.*
- *A number of uncertainties and data gaps were identified and included the role of the perched groundwater system; the hydraulic conductivities of the uppermost regional and perched aquifers; the extents of the sewer influences on groundwater flow and contaminant transport; and the actual location, dimensions and concentrations at the contamination sources (noting that some potential source areas were excluded from the investigation area).*
- *While the identified uncertainties and data gaps are considered to be critical to the outcomes of the modelling, a suggested extent of a groundwater prohibition area (based on the modelling conducted) has been presented.*

Vapour Intrusion Risk Assessment

The primary objective was to update the previous vapour intrusion risk assessment (AECOM, 2016). The vapour intrusion risk assessment has been updated using additional data sourced from two soil vapour and *two groundwater sampling events, including the use of site specific geotechnical data. To maintain consistency with previous risk assessments, the investigation area was broken into four zones. The following conclusions were made regarding potential risks to human health via the inhalation pathway:*

- *Zone 1 Commercial workers: Inhalation risks to retail/commercial workers were less than the target risk levels and are in a similar category to the SA EPA predicted indoor air trichloroethene action level 'Validation Range' which is considered to be safe. It is noted that the source concentrations here are decreasing over time, and are expected to continue to decrease.*
- *Zone 2 Residents: Inhalation risks to residents (adult and child) for all construction types (including basements) were considerably less than the target risk levels and were within the SA EPA 'Validation Range' which is considered to be safe.*
- *Zone 3 Residents: The maximum inhalation risks to residents (adult and child) calculated for all construction types from trichloroethene concentrations in groundwater at MW07 were above the SA EPA 'Validation Range' and generally accepted target risk levels. However, vapour intrusion risks modelled from groundwater data is considered less reliable than soil vapour data. As such, soil vapour data should take precedence where feasible (in this case, all construction types apart from basements, where soil vapour data was not available). The risks calculated for a slab on grade or crawl space house based on the maximum trichloroethene in soil vapour reported in that vicinity (from SV04) showed risks were approximately five times lower than when MW07 groundwater data was used. If the slab on grade risks based on soil vapour are used as a basis to calculate the basement risks, these would be multiplied by a factor of 0.17 to give a HI of 1.86 and indoor concentration of 3.6µg/m^{3}which would place the risk in a habitable basement to the EPA 'Investigation Range'. The recent soil vapour monitoring in surrounding wells in Zone 3, along with previous assessments, including widespread passive sampling (AECOM 2016), indicate that the maximum volatile chlorinated hydrocarbon concentrations measured in this area is not representative of the wider residential area in Zone 3. Five other soil vapour samples in Zone 3 showed trichloroethene concentrations an order of magnitude lower than those found in SV04. The predicted vapour intrusion risks from groundwater in Zone 3 are likely to be significantly overestimated and other environmental investigation programs in this area, including indoor air assessments, show that the area is safe. Whilst not included in this assessment, Greencap understands that multiple sampling events have been undertaken at the Laugh'n'Learn Child Care and Early Learning Centre. Trichloroethene was the only chemical of concern detected in the Child Care Centre and all detections were in the safe range of the SA EPA action levels.*
- *Zone 4 Residents: Inhalation risks to residents (adult and child) for all construction types were less than the target risk levels and are within the SA EPA 'Validation Range' which are considered to be safe.*
- *Inhalation risks to maintenance/trench workers in shallow trenches (less than 1.5 m deep) are considered to be low and acceptable, due to the lower exposure frequencies and durations expected for maintenance and excavation work and to the open air nature of the work which inhibits vapour accumulation. The potential vapour concentrations soon dissipate in shallow or wide excavations but may accumulate in deep or narrow trenches. The calculated vapour concentrations in theoretical trenches of 1.5 m in Zone 1 (near SV31) were marginally higher than the SA EPA Investigation Range and may need some additional assessment if regular entry is required. Vapour concentrations for all VHC in all trenches were an order of magnitude below the relevant Safe Work Australia Workplace Exposure Standards for Airborne Contaminants. Vapour concentrations in all trenches at 1 m deep were within the SA EPA 'Validation Range' which are considered to be safe.*
- *Inhalation risks to occasional visitors will be lower than the risks to residents or other occupiers due to lower exposure frequencies and durations, and are considered to be low and acceptable.*
- *Greencap notes that the risks associated with maximum volatile chlorinated hydrocarbon results in soil vapour have generally decreased since the completion of the previous vapour intrusion risk assessment update, as the maximum soil vapour concentrations have decreased.*

Environmental Assessment Works

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Glossary of Terms

1,2-DCA	1,2-dichloroethane
1,1-DCE	1,1-dichloroethene
1,2-DCE	1,2-dichloroethene
ADI	Acceptable Daily Intake
ADWG	Australian Drinking Water Guidelines
AER	Air Exchange Rate
AF	Attenuation Factor
AHD	Australian Height Datum
ALS	Australian Laboratory Services
ANZECC	Australia and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
AT	Averaging Time
BGL	Below ground level
Btoc	Below Top of Casing
C	Celsius
Ca	Calcium
CH4	Methane
C_{ia}	Indoor Air Concentration
Cl	Chloride
CO	Carbon Monoxide
CO2	Carbon Dioxide
CO3	Carbonate
CM	Centimetre
COPC	Contaminants of Potential Concern
COV	Coefficient of Variation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSM	Conceptual Site Model
DCE	Dichloroethene
DME	Department of Mining and Energy
DNR	Department of Natural Resources
DO	Dissolved Oxygen
DRA	Detailed Risk Assessment
EC_{inh}	Inhalation Exposure Concentration
ED	Exposure duration
EF	Exposure frequency
EPP	South Australian Environmental Protection Policy
ET	Exposure time
EV	Environmental Value
FI	Fraction Inhaled from contaminated source
GIL	Groundwater Investigation Level
GPA	Groundwater Prohibition Area
H_2S	Hydrogen Sulphide
HAA	Hendon Broader Assessment Area
HCO3	Bicarbonate
HI	Hazard Index
HIA	Hendon Industrial Area
HIL	Health Investigation Level
HQ	Hazard Quotient
HSL	Health Screening Level
ID	Identification
ILCR	Incremental Lifetime Cancer Risk

IP	Interface Probe
ITRC	Interstate Technology and Regulatory Council
JEM	Johnson & Ettinger Model
K	Potassium
km	kilometres
L	Litre
LDPE	Low density Polyethylene
LOR	Limit of Reporting
LTV	Long Term Value
m	Metre
µg	Microgram
m^3	Cubic Metre
mg	Milligram
Mg	Magnesium
MMO	Methane Monooxygenase
MT3DMS	Modular Three-dimensional Multispecies Transport Engine
mV	Millivolt
Na	Sodium
NATA	National Association of Testing Authorities Australia
NEPM	National Environment Protection (Assessment of Site Contamination) Measure
NHMRC	National Health and Medical Research Council
NJDEP	New Jersey Department of Environment
PCE	Tetrachloroethene (‘Perchloroethylene’)
PID	Photoionisation Detector
ppm	Parts Per Million
PSI	Preliminary Site Investigation
PVC	Polyvinyl Chloride
Q1	First Quaternary Aquifer
QA/QC	Quality Assurance / Quality Control
RfC	Reference Concentration
RfD	Reference Dose
RME	Reasonable maximum exposure
RMS	Root Mean Squared
RPD	Relative Percentage Difference
RSL	Regional Screening Level
RT3D	Reactive Transport Engine
SA EPA	South Australian Environment Protection Authority
SO4	Sulfate
TC	Tolerable Concentration
TCA	Trichloroethane
TCE	Trichloroethene
TDI	Tolerable Daily Intake
TDS	Total Dissolved Solids
U50	Undisturbed 50mm Core Sample
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	Vinyl chloride
VCH	Volatile Chlorinated Hydrocarbon
VOC	Volatile Organic Compound
VI	Vapour Intrusion
VIRA	Vapour Intrusion Risk Assessment
WHO	World Health Organization
WQM	Water Quality Meter

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Environmental Assessment Works

South Australian Environment Protection Authority

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1.0 INTRODUCTION

Greencap was commissioned by the South Australian Environment Protection Authority (EPA) to conduct Stage 3 Environmental Assessment Works within the Hendon Broader Assessment Area (HAA), Hendon, South Australia.

The purpose of the Stage 3 work was to undertake additional groundwater and soil vapour monitoring events to obtain additional seasonal data with respect to the distribution of volatile chlorinated hydrocarbon (VCH) compounds. In addition, the work has included groundwater fate and transport modelling to inform the boundaries of a potential groundwater prohibition area, and an update of a previously developed human health / vapour intrusion risk assessment, based on the findings of the abovementioned soil vapour monitoring events.

The location of the HAA is presented in Figure A attached. It is noted that this assessment has primarily focused on assessing the following sensitive land uses present within the HAA:

- Residential areas north west, west and south of the Hendon Industrial Area (HIA).
- The Hendon Primary School west of the HIA.

1.1 Background

The EPA has been undertaking assessment works across the HAA since 2012, primarily in relation to the presence of VCH in groundwater, emanating from the HIA.

Multiple stages of assessment have been completed to date which have comprised groundwater and soil vapour delineation work, along with the preparation of Human Health Risk Assessments to assess the potential risk to occupants (primarily those on residential or other sensitive sites) of properties that surround the HIA.

It should be noted that the central and northern portions of the HIA (including the Laugh’n’Learn Child Care and Early Learning Centre (referred to herein as Childcare Centre) west of the Tapleys Hill Road / West Lakes Boulevard intersection) are subject to separate environmental assessment works and have not been assessed as part of the Stage 3 investigation work. These excluded areas are shown in Figure A attached.

It is noted that a previous assessment (PB, 2014a) at the Childcare Centre concluded that on the basis of measured indoor air concentrations that health risks associated with the inhalation of VCH compounds at the Childcare Centre were acceptable. Subsequent temporal vapour monitoring was undertaken at the Childcare Centre by URS (URS, 2015b; URS, 2015c; URS, 2015e and URS, 2015f) which confirmed indoor air concentrations were consistently below the indoor air criteria and considered acceptable.

Works are also understood to be currently undertaken by an organisation on the northern portion of the HIA based on VCH concentrations previously identified by PB (PB, 2013b; PB, 2014a). Some of this work has been completed by CH2M HILL in which the available information indicates that soil vapour monitoring has been undertaken in the general vicinity of SV10 (refer Figure A for location) where the highest trichloroethene (TCE) concentrations were reported. Based on the soil vapour monitoring, a human health risk assessment was undertaken which concluded that the level of potential risk to residents in the area of SV10 were considered to be low and acceptable for above ground buildings. Potential risks to residents were also estimated to be within acceptable levels for buildings which include basements, provided the basement is used for purposes for which exposure is likely to be limited, such as a utility space, wine cellar etc).

1.2 Scope of Works

The scope work described in this report has comprised:

- A summary of previous investigations since April 2016 only. Summaries of other historical investigations were provided as part of the Stage 1 and Stage 2 Environmental Assessments.
- A description of the chemicals of interest.
- Two groundwater monitoring events of selected groundwater wells to attain additional seasonal data.
- Two soil vapour sampling monitoring events of selected soil vapour points to attain additional seasonal data.
- The development of a conceptual site model (CSM).
- The construction of a groundwater flow and solute transport model to predict the future extent of the VCH impacts to inform the boundaries of a potential groundwater prohibition area.
- An update of the Vapour Intrusion Risk Assessment (VIRA) previously prepared for the HAA based on the findings of the two soil vapour monitoring events.

2.0 SUMMARY OF PREVIOUS INVESTIGATIONS (AECOM, 2016)

The most recent report prepared for the HAA includes the Stage 2 assessment work (AECOM, 2016) is summarised below.

The Stage 2 assessment work comprised groundwater and soil vapour investigations to provide a better understanding of the extent of the VCH impacts identified across the HAA, as well as revising a CSM and reviewing (and reassessing) the human health risk assessment / VIRA previously completed for the HAA. The investigations focussed on residential areas north west of the Hendon Primary School, west and south of the HIA and in proximity of the Tapleys Hill Road and West Lake Boulevard intersection.

The objectives of the Stage 2 work were to:

- Delineate VCH impacts in groundwater to the north west (to less than the laboratory's limit of reporting (LOR)).
- Delineate VCH impacts in soil vapour to gain a greater understanding of the lateral and vertical extent of the VCH impacts.
- Revise and complete a CSM, with particular regard to the potential for preferential pathways associated with below ground structures or naturally occurring geological formations.
- Review and reassess a previously completed human health risk assessment / vapour intrusion risk assessment for the HAA based on the findings of the Stage 2 work.

Works included the installation and sampling of four additional groundwater monitoring wells, gauging the HAA groundwater well network (comprising 33 groundwater monitoring wells), the installation of nine additional soil vapour points, sampling of the new and existing soil vapour monitoring points (comprising 29 soil vapour monitoring points), a broad area screening of soil vapour using passive samplers (comprising 33 passive soil vapour samplers) and an assessment of the potential for a deep sewer main to act as a preferential pathway for the VCH impacts in groundwater.

The following conclusions were drawn from the Stage 2 assessment work:

- The VCH impacts in groundwater appear to be largely delineated to the north west of the HIA (down hydraulic gradient).
- Elevated soil vapour impacts were reported at the Childcare Centre site. These appeared to be localised and were not observed within the surrounding residential area. It was noted that previous assessments (PB, 2014a; URS, 2015b; URS, 2015c; URS, 2015e and URS, 2015f) at the Childcare Centre concluded that on the basis of measured indoor air concentrations that health risks associated with the inhalation of VCH compounds were acceptable.
- Elevated soil vapour impacts for tetrachloroethene (PCE) were reported within the HIA and along West Lakes Boulevard. However, given the reported concentrations did not exceed historical elevated concentrations, no further assessment in terms of vapour intrusion risk was undertaken.
- Elevated TCE impacts were reported within one soil vapour point located along the eastern boundary of the Hendon Primary School (down-hydraulic gradient of the HIA) which warranted a review of the vapour intrusion risk assessment for residential properties in the locality. An 'investigation' classification was assigned to this location (based on the TCE action level developed by SA Health and the EPA) applying to residential dwellings with basements between Tapleys Hill Road and the Hendon Primary School.
- A sewer main running south to north beneath Tapleys Hills Road was confirmed to be a receptor of groundwater and the associated VCH impacts, presumably as a result of leakage. In addition, due to this leakage, a localised influence on the groundwater flow regime was identified at several points along the sewer main alignment. The leakage however did not preclude the movement of the VCH groundwater impacts to move further west of Tapleys Hill Road.
- A review of the previously completed VIRA indicated a continued potential for indoor air concentrations to warrant further investigation for residential dwellings with basements at several locations across the HAA.
- Identified data gaps (in terms of the characterisation of the nature and extent of the identified groundwater and soil vapour VCH impacts) included limited data in relation to the VCH groundwater

plume in the vicinity of MW08, only partial responses from a door knock / survey in regards to residential properties with basements and the fact that long terms trends were yet to be established with confidence in relation to groundwater and soil vapour VCH concentrations across the HAA.

3.0 CHEMICALS OF INTEREST

The main chemicals of interest assessed and associated with the HAA include VCH compounds TCE, PCE, 1,2-dichloroethene (1,2-DCE) and vinyl chloride (VC). It is noted that 1,2-DCE is a breakdown product of TCE and comprises the sum of compounds cis-1,2-DCE and trans-1,2-DCE. Chlorinated hydrocarbon compound 1,1-dichloroethene (1,1-DCE) was also analysed as part of the assessment works , which is also a breakdown product of TCE. A detailed description of the VCH is provided below.

Mobility and Persistence of Chlorinated Hydrocarbons

VCH typically comprise one or two carbon atoms and between one and six chlorine atoms. Their widespread use began in the 1940s and increased over the next 40 years or so. Common VCH (such as TCE and PCE) have been used for a variety of purposes, including dry cleaning, degreasing, cleaning, pesticide manufacturing, and chemical intermediates.

VCH are volatile and stable under typical aerobic (oxygen rich) conditions in soil and groundwater systems. These chemicals are immiscible and can stay as a separate liquid phase within aquifers. Densities of VCH are greater than water and they can sink through water saturated media (aquifers and aquitards). Small releases of VCH can contaminate large quantities of groundwater and persist in the environment for long periods of time.

Large quantities of VCH can be stored in groundwater plumes as a slowly desorbing phase in transmissive zones, and/or as sorbed and dissolved phases in low permeability zones (Chapman and Parker, 2005).

Overall, the mobility of VCH is generally moderate to high due to their water solubility and high volatilisation potential. The persistence of these compounds is also moderate to high depending on the site conditions and presence of anaerobic zones in groundwater.

Chlorinated Hydrocarbon Biodegradation Process

General

The primary naturally occurring degradative processes affecting VCH include anaerobic and aerobic biotic processes and abiotic destruction. This process is well described in the published Wisconsin Department of Natural Resources (DNR) document: '*Understanding Chlorinated Hydrocarbon Behavior in Groundwater: Guidance on the Investigation, Assessment and Limitations of Monitored Natural Attenuation*' dated 2014 (Wisconsin DNR, 2014).

Biotic (microbial) anaerobic and aerobic degradation of chlorinated hydrocarbons involves the transfer of electrons to or from the contaminant molecule. Biotic degradation requirements include: electron donors (availability of a carbon source), electron acceptors (e.g., oxygen, nitrate, iron (III), manganese (IV), sulphate, carbon dioxide), essential nutrients, and appropriate environmental conditions (proper range of pH, temperature, salinity, redox potential).

Biotic Anaerobic Biodegradation

Areas of high organic carbon, either natural or anthropogenic (i.e. the presence of petroleum hydrocarbons) in groundwater often have depleted oxygen levels. In these scenarios, compounds such as nitrate, iron (III), manganese (IV), sulfate and carbon dioxide can serve as electron acceptors while the contaminant is anaerobically oxidised.

Highly oxidised molecules (such as PCE and TCE) can serve as electron acceptors for microbes when another carbon source is available as a primary growth substrate. This process is called reductive de-chlorination. A number of environmental conditions must exist for reductive de-chlorination to take place:

- The presence of a primary growth substrate, such as petroleum hydrocarbons.
- The presence of highly chlorinated contaminants. The fewer the chlorine atoms on a molecule, the less effective reductive de-chlorination will be. While vinyl chloride will reductively de-chlorinate to ethene, it is a slow process compared to aerobic oxidation of vinyl chloride.
- Highly reducing (anaerobic) conditions are necessary. Reductive de-chlorination will not take place under denitrifying conditions (e.g., nitrate must be absent). The process is most effective under sulfate reducing or methanogenic conditions. Vinyl chloride will only undergo reductive de-chlorination under methanogenic conditions.

- Microorganisms capable of de-chlorination must be present. Intermediates, such as cis-1,2-DCE can accumulate because the existing microorganisms cannot produce the appropriate enzymes to continue the de-chlorination process (Ellis, 2000).

In relation to the anaerobic de-chlorination within a single groundwater plume it is important to note that generally the sum of the molar concentrations of compounds in a de-chlorination sequence should not change (i.e. the sum of the molar concentrations of PCE, TCE, cis-DCE, vinyl chloride, and ethene should remain constant throughout the de-chlorination process). However, the complexity of site hydrogeology coupled with microbial kinetics and other degradative processes may obscure this relationship. In addition, the presence of multiple plumes will also influence this balance significantly.

Biotic Aerobic Biodegradation
Aerobic degradation of PCE and TCE may also occur naturally but this requires a specific environment. The following processes for aerobic degradation are discussed in a USGS paper (http://pubs.usgs.gov/wri/wri994285/text/chlorinated.html) as reproduced below:

> *Wilson and Wilson (1985) first reported that TCE was degraded under aerobic conditions by methanotrophic bacteria in a soil enriched with CH4 and oxygen (O2). Further studies revealed that the methane monooxygenase (MMO) enzyme was responsible for catalyzing the oxidation of TCE (Alvarez-Cohen and McCarty, 1991; Henry and Grbic´-Galic´, 1994). Other oxygenase enzymes such as ammonia monooxygenase (AMO) (Arciero and others, 1989; Rasche and others, 1991) and toluene dioxygenase (Nelson and others, 1988; Hopkins and others, 1993; Heald and Jenkins, 1994) also have been shown to oxidize certain chlorinated solvents. This oxidation reaction is called cometabolism because the reaction uses metabolic enzymes, but does not contribute any energy in return.*

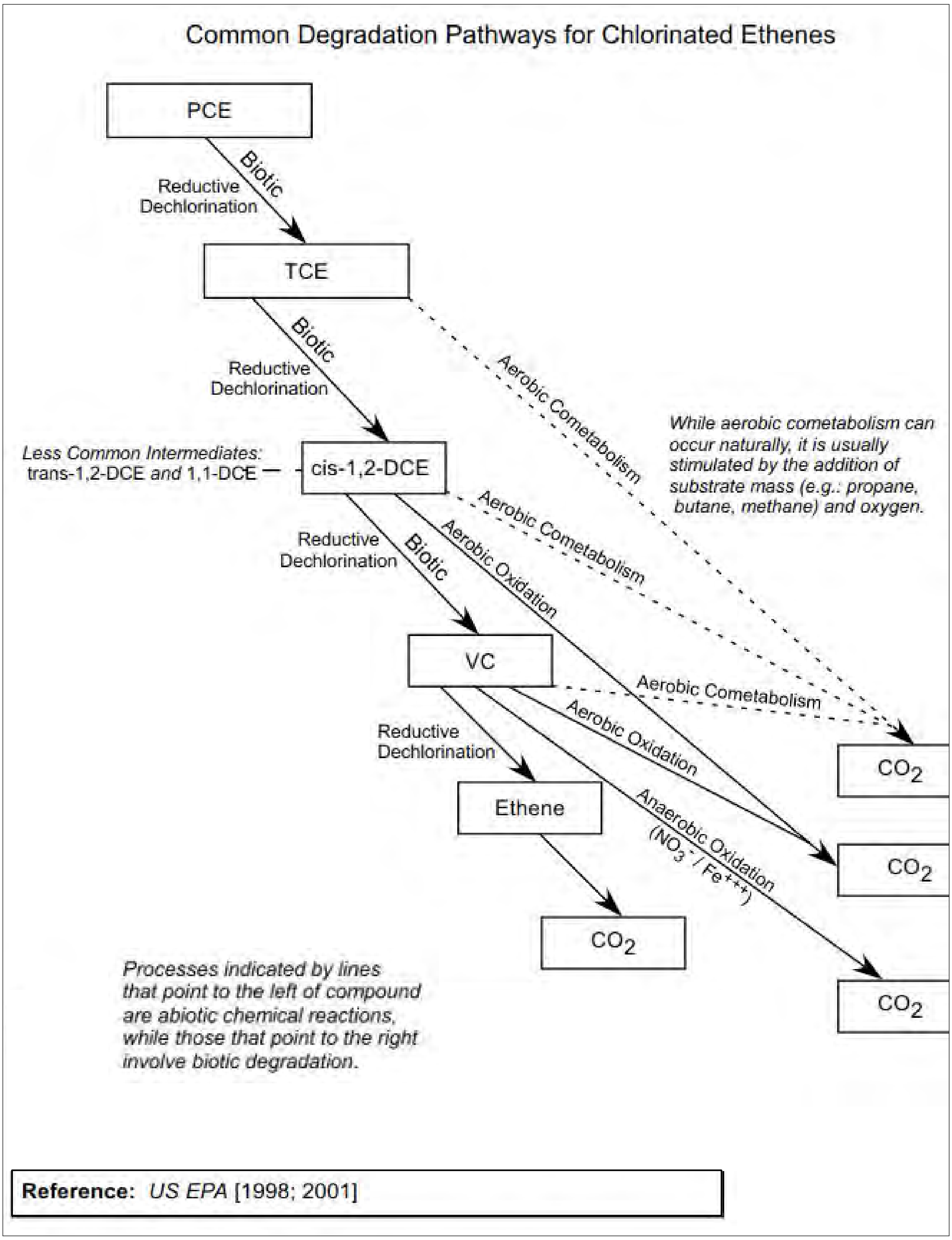
And:

> *Recent studies have reported that chlorinated solvents with only one or two chlorine atoms (the least oxidized compounds) can serve as electron donors by bacteria. Several studies have shown that VC and 1,2-dichloroethane (DCA) can serve as food under aerobic conditions (McCarty and Semprini, 1994). Iron-reducing bacteria also can mineralize VC (Bradley and Chapelle, 1996) and DCE (Bradley and Chapelle, 1997) as a food source under aerobic conditions. Direct oxidation is limited to degrading lightly chlorinated solvents such as DCA, DCE, and VC; however, direct oxidation may serve a vital role in the sequential steps of chlorinated-solvent biodegradation. Aerobic or iron-reducing zones are commonly found downgradient of methanogenic or sulfate-reducing zones. Thus, partially de-chlorinated byproducts (DCE and VC) produced by reductive de-chlorination in the methanogenic or sulfate-reducing zones may be consumed in the more oxidized zones downgradient.*

Smaller chained chlorinated compounds such as DCE and VC may accumulate in chloroethene contaminated groundwater due to incomplete reductive de-chlorination of TCE and PCE. Natural degradation of DCE into VC may continue under oxidising (aerobic) conditions (as indicated above) which may be present further downgradient of a chlorinated hydrocarbon plume.

Abiotic Degradation
The most common abiotic reactions are hydrolysis (the halogen is replaced with a hydroxyl (OH^-) group) and dehydrohalogenation (an elimination reaction that removes a halogen and a hydrogen from adjacent carbon atoms in an alkane and produces an alkene). The most well documented abiotic degradation reactions involve carbon tetrachloride, chloroform, chloromethane, trichloroethane (TCA), and chloroethane. McCarty (1997) states that TCA is abiotically converted under almost all likely groundwater conditions. The products of this abiotic transformation are acetic acid (approximately 80%) with the remaining 20% converted to 1,1-DCE. Chloroethane readily hydrolyzes to ethanol with a half-life of approximately 44 days (Wiedemeier et al., 1998). Temperature plays a significant role in biotic and abiotic reaction rates. For polychlorinated ethanes and methanes, abiotic half-lives are likely to be in the order of hundreds to thousands of years at ambient groundwater temperatures, while monochlorinated compounds have much lower half-lives (Wiedemeier et al., 1998).

Figure 1 illustrates the transformation of chlorinated ethenes via reductive de-chlorination. In general, reductive de-chlorination occurs by sequential de-chlorination from PCE to TCE to DCE to VC to ethene. Depending upon the environmental conditions, this sequence may be interrupted, with other processes then acting upon the products. During reductive de-chlorination, all three isomers of DCE can theoretically be produced. However, Bouwer (1994) reports that under the influence of biodegradation, cis-1,2-DCE is the primary by-product of TCE de-chlorination.



(Source: Wisconsin DNR, 2014)

Figure 1 – Common Degradation Pathways for Chlorinated Ethenes

4.0 FIELDWORK PROGRAM

The Stage 3 fieldwork program comprised two groundwater monitoring events and two soil vapour monitoring events, as summarised in Table 1. In addition, to provide more site specific subsurface soil data (for consideration in the update of the VIRA), two geotechnical sampling events were conducted.

A detailed methodology for each fieldwork component is provided in Sections 5.0 to 7.0 (inclusive).

Table 1 – Summary of Sampling Events

Fieldwork Component	Works Conducted	Date of Works
Groundwater Monitoring Events	Sampling Event #1	
	Gauging of 31 existing groundwater monitoring wells	31 October 2016
	Sampling of 31 groundwater monitoring wells	1 – 14 November 2016
	Collection and disposal of drum of purged groundwater	16 November 2016
	Sampling Event #2	
	Gauging of 31 existing groundwater monitoring wells	27 February 2017
	Sampling of 31 groundwater monitoring wells	1 – 14 March 2017
	Collection and disposal of drum of purged groundwater	16 March 2017
Soil Vapour Monitoring Events	Sampling Event #1 - Sampling of 28 existing soil vapour monitoring points	8 – 22 November 2016
	Sampling Event #2 - Sampling of 28 existing soil vapour monitoring points	16 – 27 January 2017
Geotechnical Sampling Events	Sampling Event #1 – Drilling and collection of u50 core samples from ten selected locations across the HAA	11 November 2016
	Sampling Event #2 –Drilling and collection of u50 core samples from ten selected locations across the HAA	25 January 2017

5.0 GROUNDWATER INVESTIGATIONS

The groundwater investigations undertaken in October/November 2016 and February/March 2017 were conducted by experienced Greencap environmental field scientists. Details are provided in the following sections.

5.1 Groundwater Sampling

The groundwater investigations comprised the sampling and analysis of 31 groundwater monitoring wells across the HAA. The groundwater wells sampled were based on the requirements of the EPA and the locations of the groundwater monitoring wells are presented in Figure B attached. It is noted that groundwater monitoring well GW01 was proposed for sampling and analysis, however, at the time of the October 2016 groundwater gauging event the monitoring well was found to be backfilled with a fine grey sand to the surface and therefore could not be gauged or sampled in either sampling event.

Groundwater Sampling Methodology

Groundwater level gauging was undertaken across the monitoring well network on 31 October 2016 and 27 February 2017, whereby depths to standing water levels were measured from the marked point on the top of the PVC well casing using a *Geotech Interface Meter* (IP). Measurements were also taken to check for any separate phase (free) product present in the wells. It is noted that during the October 2016 gauging event, groundwater monitoring wells MW30, BH22, MW28 and MW06 were not gauged as they either could not be located or were not able to be accessed. For the February 2017 gauging event, groundwater monitoring well BH22 was not gauged as it could not be accessed (obstructed by parked vehicle). However, these monitoring wells were subsequently located and sampled.

Where possible, groundwater purging and sampling was conducted using low flow (micro-purge) sampling techniques. The micro-purge pump was placed at a consistent depth above the base of each well (approximately 0.5 metres from the base of the screened section) and the standing water level was monitored during sampling to ensure a stable water level was achieved (with minimal drawdown). This facilitated the collection of representative groundwater samples from the aquifer.

It is noted that water levels could not be stabilised during the sampling of a number of groundwater monitoring wells during the sampling events due to insufficient groundwater inflow to support the low flow sampling technique. These wells included:

- November 2016 - BH22, MW07, MW10, MW20 and MW31.
- March 2017 - BH22, MW10, MW20 and MW31.

As a result, these groundwater wells were sampled using the HydraSleeve^{TM} methodology. The HydraSleeve methodology involved attaching a stainless steel weight to the bottom of the sampler and a wire clip and tether line to the top of the sampler. The sampler was lowered by the tether line and placed near the base of the screened interval. The sampler remained in the well for at least 48 hours after deployment to allow the replacement of disturbed groundwater with the fresh groundwater moving through the screen. Representative samples were collected by pulling the HydraSleeve bag upward through the well screens to the surface, aiming to fill the HydraSleeve bag with groundwater collected only from the screened interval.

Furthermore, groundwater monitoring wells GW02 (during both sampling events) and MW07 (March 2017 sampling event only) were sampled using a peristaltic pump and low flow methodologies as micro-purge pump equipment and HydraSleeve methodologies were not feasible due to the very small volumes of groundwater in the wells. It is noted that GW02 appeared to have been partially backfilled with fine gravels (possibly from the adjacent gravel surface). Redevelopment of this well using steel bailer and footvalve techniques (during the November 2016 sampling event) to attempt to remove these gravels was unsuccessful due to the grain size of gravels. It was also considered possible that surface water ingress in GW02 may have occurred prior to the November 2016 gauging/sampling event as the PVC well cap below surface flush gatic cover was fitted loosely (as identified at the time of gauging) and would not have prevented water seepage from the surface during rain events. The well cap was fitted tightly following the November 2016 gauging/sampling event. The results are therefore not considered to be reliable from this location during the November 2016 sampling event, however results are considered reliable from the March 2017 sampling event.

Water quality parameters (pH, temperature, conductivity, oxidation reduction potential and dissolved oxygen) were monitored during purging of all wells using a *YSI Quatro Professional Plus* water quality meter (WQM). Sampling was conducted when these parameters had stabilised and the water level was exhibiting minimal stable drawdown. Purge waste water was collected in portable 20 Litre drums during sampling and decanted into a 200 Litre drum stored within a predetermined location within the HAA. The wastewater was disposed of appropriately following each sampling event by a licenced liquid waste removal contractor.

Dedicated low density polyethylene (LDPE) tubing was used in each well during sampling which negated the need for decontamination of the tubing, however, the micro-purge sampling equipment (including the IP and stainless steel wire rope) was decontaminated between monitoring well locations. Rinsate blank samples were collected of the decontaminated micro-purge equipment during sampling. Rinsate blank results indicated the equipment was suitably decontaminated and cross contamination did not occur (discussed in more detail in Section 8.4). The November 2016 groundwater sampling records and equipment calibration certificates (for the IP and WQM) are attached in Appendix A and Appendix B respectively while the March 2017 groundwater sampling records and equipment calibration certificates are attached in Appendices C and D respectively.

All groundwater samples were placed in containers provided by the analytical laboratories. The samples were stored in a chilled portable cooler immediately following sampling and were delivered under similar conditions to the analytical laboratory with accompanying chain of custody documentation. The chain of custody documentation for the November 2016 and March 2017 monitoring events is attached along with the National Association of Testing Authorities Australia (NATA) laboratory certificates in Appendices E and F respectively.

5.2 Groundwater Analytical Program

Groundwater samples from each groundwater monitoring well were analysed for VCH compounds PCE, TCE, DCE and VC. Groundwater samples from ten selected wells were also analysed for natural attenuation parameters and major cations and anions per sampling event, as summarised in Table 2.

Table 2 – Summary of Additional Analysis

Sampling Event	Additional Analysis	Selected Groundwater Wells
November 2016	Natural Attenuation Parameters and Major Anions and Cations: dissolved oxygen, carbon dioxide, sulfate, ferrous/ferric iron, manganese, nitrate, sodium, potassium, magnesium, chloride, carbonate alkalinity and bicarbonate alkalinity	MW01, MW02, MW07, MW08, MW12, MW15, MW29, BH22, GW02 and GW09
March 2017		MW05, MW11, MW16, MW18, MW22, MW26, MW29, MW31, BH13 and BH95

Results of the groundwater analyses are discussed in Section 5.4. A summary of groundwater analytical results are presented in tables attached to this report. The tables also include historical results reported since 2012.

Field duplicate and blank samples were also collected during the groundwater sampling events. A discussion of the Quality Assurance/Quality Control (QA/QC) procedures undertaken is presented in Section 8.0.

The laboratories used for the groundwater investigation were Eurofins-mgt (primary laboratory) and ALS (secondary laboratory). The laboratories are accredited by NATA, and the analyses conducted are within the NATA registration of the laboratories.

5.3 Groundwater Assessment Criteria

To maintain consistency with the most recent report prepared for the HAA[1], groundwater analytical results have been compared to the following criteria based on a beneficial use assessment conducted for the site:

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[1] AECOM Services Pty Ltd - *Hendon Broader Assessment Area, Environmental Assessment (Stage 2), 29 April 2016*, ref: 60479743, Doc #002

- Groundwater Investigation Levels (GIL's) for drinking water and marine aquatic ecosystem protected environmental values (EV's) sourced from the *National Environment Protection (Assessment of Site Contamination) Measure 1999 (as amended 2013)* (NEPM).
- Drinking water guideline for TCE sourced from the *World Health Organisation Guidelines for Drinking Water Quality, 2011 (WHO, 2011)* (in the absence of other applicable criteria) .
- Long term Irrigation values sourced from the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality, 2000* (prepared by the Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ)) (ANZECC, 2000).
- Recreation water quality values sourced from *Guidelines for Managing Risks in Recreational Water, 2008* (prepared by the National Health and Medical Research Council (NHMRC) (NHMRC, 2008).
- EVs sourced from the *South Australian Environment Protection (Water Quality) Policy 2003* (EPP, 2003) for the purpose of determining site contamination that affects or threatens underground water under Section 83A of the Environment Protection Act 1993. Relevant EVs for the HAA include Irrigation, Marine Ecosystem and Potable.

5.4 Groundwater Investigation Results

Groundwater was encountered at depths between 2.34 m bgl and 4.11 m bgl during October 2016 and between 2.57 and 4.25 m bgl during February 2017 gauging events. No contamination indicators (such as hydrocarbon or solvent odours or sheens) were noted in any of the monitoring wells during the gauging or sampling, however a slight organic odour was noted during the sampling of MW18 in November 2016 and slight hydrogen sulphide odour was noted during the sampling of MW04 in March 2017.

5.4.1 Field Measured Water Quality Parameters

Groundwater quality parameters were monitored during purging and prior to sampling. The stabilised values of these parameters are presented in Table 3 for both groundwater monitoring rounds, and the parameter ranges are summarised in Table 4.

Table 3 – Field Measured Groundwater Quality Parameters

Well ID	Date Sampled	pH	Temp (Deg C)	Electrical Conductivity (µS/cm)	Oxidation-Reduction Potential (mV)	Dissolved Oxygen (ppm)
BH13	1/11/2016	7.53	20.8	4,502	72.9	0.36
	2/03/2017	7.39	22.9	4,961	53.1	0.33
BH22	8/11/2016	7.78	24.9	5,369	69.7	2.50
	10/03/2017	7.78	27.3	4,622	19.3	5.72
BH25	1/11/2016	7.37	19.7	1,271	77.3	1.95
	2/03/2017	7.50	25.5	1,449	46.2	2.59
BH95	1/11/2016	7.21	19.8	1,498	-115.9	0.16
	2/03/2017	7.00	26.5	1,465	-50.4	1.82
GW02	14/11/2016	7.39	18.9	834	28.2	0.87
	14/03/2017	7.28	28.4	6,728	31.2	3.44
GW09	3/11/2016	7.24	21.0	12,270	72.5	0.12
	6/03/2017	7.17	22.7	12,133	45.1	0.04
MW01	8/11/2016	7.39	20.2	12,677	60.2	0.11
	3/03/2017	7.34	23.5	13,742	34.7	0.54
MW02	1/11/2016	7.39	18.8	13,812	61.4	0.24
	2/03/2017	7.44	22.4	11,278	14.1	0.57
MW03	7/11/2016	7.44	19.9	6.667	75.4	0.45
	3/03/2017	7.48	22.3	8,661	32.2	0.09
MW04	1/11/2016	7.06	19.3	20,564	-122.2	0.15

Well ID	Date Sampled	pH	Temp (Deg C)	Electrical Conductivity (µS/cm)	Oxidation-Reduction Potential (mV)	Dissolved Oxygen (ppm)
	3/03/2017	7.05	24.1	19,650	-3.8	1.02
MW05	1/11/2016	7.26	19.0	14,980	58.6	0.22
	6/03/2017	7.25	22.3	11,150	45.4	1.31
MW06	7/11/2016	7.54	20.2	12,908	74.1	0.39
	3/03/2017	7.46	23.6	12,110	30.0	0.24
MW07	8/11/2016	7.70	20.5	9,728	96.9	1.20
	9/03/2017	7.26	24.3	11,208	32.8	2.35
MW08	8/11/2016	7.06	19.8	14,373	-56.1	1.10
	7/03/2017	7.05	22.7	14,422	41.6	0.42
MW09	8/11/2016	7.60	19.2	585	83.6	4.11
	7/03/2017	7.67	23.1	659	48.9	2.55
MW10	14/11/2016	8.04	21.1	2,421	76.8	2.71
	14/03/2017	8.01	25.7	3,435	48.9	2.73
MW11	8/11/2016	7.52	20.4	9,390	72.9	0.21
	6/03/2017	7.37	24.3	9,403	47.8	0.17
MW12	1/11/2016	7.23	20.2	11,290	80.0	0.09
	2/03/2017	7.46	23.0	11,271	7.4	0.37
MW15	8/11/2016	7.28	20.1	7,289	82.0	0.09
	6/03/2017	7.16	22.9	7,374	47.3	0.12
MW16	8/11/2016	7.35	20.1	8,258	-72.1	0.07
	6/03/2017	7.21	23.0	8,652	44.8	0.21
MW18	7/11/2016	7.98	18.0	3,112	76.7	4.84
	9/03/2017	8.07	26.0	3,526	52.0	5.10
MW19	8/11/2016	7.71	20.6	2,729	-65.2	0.15
	9/03/2017	7.80	24.4	2,511	-17.0	1.03
MW20	14/11/2016	7.46	19.7	29,715	76.4	0.75
	14/03/2017	7.17	25.1	30,209	50.0	0.60
MW21	7/11/2016	7.47	20.9	8,029	70.1	0.08
	3/03/2017	7.41	23.7	5,270	34.1	2.25
MW22	8/11/2016	7.42	19.8	13,677	78.1	0.85
	9/03/2017	7.33	21.2	13,696	50.6	0.24
MW26	1/11/2016	7.31	21	7,282	85.2	1.43
	2/03/2017	7.55	24.5	7,466	12.1	1.98
MW27	8/11/2016	7.50	20.0	4,313	78.8	0.10
	2/03/2017	7.51	24.3	5,095	11.8	0.36
MW28	1/11/2016	7.03	19.0	7,863	94.9	0.05
	2/03/2017	7.45	22.1	6,086	51.2	0.90
MW29	8/11/2016	7.60	20.3	5,308	77.0	0.48
	7/03/2017	7.44	24.6	4,298	48.1	0.50
MW30	8/11/2016	7.60	21.5	18,284	77.5	0.19
	7/03/2017	7.33	25.4	17,264	48.6	1.16
MW31	8/11/2016	7.72	21.9	2,472	80.0	1.82
	9/03/2017	7.96	29.0	2,542	16.1	2.66

Table 4 – Summary of Field Measured Parameters (November 2016 & March 2017)

Parameter	Results and Comments
pH	pH values indicated generally neutral to slightly alkaline groundwater conditions and were consistent between the two monitoring rounds. During November 2016, pH ranged between 7.03 (MW28) to 8.04 (MW10). During March 2017, pH ranged from 7.0 (BH95) to 8.07 (MW18).
Temperature (°C)	Temperature values showed some seasonal influence and were generally higher in March 2017 in comparison with November 2016. Temperatures ranged from 18.0°C (MW18) to 24.9°C (BH22) in November 2016 and from 21.2°C (MW22) to 29°C (MW31) in March 2017.
Estimated Total Dissolved Solids (TDS) *	Groundwater salinity in the wells ranged from fresh to saline and were generally higher in March 2017 than in November 2016, potentially due to seasonal rainwater recharge. Figure 13 in Section 9.7 shows the groundwater TDS distribution for the November 2016 monitoring event. The TDS values during November 2016 were measured to range from 370mg/L (MW09) to 19,000mg/L (MW20). The lowest TDS values (below the drinking water limit of 1,200 mg/L) measured in November 2016 were from wells BH25, BH95 and GW02. Figure 14 in Section 9.7 shows the groundwater TDS distribution for the March 2017 monitoring event. The TDS values during March 2017 were measured to range from 420mg/L (MW09) to 19,300mg/L (MW20). The low TDS values (below the drinking water limit of 1,200 mg/L) in March 2017 were from wells BH25 and BH95. The low measured TDS at some locations may be indicative of leaking water mains or greater surface water recharge in this area of the HAA. As shown in the summary tables attached (Table A), the concentrations of the solvents of concern were lower within the fresh groundwater area in comparison with the areas where more saline groundwater was present. This may potentially indicate some level of contamination dilution caused by localised recharge.
Oxidation Reduction Potential (mV)	Oxidation-reduction potential (ORP) values were generally consistent between two monitoring rounds and showed some seasonal decrease in March 2017. The majority of the measured ORP values indicate mainly oxidising groundwater conditions within HAA. Reducing conditions were evident during both sampling events in BH95, MW04 and MW19 and during the November 2016 sampling event only in MW08 and MW16. In November 2016, ORP was measured to range from -122.2 mV (MW04) to 96.9 mV (MW07). In March 2017 ORP was measured to range from -50.4mV (BH95) to 53.1 mV (BH13).
Dissolved Oxygen (mg/L)	Dissolved oxygen (DO) levels were generally consistent between two monitoring rounds. In November 2016 the measured DO values ranged from 0.05mg/L (MW28) to 4.84mg/L (MW18). In March 2017 the measured DO values ranged from 0.04mg/L (GW09) to 5.72mg/L (BH22).

Notes: * - conversion factor of 0.64 used to convert field conductivity (µS/cm) to TDS (mg/L).

5.4.2 Groundwater Flow Direction

Groundwater level gauging was undertaken prior to each sampling round (on 31 October 2016 prior to the November 2016 sampling event and on the 27 February prior to the March 2017 sampling event). The gauging results, along with the relative height (metres Australian Height Datum (m AHD), determined based on survey information provided in previous reports, are summarised in Table 5.

Table 5 – Groundwater Elevations (2016 & 2017)

Well ID	Reference Elevation * (mAHD)	Depth to groundwater level (m) - Oct 2016	Relative Height Data (mAHD) - Oct 2016	Depth to groundwater level (m) - Feb 2017	Relative Height Data (mAHD) - Feb 2017
BH13	3.848	3.08	0.768	3.265	0.583
BH22	3.866	2.600	1.266	2.628	1.238
BH25	3.619	2.553	1.066	2.930	0.689
BH95	3.959	3.088	1.540	2.568	1.391
GW02	3.810	3.112	0.698	3.256	0.554

Well ID	Reference Elevation * (mAHD)	Depth to groundwater level (m) - Oct 2016	Relative Height Data (mAHD) - Oct 2016	Depth to groundwater level (m) - Feb 2017	Relative Height Data (mAHD) - Feb 2017
GW09	3.880	2.736	1.144	2.850	1.030
MW01	4.000	3.306	0.694	3.463	0.537
MW02	4.440	3.180	1.260	3.337	1.103
MW03	4.390	3.33	1.060	3.502	0.888
MW04	4.170	3.256	0.914	3.409	0.761
MW05	4.240	3.225	1.015	3.380	0.860
MW06	4.100	3.550	0.55	3.678	0.422
MW07	3.630	3.442	0.188	3.537	0.093
MW08	3.990	3.382	0.608	3.225	0.765
MW09	4.070	3.509	0.561	3.552	0.518
MW10	4.250	3.806	0.444	3.852	0.398
MW11	4.050	2.871	1.179	3.057	0.993
MW12	4.570	3.092	1.478	3.226	1.344
MW15	4.810	3.090	1.720	3.097	1.713
MW16	4.500	3.085	1.415	3.153	1.347
MW18	3.990	3.415	0.575	3.547	0.443
MW19	3.910	3.212	0.698	3.404	0.506
MW20	4.500	3.433	1.067	3.578	0.922
MW21	4.360	3.318	1.042	3.482	0.878
MW22	4.580	4.108	0.472	4.254	0.326
MW26	5.100	3.437	1.663	3.553	1.547
MW27	4.381	2.873	1.508	3.030	1.351
MW28	4.337	2.786	1.551	2.873	1.464
MW29	3.789	2.954	0.835	3.185	0.604
MW30	3.125	2.338	0.787	2.691	0.434
MW31	4.250	3.657	0.593	3.823	0.427

Notes:* reference elevations sourced from previous Coffey, PB, URS & AECOM reports: Coffey, 1992a; PB, 2013a; PB, 2013b; PB, 2014a; AECOM, 2016.

The groundwater level gauging results were used to produce groundwater level contours (for each October 2016 and February 2017 monitoring event), which are presented as Figure D attached to this report.

Based on Figure D, the inferred groundwater flow direction was assessed to be in a north westerly direction within the eastern portion of HAA (i.e. east of Tapleys Hill Road) and in a south westerly direction within the western portion of HAA. To maintain consistency with previous assessments, no density corrections were made based on salinity variations across the HAA. It is noted that when producing the October 2016 contours, the gauging data from monitoring wells MW30, BH22, MW28 and MW06 was not included in the groundwater flow direction calculation as they were not able to be gauged on the same date as all other wells (as discussed in Section 5.1). Monitoring wells GW02 and MW20 were also excluded from the contouring as the calculated groundwater elevations were anomalous in terms of the overall groundwater elevations across the HAA. For producing the February 2017 contours, gauging data from monitoring wells BH22, MW20, MW22, GW02, BH95 and MW08 were excluded as the calculated groundwater elevations were also considered anomalous in terms of the overall groundwater elevations across the HAA. The omission of these groundwater well levels is not considered to be significant in terms of calculating the flow direction across the HAA as this would not change the overall surface of groundwater.

A local depression exists in the vicinity of MW07 (mapped during the October 2016 and February 2017 gauging events). This local depression is consistent with historical monitoring conducted across the HAA, where a suspected deep sewer main running south-north beneath Tapleys Hill Road may be acting as a groundwater drain. The indicative location of this sewer main is presented in Figure D. It is noted that the sewer mains shown in Figure D represent those below the measured groundwater level, thus considered most relevant to this assessment.

Further discussions on groundwater flow directions, hydraulic gradients and estimated groundwater flow velocity is provided in Section 9.0 (Conceptual Site Model).

5.4.3 Analytical Results

Results of the groundwater analyses are summarised in Table A attached to this report and a summary of the reported VCH exceedances of the adopted criteria for October 2016 and March 2017 monitoring events are summarised in Table 6. NATA laboratory certificates and chain of custody documentation are presented in Appendix E for October 2016 round and in Appendix F for the March 2017 sampling event. Figures presenting the spatial distribution of the reported TCE, PCE & 1,2-DCE concentrations are attached at the end of this report as Figures E to G respectively for the November 2016 sampling event and as Figures H to J respectively for the March 2017 sampling event.

Table 6 – Summary of Reported VCH Exceedances (November 2016 & March 2017)

Well ID	Date	VCH Analyte results			
		1,2-DCE (cis & trans) (µg/L)	PCE (µg/L)	TCE (µg/L)	VC (µg/L)
BH13	1/11/2016	<1.01	<0.02	0.01	<0.05
	2/03/2017	0.52	<0.02	0.02	<0.05
BH22	8/11/2016	<1.01	<0.02	<0.01	<0.05
	10/03/2017	<1.01	<0.02	0.04	<0.05
GW02	14/11/2016	0.53	<0.02	0.12	<0.05
	14/03/2017	0.92	0.06	1.4	<0.05
GW09*	1/11/2016	252-325	8.8-14	320-380	<0.3-<5
	6/03/2017	190	26	480	<10
MW01	8/11/2016	0.51	<0.02	0.13	<0.05
	3/03/2017	0.51	<0.02	0.13	<0.05
MW02*	1/11/2016	82	52	13	0.07
	2/03/2017	110-120	68-100	26-32	<0.3-<1
MW04	1/11/2016	142	24	43	<1
	3/03/2017	160	37	55	<1
MW05*	1/11/2016	121	28	73	<1
	6/03/2017	110-114	75-78	22-34	<0.3-<1
MW07	8/11/2016	53	<1	400	<0.05
	9/03/2017	62	<20	780	<20
MW08	8/11/2016	15	<1	380	<0.05
	7/03/2017	15	<8	310	<8
MW11	8/11/2016	<1.01	<0.02	<0.01	<0.05
	6/03/2017	<1.01	<0.02	<0.01	<0.05
MW12	1/11/2016	40	40	8.2	0.07

Well ID	Date	VCH Analyte results			
		1,2-DCE (cis & trans) (µg/L)	PCE (µg/L)	TCE (µg/L)	VC (µg/L)
	2/03/2017	58	31	8.7	0.07
MW15	8/11/2016	<1.01	<0.02	<0.01	<0.05
	6/03/2017	0.9	<0.02	<0.01	<0.05
MW16	8/11/2016	<1.01	<0.02	<0.01	<0.05
	6/03/2017	<1.01	<0.02	<0.01	<0.05
MW18*	7/11/2016	12-14	0.54-1	13-16	0.5-0.58
	9/03/2017	15.5	0.43	15	0.08
MW22	8/11/2016	<1.01	<0.02	<0.01	<0.05
	9/03/2017	<1.01	<0.02	<0.01	<0.05
MW26	1/11/2016	<1.01	0.31	0.01	<0.05
	2/03/2017	<1.01	0.26	0.01	<0.05
MW29	8/11/2016	<1.01	<0.02	0.03	<0.05
	7/03/2017	<1.01	<0.02	<0.01	<0.05
MW31	8/11/2016	<1.01	<0.02	<0.01	<0.05
	9/03/2017	<1.01	<0.02	<0.01	<0.05
NEPM 2013 Table 1C GILs, Drinking Water		60	50	20 ^	0.3
NHMRC 2008 Recreational water quality		600	500		3
SA Water Quality, 2003, Potable			40		0.3

Notes:

Shaded cell indicates exceedance of adopted groundwater quality criteria.

* - Duplicate samples collected as part of analysis, hence range of reported results.

^ - WHO 2011 Drinking Water Criteria

As shown in Table 6, the most significantly impacted wells (in terms of VCHs) include GW09 (TCE and DCE), MW02 (DCE and PCE), MW04 (mainly DCE), MW05 (DCE and PCE), MW07 (mainly TCE) and MW08 (TCE).

It is noted that some elevated results were also reported for natural attenuation/ion parameters (chloride, nitrate, sodium, sulfate and manganese) above the adopted groundwater criteria, however, these are not considered to be significant as they have been tested to determine the aquifer conditions and inform the potential degradation of chlorinated hydrocarbons identified in groundwater across the HAA. Further discussion on the groundwater chemistry is presented in Section 5.5.

The trends in concentrations of key chemicals of concern (VCH) are discussed in Section 5.6.

Further discussions of contaminated plume behaviour and the suspected sources of groundwater contamination are presented in CSM and Modelling sections of this report (refer Section 9.0 and 10.0 respectively).

5.5 Groundwater Chemistry

Analyses for major anions and cations were conducted for samples collected from selected groundwater monitoring wells during the recent groundwater sampling events in November 2016 and in March 2017 and during previous sampling rounds conducted by AECOM (refer Section 2.0). The results for major anions (Cl-, SO42-, HCO3- and CO32-) and major cations (Ca2+, Mg2+, Na+ and K+) for the most recent and previous events are presented in the groundwater summary tables at the end of this report.

Data collected during the most recent sampling event, as well as data from previous events, was used to construct a Piper Plot to summarise the groundwater chemistry from all sampled wells. The Piper Plot is presented as Figure 2.

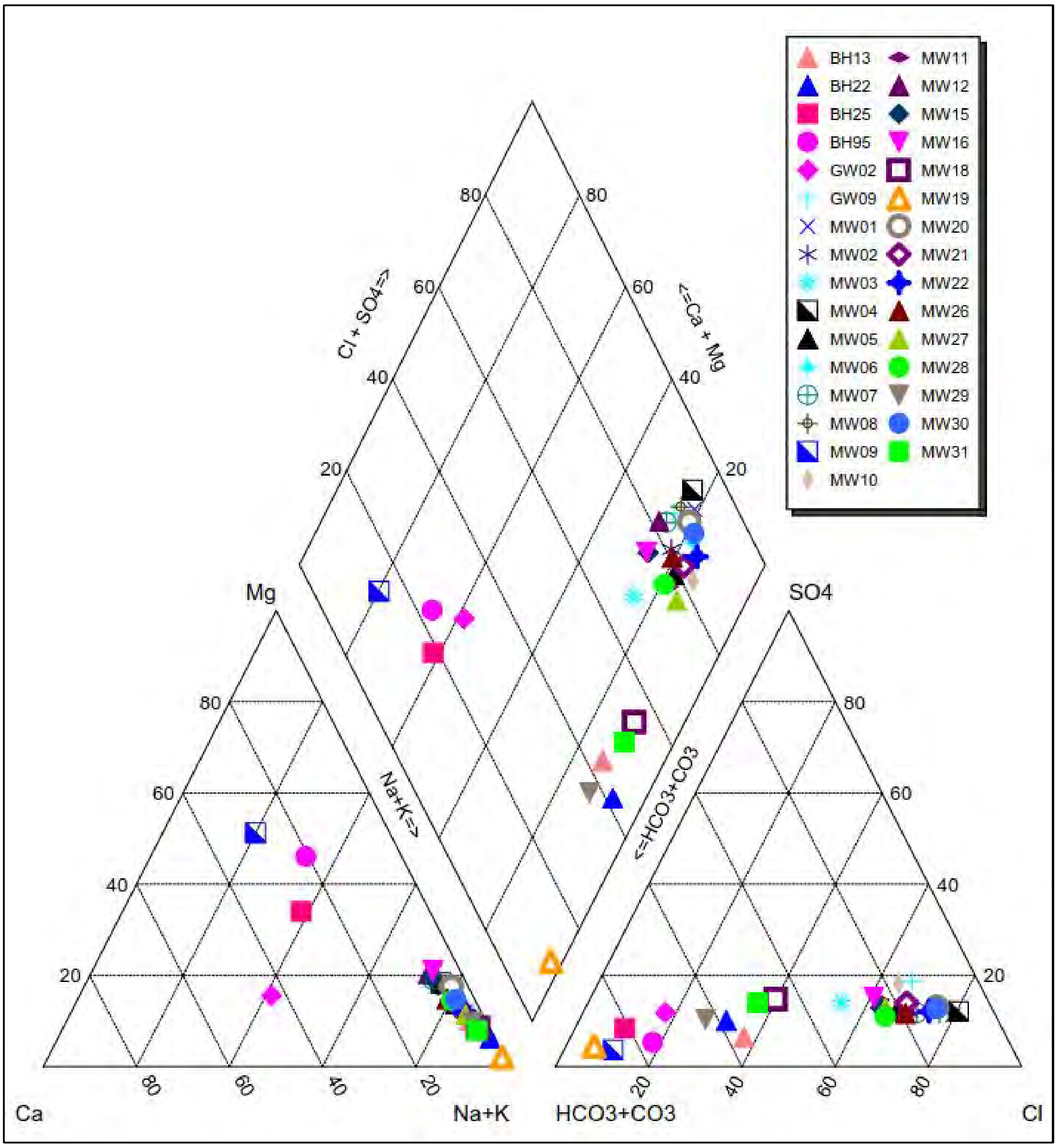


Figure 2 – Piper Plot – Wells with groundwater salinities less than 2,000 mg/L.

Figure 2 shows that the chemical signatures of the wells are positioned in three distinctive clusters as described below:

- The major cluster is characterised by a sodium chloride water type which likely represents the regional groundwater signature. The cluster includes the majority of the sampled groundwater wells within the HAA. The groundwater in these wells is generally saline.
- The cluster which includes BH13, BH22, MW18, MW29 and MW31 is represented by a sodium bicarbonate water type. It appears that the proportion of sodium does not vary significantly for these wells by the change in water type occurred due to increased proportion of the bicarbonate ion. The increased proportion of the bicarbonate ion may be due to localised rainwater recharge through topsoil which is a potential source of HCO3 from dissolved CO2. The groundwater in these wells is generally brackish.
- The cluster which includes BH25, BH95, GW02 and MW09 is represented by a calcium bicarbonate water type which is typical for fresh groundwater.

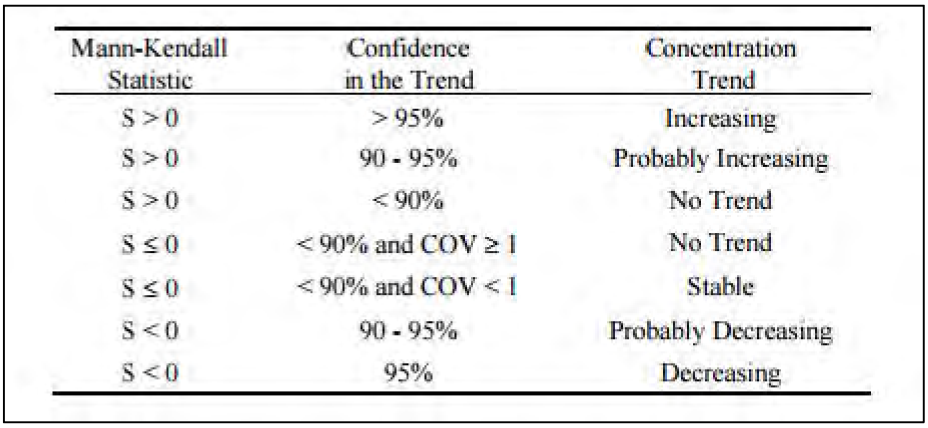
Further discussion on the groundwater salinity and the potential presence of a fresher perched aquifer at the locations where groundwater salinity was measured to be fresh, is presented in Sections 9.0 and 10.0.

5.6 Groundwater Analytical Trend Analysis

Trend analysis was undertaken for locations with reported concentrations in groundwater exceeding the adopted water quality criteria for the main contaminants of potential concern (COPC); TCE, PCE, 1,2-DCE (sum of cis & trans) and VC. The trend analysis involved Mann-Kendall tests undertaken using the GSI Mann-Kendall Toolkit. It should be noted that trend analysis was only undertaken for groundwater wells with at least four reported concentrations above the laboratory detection limits and only included groundwater wells sampled during the recent November 2016 and March 2017 monitoring events. The trend analysis incorporated groundwater sampling data from these wells collected since 2012 by Greencap and other consultants.

The Mann-Kendall test is a simple test for determining whether a time-ordered data set exhibits an increasing or decreasing trend within predetermined levels of significance. Mann-Kendall is a non-parametric test and as such, is not dependent upon the magnitude of data, assumptions of distribution, missing data, or irregularly spaced monitoring periods (Wisconsin DNR, 2014). Mann Kendall concentration trends were determined as per Table 7.

Table 7 – Mann-Kendall analysis decision matrix



Mann-Kendall Statistic	Confidence in the Trend	Concentration Trend
$S > 0$	> 95%	Increasing
$S > 0$	90 - 95%	Probably Increasing
$S > 0$	< 90%	No Trend
$S \leq 0$	< 90% and COV ≥ 1	No Trend
$S \leq 0$	< 90% and COV < 1	Stable
$S < 0$	90 - 95%	Probably Decreasing
$S < 0$	95%	Decreasing

S = Mann-Kendall statistic

COV = Coefficient of Variation

*Table sourced from application manual appendix 6 Table A.7.11.

Source: Excellance, A.F., 2006 http://www.gsi-net.com/en/software/free-software/gsi-mann-kendall-toolkit.html (Excellance, A.F., 2006).

Table 8 below summarises the trends for the wells where the concentrations of VCH compounds were reported to exceed the adopted environmental criteria and for the wells where the concentrations of VCH compounds did not exceed the criteria but showed “increasing trends”, potentially indicative of the plume(s) migration. The reported concentrations of the key VCH, and Mann-Kendall graphical outputs for key wells (included in Table 8), are available in Appendix G.

Table 8 – Groundwater Concentration Trends (VCH)

Well ID	TCE	PCE	1,2-DCE (sum of cis & trans)	VC
BH22	No Trend	-	-	-
GW02	Stable	-	Stable	Decreasing
GW09	Stable	Probably decreasing	Decreasing	-
MW02	No trend	No trend	Probably Decreasing	Stable
MW04	Probably increasing	Probably increasing	Increasing	-
MW05	No Trend	Stable	Decreasing	-
MW06	-	*Increasing	-	-
MW07	Increasing	-	Probably Increasing	-

Well ID	TCE	PCE	1,2-DCE (sum of cis & trans)	VC
MW08	Increasing	-	*Increasing	-
MW12	Decreasing	Decreasing	Decreasing	-

(-) indicates GSI Mann-Kendall analysis was not undertaken for these wells based on limited results (less than 4) or no results exceeding screening criteria

*Wells where the noted results do not exceed screening criteria, however increasing trends observed.

The majority of concentration trends determined through the Mann Kendall analysis displayed stable, probably decreasing or decreasing trends (refer Appendix G).

The increasing trends were identified for wells MW04, MW06, MW07 and MW08 indicating that the chlorinated hydrocarbon contaminated plumes have not reached steady state conditions and may still be migrating to these locations from the up hydraulic gradient sources. This has been assessed further in the CSM and Numerical Model sections (9.0 and 10.0 respectively) of this report. It is noted that duplicate results were also considered in the trend analysis (particularly where higher duplicate results were reported compared to the primary result), however, only one change in trend was identified; the 'Stable' trend identified at MW02 for vinyl chloride changed to 'No trend'.

6.0 SOIL VAPOUR INVESTIGATIONS

The soil vapour investigations undertaken in November 2016 and January 2017 were conducted by an experienced Greencap environmental field scientist. Details are provided in the following sections.

6.1 Soil Vapour Point Sampling

The soil vapour investigation comprised the sampling and analysis of 28 existing soil vapour monitoring points across the HAA using Summa canisters. The soil vapour points sampled were based on the requirements of the EPA and the locations of the soil vapour points are presented on Figure B attached.

Soil Vapour Sampling Methodology

Soil vapour sampling was undertaken following at least 1 day (24 hours) after a rainfall event. It is noted a rainfall events occurred preceding each sampling event as follows:

- Over the weekend of 12 to 13 November 2016 (13mm & 12mm respectively based on Adelaide Airport weather station data) and sampling recommenced on 16 November 2016.
- On 20 and 24 January 2017 preceding sampling on 25 January 2017 (11.8mm and 8.8mm based on Adelaide Airport weather station data).

However, the amount of rainfall preceding the sampling events was not considered significant when compared to the general guide stipulated in the *CRC Care Technical Report No. 23 (CRC Care, 2013)* which indicates that: *"As a general guide sampling from wells in open ground (not beneath buildings or concrete pavement) should occur 3-7 days after 25mm rainfall has occurred within an approximate 24 hour time period"*. Copies of the Adelaide Airport weather station summary data, relevant to each sampling event, sourced from the Australian Government Bureau of Meteorology website, are attached as Appendix H.

The following soil vapour sampling methodology was adopted for each sampling event:

- Each well was initially screened using a photoionisation detector (PID) and a landfill gas meter to measure for the presence of volatile compounds and carbon dioxide (CO_2), methane (CH_4), oxygen (O_2), carbon monoxide (CO) and hydrogen sulphide (H_2S) parameters (to determine the effectiveness of purging and to ensure these parameters stabilise prior to sample collection).
- Leak tests were conducted of the vapour points and sample trains to ensure the integrity of each vapour point or sampling equipment was not compromised and to ensure representative soil vapour was being sampled from each location. These tests (comprising a vacuum line test (shut-in test), helium leak test and isopropanol leak test) are discussed in further detail in Section 8.0 (QA/QC) along with details of duplicate sample collection and analysis.
- Following the leak testing, a clean calibrated flow regulator was connected to the top of each canister (and the soil vapour point) and the summa canister valve was opened allowing the desired volume (~800mL) to enter the 1L canister over a period of approximately 1 hour.

It is noted that carbon tube samples were also collected for backup purposes (with the intention of analysing only if a problem was identified with the summa canister results) during each sampling immediately following the collection of the summa canister sample at each soil vapour point location. The tubes were collected using a calibrated sampling pump with low flow adaptor and flow rates were verified using an in-line calibrator.

Soil vapour sampling sheets and equipment calibration certificates (for the helium meter, landfill gas meter and PID) for the November 2016 sampling event are attached as Appendices I and J respectively. Furthermore, the soil vapour sampling sheets and equipment calibration certificates for the January 2017 sampling event are attached as Appendices K and L respectively.

6.2 Soil Vapour Analytical Program

Summa canister samples collected from each location were analysed for VCH compounds PCE, TCE, DCE and VC and isopropanol (for leak testing purposes).

Results of the soil vapour analyses are discussed in Section 6.4. There is also a summary table of analytical results presented as Table D as an attachment to this report (which includes historical results).

Field duplicate samples were also collected during the soil vapour sampling events. A discussion of the Quality Assurance / Quality Control (QA/QC) procedures undertaken is presented in Section 8.0, and a summary of the QA/QC results are presented as Tables B and C attached to this report.

The laboratories used for the soil vapour investigation were EnviroLab (primary laboratory) and ALS (secondary laboratory). The laboratories are accredited by NATA, and the analyses conducted are within the NATA registration of the laboratories.

6.3 Adopted Assessment Criteria

The soil vapour analytical results for the VCH contaminants of interest have been compared to Interim soil vapour health investigation levels (HILs) for a residential land use as listed in Table 1A(2) of the NEPM.

It is noted that no guideline is available for trans-1,2-DCE, however, as described in the NEPM, the toxicity of cis-1,2-DCE '*is considered to be more toxic than trans-1,2-DCE and hence the HILs derived for the cis-isomer are adequately protective of exposures associated with the trans-isomer*'.

6.4 Soil Vapour Investigation Results

6.4.1 Measured Basic Gas Levels

The measured basic gas levels (stabilised values following removal of at least one well volume) during the November 2016 and January 2017 sampling events are summarised in Table 9.

Table 9 – Measured Stabilised Gases (November 2016 & January 2017)

Soil Vapour Point	Measured Parameters					
	Oxygen (O_2) (%)	Carbon Dioxide (CO_2) (%)	Methane (CH_4) (%)	Hydrogen Sulphide (H_2S) (ppm)	Carbon Monoxide (CO) (ppm)	PID reading (ppm)
SV01	18.0 (20.6)	2.7	0.0	0.0	0.0	2.7
	17.3 (20.6)	3.3	0.0	0.0	0.0	2.6
SV02	17.7 (20.6)	2.6	0.0	0.0	0.0	1.5
	17.2 (20.5)	3.8	0.0	0.0	0.0	0.5
SV03	19.3 (20.5)	2.1	0.0	0.0	0.0	0.0
	18.7 (20.4)	2.0	0.0	0.0	0.0	0.0
SV04	18.4 (20.4)	1.7	0.0	0.0	0.0	1.2
	16.9 (20.6)	3.1	0.0	0.0	0.0	0.0
SV05	17.2 (20.5)	2.6	0.0	0.0	0.0	1.2
	14.3 (20.2)	3.9	0.0	0.0	0.0	0.0
SV06	18.1 (20.5)	2.6	0.0	0.0	0.0	0.0
	16.6 (20.1)	3.2	0.0	0.0	0.0	0.0
SV07	16.5 (20.5)	3.2	0.0	0.0	0.0	1.9
	14.9 (20.1)	3.9	0.0	0.0	0.0	0.0
SV08	19.3 (20.9)	1.5	0.0	0.0	0.0	0.0
	17.5 (20.2)	2.0	0.0	0.0	0.0	0.0
SV11	18.8 (20.6)	3.3	0.0	0.0	0.0	0.0
	18.3 (20.4)	2.3	0.0	0.0	0.0	0.1
SV13	19.2 (20.6)	2.2	0.0	0.0	0.0	2.6
	18.7 (20.6)	2.5	0.0	0.0	0.0	0.9
SV14	19.2 (20.7)	1.0	0.0	0.0	0.0	0.0
	18.7 (20.5)	1.3	0.0	0.0	0.0	0.1
SV15M	14.6 (20.5)	5.0	0.0	0.0	0.0	0.3
	11.3 (20.4)	6.9	0.0	0.0	0.0	0.0
SV17	18.8 (20.5)	1.6	0.0	0.0	0.0	2.1
	18.1 (20.8)	1.8	0.0	0.0	0.0	0.1
SV21	16.0 (20.6)	5.1	0.0	0.0	0.0	0.2
	14.5 (20.5)	6.7	0.0	0.0	0.0	0.2
SV22	16.3 (20.5)	4.8	0.0	0.0	0.0	10.0

Soil Vapour Point	Measured Parameters					
	Oxygen (O_2) (%)	Carbon Dioxide (CO_2) (%)	Methane (CH_4) (%)	Hydrogen Sulphide (H_2S) (ppm)	Carbon Monoxide (CO) (ppm)	PID reading (ppm)
	13.4 (20.0)	6.7	0.0	0.0	1.0	8.9
SV23	18.4 (20.6)	3.9	0.0	0.0	0.0	2.1
	16.8 (20.3)	4.1	0.0	0.0	0.0	0.0
SV24	19.2 (20.5)	1.6	0.0	0.0	0.0	1.4
	18.4 (20.7)	2.0	0.0	0.0	0.0	0.0
SV25	16.2 (20.5)	3.4	0.0	0.0	0.0	0.9
	15.4 (20.7)	4.9	0.0	0.0	0.0	0.0
SV26	17.8(20.5)	3.2	0.0	0.0	0.0	3.8
	16.9 (20.0)	2.9	0.0	0.0	0.0	0.0
SV27	17.5 (20.6)	3.1	0.0	0.0	0.0	2.1
	16.0 (20.0)	3.4	0.0	0.0	0.0	0.0
SV28	15.5 (20.6)	4.9	0.0	0.0	0.0	0.0
	13.5 (20.2)	5.6	0.0	0.0	0.0	0.4
SV29	14.7 (20.3)	5.9	0.0	0.0	0.0	1.7
	12.1 (20.0)	7.5	0.0	0.0	0.0	0.1
SV30	19.3 (20.8)	2.1	0.0	0.0	0.0	0.1
	17.9 (20.2)	2.3	0.0	0.0	0.0	0.1
SV31	19.3 (20.5)	1.7	0.0	0.0	0.0	3.9
	19.4 (20.8)	1.7	0.0	0.0	0.0	3.3
SV32	16.3 (20.5)	4.0	0.0	0.0	0.0	1.2
	14.5 (20.6)	5.6	0.0	0.0	0.0	0.0
SV33	14.8 (20.4)	5.5	0.0	0.0	0.0	1.4
	14.7 (20.5)	5.7	0.0	0.0	0.0	0.0
SV34	15.7 (20.5)	4.4	0.0	0.0	0.0	0.2
	14.7 (20.5)	5.4	0.0	0.0	0.0	1.1
SV35	18.0 (20.2)	2.3	0.0	0.0	0.0	0.5
	17.1 (20.6)	3.2	0.0	0.0	0.0	0.9

Notes:

(italics) denotes measured ambient oxygen level.

As shown in Table 3, oxygen levels ranged between 11.3% (SV15M – January 2017) and 19.4% (SV31 – January 2017) over both sampling events, while CO_2 levels across the site ranged from 1.0% (SV14 – November 2016) to 7.5% (SV29 – January 2017). All measured methane, hydrogen sulphide and carbon monoxide levels were at the ambient levels (0% or 0ppm) over both sampling events. The majority of the PID readings were measured to range between 0.0ppm and 3.9ppm (negligible levels of volatiles), however, two PID readings from SV22 were measured at 8.9ppm and 10.0ppm (November 2016 and January 2017 sampling events respectively). These elevated PID reading coincide with the highest reported TCE and PCE concentrations, as discussed in Section 6.4.2.

Ambient (background) air levels were measured to be consistent across the site with CO_2, CH_4, H_2S and CO levels measured at 0% or 0ppm. Ambient oxygen levels were measured to range between 20.0% and 20.9% confirming that adequate separation from the atmosphere was achieved when sampling all soil vapour points (refer Table 9 which shows the variance from ambient levels for oxygen).

6.4.2 Analytical Results

Results of the soil vapour analyses are summarised in Table D attached to this report (historical results are also included). NATA laboratory certificates (including chain of custody documentation) for the November 2016 and January 2017 sampling events are presented in Appendices M and N respectively. Figures presenting the spatial distribution of the reported TCE, PCE & 1,2-DCE concentrations are attached at the end of this report as Figures K to M respectively for the November 2016 sampling event and as Figures N to P respectively for the March 2017 sampling event.

A number of TCE concentrations (from 17 of the 28 locations sampled) were reported to exceed the adopted NEPM HIL criteria over both sampling events, as summarised in Table 10. In addition, elevated PCE and /or cis-1,2-DCE soil vapour concentrations were reported exceeding the adopted NEPM HILs (at 4 of the 28 locations sampled), also summarised in Table 10.

Table 10 – Summary of Elevated Soil Vapour Results (November 2016 & January 2017)

Soil Vapour Point	Chlorinated Hydrocarbon Compounds			
	TCE	PCE	cis-1,2-DCE	VC
SV01*	280	5,000	<8	<5
	260 / 428	9,100 / 13,700	<17 / <20^	<11 / <5.1
SV02	120	1,700	20	<1.3
	100	1,600	10	<1
SV03	32	30	<2	<1.3
SV04*	1,500 – 1,820	<340 - 9	<20 - 20	<5.1 - <1.3
	3,200	30	26	<1
SV06	140	530	<2	<1.3
	170	790	<2	<1
SV07	32	160	<2	<1
SV08	140	20	<2	<1
SV13	160	770	3,000	<5
	160	770	3,300	<5
SV21*	1,500	20	3	<1.3
	1,300 / 1,640	9 / <340	<2 / <20	<1 / <5.1
SV22*	16,000	21,000	<100^	<60^
	19,000 / 19,000	25,000 / 24,000	<100 / <100^	<60 / <60^
SV23*	320 – 330	1,000 - 1,100	3	<1.3
	140	550	<2	<1
SV26	130	9	<2	<1
SV27	51	6	<2	<1.3
SV30	34	20	<2	<1.3
	29	30	<2	<1
SV31*	790	6,100	300	14
	890 / 1,000	13,000 / 14,000	290 / 310	<1 / <1
SV33	120	20	<2	<1.3
	95	9	<2	<1
SV34*	150 – 180	<340 - <3.4	<20 - <2	<5.1 - <1.3
	160	20	<2	<1
Adopted NEPM HIL	20	2,000	80	30

Notes:

All reported concentrations and adopted guidelines are in units of $\mu g/m^3$.

Shaded cell indicates exceedance of adopted soil vapour HIL criteria.

* - Duplicate samples collected as part of analysis, hence range of reported results.

^ LOR above adopted HIL. Raised detection limits due to high level of analyte present in the sample.

As shown in Table 4, the most significant TCE concentrations were reported from soil vapour point locations SV04, SV21 and SV22. These elevated TCE concentrations coincide with the highest reported TCE concentrations in groundwater from nearest locations MW07, MW08 and GW09 respectively (refer Figure B attached for locations).

The highest elevated PCE concentrations were reported from soil vapour point locations SV22, SV31 and SV01. The elevated PCE concentrations at SV22 and SV01 generally coincide with the reported PCE concentration in groundwater within nearest groundwater monitoring wells GW09 and MW02 respectively. No groundwater well is located in the near vicinity of soil vapour point SV31 to make any comparison.

Furthermore, the highest cis-1,2-DCE concentrations were reported from soil vapour point locations SV13 and SV31. The elevated cis-1,2-DCE concentration at SV13 generally coincides with the reported cis-1,2-DCE concentration in groundwater within nearest groundwater monitoring well MW12. No groundwater well is located in the near vicinity of soil vapour point SV31, so no similar comparison can be made.

6.5 Soil Vapour Analytical Trend Analysis

The trends in concentrations of VCH reported for soil vapour was undertaken using Mann-Kendall methodology as detailed in Section 5.6.

A trend analysis was undertaken for soil vapour points where four or more data points were available for the main contaminants of concern such as TCE, PCE and cis 1,2-DCE. Table 11 summarises the results of the trend analysis for each chemical of concern. The Mann-Kendall output charts are presented as Appendix O.

Table 11 – Soil Vapour Trend Analysis

Trend Analysis using Mann Kendal Trend with Confidence = 0.1			
Location	Chemical	Max Value Last?	Mann Kendal Trend
SV02	PCE	No	Down
SV06	PCE	No	Down
SV07	PCE	No	Down
SV08	PCE	No	Down
SV14	PCE	No	Down
SV17	PCE	No	Down
SV01	TCE	No	Down
SV02	TCE	No	Down
SV03	TCE	No	Down
SV06	TCE	No	Down
SV02	cis-1,2-DCE	No	Down
SV22	cis-1,2-DCE	No	Down
SV23	cis-1,2-DCE	No	Down

The results of the analysis generally indicate decreasing trends in soil vapour concentrations at every location assessed using Mann-Kendall methodology. This indicates that VCH in soil vapour may potentially undergo some natural degradation or volatalisation.

7.0 GEOTECHNICAL INVESTIGATIONS

As discussed in Section 4.0, two geotechnical sampling events were conducted on 11 November 2016 and 25 January 2017. The purpose of geotechnical sampling events was to provide more site specific subsurface soil data for consideration in the update of the vapour intrusion risk assessment (presented in Section 13.0).

7.1 Sampling Methodology

The investigations comprised the drilling of ten shallow soil boreholes per sampling event across the HAA and collecting U50 core samples from specific depths, as summarised in Table 12. The boreholes were drilled as close as possible to existing soil vapour points, however no closer than 3 metres. The rationale for drilling the locations no closer than 3 metres was to avoid any potential preferential pathway for ambient air to enter the soil vapour points during subsequent soil vapour monitoring events. The field logs are attached to Appendices P and Q for the November and January sampling events respectively. Photographs of the soil cores are presented as Appendix R.

The U50 core samples were bagged, sealed and kept in a chilled portable cooler immediately following sampling and were delivered under similar conditions to the analytical laboratory (Coffey Services Australia) with accompanying chain of custody documentation. Each sample was scheduled for the determination and calculation of bulk density, moisture content, dry density, degree of saturation, void ratio, specific gravity and air and water-filled porosity.

Table 12 – Summary of Geotechnical Samples

Location	Depth (m bgl)
11 November 2016	
SBG1 – adjacent existing SV31	0.7 – 0.9
SBG2 – adjacent existing SV25	0.7 – 0.9
SBG3 – adjacent existing SV28	0.7 – 1.0
SBG4 – adjacent existing SV02	0.7 – 0.9
SBG5 – adjacent existing SV03	0.7 – 0.9
SBG6 – adjacent existing SV08	0.7 – 0.95
SBG7 – adjacent existing SV32	0.7 – 0.9
SBG8 – adjacent existing SV14	0.8 – 1.1
SBG9 – adjacent existing SV15M	0.7 – 1.05
SBG10 – adjacent existing SV23	0.7 – 1.1
25 January 2017	
SBG11 – adjacent existing SV05	0.9 - 1.1
SBG12 – adjacent existing SV21	0.9 - 1.1
SBG13 – adjacent existing SV34	0.9 - 1.1
SBG14 – adjacent existing SV07	0.9 - 1.15
SBG15 – adjacent existing SV30	0.9 - 1.1
SBG16 – adjacent existing SV27	0.9 - 1.1
SBG17 – adjacent existing SV29	0.9 - 1.1
SBG18 – adjacent existing SV24	0.9 - 1.1
SBG19 – adjacent existing SV22	0.9 - 1.1
SBG20 – adjacent existing SV11	0.9 - 1.1

7.2 Sampling Results

The laboratory test certificates are attached to Appendices Q and R for the November and January sampling events respectively (accompanying the field logs). A summary of the laboratory testing results are presented in Table 13. It is noted that not all samples could be tested by the laboratory largely due to the cohensionless nature of the soil samples submitted for analysis.

Table 13 – Summary of Geotechnical Soil Laboratory Results

Sample ID	Soil classification and description	Bulk Density (t/m3	Moisture Content (%)	Dry Density (t/m3)	Void Ratio (e)	Degree of Saturation (S %)	Porosity (n)	Water Porosity	Air Porosity	Specific Gravity
SBG1*	Clayey Sand, fine – medium grained, brown	-	5.8	-	-	-	-	-	-	-
SBG2**	Sandy Clay, low plasticity, orange brown, trace of gravel	-	11.2	-	-	-	-	-	-	-
SBG3	Silty Clay, medium plasticity, brown	2.07	16.1	1.78	0.486	87.751	32.722	28.714	4.008	2.65
SBG4	Silty Sandy Clay, medium plasticity, orange brown trace of gravel	2.00	20.9	1.65	0.532	99.39	34.717	34.504	0.213	2.53
SBG5	Sandy Clay, medium plasticity, red brown.	1.98	12.1	1.76	0.496	64.19	33.153	21.280	11.873	2.64
SBG6	Silty Clay, medium plasticity, brown	2.02	15.0	1.76	0.474	82.128	32.166	26.417	5.749	2.59
SBG7**	Silty Clay, medium plasticity, brown, with some gravel	-	16.5	-	-	-	-	-	-	-
SBG8	Silty Clay, medium plasticity, brown	1.93	22.6	1.57	0.632	91.78	38.729	35.545	3.184	2.57
SBG9	Silty Clay, medium plasticity, brown	2.05	16.6	1.76	0.481	89.753	32.476	29.148	3.328	2.6
SBG10	Clayey Sand, fine to medium grained, brown. low plasticity fines	1.84	12.4	1.64	0.609	53.60	37.847	20.286	17.561	2.64
SBG11	Sandy Clay, medium plasticity, red brown, fine - coarse grained sand, trace gravel	2.04	19.9	1.70	0.59	91.41	37.03	33.85	3.18	2.70
SBG12	Sandy Clay, low plasticity, orange brown, fine - medium grained sand. Some roots.	2.13	15.5	1.85	0.46	91.24	31.41	28.66	2.75	2.69
SBG13	Silty Sand, fine - medium grained, red brown	1.83	6.0	1.73	0.53	29.79	34.78	10.36	24.42	2.65

Sample ID	Soil classification and description	Bulk Density (t/m3	Moisture Content (%)	Dry Density (t/m3)	Void Ratio (e)	Degree of Saturation (S %)	Porosity (n)	Water Porosity	Air Porosity	Specific Gravity
SBG14	Sandy Clay, low - medium plasticity, red brown / pale brown, fine - medium grained sand, trace gravel	2.14	14.2	1.87	0.43	88.64	30.06	26.65	3.41	2.68
SBG15	Sandy Clay, medium plasticity, pale brown, fine - medium grained sand, trace gravel	2.03	21.1	1.67	0.62	92.17	38.43	35.42	3.01	2.72
SBG16	Clayey Sand, fine - coarse grained, pale brown	1.98	11.8	1.77	0.520	61.241	34.227	20.961	13.266	2.69
SBG17	Sandy Clay, medium plasticity, pale brown / orange brown, fine - coarse grained sand, trace gravel.	2.15	15.9	1.86	0.45	95.29	30.93	29.48	1.46	2.69
SBG18	Silty Sand, fine - medium grained, orange brown.	1.69	3.2	1.63	0.63	13.61	38.56	5.25	33.31	2.66
SBG19***	Silty Sand, fine - coarse grained, brown, trace gravel	-	6.2	-	-	-	-	-	-	2.66
SBG20	Sandy Clay, low plasticity, orange brown, fine - medium grained sand. Some roots.	1.85	14.7	1.61	0.67	59.13	40.00	23.65	16.35	2.69

*Sample crumbled and broke when extruded, could not be measured for bulk density & porosity determination.
**Sample had large voids and gravel, could not be measured for bulk density & porosity determination.
***Sample not retained in U50 - loose in sample bag, could not be measured for bulk density & porosity determination.

8.0 QUALITY ASSURANCE AND QUALITY CONTROL

QA / QC measures for this investigation included:

- Appropriate sample labelling, storage and transport under chain of custody procedures.
- Collection and analysis of field QA/QC samples (duplicates and blanks).
- Conducting all laboratory analyses within appropriate holding times.
- Conducting leak testing prior to and during soil vapour sampling.
- Use of laboratories that hold NATA accreditation for the analyses undertaken.
- Ensuring the sampling equipment (WQM, IP, landfill gas meter, helium meter, air sampling pumps and PID) was calibrated before use.
- Analysis of laboratory QA/QC samples including duplicates, blanks, matrix spikes, matrix spike duplicates, and surrogates.

The following sections detail the QA/QC analyses and consider the analytical data quality.

8.1 Internal Laboratory Quality Assurance

The results of the internal quality assurance programs of the laboratory are presented with the NATA test certificates attached to Appendices E, F, M and N. Appropriate internal QA / QC were reported by both laboratories as follows:

- Accuracy (measured by laboratory spike and surrogate recovery samples) within 70% - 130% recovery;
- Precision (measured by duplicate sample analysis) within 30% relative percentage difference (RPD); and
- Minimum 95% completeness (measured by total number of analyses within acceptable limits).

The laboratory LOR in the groundwater and soil vapour investigation are generally acceptable to compare with relevant guidelines for the contaminants of concern. It is noted that some elevated LOR were adopted by the laboratories during the soil vapour investigations, however, given that the majority of the LOR do not exceed the relevant guidelines (and measurable concentrations were reported for the main contaminants of concern (TCE & PCE)), these are not considered significant in terms of the investigation.

8.2 Field Duplicates – Groundwater Analyses

Field duplicate groundwater samples were collected and analysed at the primary and secondary laboratories during the groundwater investigation work. A summary of the field duplicate testing is summarised in Table 14. It is noted that the frequency of duplicate analysis for all contaminants tested is within (or equal to when considering the natural attenuation and major anion and cation analytes) the frequency suggested in AS4482.1 of 1 per 20 analyses (5%) over both sampling events.

Table 14 – Field Duplicate Testing – Groundwater

Primary Sample ID & Analysis	Duplicate analysed at primary laboratory (mgt)	Duplicate analysed at secondary laboratory (ALS)
November 2016		
GW09 – VCH, Natural Attenuation Parameters, Major Anions and Cations	QA1 – VCH, Natural Attenuation Parameters, Major Anions and Cations	QA2 – VCH, Natural Attenuation Parameters, Major Anions and Cations
MW18 – VCH	QA3 – VCH	QA4 – VCH
March 2017		
MW02 – VCH	QA5 – VCH	QA6 – VCH
MW05 – VCH, Natural Attenuation Parameters, Major Anions and Cations	QA7 – VCH	QA8 – VCH, Natural Attenuation Parameters, Major Anions and Cations

A table summarising the field duplicate results for the investigation is presented as Table B attached to this report. The majority of the comparable inter and intra laboratory duplicate groundwater analyses had RPD values below the recommended comparison criteria of 50%. However, two variations were reported above 50% during the November 2016 monitoring event as follows:

- Nitrate variation of 143% between primary sample GW09 (<0.02mg/L) and inter-laboratory duplicate sample QA2 (0.12mg/L); and
- PCE variation of 60% between primary sample MW18 (1.0µg/L) and inter-laboratory duplicate sample QA4 (0.54µg/L).

The variations are likely the result of low concentrations being reported in both the primary sample and the inter-laboratory duplicate samples. The variations are not considered significant in terms of the overall investigation as the concentrations did not exceed the adopted guidelines.

No variations greater than 50% were reported during the March 2017 monitoring event.

8.3 Field Duplicates – Soil Vapour Analyses

Field duplicate soil vapour samples were collected and analysed at the primary and secondary laboratories during the soil vapour investigation. A summary of the field duplicate testing is summarised in Table 15. It is noted that the frequency of duplicate analysis for all contaminates tested is within the frequency suggested in AS4482.1 of 1 per 20 analyses (5%).

Table 15 – Field Duplicate Testing – Soil Vapour

Primary Sample ID & Analysis	Duplicate analysed at primary laboratory (Envirolab)	Duplicate analysed at secondary laboratory (ALS)
November 2016		
SV04 - VCH and isopropanol	-	QV04 - VCH and isopropanol
SV23 - VCH and isopropanol	QV01 - VCH and isopropanol	-
SV34 - VCH and isopropanol	QV03 - VCH and isopropanol	-
SV35 - VCH and isopropanol	-	QV02 - VCH and isopropanol
January 2017		
SV01 - VCH and isopropanol	-	QV08 - VCH and isopropanol
SV22 - VCH and isopropanol	QV06 - VCH and isopropanol	-
SV21 - VCH and isopropanol	-	QV09 - VCH and isopropanol
SV31 - VCH and isopropanol	QV07 - VCH and isopropanol	-

The majority of the comparable inter and intra laboratory duplicate groundwater analyses had RPD values below the recommended comparison criteria of 50%. However, variations were reported during each sampling event as follows:

<u>November 2016:</u>

- Isopropanol variations of 148%, 103% and 161% between primary samples SV04 (810µg/m^3), SV23 (64µg/m^3) and SV34 (1,100µg/m^3) and duplicate samples QV04 (<120µg/m^3), QV01 (200µg/m^3) and QV03 (<120µg/m^3) respectively.
- A PCE variation of 189% between primary sample SV35 (<3.4µg/L) and inter-laboratory duplicate sample QV02 (120µg/m^3).

<u>January 2017:</u>

- Isopropanol variations of 124%, 194% and 174% between primary samples SV31 (470µg/m^3), SV01 (8,100µg/m^3) and SV21 (1,700µg/m^3) and duplicate samples QV07 (110µg/m^3), QV08 (<120µg/m^3) and QV09 (<120µg/m^3) respectively.

The variations in isopropanol concentrations are not considered significant in terms of the investigation as all of the reported isopropanol concentrations were less than 10% of the measured shroud concentration, indicating the integrity of all soil vapour points was appropriate. The PCE variation is not considered significant in terms of the investigation given that all other duplicate analyses for this analyte were within acceptable limits and the reported PCE concentrations from the primary and duplicate samples at this locations were reported well below the adopted guideline of 2,000 µg/m^3.

A table summarising the field duplicate results for the soil vapour investigation events is presented as Table E an attachment to this report.

8.4 Blank Samples

Field and rinsate blank samples were collected during the groundwater sampling events at a rate of one per day, as shown in Table 16. Trip blank samples were also included and analysed at a rate of one per cooler/esky. Rinsate blanks were obtained from wash off water sourced from pouring deionised water over the micro-purge pump, tubing or hydrasleeve equipment while field blanks were collected by exposing vials to the air (filled within deionised water) during the sampling of a particular well on the day of sampling. The trip blanks comprised pre-filled vials of deionised water.

Table 16 – Blank Testing – Groundwater

Date	Blank Sample ID	Analyses
November 2016		
1 November 2016	FB1, RB1 and TB1	VCH
3 November 2016	FB2, RB2 and TB2	VCH
7 November 2016	FB3, RB3 and TB3	VCH
8 November 2016	FB4, RB4 and TB4	VCH
9 November 2016	FB5, RB5 and TB5	VCH
10 November 2016	FB6	VCH
14 November 2016	FB7, RB6 and TB6	VCH
March 2017		
1 March 2017	FB1, RB1 and TB1	VCH
2 March 2017	FB2, RB2 and TB2	VCH
3 March 2017	FB3, RB3 and TB3	VCH
6 March 2017	FB4 and TB4	VCH
7 March 2017	FB5 and TB5	VCH
9 March 2017	FB6, RB4 and TB6	VCH
10 March 2017	FB7	VCH
14 March 2017	FB8 and TB7	VCH

It is noted that some blank samples were not collected on a particular day during the sampling events, as summarised below.

November 2016:

Samples collected on 9 November 2016 were sent to the laboratory with samples collected on 10 November 2016, hence no additional trip blank was included with the samples. Furthermore, no rinsate sample was collected on 10 November 2016, however, this was not considered warranted given that the samples collected on 10 November 2016 were collected using new hydrasleeves deployed on 8 November 2016.

March 2017:

No rinsate blank samples were collected on 6 and 7 March 2017, however, this was not considered necessary as the wells were dedicated with tubing from the previous sampling event (November 2016) where rinsate samples were previously collected and analysed. Furthermore, no rinsate blank was collected on 10 March 2017, however, this was not considered warranted given that the sample collected on 10 March 2017 (BH22) was collected in a new hydrasleeve deployed on 2 March 2017.

No trip blank sample was collected on 10 March 2017 (when BH22 was sampled), however, this was not considered significant given that a field blank sample was collected (which travelled with the BH22 sample to the laboratory) in which all reported concentrations were below laboratory reporting limits.

All reported concentrations in blank samples were below laboratory reporting limits indicating that decontamination procedures were acceptable, cross contamination between samples and sampling equipment did not occur and there was no introduction of volatiles into the samples during sample transport. A table summarising the blank sample results is presented as Table C attached to this report.

8.5 Soil Vapour Leak Testing

As discussed in Section 6.1, prior to the soil vapour sampling taking place, leak testing was undertaken to ensure the integrity of each vapour point and to confirm that the sampling equipment was appropriate to ensure representative soil vapour was being sampled from each location. These tests comprised a vacuum line test (shut-in test), a helium leak test and an isopropanol leak test as follows:

- Vacuum line tests (shut-in tests). These were performed on each sample train (external components used to sample soil vapour: tubing, summa canisters, and regulator). The shut-in test involved assembling the sample train with the intake from the soil vapour sampling point capped/closed. The regulator was then opened allowing the sample train to be under full vacuum from the summa canister. The sample train was then allowed to sit under full vacuum for several minutes (2-5 minutes) in which the vacuum gauge was monitored for any drop in vacuum. Following the shut-in tests, the initial vacuum readings on all canisters were maintained indicating that there were no leaks within each of the sample trains.
- Helium leak tests. These were undertaken to ensure that vapour samples were representative of the targeted soil depth being sampled and that ambient air was not being drawn into the vapour point. The helium leak test methodology comprised filling a shroud (which overlaid the soil vapour point) with helium and measuring the concentration within the shroud using a GasCheck 5000 handheld helium detector. Soil vapour was then drawn from the vapour point and real-time helium concentrations measured for approximately 2 minutes. A comparison was then made between the helium concentration within the shroud and the highest measured helium concentration within the vapour point. The measured helium concentrations within all soil vapour points sampled were less than 10% of the measured shroud concentrations indicating the integrity of all soil vapour points was appropriate (refer soil vapour sampling records attached to Appendices I and K).
- Isopropanol leak tests. These were also undertaken to ensure that vapour samples were representative of the targeted soil depth being sampled and that ambient air was not being drawn into the vapour point. The adopted isopropanol leak test methodology comprised placing a rag saturated in isopropyl alcohol within the shroud during the sampling of each soil vapour point and comparing the reported isopropyl alcohol results to a reported shroud concentration. The shroud concentrations were measured and reported within summa canister samples QV05 and QV10 (November 2016 and January 2017 sampling events respectively) and are considered to be typical of the shroud concentrations present during the sampling of each soil vapour point across the HAA. The reported isopropanol concentrations within all soil vapour points sampled were less than 10% of the shroud concentrations reported from samples QV05 and QV10. This provides further evidence that the integrity of the soil vapour points sampled was appropriate (refer sampling records attached to Appendices I and K).

8.6 Data Quality Conclusions

The internal QC procedures reported the laboratories as well as the field duplicate/blank and leak testing analyses indicate the analytical data is of acceptable quality for the purposes of this investigation. In addition, in relation to the soil vapour sampling, given that the summa canister results were deemed to be of acceptable quality, carbon tube analysis was not deemed necessary.

9.0 CONCEPTUAL SITE MODEL

9.1 General

This CSM was constructed based on the review of a number of previous reports and results of recent work undertaken by Greencap.

The CSM has been developed to characterise site conditions within the HAA and to form a basis for the construction of a 3D numerical model. The 3D numerical model has been constructed with the aim of predicting the future extent of the identified groundwater contamination plumes which in turn will guide the EPA in defining the boundaries of a groundwater prohibition area (GPA). The purpose of establishing a GPA is to prohibit the extraction of groundwater to protect current and future residents from the identified historic groundwater contamination, as well as to prevent the spread of contamination.

The CSM was developed in accordance with the NEPM and the SA EPA guideline: *Site Contamination - Guideline for Assessment and Remediation of Groundwater Contamination (February 2009)* (SA EPA, 2009). The CSM is discussed in the following sections and includes:

- Regional geological and hydrogeological settings.
- Site specific geological and hydrogeological settings.
- Groundwater impacts identified and potential sources.
- Plume degradation potential.
- Modelling approach.

9.2 Regional Setting

9.2.1 Geology

The area assessed in this CSM covers the EPA defined HAA. Geomorphologically, the HAA is located on the boundary between two major land-forms; the Coastal Zone and the Lower Alluvial Plain. These major landforms are described in available publications such as: *Soils, Stratigraphy and Engineering Geology of near Surface Materials of the Adelaide Plains* (reference RB94/9) produced by the former Mines and Energy Department and CSIRO in 1994.

The landform map sourced from the RB94/9 report with the approximate location of the HAA is shown on Figure 3.

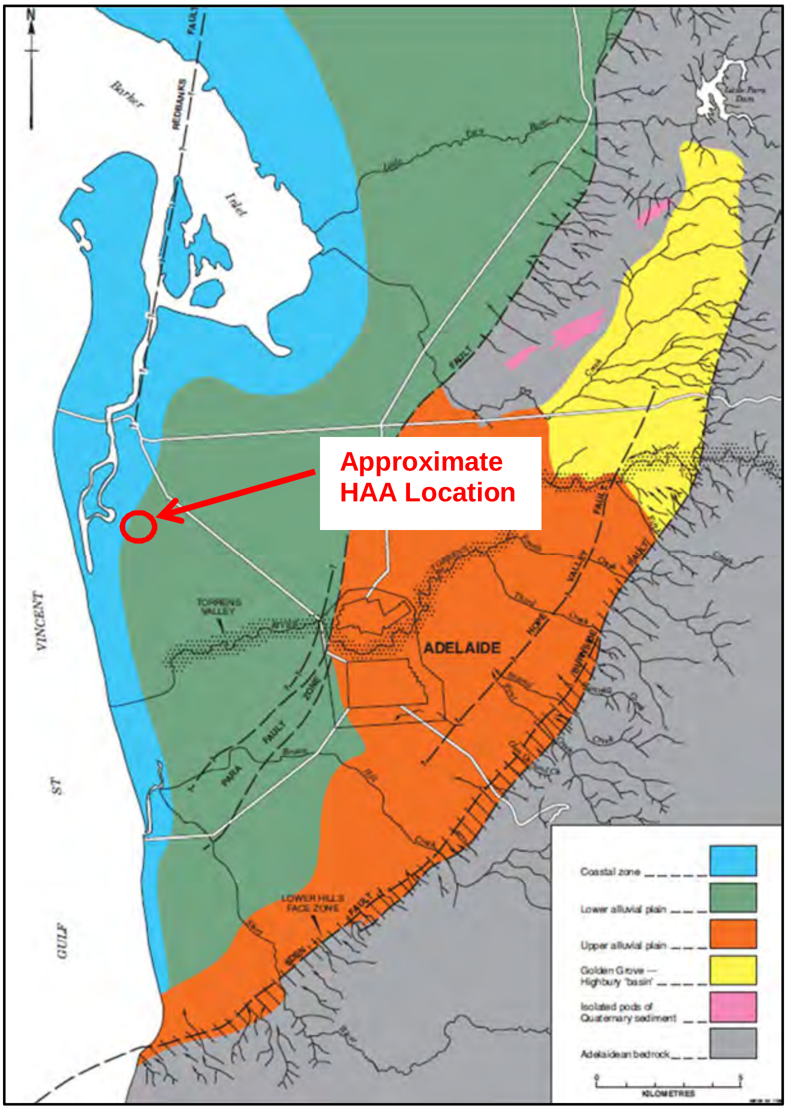


Figure 3 - Landforms of the Adelaide region (source: RB94/9)

A number of cross-sections are presented in the RB94/9 report as shown in Figure 4 where cross-section F-F generally runs across the HAA. Cross-section F-F is presented as Figure 5.

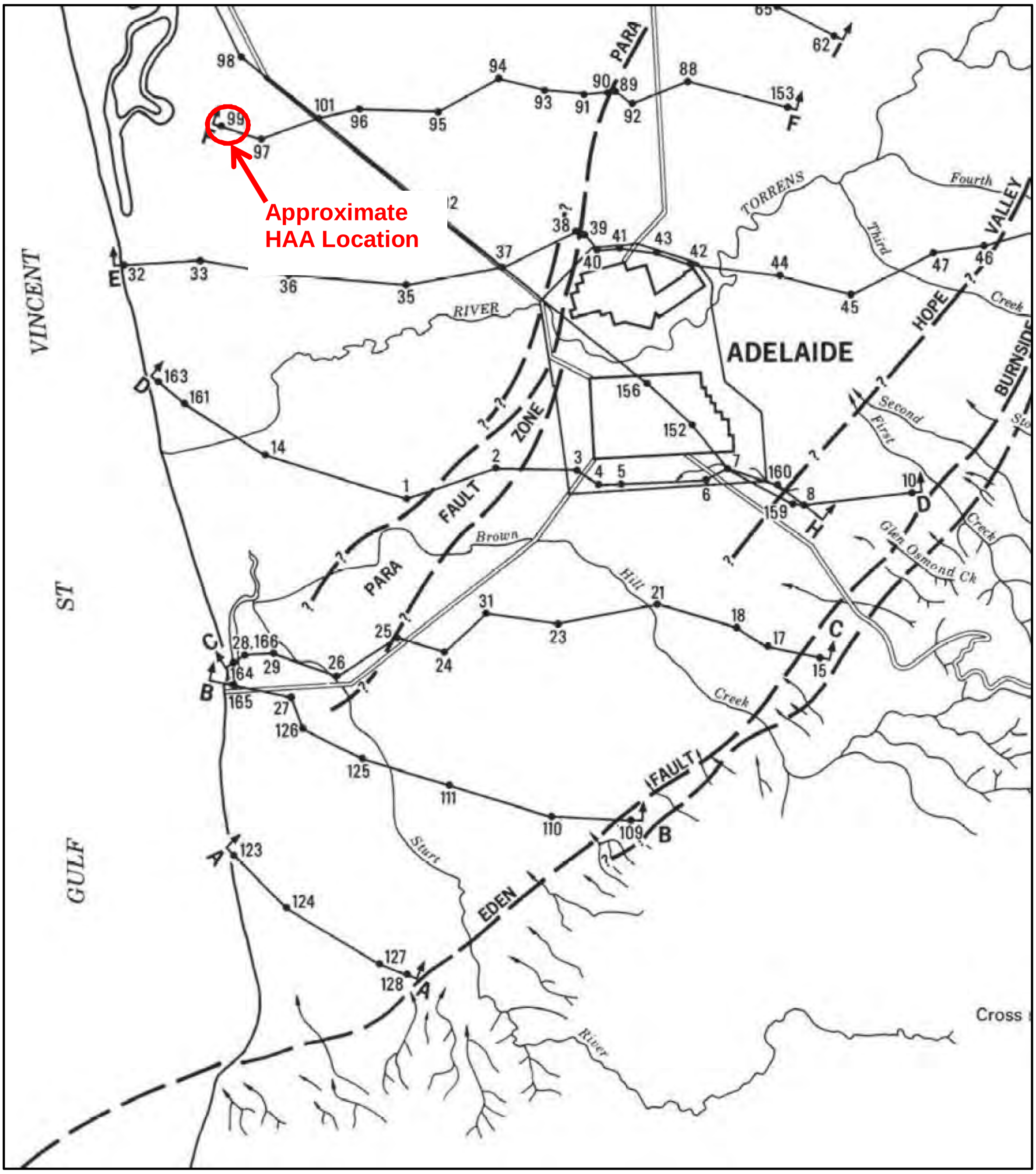


Figure 4 - West-East Cross Section Lines (source: RB94/9)

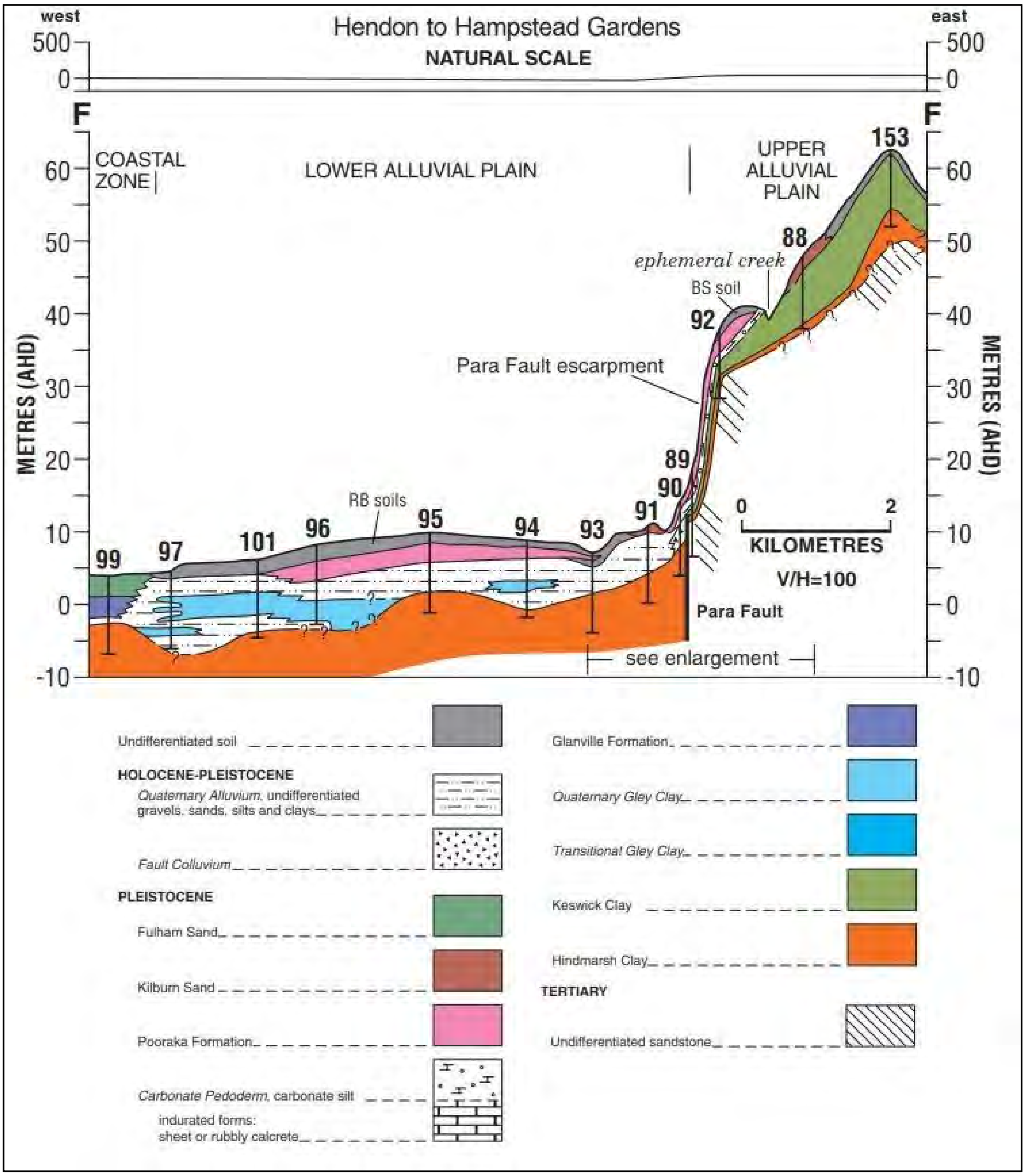


Figure 5 – F-F Cross Section and Geological Legend (source: RB94/9)

The boreholes 99, 97 and 101 are considered to be representative of the geological setting within the HAA. The borehole logs are presented in Appendix S. It is noted that borehole 99 was drilled within the Hendon Primary School and borehole 97 was drilled within the former Philips site. Cross section F-F indicates that the HAA is likely be underlain by the following:-

- Pooraka Formation – may be present within the eastern end of the HAA and may be up to 2 metres thick. The Pooraka Formation typically consists of sandy clay and clayey to sandy silt, with interbeds of layers of clay, sand and occasional gravel.
- Quaternary Alluvial material is present throughout the majority of the HAA and consists of interbedded layers of sand, sandy/silty clays and clays. The thickness of this material is up to 10 metres. The Quaternary alluvial includes a layer of Gley Clay consisting of clays and silty clays 1 - 2 metres thick. Gley is a colour name applied to soil or clay layers that have been subject to poor or impeded drainage conditions. These clays usually have greyish to greenish colours and mottle patterns.

- Glanville Formation is mainly present within the western part of the HAA. The Glanville Formation comprises shelly sand, varying to sandy marl and sandy clay. The thickness of this formation in the area is 3-4 metres.
- Hindmarsh Clay Formation underlays the alluvial material and Glanville formation throughout the HAA. Regionally the Hindmarsh Clay formation may be up to 100 metres thick and predominantly consists of clay with some sand and silt content.

The above-mentioned sequence indicates that the geological setting of the HAA is considered to be complex.

9.2.2 Hydrogeology

Groundwater Occurrence

The report "*Overview of the hydrogeology of the Adelaide metropolitan area*" prepared by Gerges (Gerges, 2006) provides a general overview of the hydrogeological settings of the Adelaide Metropolitan area.

The uppermost aquifer (or Q1 aquifer as identified by Gerges) is of most relevance in terms of the assessment of groundwater within the HAA. The uppermost aquifer generally receives direct recharge from rainfall percolating through the ground surface and therefore is the most susceptible to contamination.

The above-mentioned report presents generalised groundwater contours for the uppermost aquifer within the Adelaide metropolitan area (refer Figure 6).

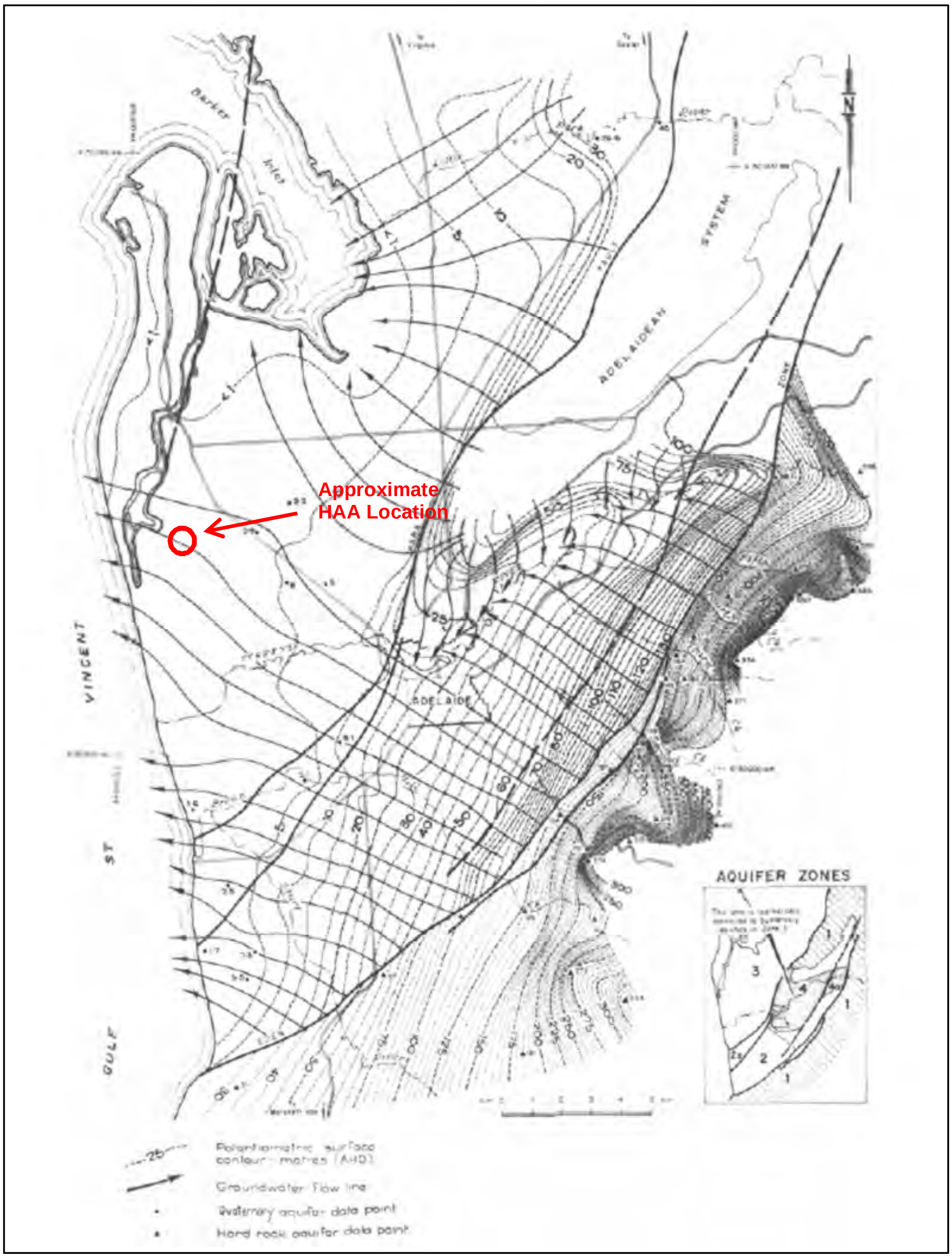


Figure 6 - Groundwater Level Contours, Uppermost aquifer (source Gerges, 2006)

Figure 6 indicates that the movement of groundwater in the uppermost aquifer within the HAA is expected to be in a north westerly direction towards West Lakes and Gulf St Vincent. The elevation of groundwater levels is expected to be less than 5 m AHD.

The borehole logs attached to Appendix S (sourced from report RB94/9) indicate that groundwater is present within the Quaternary Alluvium formation.

Recharge Sources, Discharge Areas and Other Hydraulic Boundaries

The recharge to the uppermost aquifer occurs as a result of two major mechanisms:

- rainwater infiltration across unpaved open space areas; and
- groundwater through-flow from up hydraulic gradient locations.

Infiltration recharge rates are likely to be low due to the combined effects of urbanisation and the high evaporation potential, which exceeds rainfall for most months of the year. A review of available publications indicates that the infiltration rates generally comprise less than 10% of the annual rainfall (e.g. Barnett, 1998).

Groundwater through-flow from up hydraulic gradient sources is also expected to be low to moderate as the aquifer material is generally of low permeability (mainly comprising clays and silts).

Regionally, groundwater through-flow within the uppermost aquifer occurs from the south-east. Furthermore, groundwater from the uppermost aquifer may discharge into West Lakes located approximately 350m to the west of the HAA or into the St Vincent Gulf located further to the west.

It is noted that there are no natural watercourses identified within and in the vicinity of the HAA deep enough to intersect the groundwater flow and to act as other discharge areas for the shallow aquifer system.

9.3 Hendon Broader Assessment Area (HAA) Settings

A review of groundwater well construction logs included in previous reports completed by other consultants, indicates that the subsurface material across the HAA is represented by inter-bedding of sand, silty sand, silty clay and clay layers. As indicated in the 2013 PB report (PB, 2013b) '*the soil profile encountered during this investigation generally consisted of variable fill material (of 0.2 to 0.6 m thickness) underlain by alternating layers of fine grained, low to medium plasticity clayey sand/sandy clay. Layers of fine to coarse grained sand, of varying thickness, were encountered at depths of between 1.5 and 3.5 mBGL and medium to high plasticity silty clay from approximately 3.5 mBGL.*'

The abovementioned geological profile is considered to be generally consistent with the regional geological settings discussed in Section 9.2.1.

During the installation of groundwater wells within the HAA, groundwater cuts (the top of the uppermost aquifer) were encountered at depths ranging from 2.4m (at MW09 - potentially perched water as discussed in Section 9.7) to 5.2m (at MW14 and MW24).

During the gauging event conducted by AECOM in January 2016, the depth to groundwater ranged from approximately 3.18m to 4.34 m below top of casing (btoc). During the gauging event conducted by Greencap in October 2016 the depth to groundwater ranged from 2.39m to 4.11 m btoc. The differences in water levels are likely to be attributable to typical seasonal changes associated with the winter groundwater recharge. Groundwater level gauging conducted in February 2017 showed that depths to groundwater levels were within the October 2016 and January 2016 groundwater levels (i.e within the seasonal groundwater level fluctuation amplitude).

A review of the previous reports also indicates that groundwater levels are likely to be influenced by a sewer main, which runs at depth below the groundwater level along Tapleys Hill Road and Farman Avenue (as shown in Appendix T, which includes a copy of a map prepared by PB in 2014).

Two deeper groundwater wells MW21 and MW22 were constructed by PB in 2013 in the proximity of shallow wells MW03 and MW20 respectively. PB indicated that these wells were installed to further characterise the vertical spread of groundwater contamination. In the reports reviewed, no indication was evident that the deeper wells were installed in the second from the surface aquifer system, hydraulically disconnected from the uppermost aquifer.

The locations of historical and existing groundwater wells located within the HAA are presented in Figure 7. In addition, a schematic cross section plotted from north west to south east across the HAA is presented in Figure 8 (together with groundwater levels, encountered water cuts and positions of sewer mains).

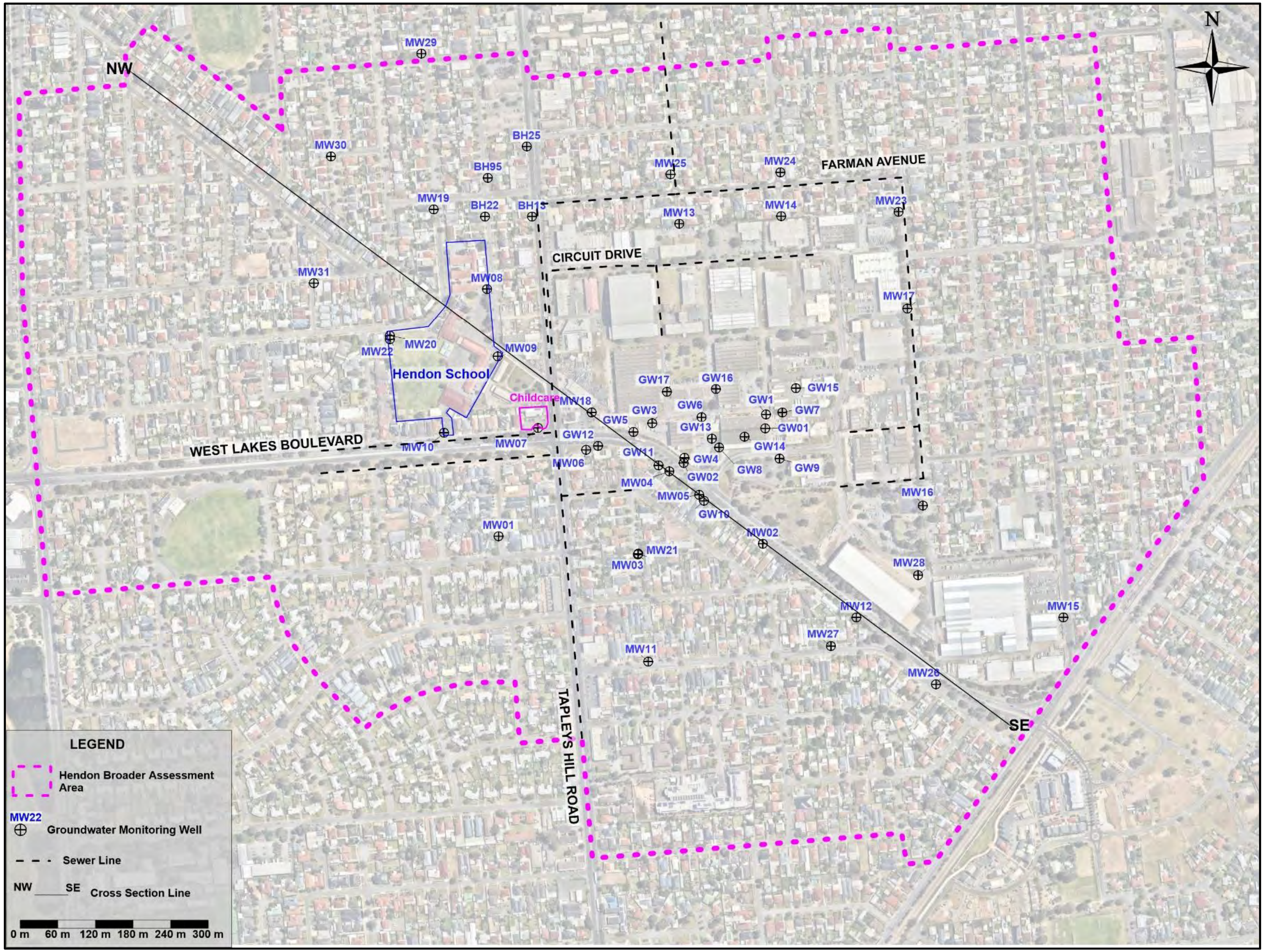


Figure 7 - Groundwater Well Locations (Existing and Historical) and Cross Section Line

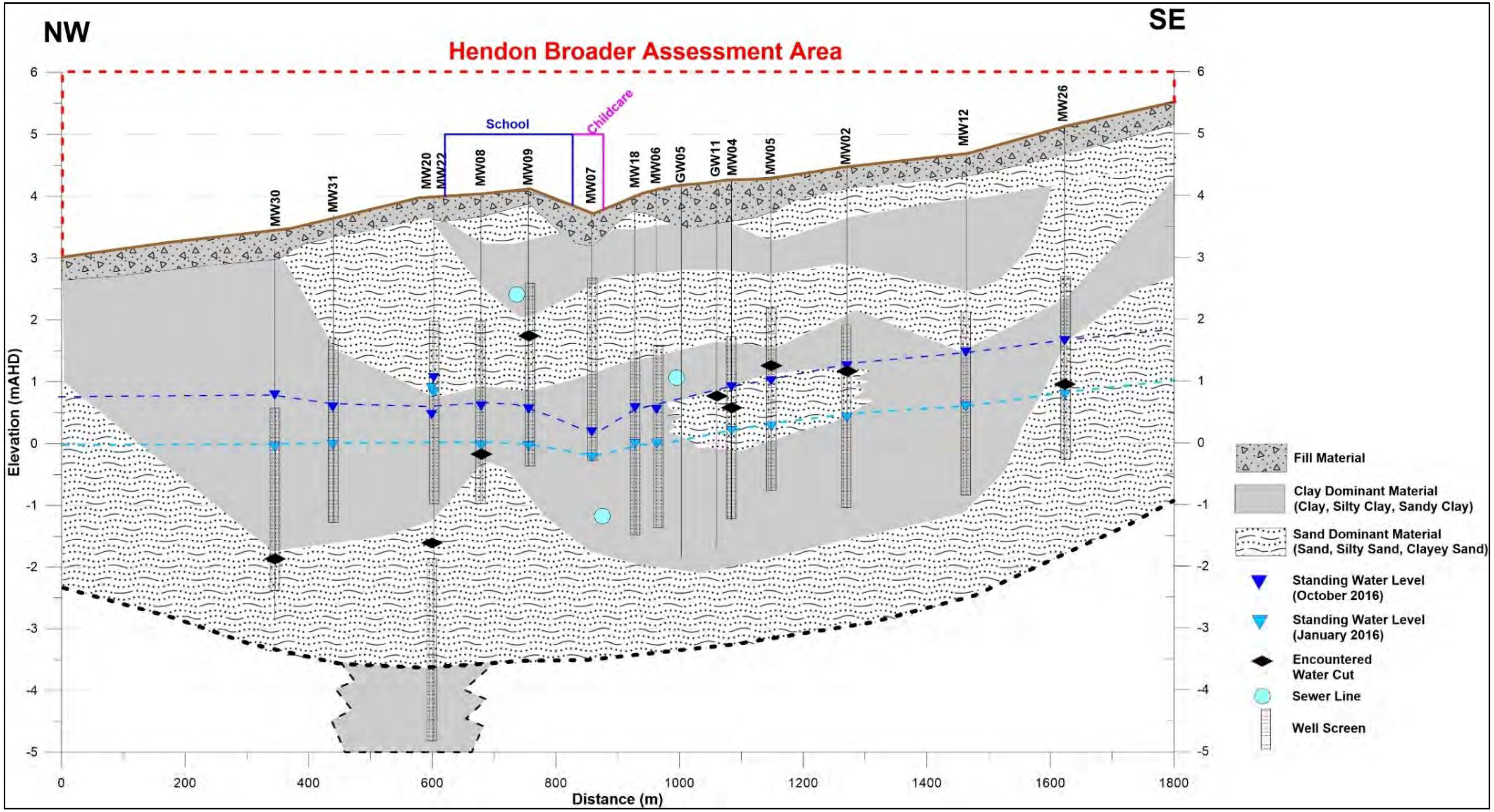


Figure 8 – Schematic Interpretive Cross Section

Figure 8 shows a small depression in groundwater elevation at MW07, interpreted by previous investigations to be caused by a deep sewer main acting as a localised groundwater discharge area. It is also noted that groundwater levels measured at MW20 and MW22 are not consistent with the groundwater levels measured in other wells across the cross sectional area. Reasons for these discrepancies have not been discussed in previous reports and are considered to be local anomalies.

9.4 Groundwater Level Seasonal Changes

Groundwater level hydrographs plotted using gauging data sourced from previous reports, together with the most recent gauging conducted by Greencap, are shown in Figure 9.

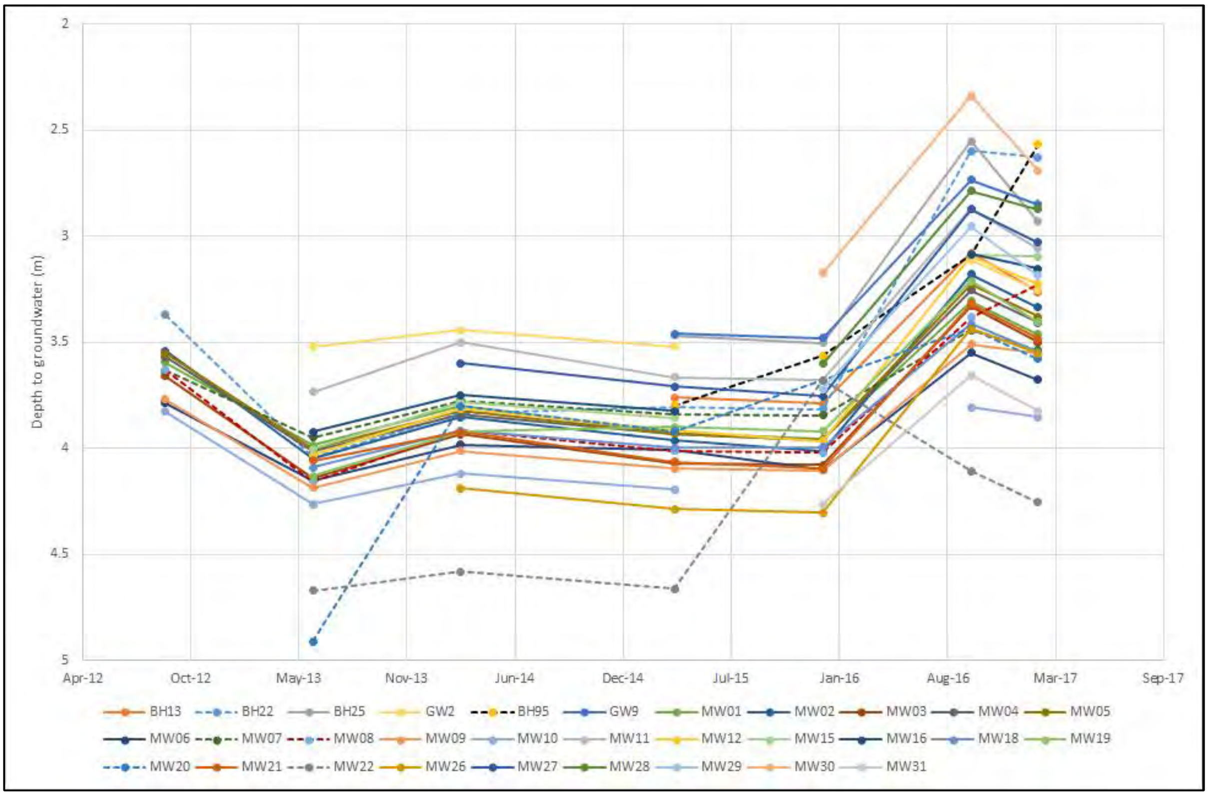


Figure 9 – Groundwater Level Hydrographs

Groundwater wells where groundwater levels show fluctuation patterns inconsistent with the majority of the wells are highlighted in Figure 9 as dashed lines (including BH22, BH95, MW07, MW08, MW20 and MW22). The groundwater level fluctuation pattern for MW07 is likely to be influenced by the deep sewer main located in the vicinity of this well (based on information presented in previous reports). The reason for the changes in groundwater levels in the other abovementioned wells has not been confidently identified during previous investigations. It is also noted that the groundwater level fluctuation pattern at the shallow/deep pair MW03/MW21 appears to be relatively similar and the groundwater level fluctuation at the shallow/deep pair MW20/MW22 do not appear to be consistent. These inconsistencies have not been confidently interpreted in the reports reviewed.

9.5 Groundwater Level Contours and Flow Direction

The scope of work undertaken by Greencap does not include gauging (or sampling) of groundwater wells MW13, MW14, MW17, MW23, MW24 and MW25 (refer Figure 7 for locations of these wells). The most recent gauging of the majority of groundwater wells constructed within the investigation area was conducted by AECOM in January 2016 (AECOM, 2016). The groundwater contours for January 2016 are included in the AECOM report and reproduced as Figure 10. The data for wells showing inconsistency in groundwater level fluctuation (refer section above) was excluded from the contouring.

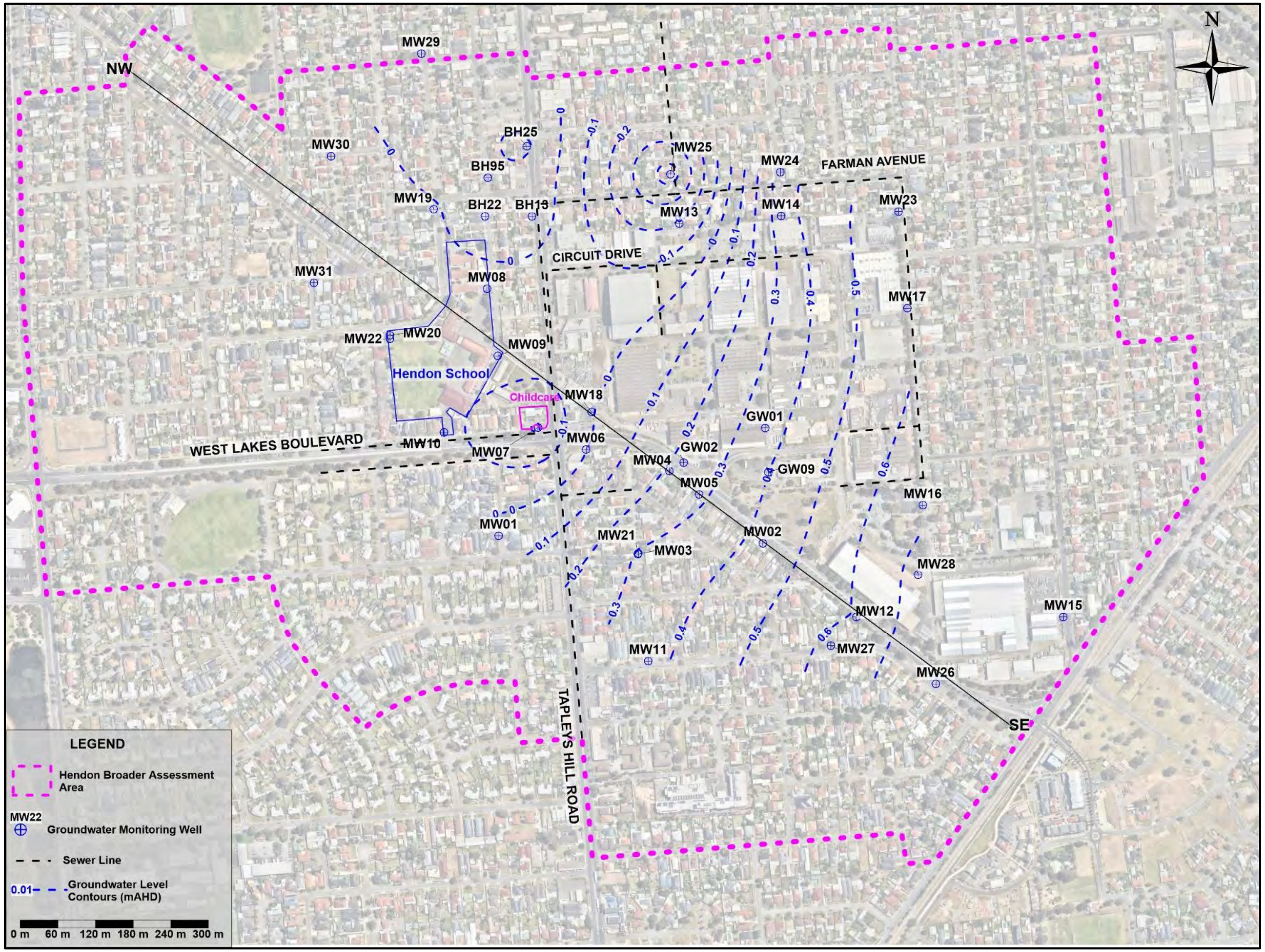


Figure 10 - Groundwater Level Contours (AECOM, 2016)

The January 2016 contours were interpreted to show the following:

- The Groundwater flow across the HAA generally occurs to the north west.
- The groundwater contour pattern is influenced by low groundwater levels measured in MW07 and MW25; both potentially influenced by some groundwater discharge into the deep sewer main located in the vicinity.
- The hydraulic gradient estimated for the south eastern portion of the HAA was 0.0011.
- The hydraulic gradient for the north western portion of the HAA appeared to be flatter and was estimated using water levels measured in MW19 and MW30 as well as in BH25 and MW29 located along the inferred groundwater flow direction. The hydraulic gradient was estimated to be 0.0002 (i.e. an order of magnitude lower than in the south-eastern portion of the HAA).

Groundwater contour plans plotted using the results of the groundwater level gauging events conducted in October 2016 and February 2017 by Greencap are presented on Figure C (attached to this report). The contours presented in Figure C show that hydraulic gradients during these months were slightly steeper and were estimated to be 0.0015 across the south-eastern portion of the HAA. It is important to note that groundwater wells located within the central northern portion of the Investigation area were not gauged during the most recent gauging events conducted by Greencap as these wells were not included in the approved scope of work for this project (refer Figure A for areas excluded from this assessment).

9.6 Hydraulic Conductivity and Groundwater Flow Velocity

The hydraulic conductivity of the uppermost aquifer material was estimated by Coffey in 1992 (Coffey, 1992) and by PB in 2012 (PB, 2013a). No other site specific hydraulic conductivity estimates were available in the reports reviewed. Hydraulic conductivity results are summarised in Table 17.

Table 17 – Hydraulic Conductivities (PB and Coffey data)

Well name	Material at the screed interval	Hydraulic Conductivity (m/day)
Coffey 1992		
GW01	Clay Sand to Sandy Clay	0.22
GW03	Predominantly Silty Clay	0.12
GW04	Predominantly Clay Silt	0.16
GW05	Clay Silt to Silty Clay	0.11
GW06	Silty Clay to Clay	0.19
GW08	Silty to Sandy Clay	0.56
PB 2012		
GW09	Clayey Sand to Sand	2.9
MW01	Sandy Clay to Gravelly Sand	3.4
MW04	Clayey Sand to Silty Clay	3.4
MW06	Silty Clay	0.08
MW09	Sand to Clayey Sand	3.4
Averages		
Sand Dominant Material		3.2
Clay Dominant Material		0.2
Across the HAA		1.7

Table 17 shows that the range of estimated hydraulic conductivities generally follows the encountered material types (i.e. higher hydraulic conductivity for the material where sand dominates and vice versa).

Using the average hydraulic conductivities included in Table 17, the hydraulic gradient estimated in Section 9.5 and an assumed effective porosity of the aquifer material of 0.2, the velocity of groundwater flow across the area was calculated to be in the order of 6 m/year. This value is within the range of between 3.5 and 12 m/year estimated by PB in the 2014 report.

It is noted that the hydraulic conductivities were mainly estimated for the wells located within the south-eastern portion of the HAA, and no hydraulic conductivity values were available for the north western portion of the HAA, where the hydraulic gradient was estimated to be an order of magnitude lower (refer Figure 7 for well locations). The lower hydraulic gradient (refer Section 9.5) may be a result of either an increase in aquifer thickness or an increase in hydraulic conductivity of the aquifer material (or a combination of both).

9.7 Perched Groundwater System(s)

9.7.1 Royal Park

At a later stage of the project, the EPA provided a series of documents related to investigations conducted on a former ESSO site in Royal Park (for Mobil Oil Australia Pty Ltd) located within the HAA. Some of the monitoring wells from this site (i.e. BH13, BH22, BH25 and BH95) have been sampled as a part of the recent groundwater monitoring events conducted by Greencap.

A detailed review of the reports related to the Royal Park site have not been undertaken, however a brief review of the "*Detailed Risk Assessment, Former ESSO Royal Park Service Station, 1356-138 Tapleys Hill Road, Royal Park, South Australia*" report prepared by Coffey in July 2011 (Coffey, 2011) was conducted.

The review indicated the following:

- There was a shallow, assessed to be 'perched', aquifer identified within the vicinity of the former service station in Royal Park.
- This perched aquifer was characterised by higher groundwater levels in comparison with the deeper (likely regional uppermost) aquifer.
- The groundwater flow direction in the perched aquifer was assessed to be to the south west and groundwater in the deeper regional uppermost aquifer was assessed to be to the north west (i.e. similar to the groundwater flow direction assessed for the south eastern portion of the HAA).
- There are pairs of groundwater monitoring wells installed in both aquifers as illustrated on Figures 11 and 12 below (sourced from the Coffey 2011 detailed risk assessment (DRA) report).
- There is no BH95 groundwater monitoring well referenced in the Coffey DRA report. Instead there is a pair of shallow and deep wells (BH23 and MW95, with BH23 installed within the perched groundwater system). There is the potential for BH23 to have been sampled instead of MW95 during some previously monitoring events, which is reflected on the groundwater level hydrographs presented in Figure 9 (Section 9.4).

Groundwater sampling showed the presence of VCH during the 2010 sampling event, as shown in Table 18. The VCH impacts appear to have been reported in the groundwater wells installed deeper than those targeting the perched aquifer.

Table 18 – Chlorinated Hydrocarbons reported in Royal Park groundwater wells (µg/L)

Well name	1,1-DCE	cis-1,2-DCE	trans-1,2-DCE	PCE	TCE	VC
BH01	<5	<5	<5	<5	36	<50
BH22	<5	18	6	<5	367	<50
BH47	<5	<5	<5	<5	29	<50
BH50	<5	8	17	<5	<5	<50
BH51	<5	12	<5	<5	245	<50
BH72	<5	6	<5	<5	<5	<50

The presence of VCH compounds in the Royal Park wells may be a result of the chlorinated hydrocarbon plume migrating from the sources discussed in Section 9.8, or they may have originated from an alternative source within the Royal Park area.

It should be noted that neither the perched water aquifer nor the potential sources of VCH concentrations within the Royal Park area will be considered during the preparation of the numerical groundwater model (discussed in Section 10.0) as the results of these investigations are outside the project scope of work.

9.7.2 Hendon Broader Assessment Area

Groundwater salinity contours plotted using the results of the groundwater sampling events conducted in November 2016 and in March 2017 are presented in Figures 13 and 14 respectively. The salinity contours confirm the presence of fresh groundwater within historical groundwater wells installed during the Royal Park Mobil investigations, and at MW09. The fresh groundwater at MW09 may also be influenced by the presence of perched groundwater particularly because a shallow groundwater strike was encountered during the installation of this well (as reflected in Figure 8).

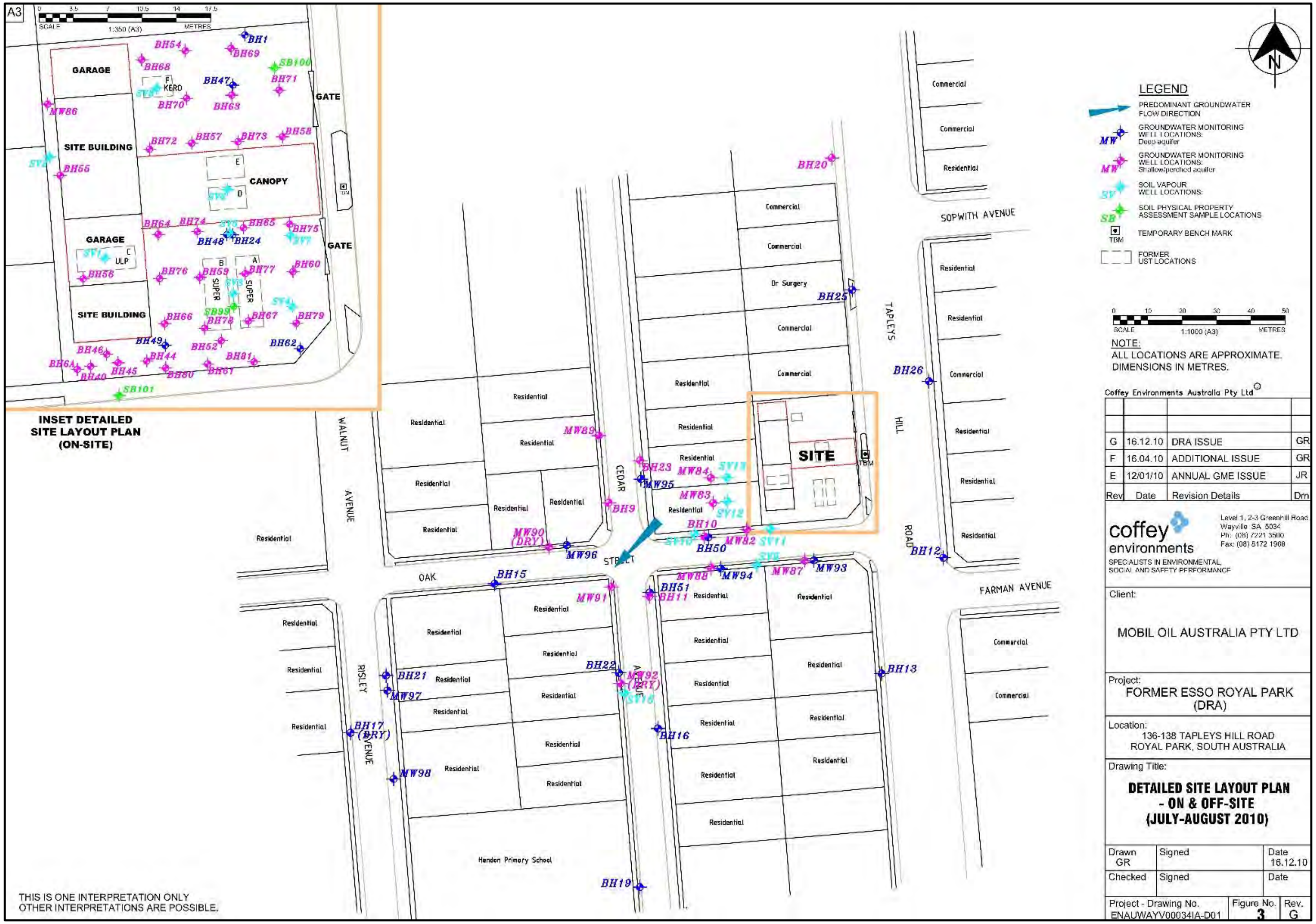


Figure 11 – Royal Park shallow and deep well locations (source Coffey, 2011)

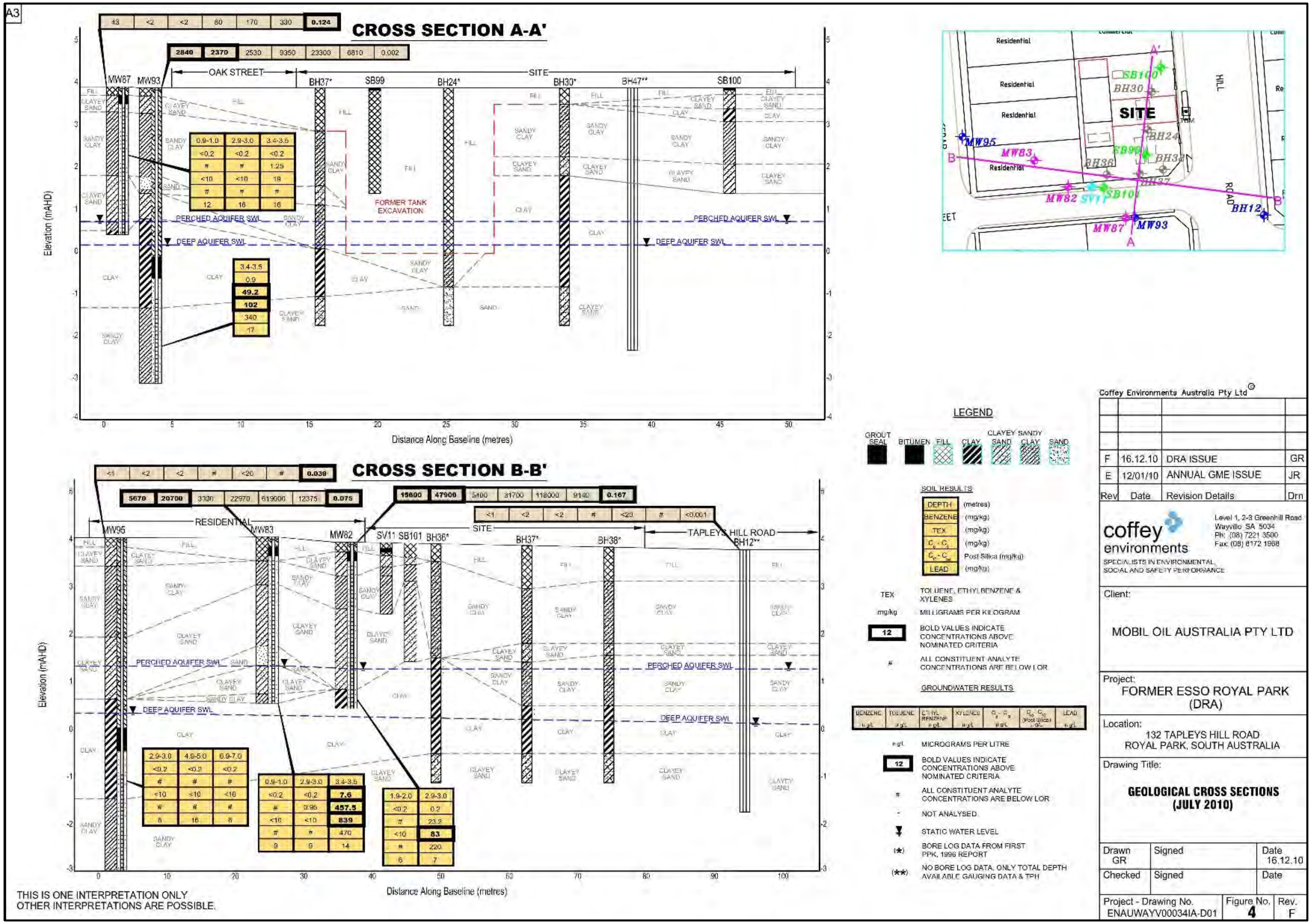


Figure 12 – Sections and Shallow/Deep Well Completions (source: Coffey, 2011)

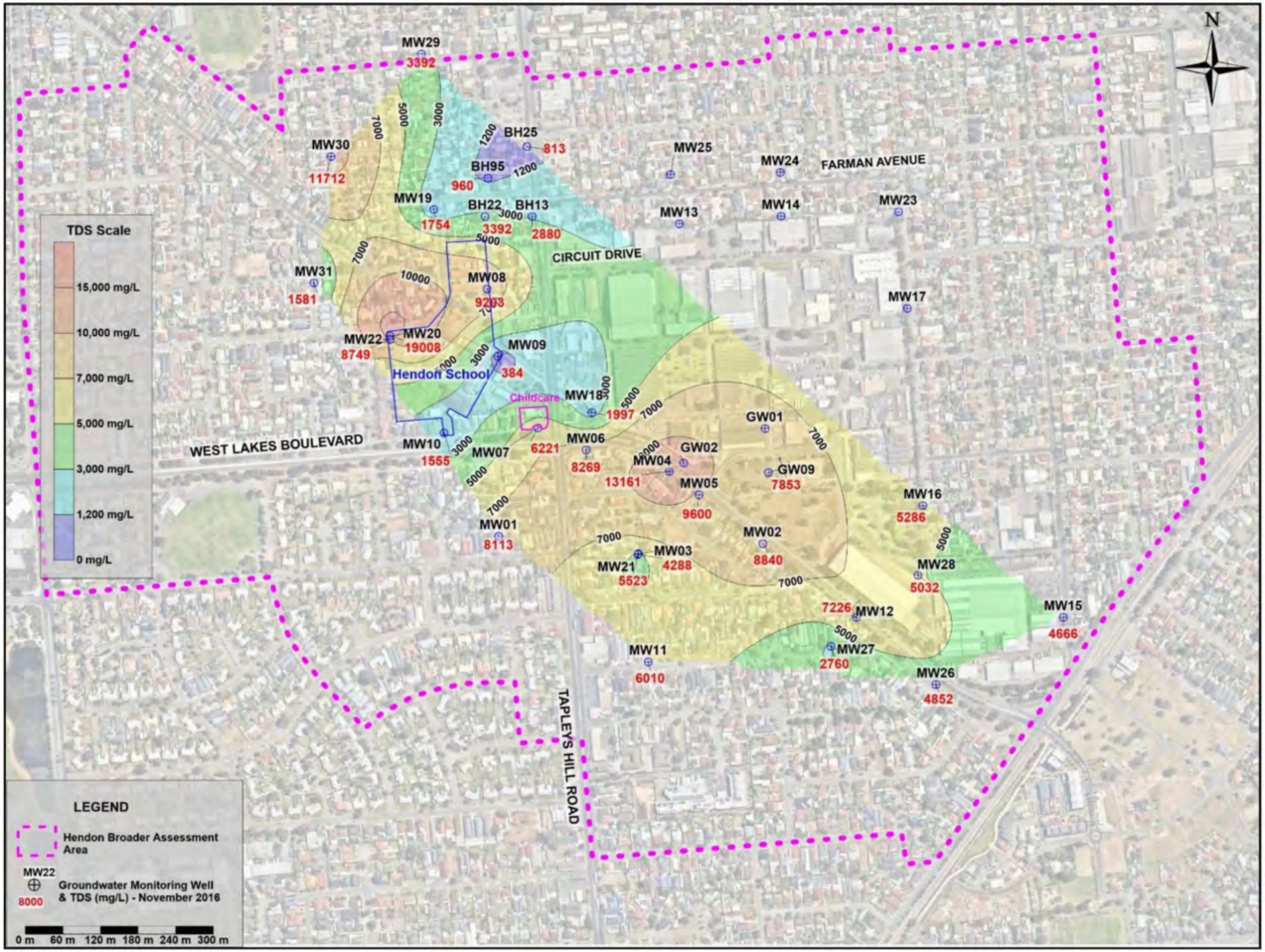


Figure 13 – Groundwater Salinity Contours (November 2016)

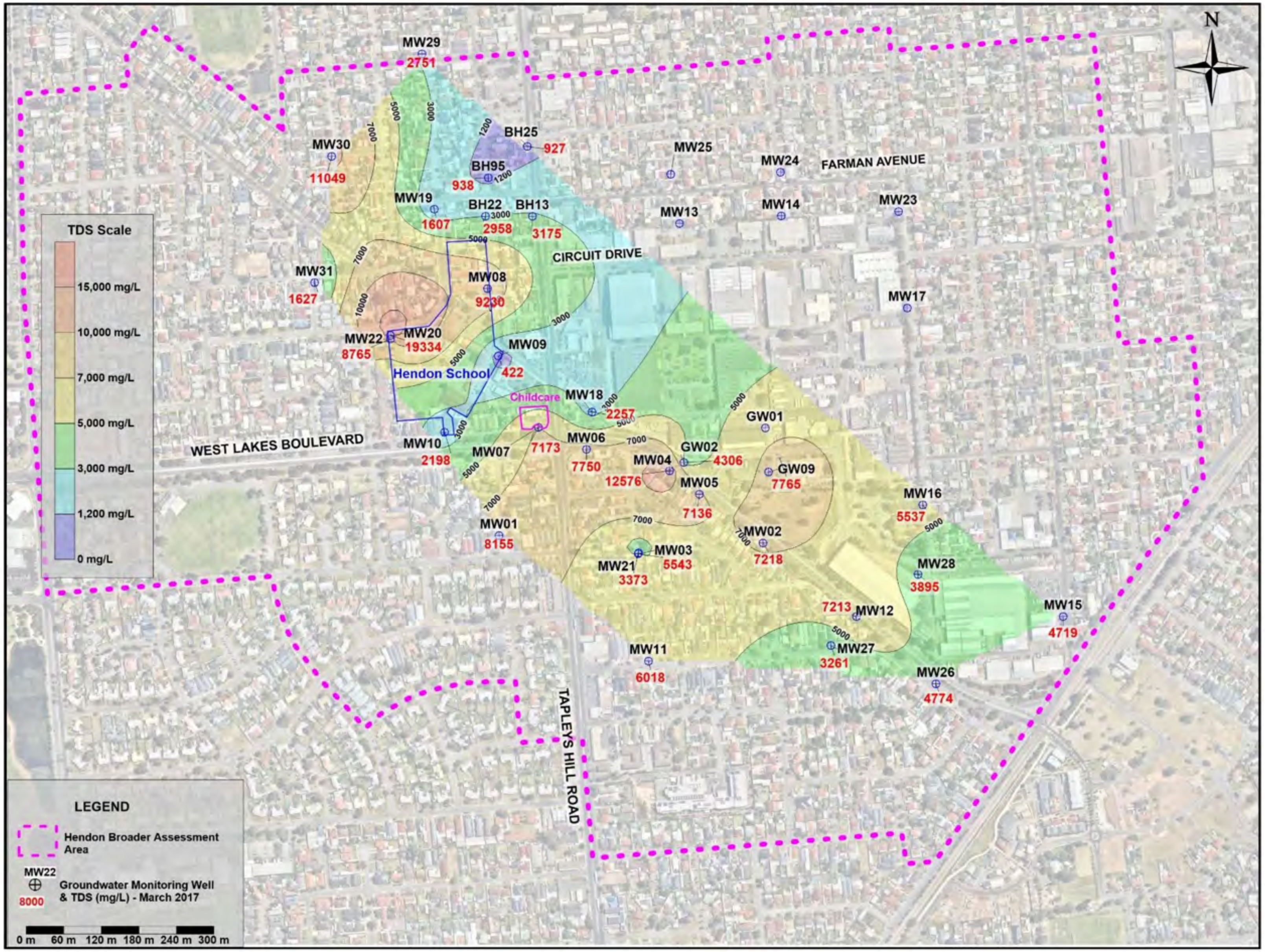


Figure 14 – Groundwater Salinity Contours (March 2017)

9.8 Groundwater Contamination

9.8.1 Chemicals of Concern

The primary chemicals of concern identified in the groundwater of the uppermost aquifer include a range of VCH. There are two major groups of VCH interpreted by previous investigations: a) parent chemicals such as PCE and TCE and b) daughter chemicals (resulted from de-chlorination of primary chemicals) such as 1,1-DCE, cis 1,2-DCE, trans 1,2-DCE and VC.

The distribution of these chemicals in groundwater and the inferred extents of the VCH plumes are presented in documents prepared by other consultants and in Figures E to J (inclusive) attached to this report.

The plume extents generally demonstrate the potential for multiple sources of groundwater impacts within the HAA as discussed in the sections below.

9.8.2 Contamination Sources and Plume Extents

The review of previous reports (particularly the PB 2014 report (PB 2014a, Section 16.0)) indicated that the groundwater contamination has potentially originated from the following locations (sources):

- PCE source(s) in the vicinity of and/or south-east of GW9 within the HIA (i.e. industrial area and the property at 3-5 Philips Crescent (PCE/TCE/1,2-DCE)).
- Possible 1,2-DCE source to the east of MW12/MW02.
- Possible TCE source(s) within the vicinity of GW2 and GW9 and another possible TCE source within the vicinity of MW07 (i.e. a property between well MW18 and Tapleys Hill Road).
- The deep sewer main beneath Tapleys Hill Road, the western portion of Circuit Drive and Farman Avenue may act as a preferential pathway for the subsurface migration of the VCH impacts therefore possibly creating additional groundwater sources in this area.

An additional assessment to locate potential chlorinated hydrocarbon sources was undertaken using the maximum reported concentrations from groundwater wells installed by Coffey in 1992 and by PB & AECOM between 2012 and 2015.

Figures 15 and 16 present the maximum reported concentrations of parent VCH compounds PCE and TCE respectively together with potential shapes of the inferred plumes for each chemical and inferred positions of the sources. The plume shapes were plotted to include all historically elevated concentrations and were aligned to follow the potential groundwater flow direction at these locations.

Figure 17 presents the inferred extents of the DCE plumes together with maximum reported DCE concentrations calculated by adding maximum concentrations of 1,1-DCE, cis 1,2-DCE and trans 1,2- DCE compounds.

Figure 18 presents maximum reported concentrations of VC in groundwater. It is noted that VC concentrations could not be aligned into a groundwater plume based on its relatively sporadic distribution.

It is important to note that the chemical concentrations presented on Figures 15 to 17 should not be used for assessing the plumes' behaviours, as the maximum concentrations used were sources from different monitoring events, separated by years.

Comparison of Figures 15, 16 and 17 shows that the inferred extents of the DCE plumes closely follow the inferred extents of the TCE and PCE plumes. This suggests that the DCE impacts may be a result of the natural degradation (de-chlorination) of PCE and TCE impacts. The figures also show that a depression in groundwater level in the vicinity of MW07 causes plume deflection towards this location (as also noted by PB in 2014). Furthermore, Figures 15 to 17 are generally consistent with PB's source identification results.

The separate plumes are considered only to be an option for modelling purposes. Alternatively, it may be possible that the northern two plumes shown on Figures 15 to 17 may be part of a single plume sourced from the 3-5 Philips Crescent site and dragged towards the deep sewer main located along Tapleys Hill Road.

At a later stage of this project an additional document was provided by the EPA titled: "*Preliminary Site Investigation, Hendon Industrial Area, Hendon, South Australia*" prepared by CH2M HILL in May 2015 (CH2M HILL, 2015c). A detailed review of this report has not been undertaken, however, based on the detailed site history studies presented in this report, it is understood that within the HIA there have been a significant number of potential locations where chlorinated hydrocarbon use was highly likely. A copy of Figure 7 sourced from the abovementioned report which presents the 'High Risk Areas of Potential Concern' identified by CH2M HILL is presented as Figure 19. These areas, together with the potential source areas discussed earlier in this section, will form the basis for positioning contamination sources in the numerical groundwater model (refer Section 10.0).

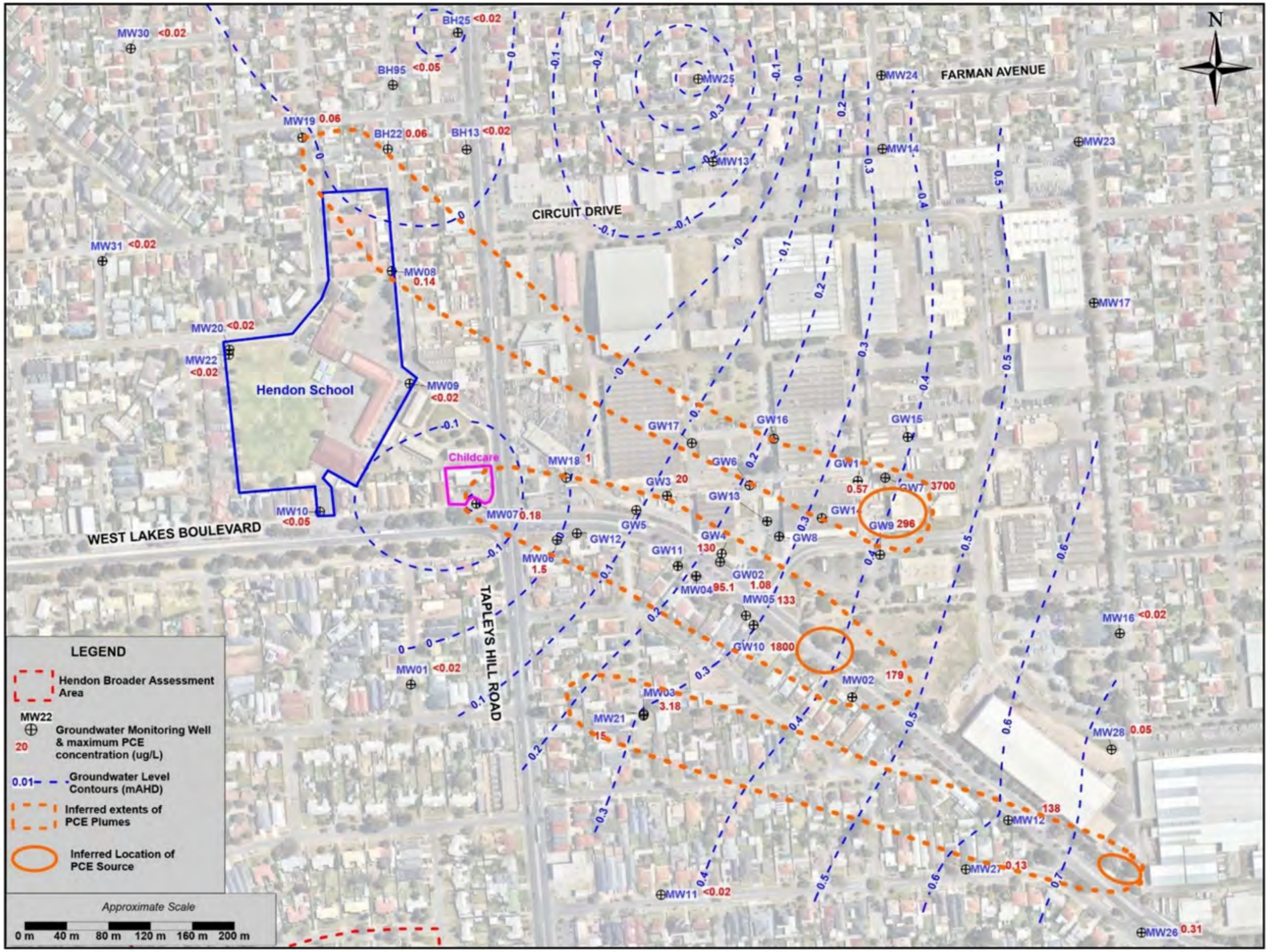


Figure 15 – Inferred PCE Plumes and Sources

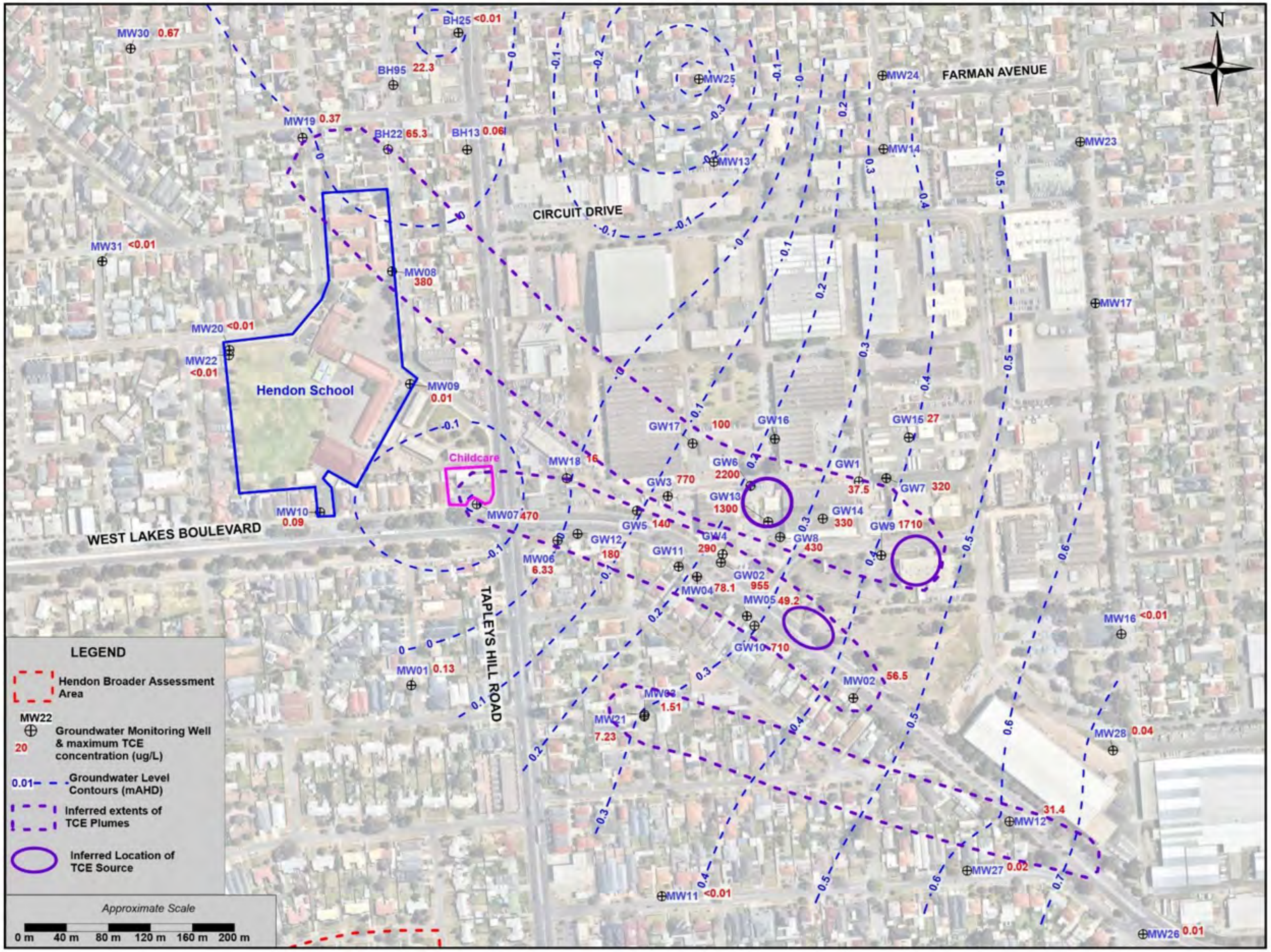


Figure 16 – Inferred TCE Plumes and Sources

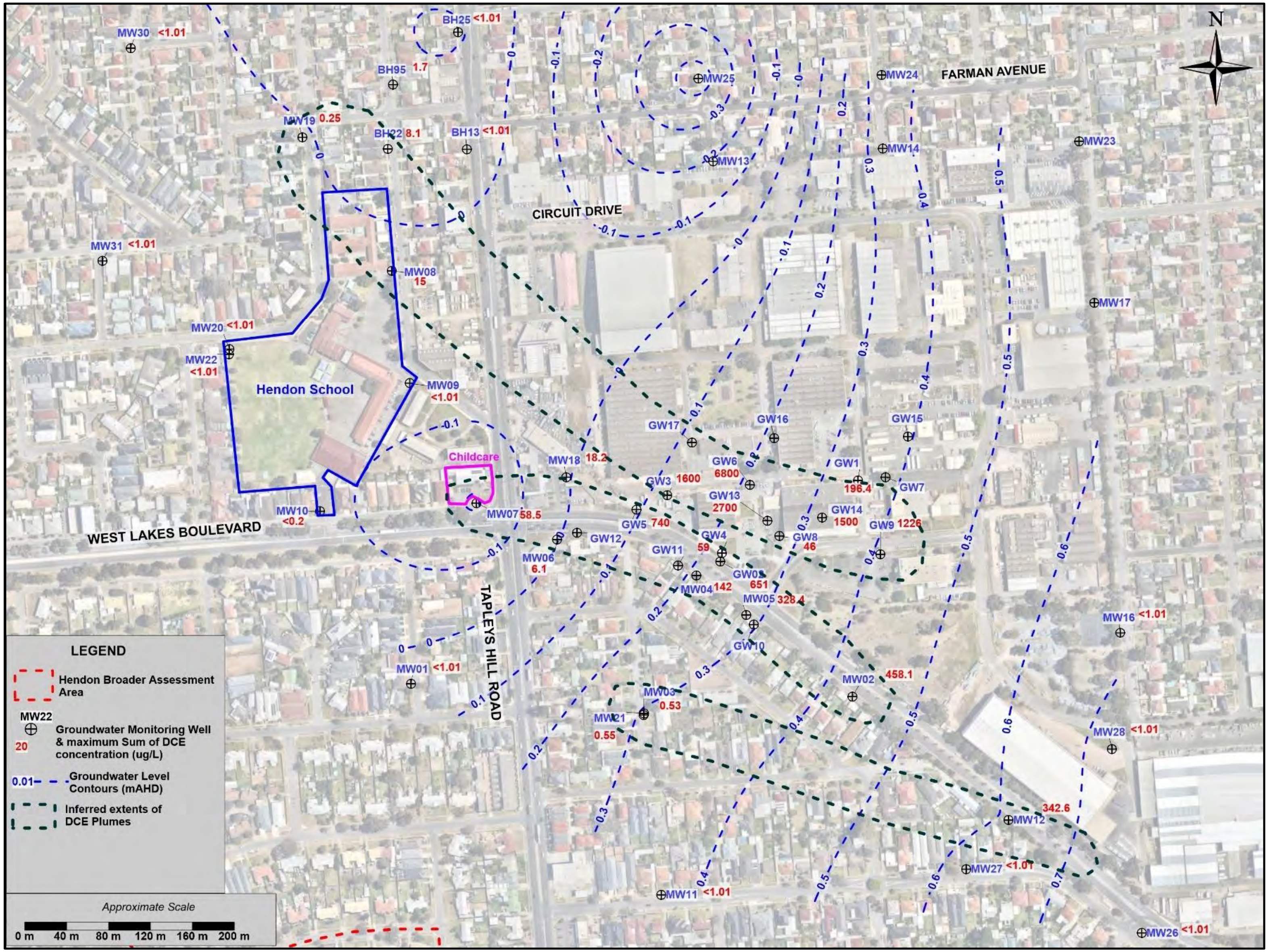


Figure 17 – Inferred DCE Plumes in Groundwater

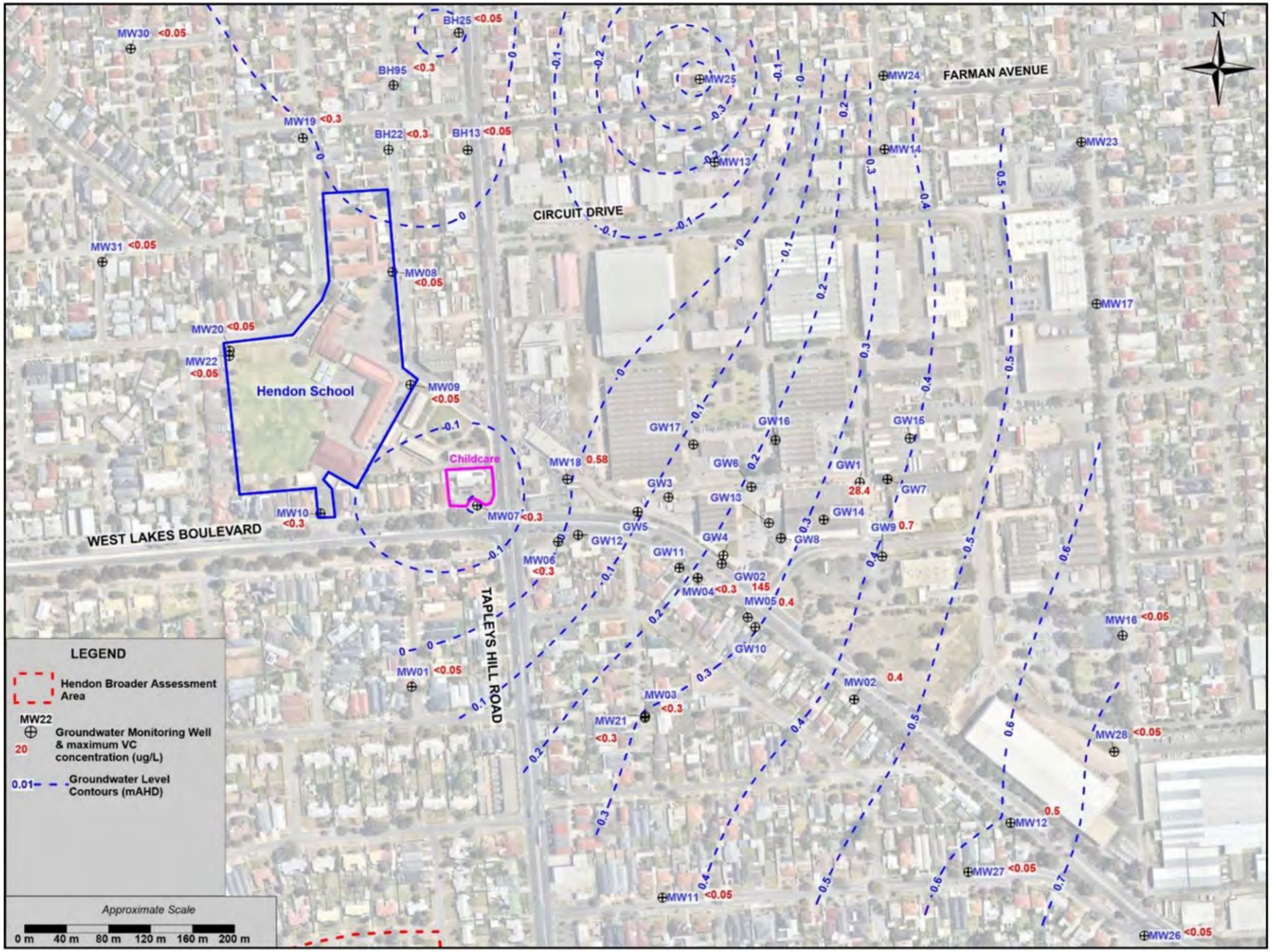


Figure 18 – Maximum VC Concentrations in Groundwater

Figure 19 – High Risk Areas of Potential Concern (Source: CH2M HILL, 2015c)

9.8.3 History of Chlorinated Hydrocarbon Sources and Plume Travel Time

A site history assessment for the HAA was undertaken by Coffey in 1992 (primarily for the 3-5 Philips Crescent site) and by CH2M HILL (CH2M HILL, 2015c) as discussed in Section 9.8.2.

Based on this information, chemicals (possibly including chlorinated hydrocarbons) were potentially present on the site as early as 1947. The areas where chlorinated hydrocarbons may have been used are shown on Figure 19. Furthermore, as indicated in the 1992 Coffey report, chlorinated hydrocarbons associated with plating shop and electronic equipment manufacturing activities may also have been introduced in 1977/1978. The liquids (potentially including a mixture of VHC) used on the site were stored in a number of above and below ground tanks from which leakage may have resulted in the groundwater contamination identified.

With reference to Figures 15 to 17, it appears that the plumes have travelled approximately 400 metres from the central portion of the 3-5 Philips Crescent site to MW08. Using the highest groundwater flow velocity estimated by PB of 12 m/year the contamination of groundwater potentially occurred in 1980. However, considering that the presence of TCE was reported at groundwater well MW30 located some 800m from the Philip Crescent site, the groundwater contamination may have occurred as early as 1950.

Using the estimated hydraulic gradient range between 0.0011 and 0.0015 (Section 9.5) and the flow velocity of 12m/year, the hydraulic conductivity of the aquifer material would range between 4.4 and 6 m/day which is higher than the range of hydraulic conductivities estimated during previous investigations (refer Section 9.6). This suggests that additional testing of aquifer properties is warranted to gain a better understanding of the full range of hydraulic conductivities and / or the potential presence of preferential pathways.

9.8.4 Chlorinated Hydrocarbon Degradation Potential

In their 2014 report, PB undertook an assessment of the PCE, TCE and DCE ratios to evaluate the de-chlorination potential causing PCE to breakdown to TCE and then further to DCE. The PB report concluded that the ratios of these chemicals is complicated by the presence of potential additional sources of TCE and even DCE. PB also indicated that the groundwater environment is characterised by positive reduction-oxidation potential which does not support the active de-chlorination of PCE and TCE.

Additional steps to evaluate the degradation were undertaken as follows:

- Typically the ratio between the parent and daughter products tends to decrease from the source towards the downgradient end of a plume. To assess this, concentration ratios including PCE:TCE and TCE:1,2-DCE (based on the sampling conducted in November 2016), are plotted on Figures 20 and 21 respectively.
- Similarly, it is expected that the concentrations of VCH compounds expressed in molar fractions would show an increase in proportion of daughter products towards the downgradient boundary of a plume. Molar fractions of PCE, TCE and 1,2-DCE compounds were plotted along the general groundwater flow direction to illustrate the chlorinated hydrocarbon degradation over distance. Two graphs presenting these results for the March 2014 and November 2016 events are shown on Figures 22 and 23 respectively.

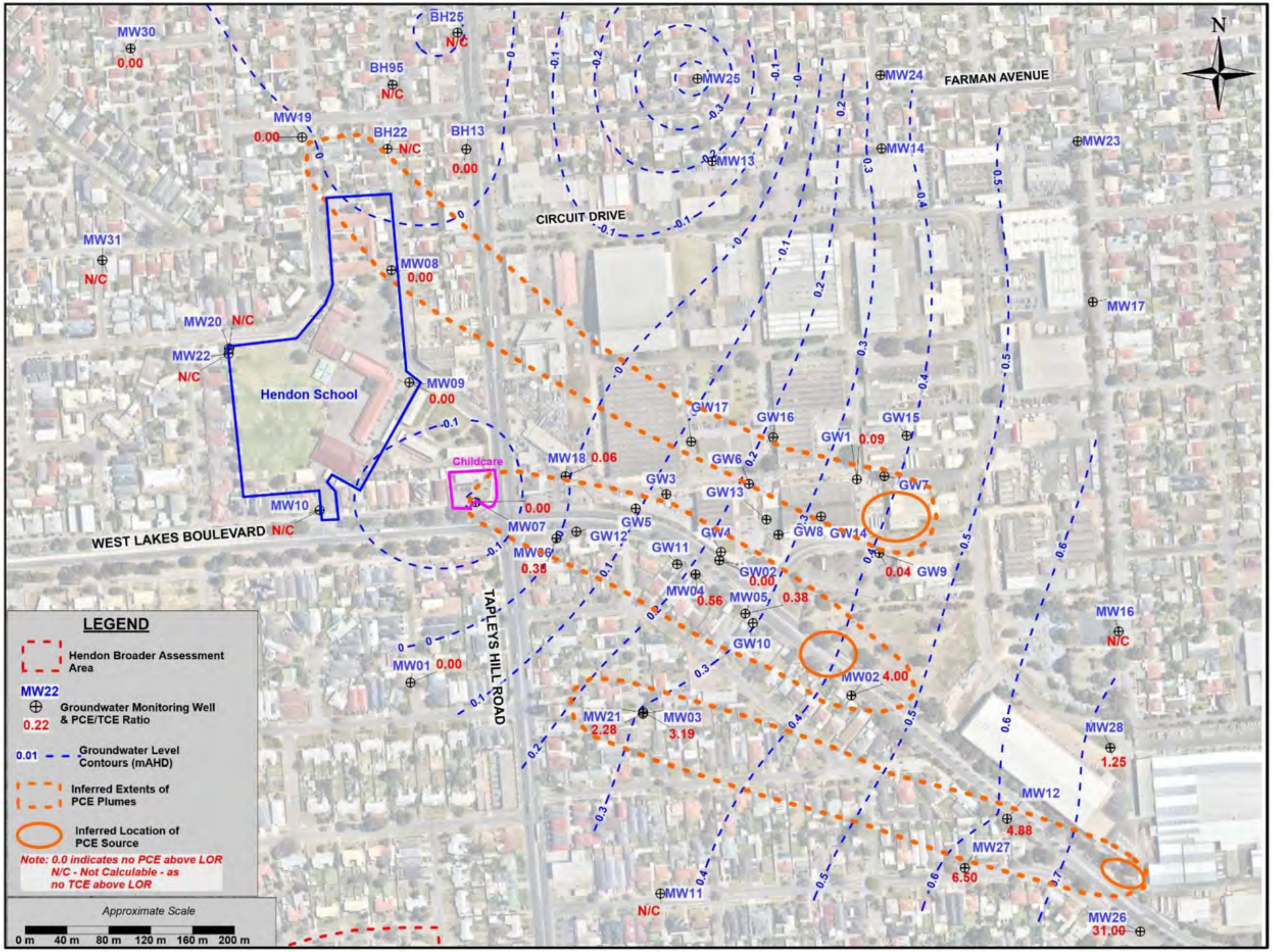


Figure 20 – PCE/TCE Ratio along Inferred PCE Plumes

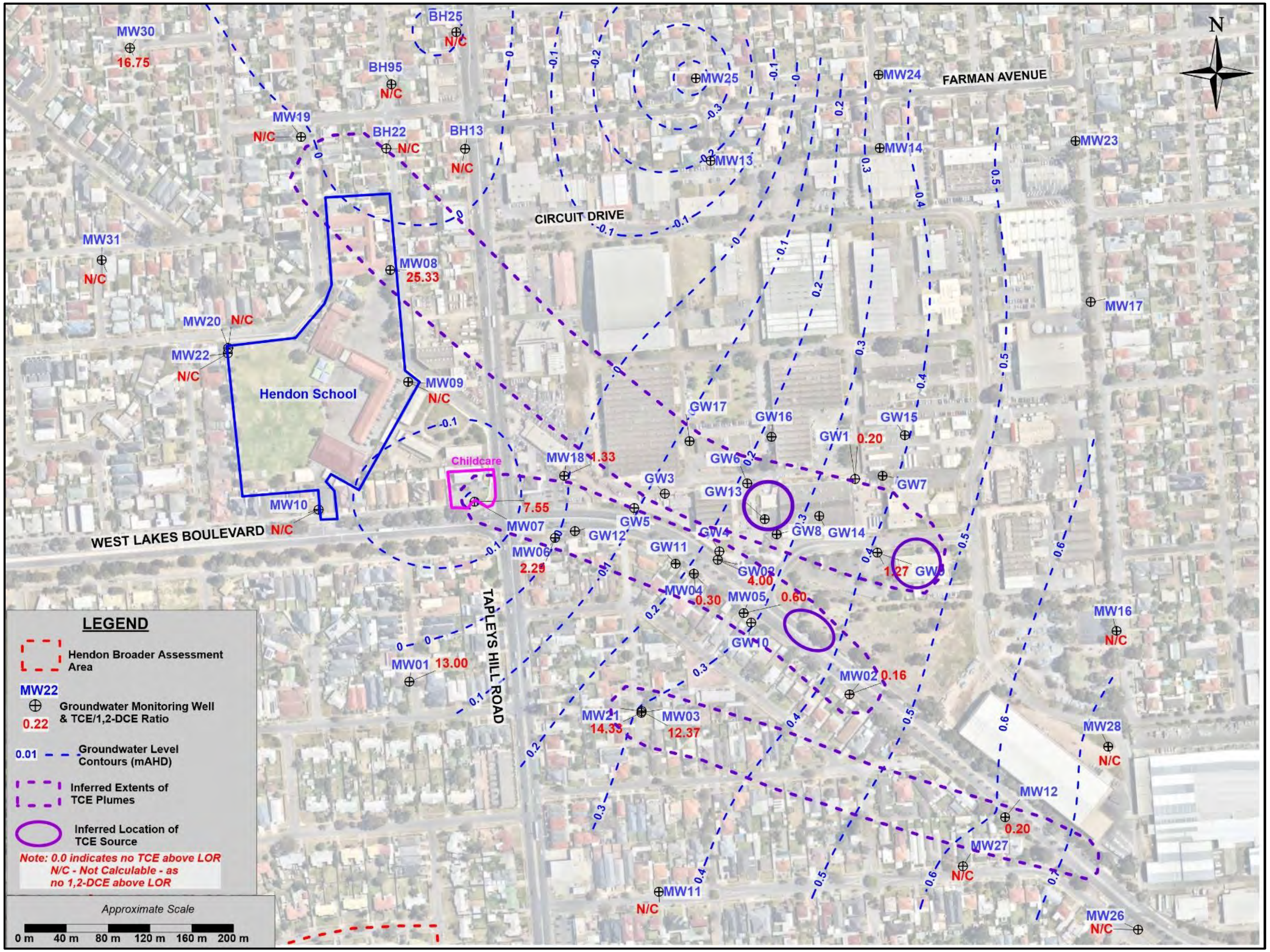


Figure 21 – TCE/1,2-DCE Ratio along Inferred TCE Plumes

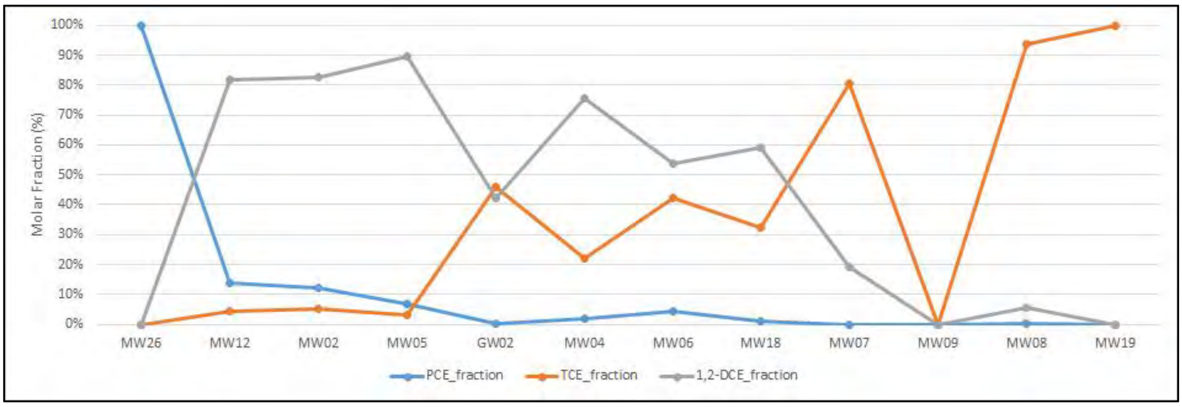


Figure 22 – VCH Molar Fractions (March 2014)

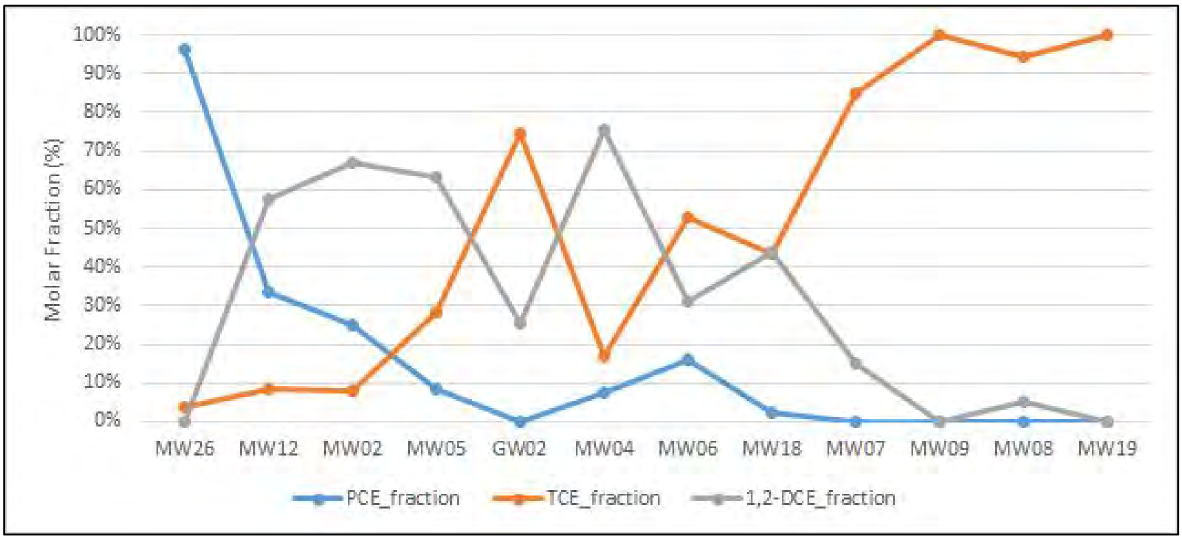


Figure 23 – VCH Molar Fractions (November 2016)

Figures 20 to 23 generally indicate that the parent/daughter product ratios are either stable or increasing from the inferred source areas towards the down gradient edges of the inferred plumes. It is therefore concluded that degradation of PCE is likely to be occurring, however the degradation of TCE and DCE, although it is evident, is unlikely to be occurring at significant rates.

10.0 NUMERICAL MODEL

10.1 Modelling Approach

10.1.1 CSM Summary and Modelling Plan

A summary of the CSM in relation to the construction of the 3D numerical model is provided as follows:

- The geological setting of the HAA is complex. Significant variations in the subsurface material (as presented in the available groundwater well logs) does not enable the boundaries of geological units such as clays and sands to be confidently determined across the HAA. As a result, this cannot be confidently replicated within the 3D model domain.
- Hydraulic conductivity estimates during previous investigations were only conducted for a limited number of wells located to the south-east of Tapleys Hill Road. This indicates that the coverage of these values is not sufficient to enable confident delineation of different hydraulic conductivity zones in the model. In addition, it appears that the distance the inferred plumes has travelled is greater than would be calculated based on the estimated range of hydraulic conductivities (refer Table 17). This means that the actual overall hydraulic conductivity of the impacted uppermost aquifer is likely to be 5 m/day or greater.
- The exact location(s) of the potential sources of groundwater impacts and their dimensions have not been defined sufficiently to enable accurate replication within the numerical model.
- The chlorinated hydrocarbons identified as the primary chemicals of concern (to be assessed by the model) are unlikely to undergo significant degradation/de-chlorination and the overall distribution of the parent and daughter products in groundwater is further complicated by the presence of multiple sources/plumes. This complex situation makes it difficult to model the de-chlorination process with certainty.
- It is understood that the primary role of the 3D numerical model is to assess the potential extents of groundwater contamination in the future (or when plume reaches steady state) and the results of this will be used by the EPA to define boundaries of a GPA.

Based on the above, and as agreed with the EPA during a meeting held on 9 March 2017, the following modelling strategy was developed:

- Each VCH, including PCE, TCE and cis-1,2-DCE, has been modelled individually. Trans-1,2-DCE and VC have not been included due to their rather sporadic distribution and low concentrations reported.
- The sources of contamination have been set to be constant and assigned with maximum concentrations reported since 1992. It is noted that the investigations conducted in 1992 were the first groundwater monitoring events providing information regarding the positions of potential contamination sources. In addition, the reported concentrations of the chlorinated hydrocarbons in groundwater in 1992 are closer to the potential release time and would be more indicative of the actual concentrations at the sources.
- Reactive transport engine (RT3D) have not been used because the de-chlorination of parent VCH compounds into daughter VCH compounds is unlikely to be the dominant process influencing their concentrations in groundwater, which is further complicated by the presence of multiple plumes undergoing various degradation rates. Instead, the use of the Modular Three-dimensional Multispecies Transport engine (MT3DMS) for the simulation of advection and dispersion of contaminants in groundwater systems was agreed to assist in defining the future GPA boundaries.
- The uppermost aquifer has been modelled as a single layer. However, an additional layer for deeper screens was included during model calibration.
- The model domain has been represented by a uniform hydraulic conductivity zone with initial value of 5 m/day. This value was adjusted during the model calibration.
- An influence from the deep sewer main has been modelled by using ‘drain’ boundary conditions in the vicinity of groundwater wells indicated by depressions in groundwater levels.
- A steady state flow model has been constructed.
- Calibration of the flow model has been undertaken to achieve a match between the measured and modelled groundwater levels reported in January 2016. Calibration has been undertaken by varying the hydraulic conductivities and boundary conditions (including the drain boundary which represents the sewer main).

- The VCH contamination sources have been introduced in the model as constant concentration sources as a conservative assumption, and due to the absence of reliable information on the sources locations, dimensions, etc.
- Calibration of the transport model have been undertaken by varying source positions, dimensions and source concentrations, together with plume dispersion, to achieve that modelled concentrations to be similar or higher than reported concentrations. This simulates conservative conditions to assist in defining the GPA boundaries.
- The transport model has been run until the simulated VCH concentrations in groundwater reach steady state conditions.

10.1.2 Objectives

The primary objective of the numerical modelling is to assist the EPA to define the boundary for a proposed GPA, based on the EPA's intention to 'to ensure that the pathway of direct exposure to contaminated groundwater is not realised' between the contaminated plumes and local residents.

10.1.3 Methodology

The methodology for evaluating the groundwater levels and flow, together with the movements of groundwater impacted by VCH within the uppermost aquifer, involves the construction and calibration of a groundwater flow and solute transport model. The model is then used to simulate the migration of the impacted groundwater in the inferred down-hydraulic gradient direction towards the western boundary of HAA. The model elements are discussed in Sections 10.2 to 10.4 below. Screenshots illustrating the selection of model engines, simulation time, run type, solver, layer settings, parameters, etc are provided in Appendix U.

10.1.4 Model Consistency with Guideline

The groundwater model described in this report has been developed as a 'Class 2' model, generally consistent with the Australian Groundwater Modelling Guidelines (Barnett *et. al*., 2012). Descriptions of the model classifications are provided in Appendix V.

10.1.5 Model Coding

The model is a two layer finite difference groundwater flow and solute transport model and has been constructed using the industry standard MODFLOW numerical code. The MODFLOW code operates under the Visual Modflow graphical user interface which supports multiple flow and transport engines including MODFLOW-2000, MODFLOW-2005, SEAWAT, MODPATH, MT3DMS, MT3D99 and RT3D. The model was undertaken using the Visual Modflow Classic (Version 2011.1 Pro).

The model engines selected for the HAA model were MODFLOW2005 for the flow model and default version of MT3DMS for the transport model. In the MT3DMS no reaction codes were included and potential sorption would be modelled using linear isotherm (equilibrium controlled) code (refer Appendix U).

10.2 Model Domain

The model extent covers an area of about 5.5 km east-west and 4 km north-south (Figure 24). The boundaries of the model domain were designed to cover all areas of interest within the HAA with constant head boundary conditions positioned away from the areas of interest to exclude their direct influence on other boundary conditions (such as drains). The grid cell sizes range from 20x20m within the area outside the HAA to 10x10m within the HAA. Intermediate (between 10 and 20m) cell sizes were also used on the boundary of the HAA to minimize model convergence problems. The overall model domain has 366 columns and 258 rows with approximately 94,000 cells.

10.3 Model Layers and Elevations

A two layer model was constructed. The upper surface elevation of the first layer (layer 1) was based on topographic data from Google Earth and data from NatureMaps (https://data.environment.sa.gov.au/NatureMaps/Pages/default.aspx).

The base of layer 1 was set to -1.3 mAHD representing the base of the clayey material (refer Figure 8) land was positioned to include the screened intervals of all shallow wells. The base of the layer 2 was assigned to

-6 mAHD to include the screened intervals of the deep wells (MW21 and MW22). The separation of the uppermost aquifer into two layers was considered appropriate to overcome the transport model limitation to calculate concentrations of chemicals within each model cell and therefore to obtain different concentrations for the deep/shallow pairs of wells (refer Section 1.3).

The section across the model domain from east to west through shallow/deep well pair is shown in Figure 25 together with constant head boundaries. The section across the model domain is through the same well pair but directed from north to south as shown in Figure 26.

10.4 Flow Model

The Flow Model boundary conditions included:

- Constant head boundaries positioned along the eastern and western extents of the model domain.
- The default ‘no-flow’ boundaries along the northern and southern edges of the model.
- Drain boundary conditions positioned at the locations of the deep sewer mains identified in previous reports prepared by PB, URS and AECOM.

The hydraulic conductivity for the model was initially set at 5 m/day across the model domain. Additional lower hydraulic conductivity zones around the drain boundaries were included in the model for calibration purposes based on the cross-section presented in Figure 8. The locations of drains and hydraulic conductivity zones are shown in Figure 27.

Constant heads along the eastern and western boundaries were initially set to be -1.16 mAHD and 1.64 mAHD respectively. The hydraulic conductivity and boundary condition values were adjusted during the flow model calibration. Groundwater levels gauged by AECOM during January 2016 (Figure 10) were used for the flow model calibration.

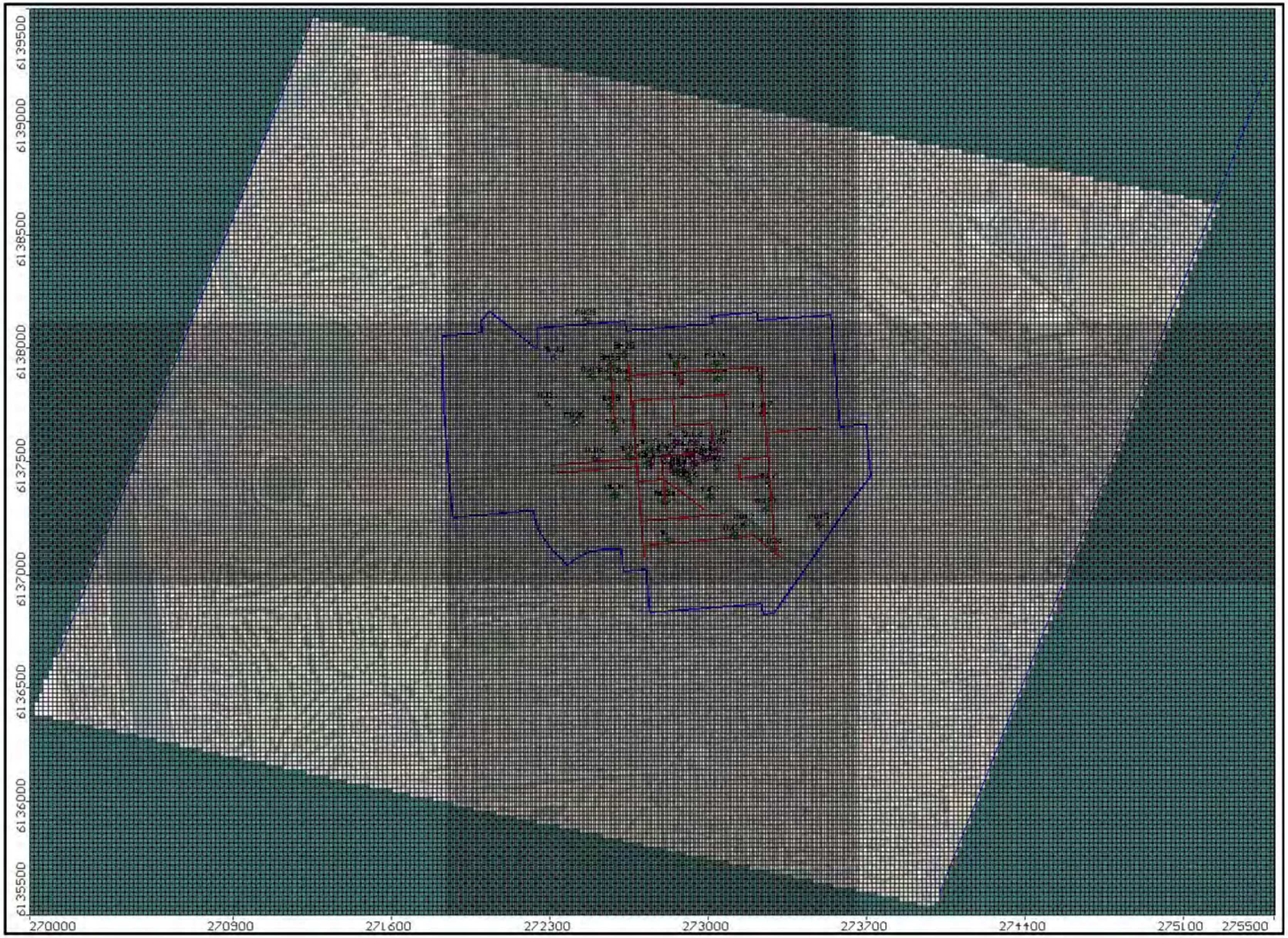


Figure 24 – Model Domain

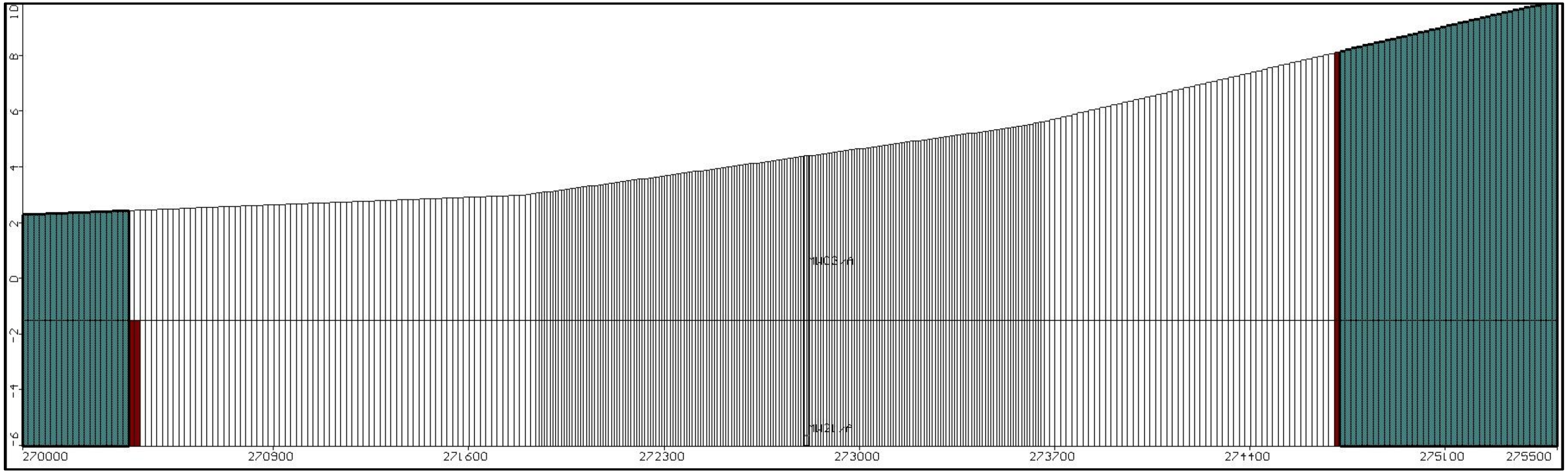


Figure 25 – Model East-West Section

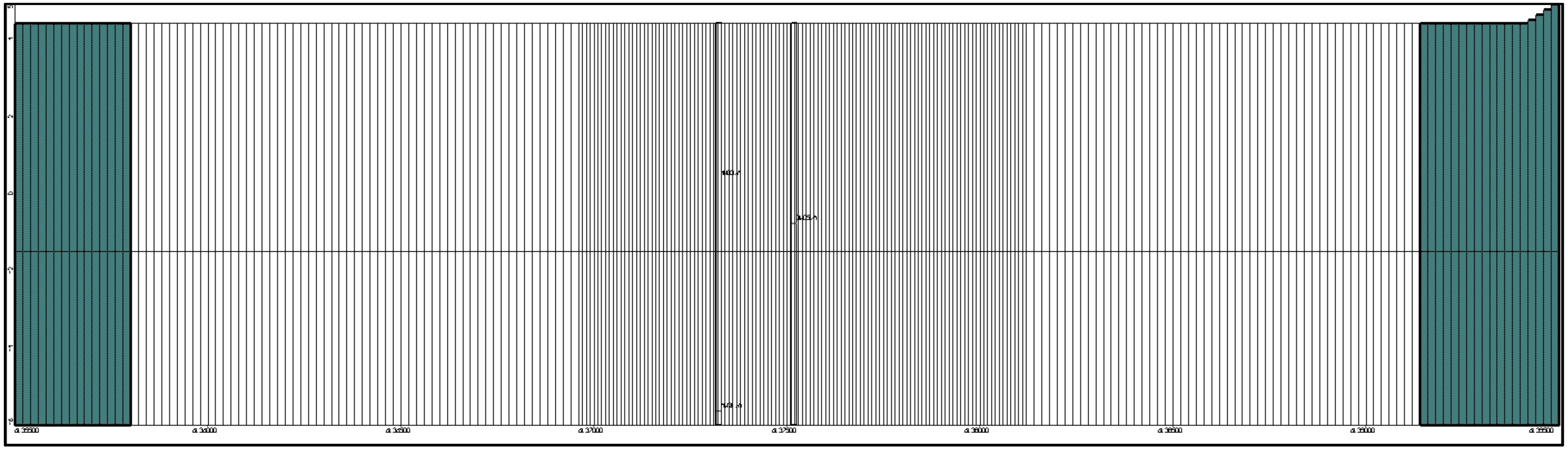


Figure 26 – Model North-South Section

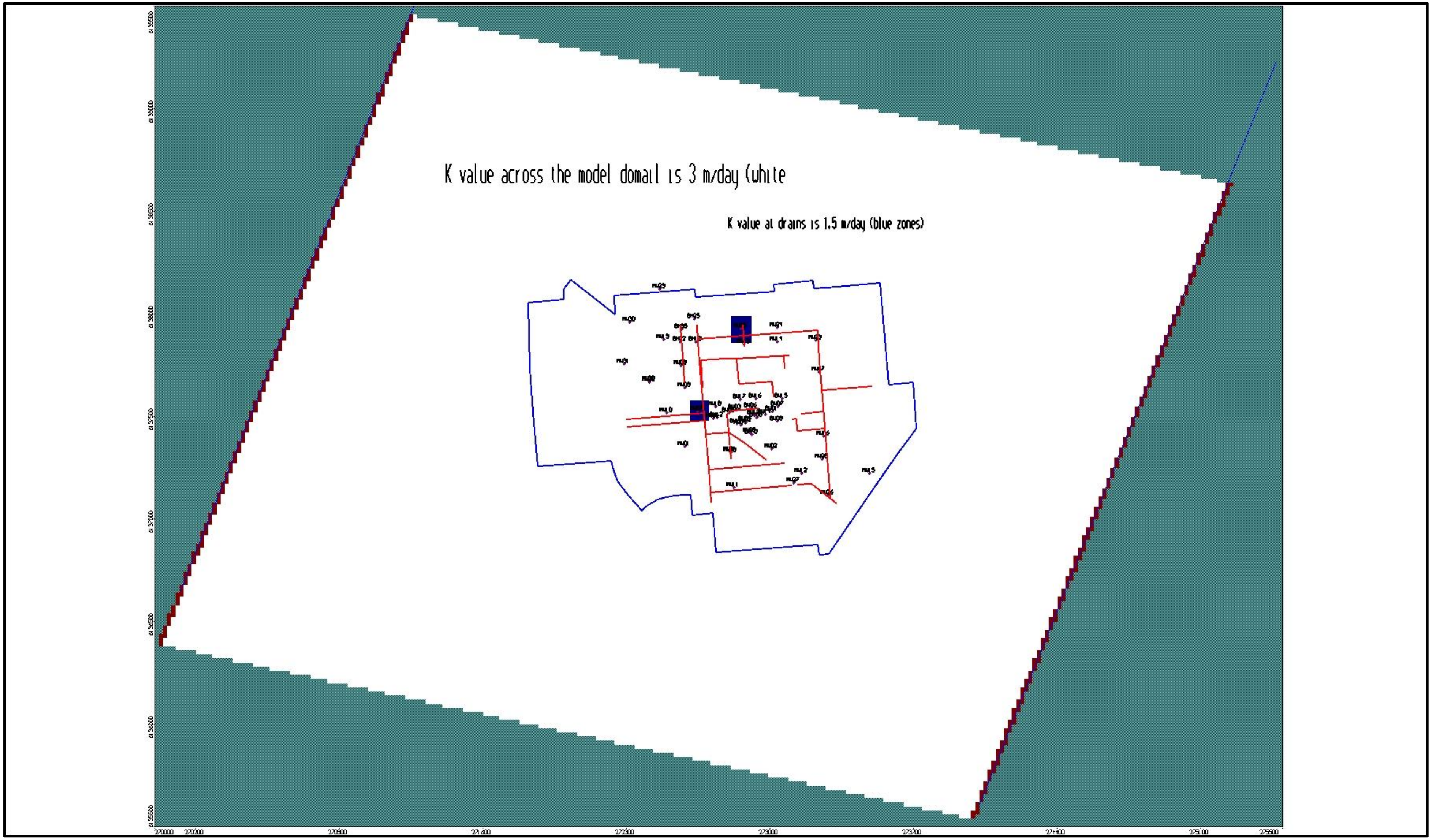


Figure 27 – Hydraulic conductivity zones within the model domain

10.5 Flow Model Calibration

A steady state flow model was constructed to simulate the flow of groundwater from the south east to the north west (refer Section 9.5). Calibration of the flow model was evaluated using a range of methods, as recommended in the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), to achieve model performance criteria and address potential model uniqueness issues. These evaluation methods included:

- The calculation of the Root Mean Squared (RMS) error term, targeting a value of 5% to 10% as an agreed acceptable model calibration error when comparing modelled water level against the observed water levels; and
- Ensuring a model water balance error term of less than 1%.

During the calibration process, adjustments were made to the hydraulic conductivities, boundary condition levels, drain extents and conductance. The calibrated input parameters for the flow model are presented in Table 19.

Table 19 – Flow Model Input Parameters

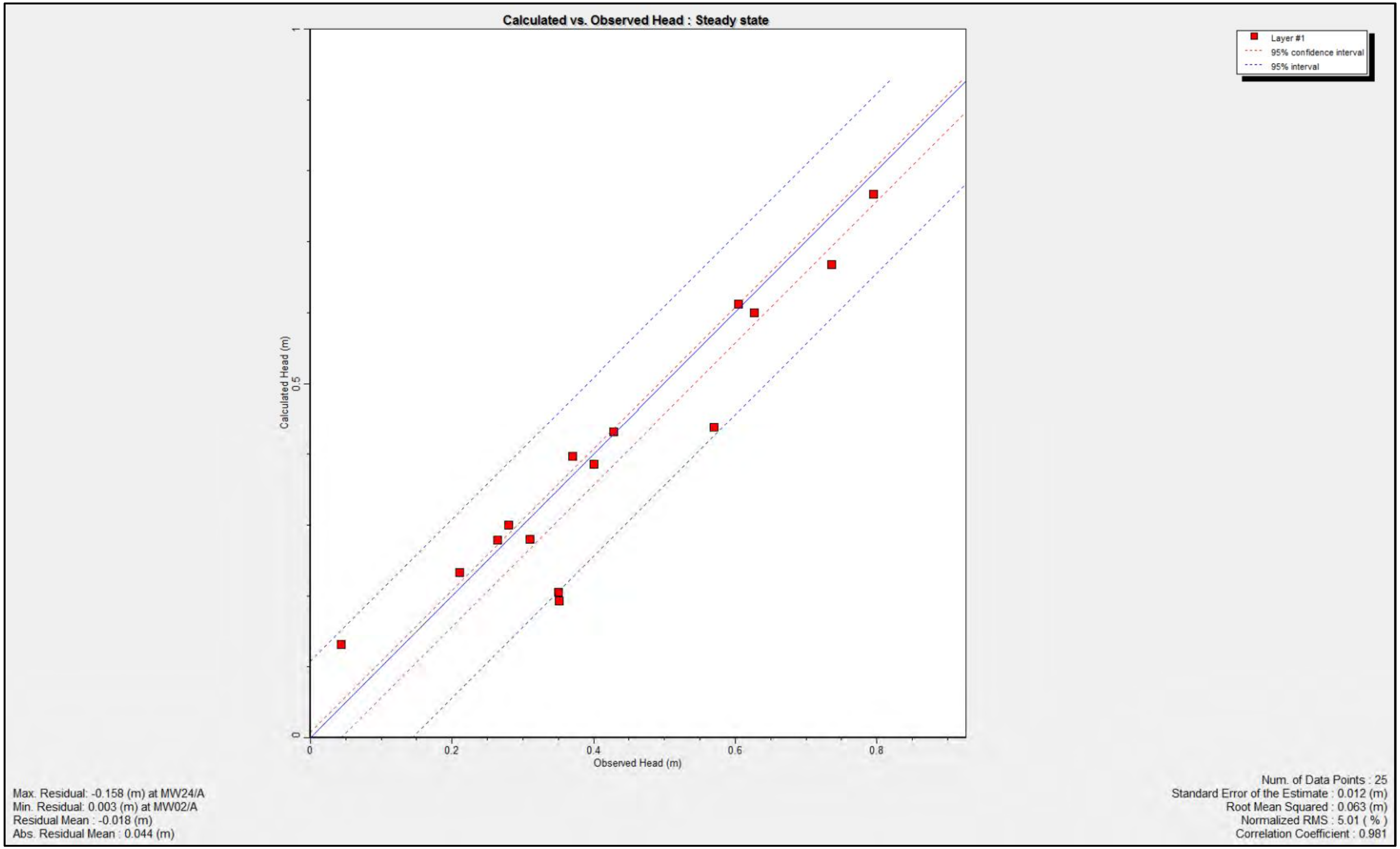
Parameter	Initial	Calibrated
South Eastern Constant Head boundary (mAHD)	1.64	1.98
North Western Constant Head boundary (mAHD)	-1.16	-1.16
Hydraulic Conductivity (m/day) across the model domain	5	3
Hydraulic conductivity at sewer mains (m/day)	3	1.5
Drain boundary conductance (m^2/day) along West Lakes Boulevard (near MW07)	0.8 to 0.9	0.55 to 0.65
Drain elevation ranges (mAHD) along West Lakes Boulevard (near MW07)	-1.091 to -1.150	-1.091 to -1.150
Drain boundary conductance (m^2/day) along Tapleys Hill Road (near MW07)	0.8 to 0.9	0.55 to 0.65
Drain elevation ranges (mAHD) along Tapleys Hill Road (near MW07)	-1.179 to -1.208	-1.179 to -1.208
Drain boundary conductance (m^2/day) along Farman Avenue (near MW25)	1.1 to 1.2	0.69 to 0.8
Drain elevation ranges (mAHD) along Farman Avenue (near MW25)	-1.475 to -1.490	-1.475 to -1.490

It is important to note that only groundwater wells which are considered likely to be a part of the same groundwater system (as discussed in Section 9.4) were used in the flow model calibration. This excludes a number of wells located to the west of Tapleys Hill Road which appear to have been influenced by the presence of the perched water aquifer (Section 9.7).

The acceptable RMS for the calibrated model and observed versus calculated-by-model water levels are shown on Figure 28. Groundwater wells excluded from this calibration graph were BH13, BH22, BH25, BH95, MW20 and MW22 due to the following:

- Groundwater levels in monitoring wells BH13, BH22, BH25 and BH95 are potentially been influenced by the presence of the perched aquifer.
- Groundwater levels in MW20 and MW22 were not consistent with the groundwater levels in the nearby well (refer Figure 8). In addition, the seasonal fluctuation of groundwater levels in these wells was not consistent with the seasonal fluctuation in the majority of the wells (Figure 9, Section 9.4).

Figure 29 presents the AECOM January 2016 groundwater level contours against contours based on the model simulation. This figure shows general consistency between the contour pattern plotted using groundwater level gauging and contour pattern plotted using the groundwater levels simulated by the model.



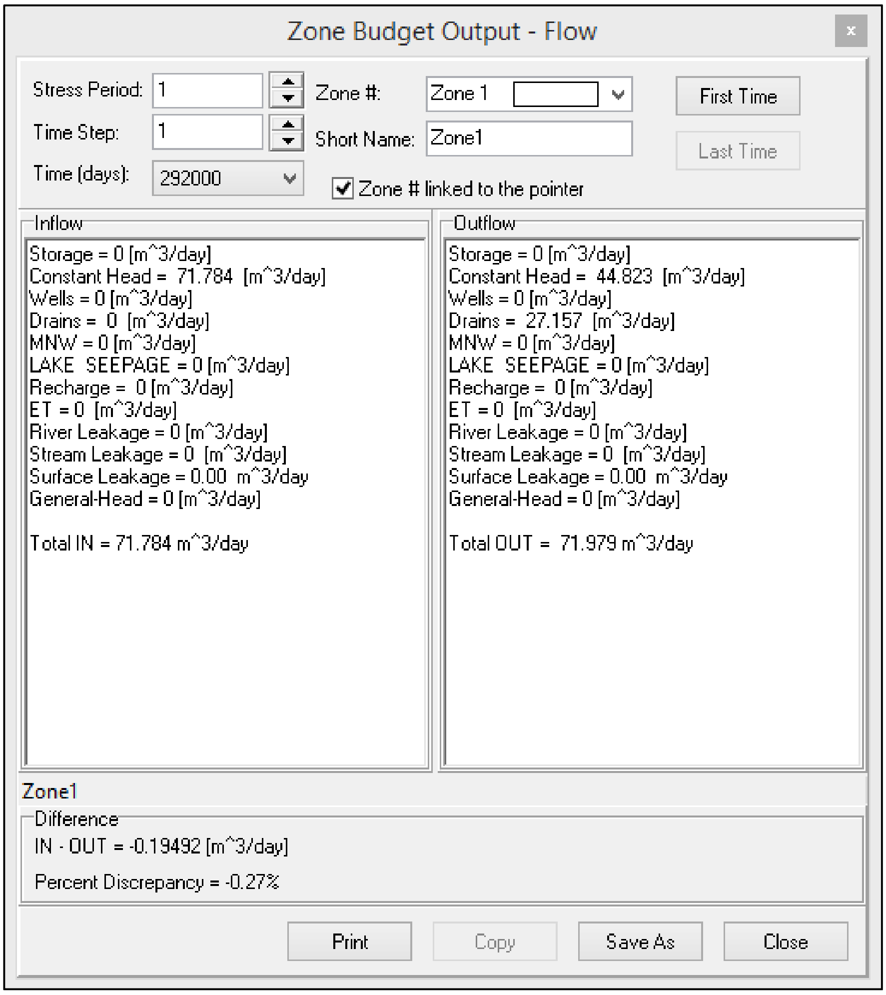
Max. Residual: -0.158 (m) at MW24/A
Min. Residual: 0.003 (m) at MW02/A
Residual Mean : -0.018 (m)
Abs. Residual Mean : 0.044 (m)

Num. of Data Points : 25
Standard Error of the Estimate : 0.012 (m)
Root Mean Squared : 0.063 (m)
Normalized RMS : 5.01 (%)
Correlation Coefficient : 0.981

Figure 28 – Flow Model Calibration Results

Figure 29 – Groundwater Contours – Measured (AECOM 2016) vs Simulated Model

Figure 30 presents the model water balance showing less than 1% error.



Stress Period: 1
Time Step: 1
Time (days): 292000
Zone #: Zone 1
Short Name: Zone1
☑ Zone # linked to the pointer

```
Inflow
Storage = 0 [m^3/day]
Constant Head =  71.784  [m^3/day]
Wells = 0 [m^3/day]
Drains =  0  [m^3/day]
MNW = 0 [m^3/day]
LAKE  SEEPAGE = 0 [m^3/day]
Recharge =  0 [m^3/day]
ET = 0  [m^3/day]
River Leakage = 0 [m^3/day]
Stream Leakage = 0  [m^3/day]
Surface Leakage = 0.00  m^3/day
General-Head = 0 [m^3/day]

Total IN = 71.784 m^3/day
```

```
Outflow
Storage = 0 [m^3/day]
Constant Head =  44.823  [m^3/day]
Wells = 0 [m^3/day]
Drains =  27.157  [m^3/day]
MNW = 0 [m^3/day]
LAKE  SEEPAGE = 0 [m^3/day]
Recharge =  0 [m^3/day]
ET = 0  [m^3/day]
River Leakage = 0 [m^3/day]
Stream Leakage = 0  [m^3/day]
Surface Leakage = 0.00  m^3/day
General-Head = 0 [m^3/day]

Total OUT =  71.979 m^3/day
```

```
Zone1
Difference
IN - OUT = -0.19492 [m^3/day]
Percent Discrepancy = -0.27%
```

Figure 30 – Flow Model Balance

As shown on Figure 30, the model estimates that the groundwater inflow into the sewer main (represented in the model as ‘drains’) would be approximately 27 m^3/day. Some verification for this estimate was undertaken using the results of the sewage sampling conducted by AECOM in March 2016 as discussed below.

The results of investigations showed that the salinity of the sewage effluent increased along the sewer main from south to north, which was considered to be potentially associated with the contribution from the groundwater inflow in the sewer main. Concentrations of chloride were used to estimate the groundwater contribution. Based on the information presented by AECOM, the chloride concentrations increased between SW01 and SW05 from 530 mg/L to 1,630 mg/L, potentially due to the groundwater inflow into the sewer. The chloride concentrations in groundwater along the sewer was determined by AECOM and estimated to be approximately 4,000 mg/L.

Based on the published 2011 census data, the population in the Hendon suburb was 1,373 and the average water use per person was approximately 150 L/day. Estimated from the Hendon suburb boundaries, it has been assumed that approximately one third of the Hendon suburb population would contribute to the sewage flow within the study area, indicating that daily flow through the sewer would be approximately 65 m^3/day or 0.8 L/sec.

The groundwater inflow was calculated using the following equation $V_{gw}=V_{sew}*(Cl_{d/s}-Cl_{u/s})/(Cl_{gw}-Cl_{d/s})$, where V_{gw} – groundwater flow, V_{sew} – sewer flow; $Cl_{d/s}$ – chloride concentrations in sewer downstream; $Cl_{u/s}$ – chloride concentration in sewer upstream; Cl_{gw} chloride concentration in groundwater.

The groundwater inflow rate was calculated to be approximately 30 m^3/day which is similar to the model results of 27 m^3/day (Figure 30).

Based on the RMS and the water balance, it was concluded that the calibration results were appropriate for the model to address its objectives.

10.6 Transport Model

As discussed previously, the chemicals assessed in the model include PCE, TCE and cis-1,2-DCE, given that higher concentrations were reported for these chemicals compared to other VCH such as trans-1,2-DCE and VC (as shown in the attached groundwater result summary tables and discussed in Section 5.4.3).

The transport model was constructed as agreed with the EPA (refer Section 10.1.1) and based on the following assumptions:

- The sources of contamination have been conservatively set to be constant and assigned with maximum concentrations reported in the groundwater wells since 1992.
- The MT3DMS has been used for the simulation of advection and dispersion of contaminants in groundwater systems. No chemical sorption and no reactive transport (degradation PCE and TCE into DCE and VC) has been simulated.
- The aim of the conservative approach to the source of groundwater contamination is to assist in defining the future GPA boundaries (approaching worst case scenario).
- In the transport model, the VCH contamination sources have been introduced as constant concentration sources boundary conditions positioned in the top layer of the model. This is considered to be appropriate because the actual sources of groundwater contamination are/were likely to be located at or near the surface (e.g. leakages from above or underground tanks or loss of chemicals from processing plants (metal plating), etc).
- Due to the absence of reliable information on the actual source locations and dimensions, the positions of the sources have been defined using the highest concentrations in groundwater wells, as well as highest concentrations in the soil vapour monitoring points.
- During the transport model calibration, the source locations/dimensions were varied to achieve a reasonable match between the mapped and simulated plume configuration and extensions. Dispersion values were also be varied to attempt to match the shapes of the mapped and simulated plumes.
- After the calibration, the transport model was run until the simulated VCH concentrations in groundwater reach steady state conditions (i.e. the plumes reached their maximum extents and concentrations under the modelled conditions).
- To minimise the model computing time, a total of nine separate models were constructed (three for each chemical of concern (i.e. three for PCE, three for TCE and three for cis-1,2-DCE)).

The dispersivity values initially assigned in the model were:

- Longitudinal dispersivity – 1 metre.
- 1/10 ratio of Horizontal to Longitudinal Dispersivity.
- 1/100 ratio of Vertical to Longitudinal Dispersivity.
- No molecular diffusion coefficient was considered.

The initial positions of the contamination sources were based on Figures 15 to 17. However, during the initial transport model calibration the positions of these sources and assigned concentrations required some adjustment.

An additional assessment of the potential sources of contamination in groundwater was undertaken for each chemical using the results of the site history assessment conducted by CH2M HILL (CH2M HILL, 2015c) including a 'High Risk Areas of Potential Concern' map (Figure 19) and the results of soil vapour sampling conducted by Greencap and previous consultants.

The VCH modelled are likely to be very persistent in the environment, but may still be degrading naturally. As such, additional research was undertaken to assess natural long term decay of PCE, TCE and DCE. The aim of this research was to ensure that the constant sources in the model are assigned for a conservative but realistic time frame beyond which the existence of the sources would likely to be discontinued.

The results of the additional assessment of the potential sources for each chemical of concern, as well as information relating to natural decay are discussed in the sections below.

10.6.1 Chlorinated Hydrocarbon Half-Lives

A literature review of the half-lives of VCH indicated that the compounds are very stable in the environment but still undergo some natural decay. The half-life values for PCE, TCE and DCE presented in various publically available documents are shown to have quite significant ranges (depending on the environment they are present in).

The document 'Description, Properties, and Degradation of Selected Volatile Organic Compounds Detected in Ground Water — A Review of Selected Literature' prepared by USGS in 2006 presents half-lives for PCE of 3,246 days and for TCE of 1,210 days (refer https://pubs.usgs.gov/of//2006/1338/pdf/ofr2006-1338.pdf) (USGS, 2006a).

However, another USGS document (https://pubs.usgs.gov/sir/2006/5056/section5.html) (USGS, 2006b) suggests that half-lives for abiotic degradation of TCE and DCE may be as long as 108 years (Jeffers and others, 1989). As such, the model has conservatively assumed than no VCH decay occurs, and the modelled source concentrations remain constant for the entire duration of the model run (when plume reaches steady state conditions).

10.6.2 PCE

A plan presenting the approximate location of the high risk areas identified by CH2M HILL (CH2M HILL, 2015c), together with other areas where CH2M HILL identified the potential use of chlorinated hydrocarbons, is presented as Figure 31.

Highly elevated concentrations of PCE were historically reported within groundwater wells GW10 (1,800 µg/L – Coffey, 1992b) and GW07 (3,700 µg/L – Coffey, 1992a). Highly elevated concentrations of PCE were also reported in soil vapour samples at SV01, SV22 and SV31 (refer soil vapour results presented in Table D attached).

The maximum reported PCE concentrations in groundwater, the soil vapour point locations and the inferred locations for potential sources of PCE initially included in the model, are also shown on Figure 31.

It is important to note that although PCE degradation in groundwater was assessed to be occurring (refer Section 9.8.4), the presence of highly elevated concentrations of PCE in soil vapour indicates the potential sources of groundwater impacts may still be active. Therefore, for transport modelling purposes, it has been assumed that the sources of impacts are constant and will not degrade over time.

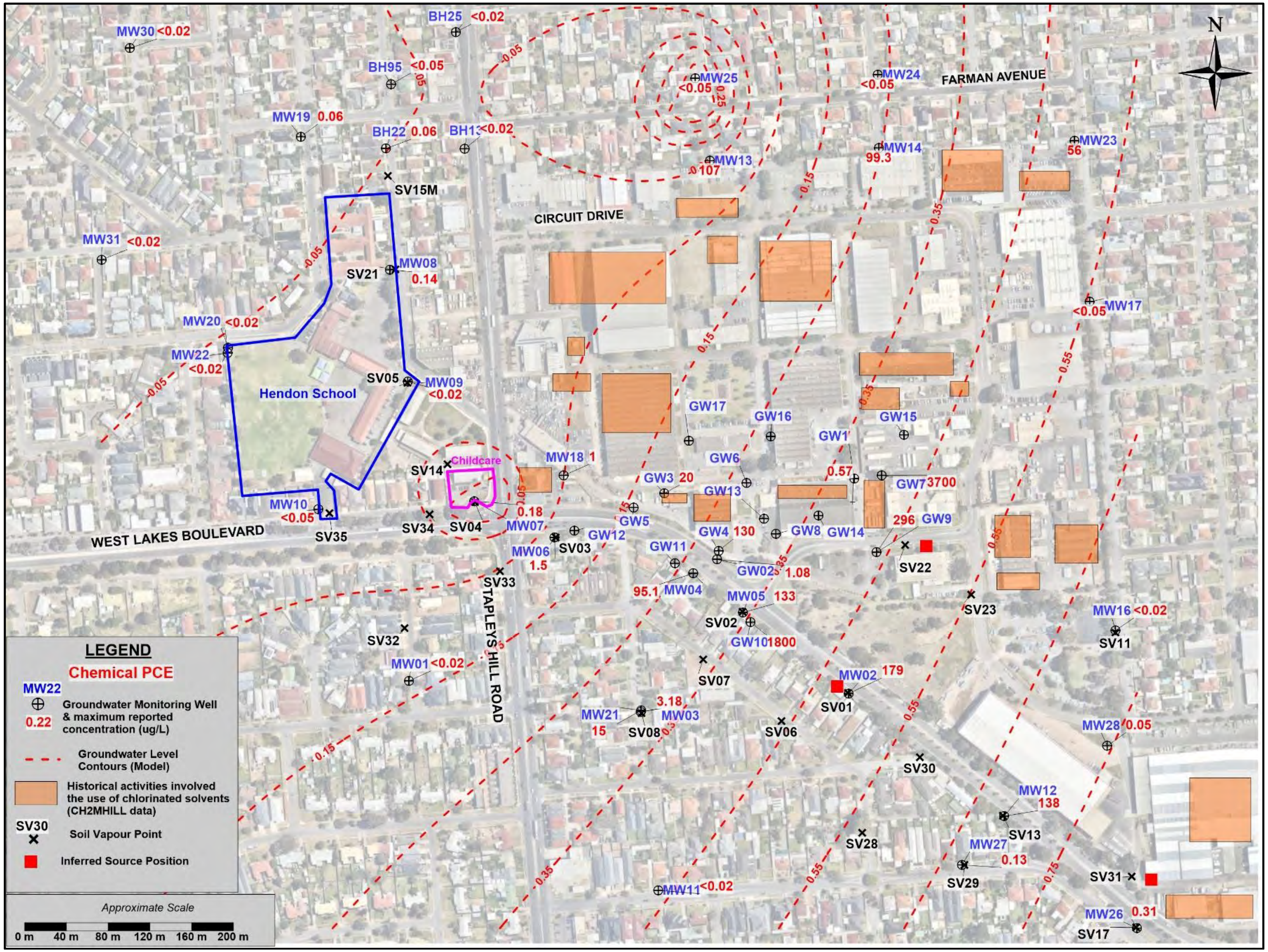


Figure 31 – PCE Sources Adopted for Modelling Purposes

10.6.3 TCE

Highly elevated concentrations of TCE were historically reported from groundwater wells GW06 (2,200 µg/L – Coffey, 1992a), GW10 (710 µg/L – Coffey, 1992b) and GW13 (1,300 µg/L – Coffey, 1992b). During more recent sampling rounds, elevated concentrations of TCE were also reported at GW02 (955 µg/L – 2014 data), GW09 (1,710 µg/L – PB, 2013b), MW07 (780 µg/L – March 2017 sampling round) and MW08 (380 µg/L – AECOM, 2016).

Elevated concentrations of TCE in soil vapour samples were also identified at SV02, SV04, SV21 and SV22 (ranging from 100 µg/m^3 to 25,000 µg/m^3 - refer soil vapour results presented in Table D attached). The maximum reported TCE concentrations in groundwater wells, vapour point locations and the inferred locations for the potential sources of TCE adopted in the model, are shown on Figure 32. The abovementioned maximum groundwater concentrations were assigned as the source concentrations at these locations.

As discussed previously in Section 9.8.4, the degradation of TCE occurs at a very slow rate. Furthermore, the presence of elevated concentrations of TCE in soil vapour indicates the potential sources of groundwater impacts may still be active. Therefore, for the transport modelling, it is assumed that the sources of TCE impacts are constant and will not degrade over time.

10.6.4 cis-1,2-DCE

Highly elevated concentrations of cis-1,2-DCE were historically identified at groundwater wells GW03 (1,600 µg/L – 1992 data), GW06 (6,800 µg/L – 1992 data), GW13 (2,700 µg/L – 1992 data) and GW14 (1,500 µg/L – 1992 data). During more recent sampling rounds, elevated concentrations of DCE were also reported at GW02 (651 µg/L – 2014 data) and GW09 (1,226 µg/L – 2012 data).

Elevated concentrations of DCE in soil vapour samples were also identified at SV13 (ranging from 3,000 µg/m^3 to 12,000 µg/m^3 historically - refer soil vapour results presented in Table D attached). The maximum reported DCE concentrations in groundwater, vapour point locations and the inferred location for the potential sources of DCE included in the model are shown on Figure 33. The abovementioned maximum concentrations were assigned as the source concentrations at these locations.

As with PCE and TCE, constant sources of impacts were assumed for the purposes of transport modelling.

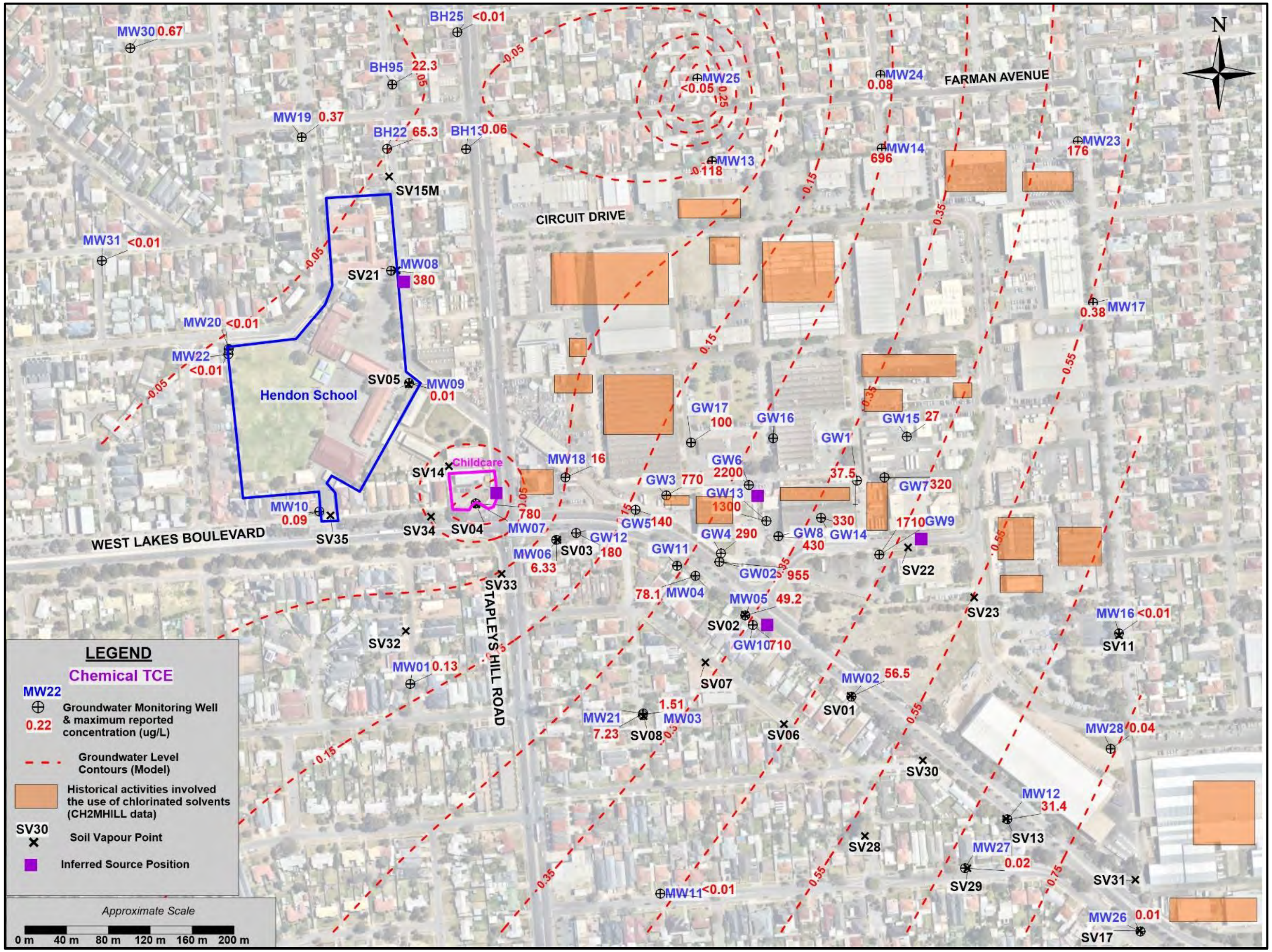


Figure 32 – TCE Sources Adopted for Modelling Purposes

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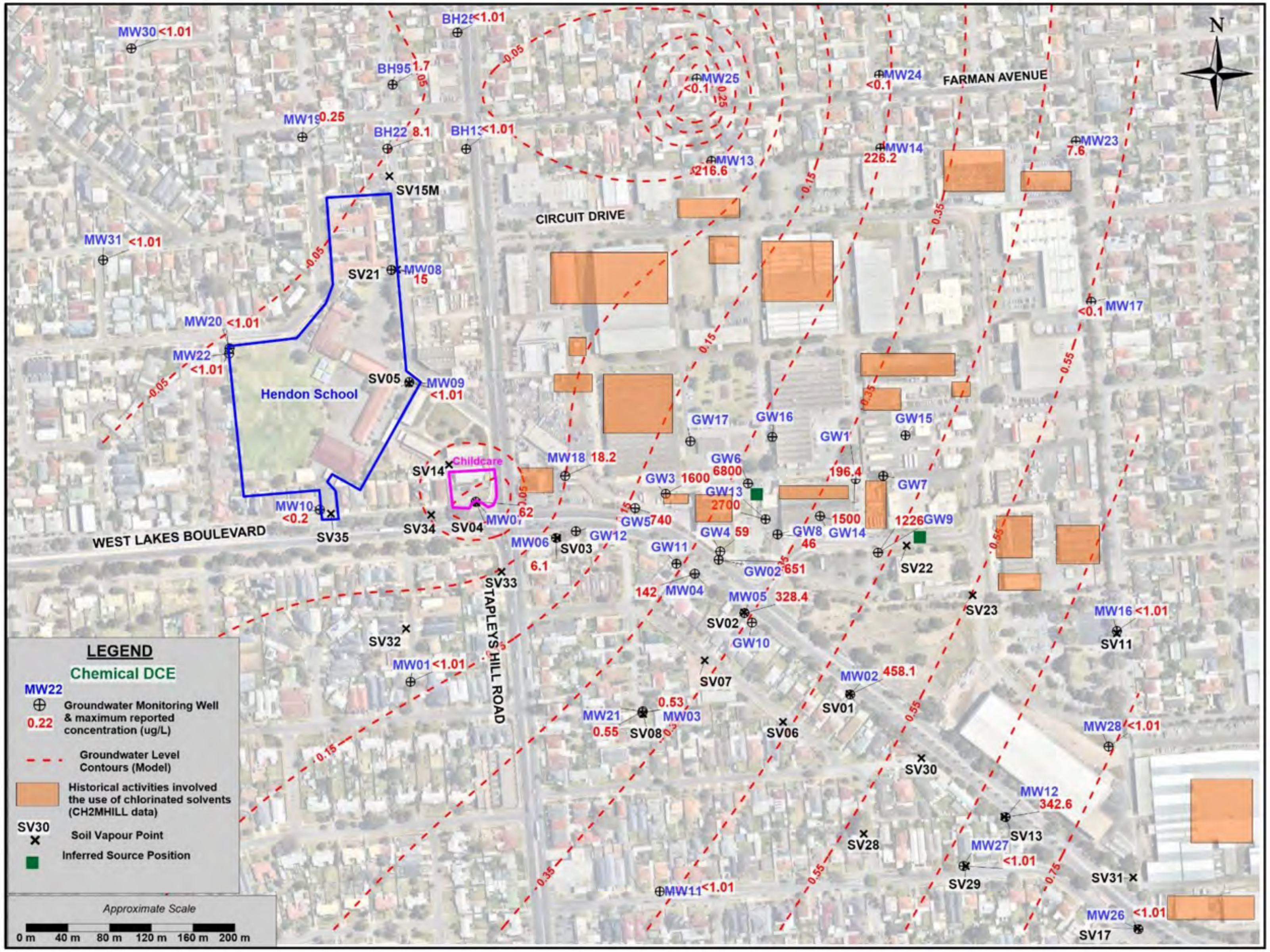


Figure 33 – DCE Sources Adopted for Modelling Purposes

10.7 Transport Model Calibration

Numerous attempts were made to calibrate the concentrations of chemicals of concern along the groundwater flow path, both with and without the influence of the sewer main. The results generally showed that if the sewer main influence was active for decades, significant concentrations of the chemicals of interest may not be able to travel beyond Tapleys Hill Road, along which the sewer main is positioned (Figure 7). Some adjustments were made to the drain surrounds to limit its influence. This involved cutting the modelled extents of the sewer mains and adding lower hydraulic permeability zones around potentially active (i.e. intersecting groundwater flow) parts of the drains.

The locations of the constant sources and initial concentrations were adjusted during model calibration to match (as best as possible) the extents and concentrations of VCH impacts reported at groundwater wells both historically and more recently. It was considered appropriate where the concentrations predicted by the model were similar, or higher than concentrations reported for groundwater samples.

The final concentrations assigned to the sources are illustrated on Figure 34. It should be noted that additional sources of TCE impacts in groundwater were added in the proximity of wells MW07 and MW08. This was undertaken because the model did not predict the identified elevated concentrations at these locations if the inferred TCE sources were only positioned within the HIA to the east of Tapleys Hill Road, due to the influence from the sewer main and the modelled groundwater flow. A review of Google Maps indicates that there are car servicing facilities (e.g. Seaton Crash Repairs) identified in the CH2M HILL Preliminary Site Investigation (PSI) (CH2M HILL, 2015c) as a potential VCH source area.

10.8 Transport Model Results

Each chemical of concern (i.e. PCE, TCE and cis-1,2-DCE) was modelled as a number of constant sources as illustrated in Figure 34. The transport model was run for a duration of 800 years, assessed to be sufficient to observe steady state conditions in the concentrations of chemicals of concern at key well locations. The results of each modelled chemical simulation are discussed below.

10.8.1 PCE results

The PCE plume extents (as simulated by the model), assuming that the groundwater contamination occurred in 1980 within the upper layer of the model where the well screens are positioned is shown on Figure 35. The outer contour represents a PCE concentration of 1 µg/L. As shown on Figure 35, during this period of time (i.e. between 1980 and 2017) the plume has not been significantly influenced by the presence of the sewer main. [Grab your reader's attention with a great quote from the document or use this space to emphasize a key point. To place this text box anywhere on the page, just drag it.]

Figure 36 presents the PCE plume, as simulated if groundwater contamination occurred 1950. Figure 36 shows that the PCE plume reaches MW07, which historically has had traces of PCE. This suggests that the PCE contamination may have occurred early than 1980. The plume shape is notably influenced by the sewer main indicating that the sewer may work as a hydraulic sink. The predicted concentrations are higher than reported concentrations at key wells; GW09, MW02, MW04, MW05 and MW12 (Appendix W), indicating the model is conservative (as was intended) because it does not take into account any PCE degradation at the sources or within the plume area.

Figure 37 shows the PCE plume extent when the model was run for a period of 800 years. Over this period of time, the PCE plume is considered to be at steady state and unlikely to expand any further. The plume extent towards MW30 potentially represents only a small portion of contaminated groundwater which passes the area influenced by groundwater drainage by the sewer. Further investigations in proximity of the sewer mains should be undertaken to evaluate the drainage into the sewer more confidently.

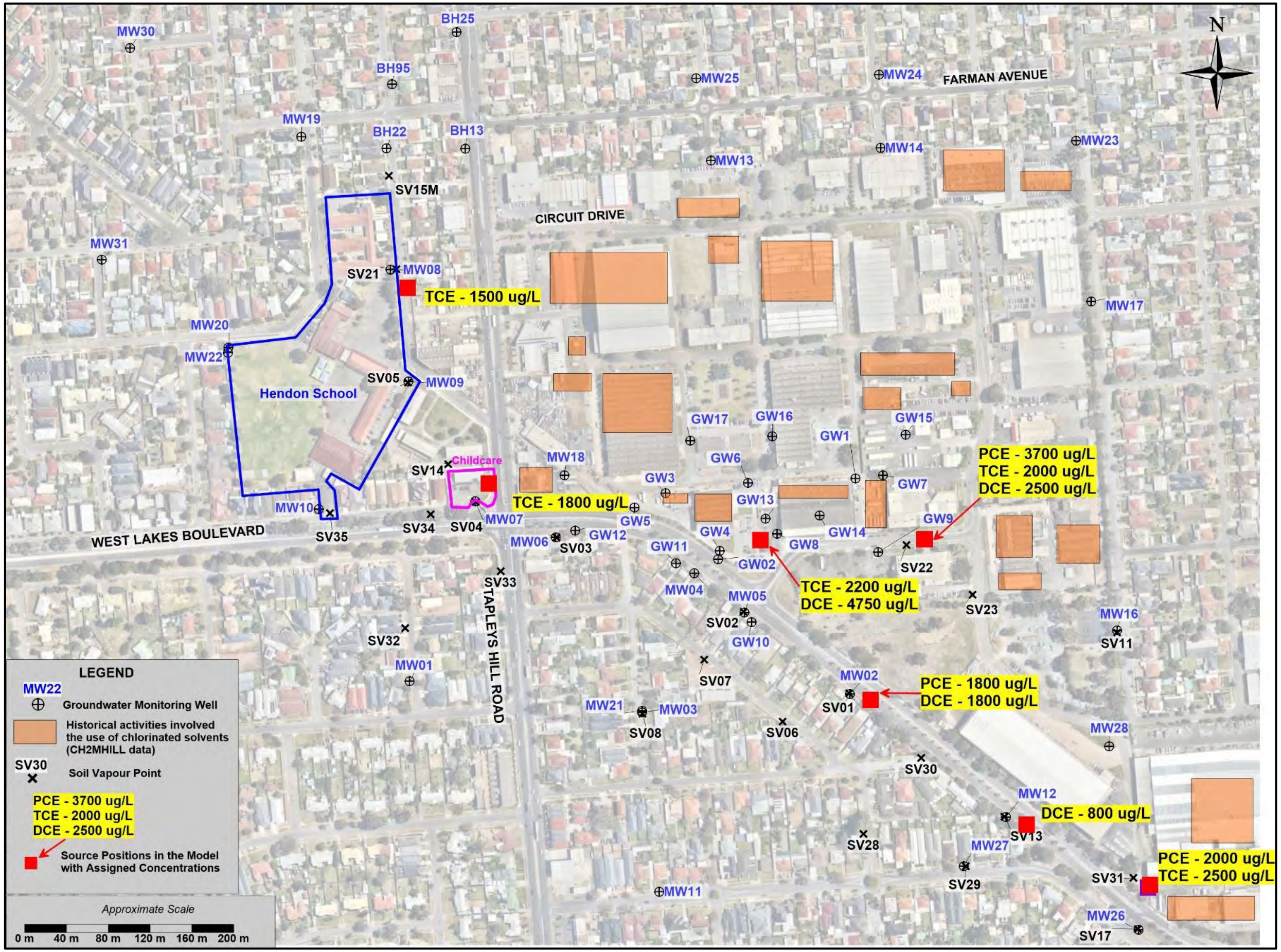


Figure 34 – Constant Source Concentrations

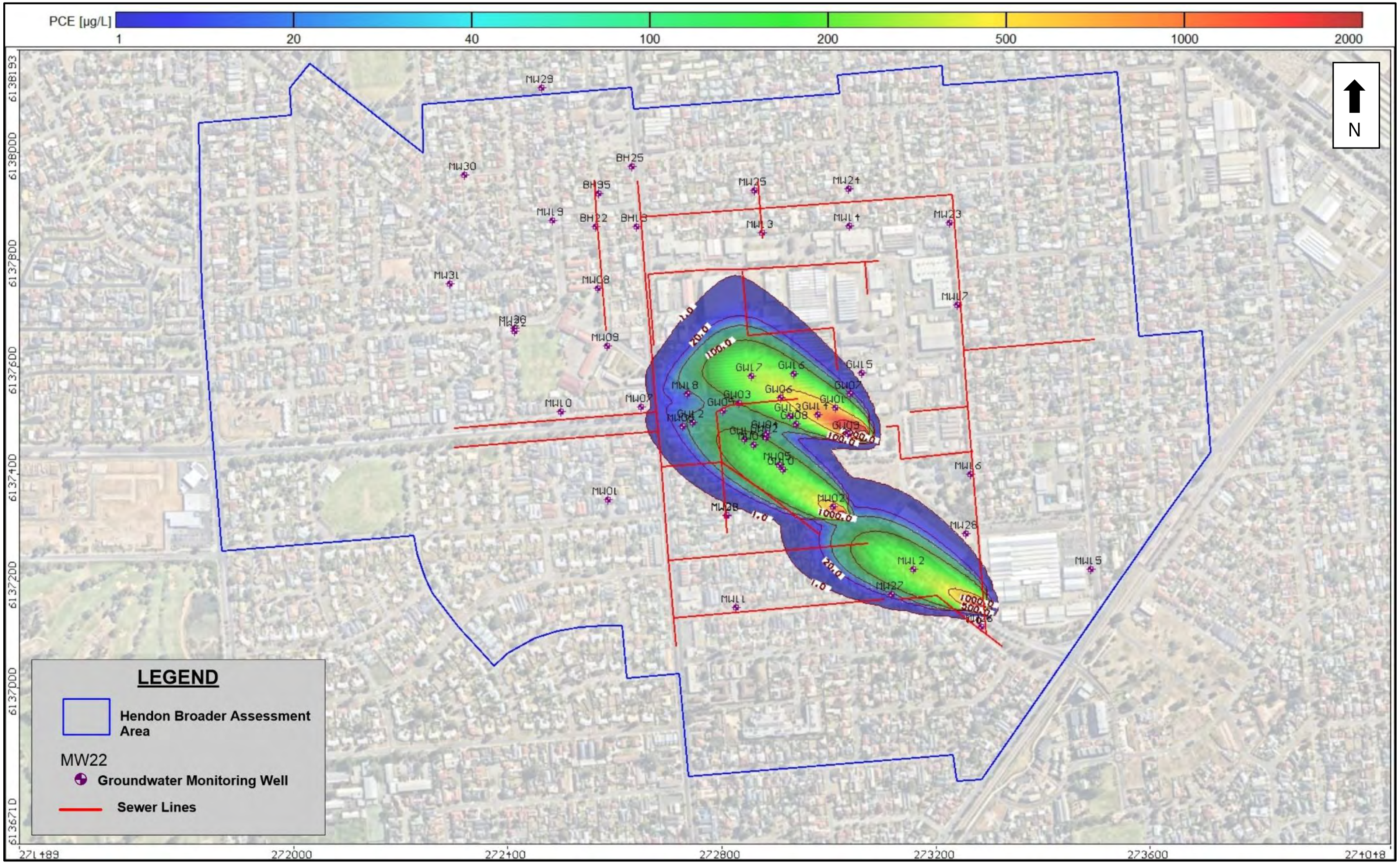


Figure 35 – Simulated PCE Plume 2017 (Contamination Occurred in 1980)

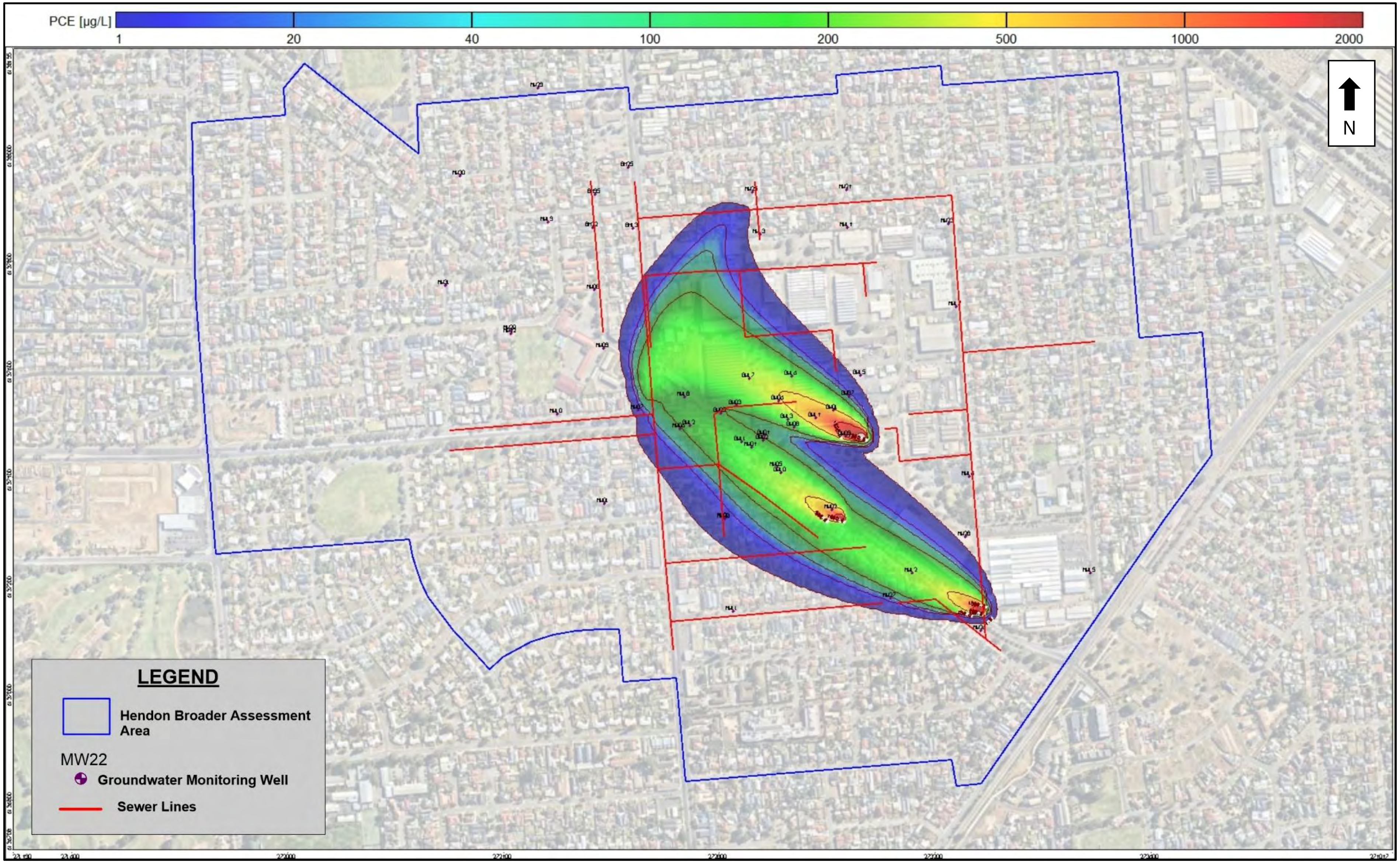


Figure 36 – Simulated PCE Plume 2017 (Contamination Occurred in 1950)

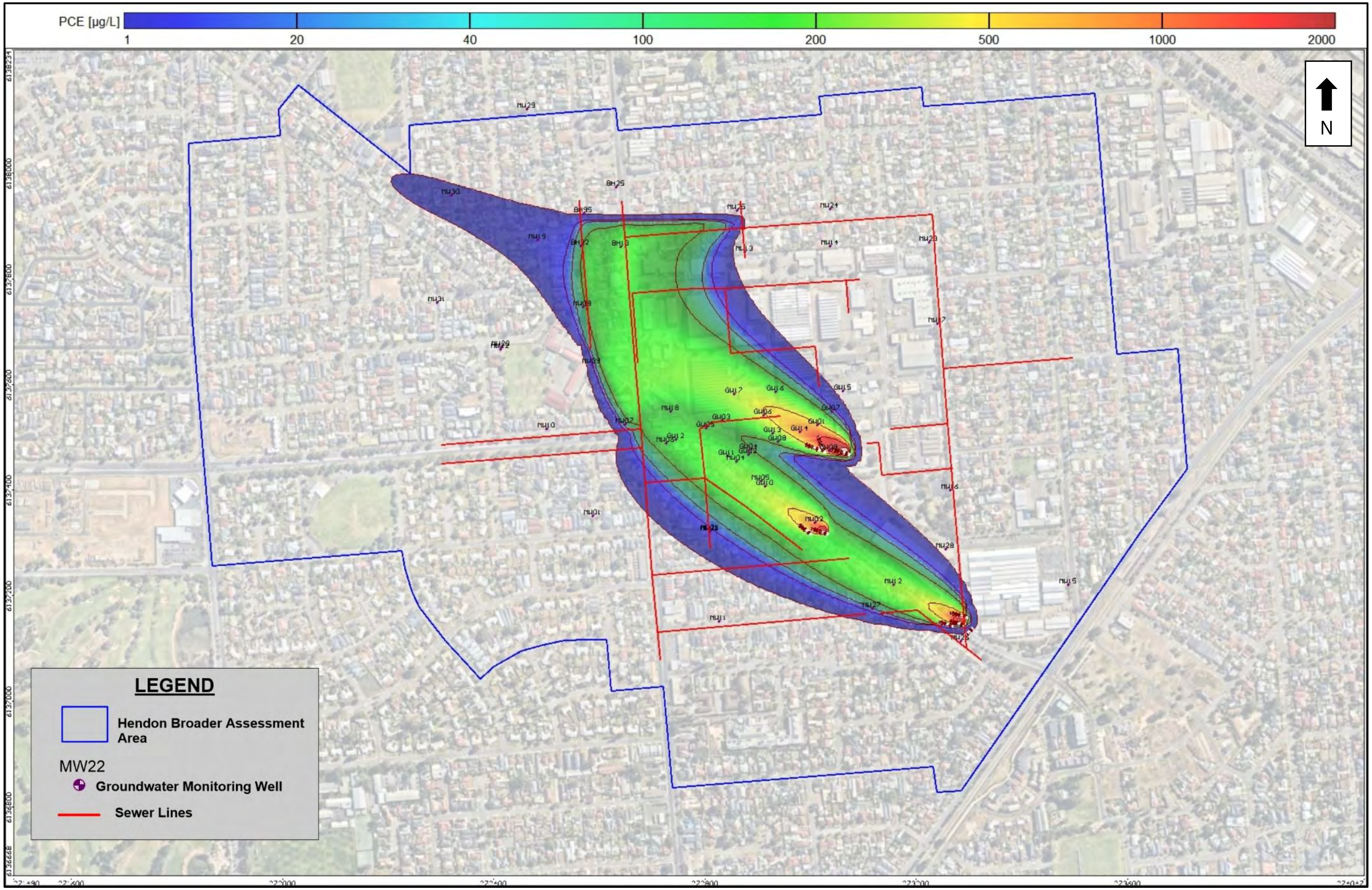


Figure 37 – Simulated PCE Plume after 800 years

10.8.2 TCE results

The TCE plume extents as simulated by the model), assuming that the groundwater contamination occurred in 1980 within the upper layer of the model where the well screens are positioned is shown on Figure 38. The outer contour represents the TCE concentration of 1 µg/L. The model predicts multiple plumes from different sources, as shown on Figure 34. The plume(s) over this period of time have not been significantly influenced by the presence of the sewer mains. The predicted concentrations at MW07 and MW08 are a result of the additional sources placed in the vicinity of these wells (for calibration purposes only). However, the presence of these sources may exist if no preferential pathways to facilitate TCE migration from the HIA are present. To confirm this, or otherwise, additional investigation at these areas would be necessary.

Figure 39 presents the TCE plume, as simulated if groundwater contamination occurred in 1950. Figure 39 shows that there is a gap between the main plumes emerging from the HIA to the east of Tapleys Hill Road and the plume at the location of MW08 (considered in the model to be associated with a different source). The TCE plume is shown to migrate towards MW09 (where traces of TCE were reported in November 2016) which further suggests that the TCE contamination potentially started early than 1980. Similarly to the PCE plume, the shape of the TCE plume is notably influenced by the sewer mians indicating that the sewer may work as a hydraulic sink.

The concentrations were predicted to be higher than reported concentrations at key wells; MW02, MW04, MW05, MW12 and MW18 (Appendix X), indicating the model is conservative (as was intended) because it does not take into account any degradation of TCE at the sources or along the length of the plume.

The predicted concentrations at MW07 and MW08 show steady state TCE concentrations at levels similar or above the reported concentrations at these wells indicating there is potential for additional groundwater contamination sources in their vicinity.

Figure 40 shows the TCE plume extent when the model was run for a period of 800 years. Over this period, the TCE plume is considered to be at steady state and unlikely to expand any further. The tongue like plume extent towards MW30 potentially represents only a small portion of contaminated groundwater which passes the area influenced by groundwater drainage by the sewer main.

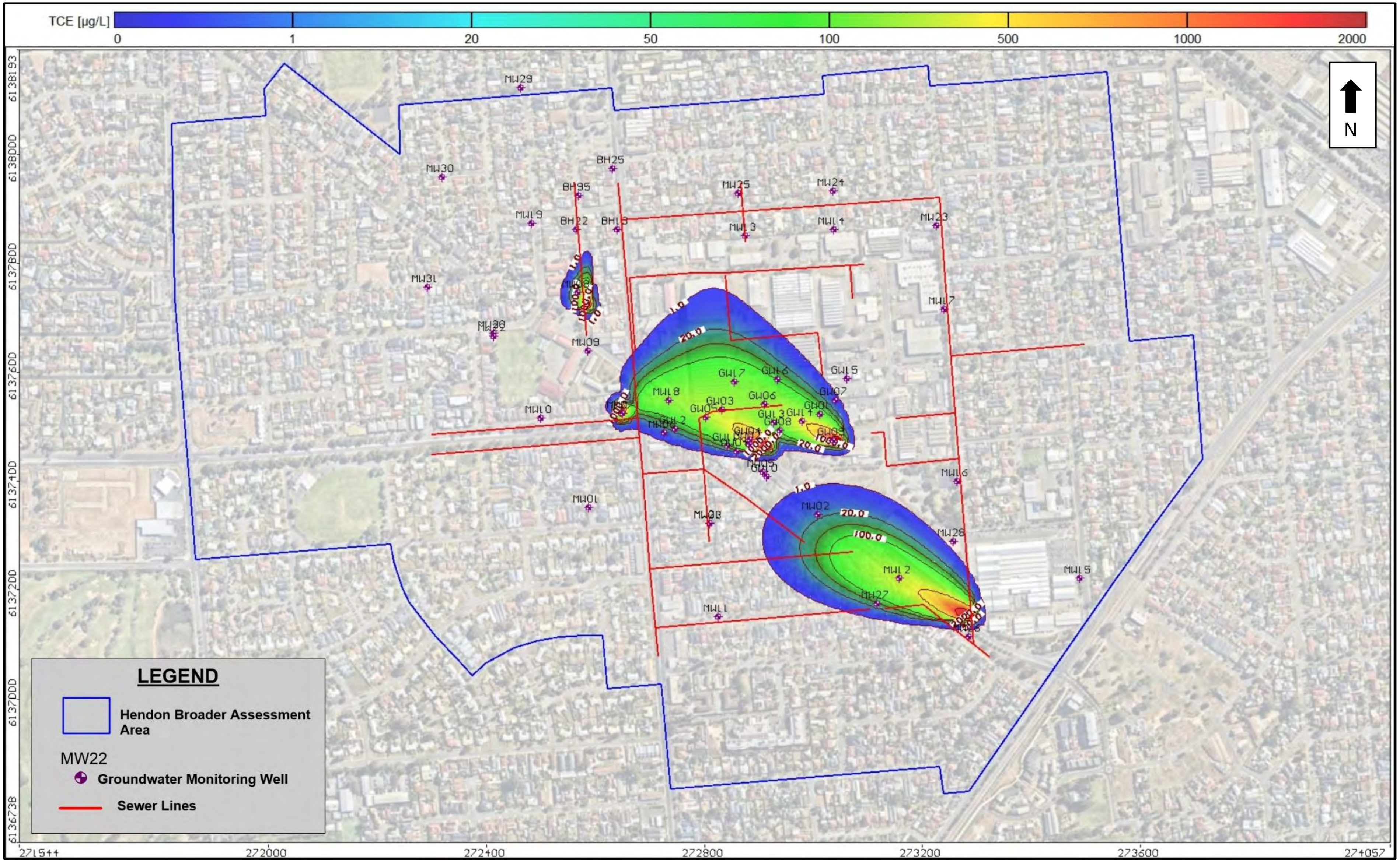


Figure 38 – Simulated TCE Plume (Contamination Occurred in 1980)

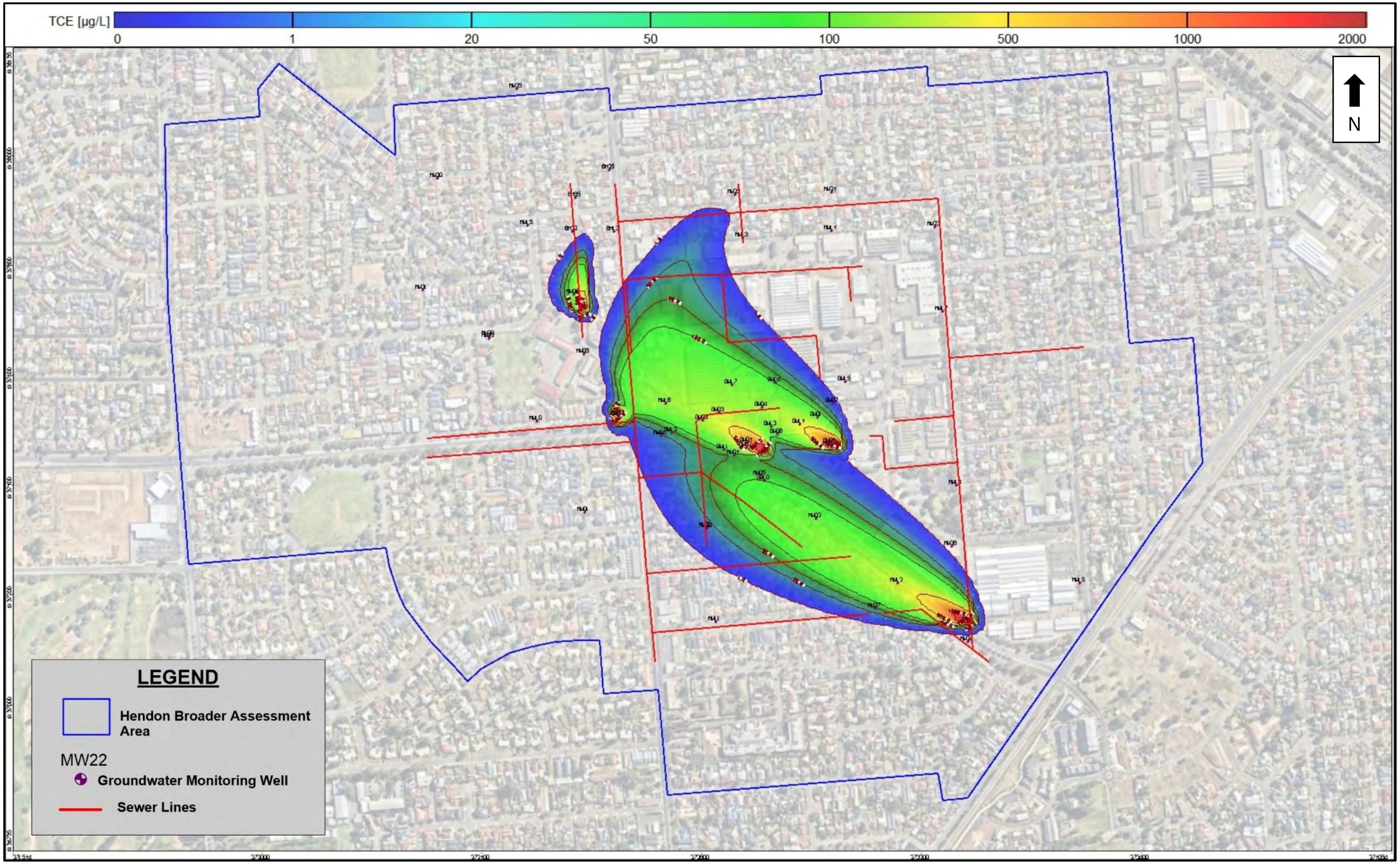


Figure 39 – Simulated TCE Plume (Contamination Occurred in 1950)

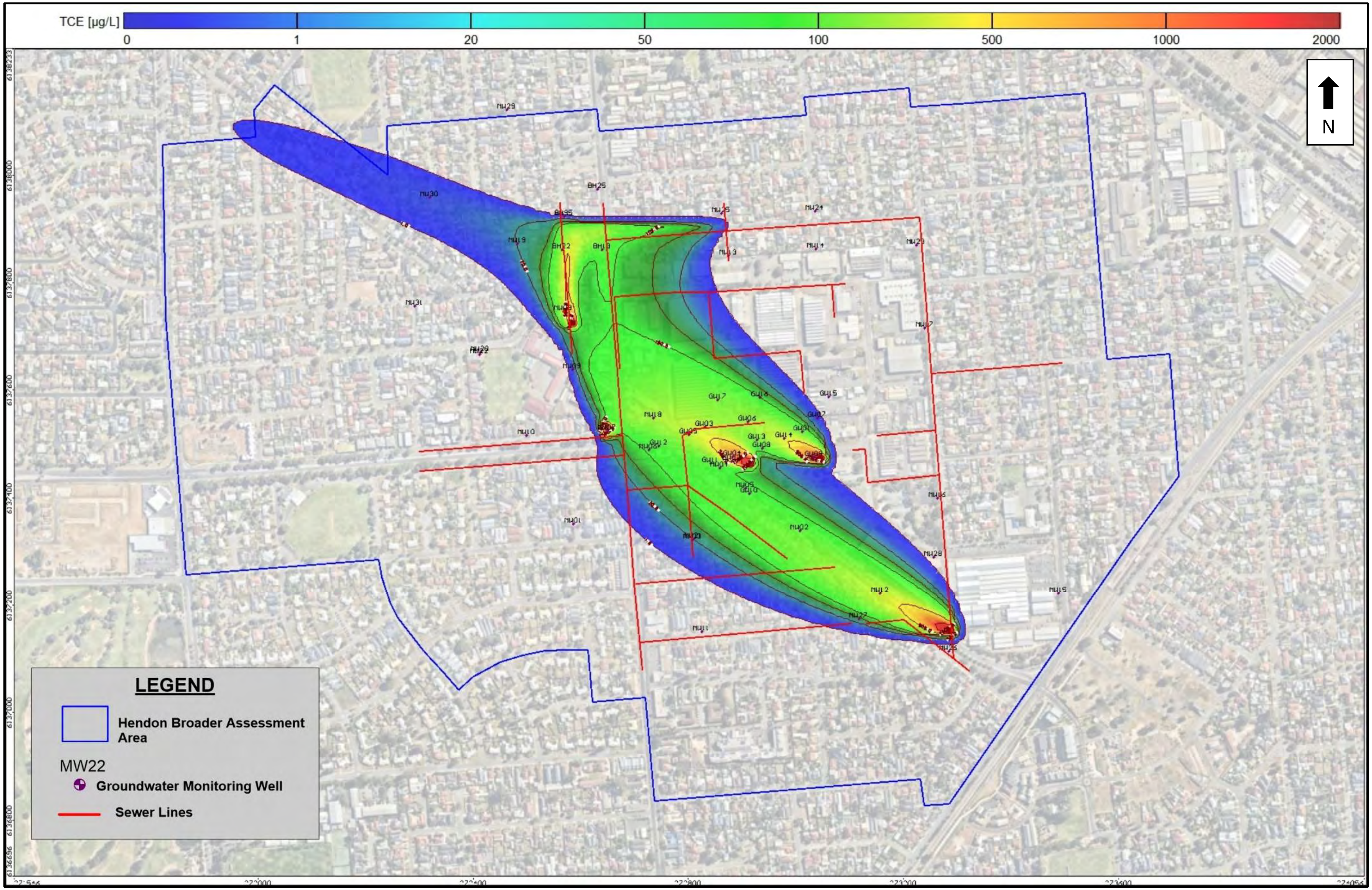


Figure 40 – Simulated TCE Plume after 800 years

10.8.3 DCE results

The cis-1,2-DCE plume extents (as simulated by the model) assuming that the groundwater contamination occurred in 1980 within the upper layer of the model where the well screens are positioned is shown on Figure 41. The outer contour represents the cis-1,2-DCE concentration of 1 µg/L. The model predicted multiple plumes from different sources (Figure 34). The plume over this period of time has not been significantly influenced by the presence of the sewer mains.

Figure 42 presents the cis-1,2-DCE plume, as simulated if groundwater contamination occurred in 1950. Figure 42 shows that the DCE plume has not reached the location of MW08 after 70 years where up to 15 µg/L of cis-1,2-DCE was reported. Considering the presence of potential sources of VCH compounds along the northern border of the HIA (identified by CH2M HILL in their PSI report (CH2M HILL, 2015c)) the concentrations of cis-1,2-DCE may be a result of additional plumes emerging from the northern area, which was excluded from the approved scope of work for this project. After running the model for 70 years, the model predicted the presence of DCE concentrations at MW07 which is supported by the groundwater sampling results (refer groundwater results presented in Table A attached) and indicates that the source release of contamination impacting groundwater occurred earlier than 1980.

The DCE concentrations were predicted to be very close to the maximum reported values (or slightly higher than reported concentrations) at key wells; GW01, GW02, GW09, MW02, MW04, MW05, MW12 and MW18 (Appendix Y), indicating the model is conservative because it does not take into account any degradation of DCE at the source(s) or along the length of the plume .

The DCE concentration at MW07 was predicted by the model to be lower than the actual concentration reported recently at this location, indicating the potential for an additional source in the vicinity, as discussed for TCE in Section 10.8.2.

The simulated concentration at MW08 was predicted by the model to occur at a later time (after 2100) as a result of the plume migration from the HIA. This suggests that there may be an additional contamination source in the vicinity of this location, as mentioned above.

Figure 43 shows the DCE plume extent when the model was run for a period of 800 years. Over this period, the DCE plume is considered to be at steady state and unlikely to expand any further. The tongue like plume extent towards MW30 potentially represents only a small portion of contaminated groundwater which passes the area influenced by groundwater drainage by the sewer similar to the predicted TCE and PCE plumes.

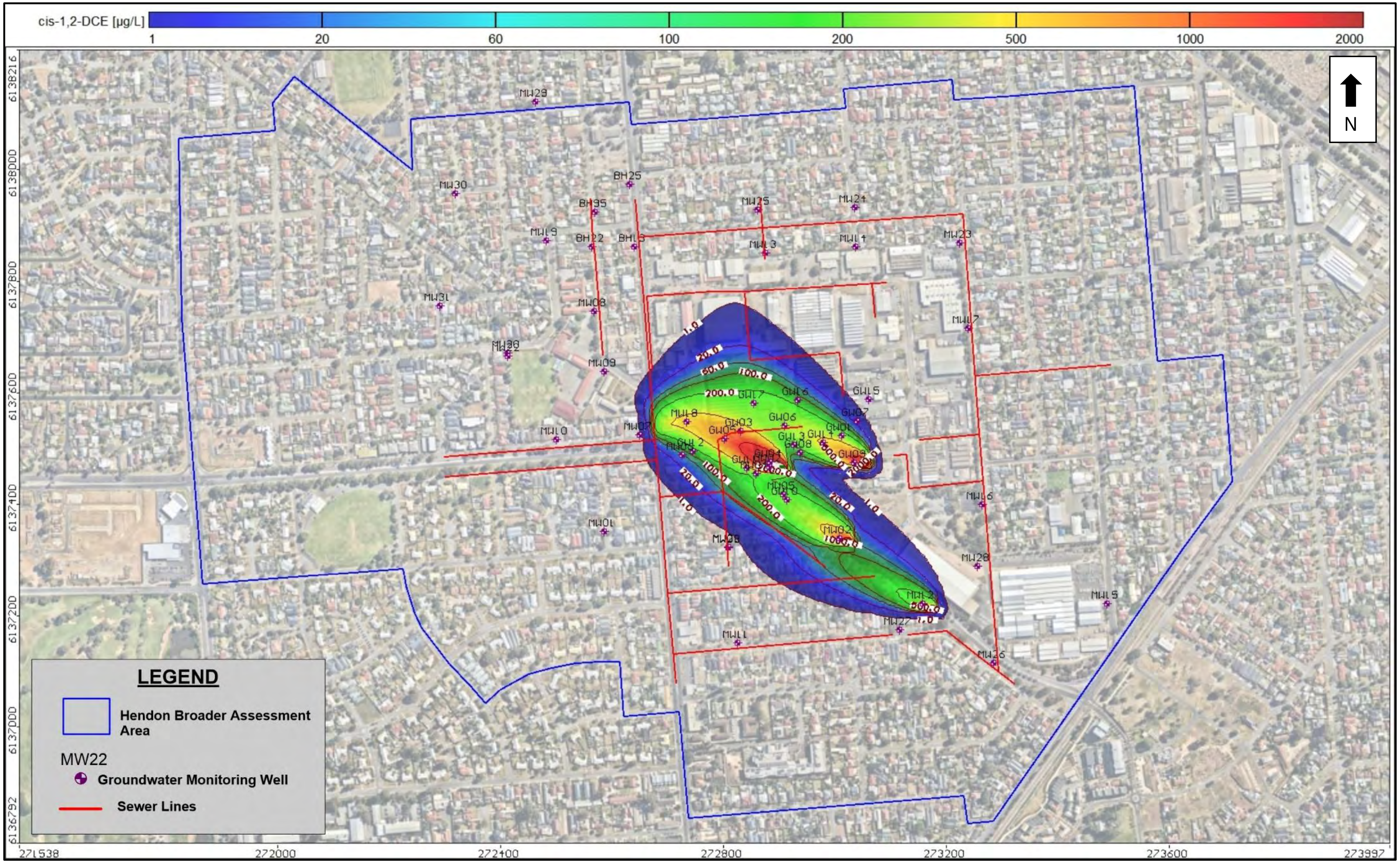


Figure 41 – Simulated cis-1,2-DCE Plume 2017 (Contamination Occurred in 1980)

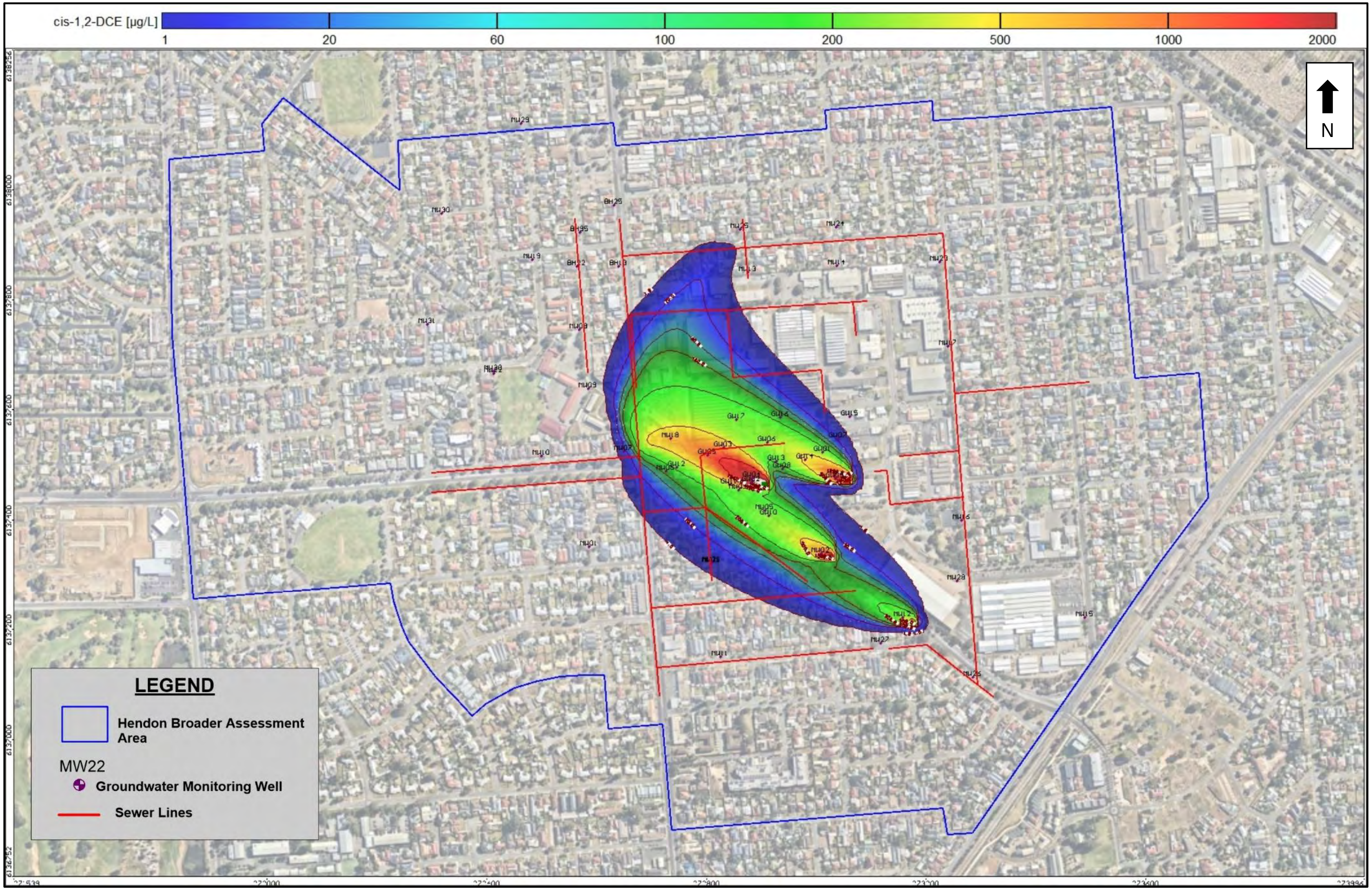


Figure 42 – Simulated cis-1,2-DCE Plume 2017 (Contamination Occurred in 1950)

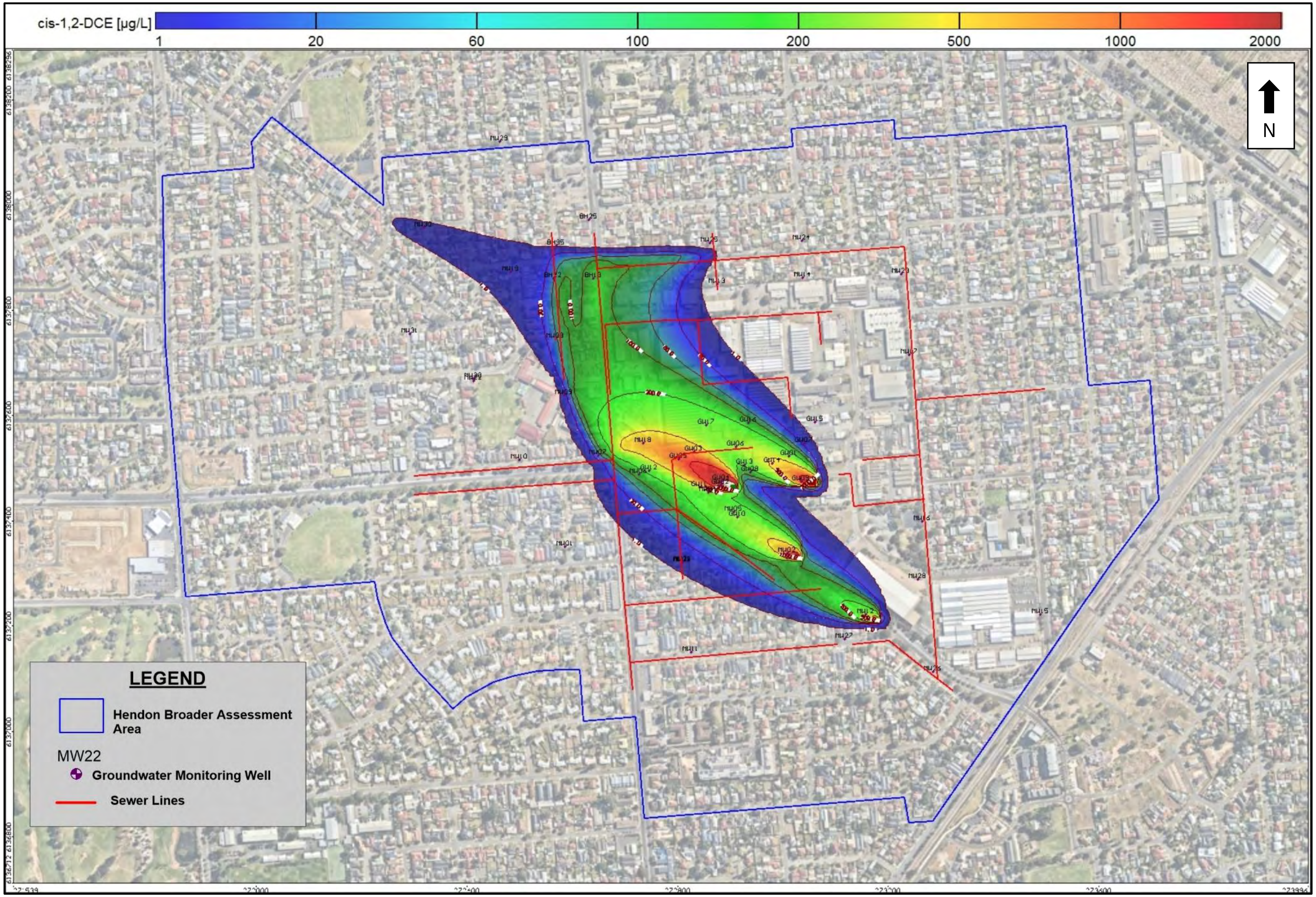


Figure 43 – Simulated cis-1,2-DCE Plume after 800 years

10.9 Model Sensitivity Analysis

10.9.1 Flow Model

The major steady state flow model parameters include constant head boundaries, hydraulic conductivity and the drain boundary associated with the sewer main. All of these parameters were estimated initially (i.e were only partially based on the field measurements) and calibrated during the modelling to achieve a reasonable match between the gauged and simulated groundwater levels. This indicates that all of these parameters are very sensitive to the model outcomes. To illustrate this further, sensitivity checks were conducted on hydraulic conductivity (which would influence the migration of the plumes and the overall water balance in the model) and the drain boundary conductance (which would also change the water balance and groundwater levels in the area). The results are presented below.

Hydraulic Conductivity
During the first sensitivity check, hydraulic conductivities of the aquifer materials were doubled (from 3 m/day to 6 m/day). This resulted in the RMS error increasing from 4.8 to 10.7% and the predicted groundwater levels being overestimated by the model in comparison with the field gauged levels. This increase also resulted in an increase in the water inflow into the model from the upgradient boundary and subsequent increase in the water balance error to 12.6%. It appeared that the hydraulic conductivity parameter is very sensitive and additional testing of hydraulic conductivities of the uppermost aquifer would be required.

Drain Conductance
During the second sensitivity check, the drain conductance was increased by 1.5 times. The RMS error also increased to 8.8% indicating that the model was slightly less sensitive to this parameter but the model predicted levels were lower than gauged levels as the drain influence has increased. In addition, the water balance error increased to 7.9%. The above indicates that the drain conductance is also an important parameter and the drain influence on the groundwater regime should also be investigated.

10.9.2 Transport Model

As discussed in Section 9.1, broad transport model calibration of the VCH compounds was undertaken by:

- Varying locations, dimensions and concentrations of the contamination sources to simulate plume migration through groundwater wells where the elevated concentrations of VCH compounds were reported.
- Varying dispersivity values to minimise the plume spread to the areas where the presence of chemicals in groundwater wells were not reported (unless the wells are located down the inferred hydraulic gradient from impacted wells and contaminated plume may not have reached these locations yet).
- Simulating the modelled PCE, TCE and cis-1,2-DCE concentrations to be similar or above the reported concentrations of these chemicals at the monitoring wells given that this transport model does not take into account the natural degradation and de-chlorination of the chemicals in groundwater.

It is obvious that all transport model parameters are very sensitive and their variations would change the modelling outcomes significantly.

To illustrate this a sensitivity run was conducted for the dispersivity of the plume. The longitudinal dispersivity value was increased three times from 1 metre to 3 metres. This resulted in slightly wider plumes with lower predicted concentrations at key well locations. This indicates that the dispersivity value is a sensitive parameter influencing the overall predicted plume extents. Installation of additional groundwater monitoring wells would assist in calibrating the plume dispersion more confidently.

11.0 MODEL UNCERTAINTIES AND DATA GAPS

The numerical model has a range of limitations as it is a simplified representation of a complex reality, but generally hydrogeological models can be improved as more data becomes available. For example, additional hydrogeological investigations may provide a better understanding of the hydraulic properties of various aquifer materials and the processes controlling the chemical distribution and their migration.

The model for the HAA was developed using numerous assumptions which are based on a number of uncertainties for the parameters used in the model. The uncertainties and identified data gaps for the flow and transport model are discussed in the sections below.

11.1 Flow Model Uncertainties

The model discussed in the previous sections has been built to represent the groundwater flow and chemical transport within a single, shallow (uppermost), aquifer system, for which recharge and discharge areas were represented by constant head boundaries. Furthermore, the model was calibrated to simulate groundwater flow across the HAA and achieve a close match between the modelled and measured groundwater levels at the monitoring well locations.

11.1.1 Constant Head Boundary Levels

In the flow model, groundwater levels for the constant head boundaries were adjusted several times to obtain a close match in groundwater levels in the wells for the selected gauging round (January 2016) which included gauging data for the majority of the wells to provide the best coverage across the HAA. However, it should be noted that the assigned levels for the constant head boundaries were estimated and not based on any groundwater gauging near the boundaries of the model. This results in uncertainties with respect to groundwater levels.

11.1.2 Sewer Mains

Another significant uncertainty is the influence from the deep sewer mains which, as assessed, act as a drain and intersect the groundwater flow (or at least portion of). This influences groundwater levels in the vicinity of the sewer and subsequently the migration of the contaminated plumes. The judgement in relation to the role of the sewer mains was based on low groundwater levels measured in two wells (MW07 and MW25) located in close proximity to the sewer mains and the results of sewage sampling indicating some downstream increase in sewage salinity and the presence of VCH (AECOM, 2016 report).

The model includes drain boundaries (representing the sewer mains) positioned in the vicinity of the subject wells to simulate the low groundwater levels. In addition to the drain conductance (drain permeable properties in the model), the area around the drain was also set to have lower hydraulic conductivity zones to minimize the drain influence to achieve better match between simulated and measured water levels in at the wells located away from drains.

However, the sewer trunk main runs along Tapleys Hill Road for the entire extent of the HAA and may potentially influence groundwater levels at other locations. There are also a number of deep sewer lines which join the sewer trunk main on both sides of the road (Appendix T) which may also influence the groundwater flow regime. This is a significant unknown in the model and may be a source of significant variation in terms of the transport, extents and concentrations of the contaminated groundwater plume(s).

11.1.3 Perched Groundwater and Western Area

Based on the previous assessments conducted within areas west of Tapleys Hill Road (Coffey, 2011; PB 2014a), a different groundwater flow pattern was observed compared to that observed in areas located east of Tapleys Hill Road. The difference in the groundwater flow pattern was assessed to be a result of a perched aquifer located above the main regional aquifer within which the transport of contaminants from the east would occur (refer Section 9.7 discussing the Royal Park Mobil investigations).

The groundwater flow direction within the vicinity of a former service station in Royal Park appeared to be in a south westerly direction (Figure 11) compared to the north westerly direction assessed for the area east of Tapleys Hill Road. At the same time, groundwater contours plotted using only the wells installed in the regional aquifer demonstrated a north westerly flow direction, while groundwater contours plotted using only wells installed within the perched aquifer demonstrated a radial groundwater flow from the centre of the perched groundwater mound (copies of the figures from the Royal Park DRA are included in Appendix Z).

The Coffey DRA report suggests that there was some interconnection between the perched and regional aquifers identified which influences the groundwater flow direction in this area. However, additional assessment would be required to assess the extent of this interconnection. No perched aquifer systems have been included in the current model.

11.1.4 Hydraulic Conductivity

The uppermost aquifer material in the model was assigned a single hydraulic conductivity value. However, as shown on Figure 8, the aquifer material is not uniform which creates uncertainty in the hydraulic conductivity used in the model. Several aquifer tests, involving slug tests, were conducted within the area to the east of Tapleys Hill Road but there were no aquifer test results available for the western area. The slug tests conducted within the eastern area showed a significant range in the estimated hydraulic conductivities from 0.08 to 3.4 m/day (Table 17) indicating the presence of high and low conductivity zones which may influence the plume migration pattern. As discussed in Section 9.6, the groundwater contour pattern indicates that there may be higher hydraulic conductivities of the aquifer material within the western area in comparison to the eastern area.

11.1.5 Flow Model Data Gaps and Their Rectification

Hydraulic Boundaries

The modelled groundwater levels assigned to the constant head boundaries are identified as a data gap. This data gap may potentially be rectified by gauging existing groundwater wells which may be present in the vicinity of the constant head boundary areas or by installing additional wells at up hydraulic gradient locations within or outside the HAA. This would allow for refinement of the boundary conditions.

Sewer Mains

The extent of the actual influence of deep sewer mains on the groundwater flow regime is a data gap. Only three groundwater wells have been installed in the proximity to the deep sewer mains; BH13, MW07 and MW25, two of which show lower groundwater levels (MW07 and MW25) potentially associated with the sewer influence. The sewage samples collected by AECOM from manholes along the sewer main (along Tapleys Hill Road) identified the presence of VCH compounds and an increase in salinity (indicative of groundwater discharge). However, there are limited groundwater wells installed in the vicinity of these manholes (MW07, BH13) to verify the actual influence of the sewer on the groundwater levels.

To rectify this data gap additional investigations would need to be undertaken in the vicinity of deep sewer mains particularly within the areas where concentrations of VCH in groundwater have been reported.

Perched Aquifer

Influence of the perched aquifer on the regional aquifer and on the overall groundwater flow is a data gap. A perched aquifer was identified within the vicinity of a former service station in Royal Park which is within the HAA. Fresh groundwater was also noted at MW09 (possible indication of perched groundwater). To rectify this data gap additional investigations to assess the distribution of the perched aquifer(s) and its interconnection with the regional, uppermost aquifer, would be required. The results of these investigations and assessments would assist in refining the model and its capacity to simulate less conservative scenarios.

Hydraulic Conductivity

The hydraulic conductivities of the uppermost aquifer is critical for the model to assess the actual ranges of this parameter and its spatial distribution, particularly for the western portion of the HAA where both perched and regional aquifers are likely to be present. This data gap could be rectified by conducting additional aquifer tests (slug tests or pumping tests) to better define hydraulic conductivity zones within the model.

11.2 Transport Model

11.2.1 Uncertainties

The transport model conservatively assumed that the sources of groundwater contamination and the dissolved groundwater plumes do not undergo any degradation. This was assumed to overcome a number of uncertainties, including the degree of variability in the degradation of parent VCH compounds across the modelled area and the reduction in concentrations at the sources as a result of dissolution and volatalisation.

The greatest uncertainties in the transport model were the locations, lateral/vertical extents and concentrations of the source areas included in the model. It is also noted that the scope of work conducted did not include an assessment of the central northern portion of the HIA (groundwater wells MW13, MW14, MW17, MW23, MW24 and MW25) where additional sources of groundwater impacts are likely to be present (but not included in the model). These additional sources may influence the overall model prediction which has been used to suggest the extent of GPA (Section 12.0). The limiting factor for the migration of plumes in this area is the presence of groundwater 'sink' at MW25 (sewer main influence) which, as predicted by the model, appears to be capable of diverting plumes to this location and limiting their migration with the groundwater flow to the west, north west.

Another uncertainty in the transport model is the assumed dispersivity value which controls plume widths, lengths and resulting concentrations. This uncertainty is very common for most of transport models because plume dispersion cannot simply be measured in the field and is typically based on text book values or defined during model calibration when sufficient monitoring points and sufficient monitoring event data is available to decrease the uncertainty in this parameter.

11.2.2 Transport Model Data Gaps and Their Rectification

Additional assessment and investigations would be necessary to verify the source areas included in the model and assessment for the potential of additional sources to be present within the northern part of the HIA (including in the vicinity of a former service station in Royal Park).

Dispersivity of the plumes can be rectified by undertaking additional sampling rounds for all existing groundwater wells.

11.3 Uncertainties Summary and Future Improvements

All uncertainties discussed in the sections above are critical to the outcomes of the modelling. For example, if the influence from the sewer mains have been over estimated, then the contaminated plumes may migrate a significant distance with higher resulting concentrations compared to those predicted by the model. Furthermore, if there are additional groundwater contamination sources (say within the northern part of the HIA or within the vicinity of a former service station in Royal Park) then additional plumes may be emerging from these sources and contributing to the future plume extents and concentrations.

Alternatively, if additional information indicates that there are no ongoing sources of groundwater contamination in all or in some areas where potentially contaminating activities occurred historically, then the ongoing source assumption can be removed from the model and the residual plumes would be predicted to have smaller extents.

In summary, additional work focused on the reduction of the identified uncertainties would be required to construct a more realistic groundwater flow and transport model for the site.

12.0 SUGGESTED GROUNDWATER PROHIBITION AREA (GPA)

The numerical model predicted that VCH plumes emerging from the modelled sources of groundwater impacts would move in a north westerly direction as a result of groundwater flow.

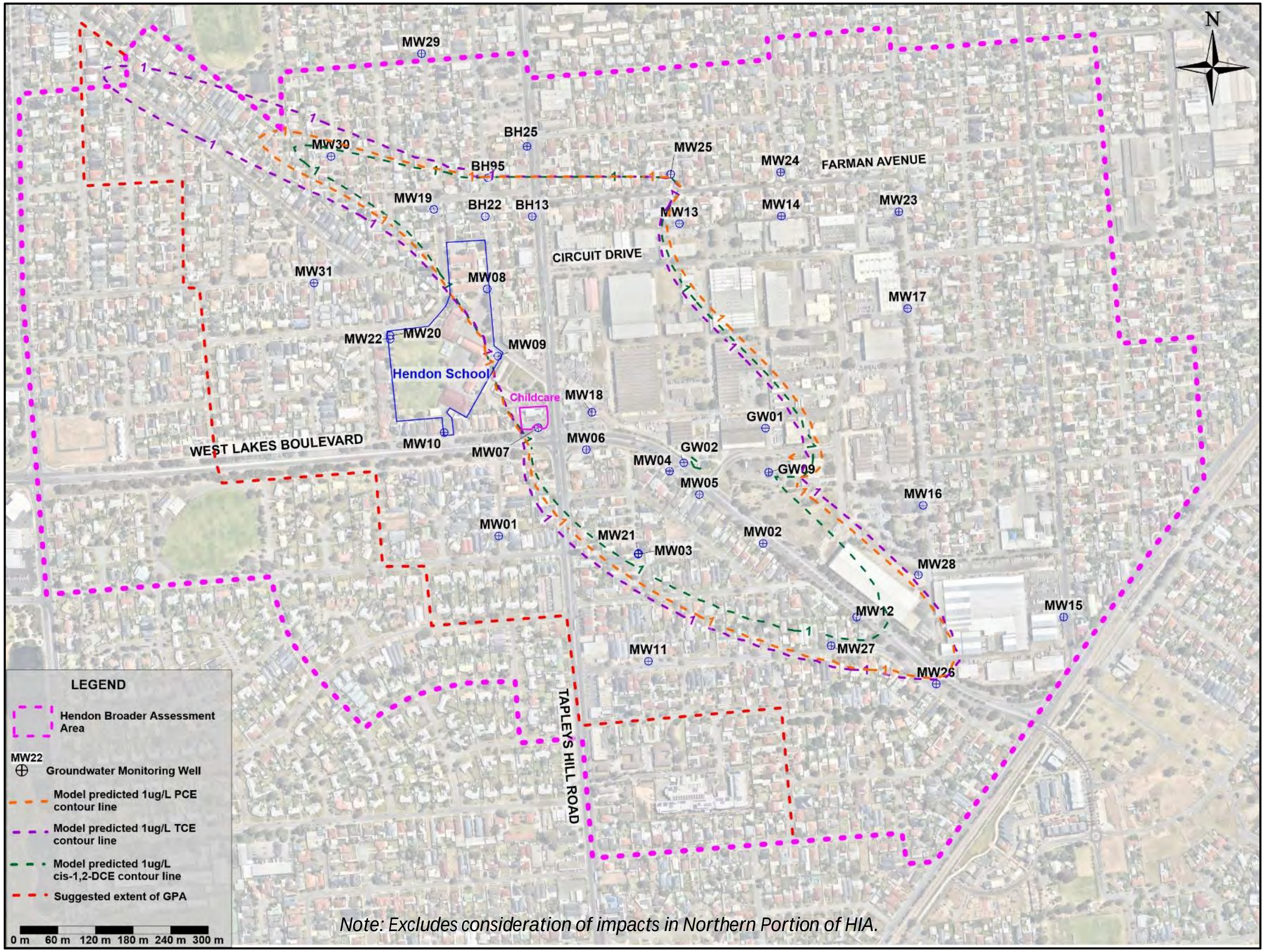
The concentrations of the chemicals modelled including PCE, TCE and cis-1,2-DCE were simulated to be higher at key groundwater wells compared to the concentrations reported for groundwater samples collected from these wells, in order to overcome uncertainties with chemical degradations within the sources and the plumes. This indicates that the model constructed is conservative.

Despite the conservative assumptions used in the model, the extents of the plumes were not predicted to migrate notably beyond the HAA over 800 years, when plumes would reach steady state conditions. The important driver which appears to limit the plume migration is the presence of sewer mains which at some locations, as assessed by previous consultants, act as a localised drain intercepting a portion of groundwater flow. Although the deep sewer mains (running below groundwater levels) have significant coverage within the HAA, their influence was only noted at two groundwater well locations MW07 and MW25 (refer Figure 7, Figure 10 and Appendix T). The sewer influence may be over or underestimated by the model due to the absence of sufficient number of groundwater wells in the vicinity to map the sewer influence more confidently.

It should be noted that the model does not take into account potential VCH sources which may be located within the northern portion of the HIA between Farman Avenue and Circuit Drive and to the south of Circuit Drive. Additional sources may also be located within the vicinity of a former service station in Royal Park. Therefore, the predicted steady state extent of the plumes may be underestimated.

Based on the above, the suggested GPA (excluding consideration of impacts in the central northern portion of the HIA) could include the north eastern portion of the HAA, however, the western and southern boundary of the suggested GPA may be moved closer to groundwater wells MW31, MW22, MW10, MW01 and MW11, as illustrated on Figure 44. It is understood that the suggested GPA would prohibit any use of groundwater for human consumption. In addition, the suggested GPA should also prohibit dewatering activities (for construction purposes), however, if this is unavoidable, the proposed dewatering exercise should be simulated in the model and approved by the EPA prior to its implementation.

The suggested extent of the GPA may be defined more confidently if the data gaps identified in Section 11.0 are addressed and information incorporated into the updated groundwater flow and transport model for the HAA area.



Note: Excludes consideration of impacts in Northern Portion of HIA.

Figure 44 – Suggested Extent of GPA

13.0 VAPOUR INTRUSION RISK ASSESSMENT UPDATE

13.1 Scope

The primary objective of this Stage 3 assessment is to update the VIRA conducted by AECOM in April 2016 (AECOM, 2016). The VIRA has been updated using additional data sourced from two soil vapour sampling events undertaken in October 2016 and January 2017 and two groundwater sampling rounds conducted in October/November 2016 and March 2017. Results of groundwater and soil vapour sampling along with results of geotechnical sampling (October 2016 and January 2017) are included in this report (refer Sections 5.0, 6.0 and 7.0).

The VIRA was conducted to address the potential risk to the health of local residents, commercial/retail workers (the primary receptors) and maintenance/trench workers related to volatile chemicals identified in groundwater and soil vapour. The primary COPC were deemed to be VCH, principally TCE, PCE and cis-1,2-DCE.

13.2 Methodology

The assessment was undertaken through a review of information provided by the EPA, previous site investigations by AECOM and URS (AECOM, 2016 and URS 2015a-f (inclusive), and reported groundwater and soil vapour analytical results from historical site sampling events including most recent events conducted by Greencap. The site zoning plan introduced by AECOM and others was adopted in this VIRA as follows (refer Figure R attached):

- Zone 1 has been identified as a commercial/industrial zone; and
- Zones 2-4 are primarily residential or other sensitive uses.

The assessment was undertaken for the primary potential receptors in these zones, namely commercial/retail workers in Zone 1, child and adult residents in Zones 2-4 and maintenance/trench workers in all zones.

Generic land use scenarios and construction types have been considered including dwellings with slab on grade, crawl space and basement construction, and commercial premises with slab on grade and crawl space construction.

The VIRA was based on maximum PCE, TCE and cis-1,2-DCE concentrations reported in groundwater and soil vapour in each of the four nominal zones as defined above.

The VIRA required estimating vapour concentrations in indoor and outdoor air, which was conducted using the Johnson & Ettinger vapour model (JEM) (USEPA, 2004). A review by Davis et al (CRC CARE, 2009) identified this model as suitable for use.

The VIRA was undertaken in accordance with current national guidelines, primarily the NEPM; Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards (enHealth, 2012a); the Australian Exposure Factor Guide (enHealth, 2012b); CRC CARE Technical Reports; as well as a range of international guidance from US EPA, WHO and ITRC.

13.3 Modelling Indoor Air Concentrations

The JEM was used to predict indoor air concentrations and potential health risks, using initial input parameters to model conservative scenarios. The JEM incorporates one dimensional diffusion through the unsaturated zone and advection and diffusion through the building slab. For more information on the vapour intrusion (VI) model input parameters, see USEPA, 2004.

If the conservative scenarios indicate the potential vapour intrusion and health risks are low and acceptable, the modelling process can cease; otherwise more realistic or site-specific parameters can be used.

Input Parameters to Estimate Indoor Air Concentrations

The input parameters to the model were a mix of site-specific parameters from Greencap's field investigations (recent geotechnical data collected from the upper 1.5m of the soil profile) and previous reports (AECOM, 2016) as well as conservative default values where relevant or where reliable site specific parameters were unavailable. The input parameters used in the initial modelling are provided in Table 20 and are generally considered to be at the 'conservative but realistic' end of the range.

Building Characteristics

This assessment considered the following scenarios:

- Residential – Slab on grade
- Residential – Crawl space
- Residential – Basement (only for the groundwater scenario)
- Commercial/Retail - Slab on grade
- Commercial/Retail – Crawl space

Maintenance/trench workers were also considered, and the details of that assessment are provided in Section 13.8.

Table 20 – Model Input Parameters

Parameter	Value	Reasoning
Soil and groundwater characteristics		
Average temperature – soil and groundwater	22°C	Based on annual average ambient temperature and average recorded groundwater temperature across site = 21.5°C (2 sampling rounds)
Depth to impacted groundwater	3.5 m	Reported groundwater depths 3.5 m – 5 m across the assessment site.
Soil Characteristics - Based on Geotechnical Data in each Zone		
Zone 1		Based on the mean of 4 samples collected at 0.7 – 1.1 m depth (SBG1, SBG10, SBG19, SBG 20)
Soil Stratum A (surface layer) 0-1.5 m	Sandy Clay.	Predominant descriptor for the 4 samples
Soil bulk dry density	1.62 g/cm^3	Mean of 4 samples. Range = 1.61 – 1.64. Consistent with Default value for Sandy Clay of 1.625 (Friebel & Nadebaum 2011)
Soil total porosity	0.39	Mean of 4 samples. Range = 0.38 – 0.40. Consistent with Default value for Sandy Clay of 0.387 (Friebel & Nadebaum 2011)
Soil moisture	6%	Close to lowest measured soil moisture. Range = 5.8 – 14.7%. Lower than Default moisture content for sand in vadose zone of 8% (Friebel & Nadebaum 2011)
Soil water-filled porosity	0.10 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density
Soil Stratum B 1.5 – 3.5 m	Silty Clay	Based on sampling log descriptors (From AECOM 2016) 2 samples collected at one location, SV22 (2 depths).
Soil bulk dry density	1.56 g/cm^3	Based on AECOM geotechnical data, 2 samples at SV22.
Soil total porosity	0.41	Based on AECOM geotechnical data. 2 samples range = 0.406 – 0.42.
Soil moisture	25%	AECOM reported soil moisture of 24.9 – 26.4. Higher than Default value for silty clay in vadose zone (Friebel & Nadebaum 2011)
Soil water-filled porosity	0.39 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density.
Zone 2		Based on average of 10 samples collected at 0.7–1.1 m depth (SBG2, SBG3, SBG 4, SBG5, SBG6, SBG14, SBG15, SBG 16, SBG 17, SBG 18); with weighting towards samples taken near soil vapour sampling locations of interest, SV01 and SV13.
Soil Stratum A (surface layer) 0-1.5 m	Sandy Clay	Predominant descriptor for the 10 samples
Soil bulk dry density	1.8 g/cm^3	Range = 1.63 – 1.87. Mean = 1.75
Soil total porosity	0.35	Range = 0.301 – 0.386. Mean = 0.34
Soil moisture	14%	Range = 3.2 – 21%. Mean = 14.1% The 3 samples near SV01 and SV13 had higher soil moisture (average = 19%; adopted a lower, more conservative moisture value, mid-way between Default moisture value for sand and clay in vadose zone (Friebel & Nadebaum 2011)
Soil water-filled porosity	0.26 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density
Soil Stratum B 1.5 – 3.5 m	Sandy Clay	Based on sampling log descriptors (From AECOM 2016) 4 samples collected at 3 locations, SV25, SV27, SV30.
Soil bulk dry density	1.7 g/cm^3	Based on AECOM geotechnical data, 4 samples; Range = 1.62 – 1.79. Mean = 1.72
Soil total porosity	0.36	Based on AECOM geotechnical data. 4 samples range = 0.325- 0.39. Mean = 0.36
Soil moisture	10%	AECOM reported soil moisture of 7.7 – 22%. Mean = 15%. Adopted value is lower than mean, more conservative.
Soil water-filled porosity	0.17 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density.
Zone 3		Based on average of 3 samples collected at 0.7 – 1.1 m depth (SBG7, SBG8 and SBG13) with some weighting towards samples taken near soil vapour sampling location of interest, SV04.
Soil Stratum A (surface layer) 0-1.5 m	Silty Sand.	Predominant descriptor for the 3 samples
Soil bulk dry density	1.7 g/cm^3	Range = 1.57 – 1.73. Mean = 1.65 Consistent with Default value for SAND of 1.66 (Friebel & Nadebaum 2011)
Soil total porosity	0.35	Range = 0.348 – 0.387. Mean = 0.37. Adopted values in close to measured value SBG13, near SV04.
Soil moisture	10%	Range = 6–22.6%. Mean = 15% Adopted value is lower than mean, Close to lowest reported soil moisture, reflects SV04 environment.
Soil water-filled porosity	0.17 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density
Soil Stratum B 1.5 – 3.5 m	Sandy Clay	Based on sampling log descriptors (From AECOM 2016) 6 samples collected at 2 location, SV32, SV35 (3 depths).
Soil bulk dry density	1.6 g/cm^3	Based on AECOM geotechnical data, 6 samples at SV32, SV35. Range = 1.47 – 1.64. Mean = 1.56.
Soil total porosity	0.42	Based on AECOM geotechnical data. 6 samples range = 0.387 – 0.464. Mean = 0.417.
Soil moisture	15%	AECOM reported soil moisture of 6–30%. Mean = 19.3%. Adopted value is lower than mean, more conservative, reflective of potentially drier conditions; mid-way between Default moisture value for sand and clay in vadose zone, and between moisture in sand in vadose and capillary zones.
Soil water-filled porosity	0.24 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density.
Zone 4		Based on average of 3 samples collected at 0.7 – 1.1 m depth (SBG9, SBG11 and SBG12); with some weighting towards samples taken near soil vapour sampling locations of interest, SV21.
Soil Stratum A (surface layer) 0-1.5 m	Sandy Clay.	Predominant descriptor for the 3 samples.
Soil bulk dry density	1.8 g/cm^3	Range = 1.7 – 1.86. Mean = 1.8
Soil total porosity	0.32	Range = 0.314 – 0.37. Mean = 0.34
Soil moisture	16%	Range = 15.5–19.9%. Mean = 17.3%. The sample nearest to SV21 had lower soil moisture, 15.5%. Adopted value is mid-way between Default moisture value for sand and clay in vadose zone (Friebel & Nadebaum 2011)
Soil water-filled porosity	0.29 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density
Soil Stratum B 1.5 – 3.5 m	Sandy Clay	Based on sampling log descriptors (From AECOM 2016); 2 samples collected at 1 location, SV21.
Soil bulk dry density	1.6 g/cm^3	Based on AECOM geotechnical data, 2 samples; Range = 1.57 – 1.65.

Parameter	Value	Reasoning
Soil total porosity	0.38	Based on AECOM geotechnical data. 2 samples range = 0.362- 0.408. Mean = 0.38
Soil moisture	15%	AECOM measured soil moisture of 6.6 – 25%. Mean = 16%. Adopted value is lower than mean, more conservative.
Soil water-filled porosity	0.17 cm^3/cm^3	Calculated from Soil Moisture x Dry Bulk Density.
Capillary zone		
Depth	30 cm	Default for sandy clay and silty clay in capillary zone (JE Model, USEPA 2004)
Soil Moisture	21%	Default for sandy clay and silty clay in capillary zone (JE Model, USEPA 2004)
Water-filled porosity	0.35	Default for sandy clay and silty clay in capillary zone (JE Model, USEPA 2004)
Building characteristics		
RESIDENTIAL		
SLAB ON GRADE		
Floor (slab) thickness	10 cm	Minimum floor thickness; Default value (JEM; Friebel & Nadebaum 2011)
Emission Area: Length x width Volume: Length x width x height	15 m x 10 m = 150 m^2 15 x 10 x 2.4 = 360 m^3 = 360,000,000 cm^3	Default, Friebel & Nadebaum 2011. (Surface area make little appreciable difference to the output, as the assumed infiltration from the subsurface is proportional to the surface area.) Volume/Height is a sensitive parameter.
Air exchange rate (AER)	0.6 changes per hour	Default, Friebel & Nadebaum 2011
Soil/building pressure differential	40 g/cm-s^2	JEM Default value. Note: By setting Q_{soil}, differential pressure parameters do not affect the results of the vapour intrusion modelling (Friebel & Nadebaum 2011). Similarly with soil permeability parameters.
Floor crack width	0.3 cm	Default value, JEM; Friebel and Nadebaum 2011.
$Q_{building}$	3600 L/min	Calculated from Building volume X AER = 216,000,000 cm^3/hr = 3600 L/min
Q_{soil}	108 L/min	Calculated from ratio with $Q_{building}$ and US EPA VI Database Attenuation Factor; $Q_{soil} = Q_{building}$ x 0.03
CRAWL SPACE		
Floor (slab) thickness	0	No slab.
Emission Area: Length x width Volume: Length x width x height	15 m x 10 m = 150 m^2 15 x 10 x 2.4 = 360 m^3 = 360,000,000 cm^3	Default, Friebel & Nadebaum 2011 (Surface area make little appreciable difference to the output, as the assumed infiltration from the subsurface or through the floor is proportional to the surface area.) Volume/Height is a sensitive parameter.
Air exchange rate (AER)	0.6 changes per hour	Default, Friebel & Nadebaum 2011. For crawl space dwellings, this AER is likely to be conservative given much higher ventilation rates have been reported in 'typical' crawl spaces; difficult to quantify.
Soil/building pressure differential	0	Building not in contact with soil, no pressure differential or pressure driven flows. Note: By setting Q_{soil}, differential pressure parameters do not affect results of vapour intrusion modelling. Similarly with soil permeability parameters.
Floor crack width	300 cm	In assuming absence of slab for crawl space dwelling, a crack ratio of 100% was adopted in the modelling. This is equivalent to the assumption of 0.01% crack ratio in slab default value of 0.3 cm of floor-wall seam crack width.
$Q_{building}$	3600 L/min	Calculated from Building volume X AER = 216,000,000 cm^3/hr = 3600 L/min
Q_{soil}	3600 L/min	Same as $Q_{building}$. – assume building in equilibrium with outside air.
BASEMENT		
Emission Area: Length x width Volume: Length x width x height	15 m x 10 m = 150 m^2 15 x 10 x 2.4 = 360 m^3 = 360,000,000 cm^3	Assumed same dimension as default house dimension (for habitable basement attached to a house).
Air exchange rate (AER)	0.6 changes per hour	Assumed same as default AER for house. (This is a sensitive parameter; increase/decrease leads to changes in indoor air concentration.)
$Q_{building}$	3600 L/min	Calculated from Building volume X AER = 216,000,000 cm^3/hr = 3600 L/min
Q_{soil}	108 L/min	Calculated from ratio with $Q_{building}$ and US EPA VI Database Attenuation Factor (75th %); $Q_{soil} = Q_{building}$ x 0.03
COMMERCIAL		
SLAB ON GRADE		
Emission Area: Length x width Volume: Length x width x height	20 m x 20 m = 400 m^2 20 x 20 x 3 = 1200 m^3 = 1,200,000,000 cm^3	Default, Friebel & Nadebaum 2011
Air exchange rate (AER)	0.83 changes per hour	Default, Friebel & Nadebaum 2011
$Q_{building}$	16,932 L/min	Calculated from Building volume X AER = 996,000,000 cm^3/hr = 16,932 L/min
Q_{soil}	508 L/min	Calculated from ratio with $Q_{building}$ and US EPA VI Database Attenuation Factor; $Q_{soil} = Q_{building}$ x 0.03
Other model inputs		Same as for Residential Slab on Grade.
CRAWL SPACE		
Emission Area: Length x width Volume: Length x width x height	20 m x 20 m = 400 m^2 20 x 20 x 3 = 1200 m^3 = 1,200,000,000 cm^3	Default, Friebel & Nadebaum 2011
Air exchange rate (AER)	0.83 changes per hour	Default, Friebel & Nadebaum 2011
$Q_{building}$	16,932 L/min	Calculated from Building volume X AER = 996,000,000 cm^3/hr = 16,932 L/min
Q_{soil}	16,932 L/min	Same as $Q_{building}$. – assume building in equilibrium with outside air.
Other model inputs		Same as for Residential Crawl Space.
Exposure characteristics		

Parameter	Value	Reasoning
Averaging Time (child and adult combined)	70 years (carcinogen) 35 years (non-carcinogen)	enHealth 2012
Exposure Duration – resident (child and adult) Exposure Duration – worker	35 years - Assumed length of residence 30 years – Assumed working lifetime	enHealth 2012 *Note: This value is used in Basement scenario model, as if basement has a full-time resident; this is considered very conservative.*
Exposure frequency – resident (child and adult) Exposure frequency – worker	24 hour/day x 365 days/year 40 hr/wk x 48 wks = 1920 hrs/8760 hours	Most conservative value; more conservative than enHealth 2012 (20 hrs/day). Initial estimate which can be modified if appropriate. *The 'Resident' value is used in the Basement scenario model, as if the basement has a full-time resident; this is considered very conservative.*

Advective Flow (slab on grade construction)

Based on advice from Friebel & Nadebaum 2011, the advective flow of air from sub-slab into the building has been specified by setting an attenuation factor for sub-slab to indoor air based on data from the USEPA Vapor Intrusion Database (USEPA 2012). Thus Q_{soil} was calculated based on the ratio with $Q_{building}$ and the adopted Attenuation Factor (AF), using the formula:

$Q_{soil}/Q_{building}$ = AF = 0.03 (95th percentile of Attenuation Factors from US EPA Vapour Intrusion Database).

Where $Q_{building}$ = total air volumetric flow rate through the building
= Building Volume X Air Exchange Rate.

Thus $Q_{soil} = Q_{building}$ x Attenuation Factor = $Q_{building}$ x 0.03

Friebel and Nadebaum used an AF of 0.005 in the Health Screening Level (HSL) derivation, based on 75th percentile from the 2008 version of the USEPA database. This database has been updated, and the 2012 database shows a 75th percentile Attenuation Factor for subslab soil vapour of 0.007.

Greencap has adopted the 95th percentile AF for this evaluation. Changing the AF from 0.005 to 0.007 to 0.03 increases Q_{soil}, however it does not make any appreciable difference in the modelling results except for vapour samples taken at shallow depths, ie in the sub-slab region.

If building height or air exchange rate (AER) increases, this would lead to decreased indoor air concentration. AER directly affects dilution of vapours entering a building and the indoor air concentration. However the $Q_{soil}/Q_{building}$ ratio is also affected and has a non-linear effect close to the surface by changing the advective flow from sub-slab to building. This is most noticeable for soil vapour at shallow depths

Note: Vapour Intrusion from groundwater is not sensitive to changes in Q_{soil}, at least to depths below 2m.

13.4 Vapour Intrusion Assessment Based on Groundwater Concentrations

The vapour intrusion risk was initially modelled based on the dissolved VCH concentrations in groundwater.

The maximum measured concentrations from each zone in the two most recent groundwater monitoring events conducted by Greencap in 2016-2017 were modelled separately for each zone to predict the potential indoor air concentrations (C_{ia}) in the various building types above the current observed site contamination.

There are no formal published screening criteria in Australia to assess vapour inhalation potential from VCH in groundwater. Greencap has adopted inhalation screening levels for VCH in groundwater based on the following criteria:

- Whether the analyte detected is considered volatile; and
- Whether the concentration reported exceeds available screening guidelines. The following guidelines were considered for the purpose of screening:
    - Australian Drinking Water Guidelines (ADWG), 2011 updated 2016 [2]
    - World Health Organization Drinking Water Guidelines (WHO DWG) 2017
    - USEPA Regional Screening Levels (USEPA RSLs, 2016)
    - NJDEP (New Jersey Department of Environment) Vapour Intrusion Screening Levels.

The NJDEP 2013 Groundwater Screening Levels for Sandy Loam[3] were considered to be appropriate screening criteria for considering vapour intrusion risks. The NJDEP Screening Levels were multiplied by a factor of 10

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[2] Australian Drinking Water Guidelines have been set for PCE at 50 µg/L (NHMRC, NRMMC (2011). Australian regulatory authorities considered that insufficient data was available to set an Australian guideline for TCE. The World Health Organization set a health-based drinking water guideline value for TCE of 20 µg/L (provisional guideline, because of uncertainties in the health database) (WHO 2017). Drinking Water guidelines are based on ingestion of larger quantities than would be expected from incidental ingestion or contact or from inhalation of vapours, and are considered very conservative for assessment of vapour inhalation risk.

[3] Adapted from NJDEP 2013, NJDEP Vapour Intrusion Screening Levels, Table 3. Ground Water Screening Levels for Alternate Soil Textures: Soil type Sandy Loam. New Jersey Department of Environment. http://www.nj.gov/dep/srp/guidance/vaporintrusion/vig_tables.pdf

to bring into line with Australian and WHO Acceptable Risk values for cancer (1 x 10^{-5}) and adopted as screening criteria for the site. The adopted screening criteria are shown in Table 21.

Table 21 – Adopted VCH Screening Criteria - Groundwater

Contaminant	Adopted Screening Criteria, µg/L
PCE	2000
TCE	110
Cis-DCE	500 (based on WHO DWG (2017) x 10)

Table 22 shows the maximum concentrations of the COPC in groundwater from the two recent monitoring rounds compared with the adopted screening criteria. Highlighted cells denote adopted criteria exceedances.

Table 22 – VCH in Groundwater in Zones 1–4 - Maximum Recent Concentrations (Greencap 2016-2017)

Zone	Monitoring Well	COPC (µg/L)		
Screening Level (Inhalation Risk)		PCE	TCE	Cis-DCE
		2,000	*110*	*500*
Zone 1	GW09	26	480	325
Zone 2	MW05	78	73	120
Zone 3	MW07	<20	780	53
Zone 4	MW08	<8	380	15

Table 22 shows that all maximum reported groundwater concentrations on-site (in each of the four zones) were less than the adopted criteria with the exception of TCE. However, the maximum concentrations of all volatile COPCs in each zone were considered as part of the VIRA update.

13.4.1 Predicted Indoor Air Concentrations

The JEM was used to predict indoor air concentrations (C_{ia}) based on the VCH concentrations in groundwater, for the residential and commercial exposure scenarios as described previously, for the four identified zones. Indoor air concentrations were predicted for the maximum VCH groundwater results reported for each zone (shown in Table 22) for commercial/industrial use in Zone 1 and Residential use in Zones 2-4.

The model used similar input parameters as for the soil vapour modelling (refer to Table 20), with the addition of soil characteristics to account for the deeper soil profile extending to the groundwater source.

Input parameters to the model included:

- Groundwater depth: 3.5 m (350 cm) below grade.
- Average Groundwater Temperature: 22^{o}C.
- The source was assumed to be an Infinite Source.

Other input parameters – e.g. building characteristics – were the same as those used in the soil vapour model which are presented in Table 20.

It is noted that vapour intrusion risk assessment from groundwater sources may be less reliable than using soil vapour data, as more fate and transport modelling is required to determine the likely vapour that may be produced. The soil vapour monitoring program has already directly measured the vapour existing on the site, and it includes the component originating from the groundwater source as well as any other sources. However, groundwater assessment has been included for completeness, to indicate potential risks if houses have a basement construction. The existing soil vapour data cannot be used as readily to assess basement constructions as for slab on grade or crawl space constructions, as a basement would likely remove most of the soil containing the measured vapour. Modelling from the groundwater data can be used to estimate vapour concentrations that may be produced from the dissolved concentrations in the groundwater and which may then migrate upwards through the deeper soil profile (e.g. at the level of a single storey basement, around 2.4 m depth, approximately 1 m above the water table).

Table 23 shows the results of the modelling from groundwater, with Attenuation Factors and Indoor Air Concentrations. Shaded cells denote a calculated concentration higher than the inhalation reference concentration (RfC). Comparison has also been made to the Indoor Air Level Response Ranges released by the EPA for TCE, based on the predicted indoor air concentrations.

Table 23 – Predicted Indoor Air Concentrations in Zones 1-4 based on Groundwater concentrations

Location	Depth, m	COPC	Concentr-ation C_{source} (µg/L)	Attenuation Factor α (unitless)	Indoor Air Concentration, C_{ia}, (µg/m^3)	Inhalation Reference Conc, RfC (µg/m^3)	SA EPA Action Level for TCE (µg/m^3) * - No Action (ND) - Validation (0 - 2) - Investigation (2 - <20) - Intervention (>20)
Commercial/Retail - Zone 1							
Commercial/Retail - Slab on Grade OR Crawl Space							
GW09	3.5	PCE	26	3.5 x 10^{-7}	0.006	40	-
		TCE	480	6 x 10^{-7}	0.1	2	Validation *
		DCE	325	2 x 10^{-6}	0.06	7	-
Residential – Zones 2 - 4							
Residential - Slab on Grade OR Crawl Space							
MW05 (Zone 2)	3.5	PCE	78	2.4x 10^{-6}	0.12	40	-
		TCE	73	4.4 x 10^{-6}	0.12	2	Validation
		DCE	120	1 x 10^{-5}	0.18	7	-
MW07 (Zone 3)	3.5	PCE	<20	3 x 10^{-5}	0.4	40	-
		TCE	780	3.4 x 10^{-5}	9.7 [#]	2	Investigation
		DCE	53	3.7 x 10^{-5}	0.3	7	-
MW08 (Zone 4)	3.5	PCE	<8	1 x 10^{-6}	0.005	40	-
		TCE	380	1.4 x 10^{-6}	0.2	2	Validation
		DCE	15	2.6 x 10^{-6}	0.006	7	-
Residential – Basement							
MW05 (Zone 2)	3.5	PCE	78	5 x 10^{-6}	0.2	40	-
		TCE	73	9.1 x 10^{-6}	0.24	2	Validation
		DCE	120	2.7 x 10^{-5}	0.5	7	-
MW07 (Zone 3)	3.5	PCE	<20	6.6 x 10^{-5}	0.85	40	-
		TCE	780	7.5 x 10^{-5}	21 ^	2	Intervention
		DCE	53	8.1 x 10^{-5}	0.64	7	-
MW08 (Zone 4)	3.5	PCE	<8	7.6 x 10^{-6}	0.04	40	-
		TCE	380	1.2 x 10^{-5}	1.6	2	Validation
		DCE	15	2.7 x 10^{-5}	0.06	7	-

[#] This location (MW07) returned a calculated indoor air concentration for TCE that was higher than the residential Indoor Air Reference Concentration (2 µg/m^3), and the SA EPA 'Validation Level' (also 2µg/m^3) using zone-specific geotechnical data for all construction types (slab on grade, crawl space and basement construction). The 'Investigation Level' is considered to have no immediate health concern but may need further investigation or management.

^ The basement scenario above MW07 has a calculated indoor air concentration slightly higher than the 'Investigation Level' (2 - <20 µg/m^3) and may require further action if the basement was inhabited for long term use. See further discussion on acceptable risk in the following sections.

* The SA EPA Action Level ranges for TCE have been derived for sensitive land uses. Therefore for Zone 1 (Commercial/Retail), to allow comparison to the SA EPA Action Level ranges (No Action, Validation, Investigation etc), the calculated Hazard Indices described in Section 13.7.2 (both <1) were adopted. This is due to the fact that a hazard Index of <1 is equivalent to results within the 'Validation' range of the SA EPA Action Levels (refer Section 13.7.1).

13.5 Vapour Intrusion Assessment Based on Soil Vapour Measurements

In order to calculate the potential for VCH impacted soil vapours to migrate and impact on habitable spaces, the JEM was used to estimate the concentrations of COPC in indoor air due to migration from the subsurface contamination sources (i.e. soil vapour and groundwater).

Soil vapour results were used as the primary contamination source, as soil vapour includes contributions from contaminants in groundwater and potential soil impacts if any are present. Measured soil vapour is expected to give a better estimate of the total potential indoor air concentration than groundwater concentrations as it does not contain the uncertainties associated with fate and transport modelling of vapour from groundwater migrating upwards through the soil profile.

13.5.1 Soil Vapour Results

The maximum measured soil vapour results in the two most recent soil vapour sampling events conducted by Greencap in 2016-2017 were modelled separately for each zone to predict the potential indoor air concentrations, C_{ia}, in the various building types above the current observed site contamination. The maximum concentrations of the COPC in each of the four zones are shown in Table 24. Highlighted cells denote adopted criteria exceedances.

Table 24 – Soil Vapour VCH in in Zones 1–4 - Maximum Recent Concentrations (Greencap 2016-2017)

Zone	Vapour Point	Depth (m)	COPC ($\mu g/m^3$)		
			PCE	TCE	Cis-DCE
NEPM Interim HIL A/B			2,000	20	80
Zone 1	SV22	2	25,000	19,000	<100
	SV31	1.5	14,000	1,000	310
Zone 2	SV01	1.5	13,700	428	<20
	SV13	1.8	770	160	3,300
Zone 3	SV04	1.1	30	3,200	26
Zone 4	SV21	2	20	1,640	3

Note: All of these results show decreased concentrations compared with those used in the AECOM 2016 VIRA update.

If any of the results indicate a potentially unacceptable risk in any of the zones, other (lower) concentrations were to be examined to determine if other risks may be present.

13.5.3 Predicted Indoor Air Concentrations

Indoor air concentrations, C_{ia}, were predicted for the residential and commercial exposure scenarios as described above, for the four zones. The indoor air concentration (C_{ia}) was predicted for the maximum VCH soil vapour results reported for each zone (shown in Table 22) for commercial/industrial use in Zone 1 and Residential use in zones 2-4.

Table 25 shows predicted indoor air concentrations in standard residential and commercial scenarios, based on the maximum measured VCH soil vapour concentrations on-site. Shaded cells denote a calculated concentration higher than the inhalation reference concentration (RfC). Comparison has also been made to the Indoor Air Level Response Ranges released by the EPA for TCE, based on the predicted indoor air concentrations.

Table 25 – Predicted Indoor Air Concentrations in Zones 1-4, based on Soil Vapour

Location	Depth, m	COPC	Soil Vapour, C_{source} ($\mu g/m^3$)	Attenuation Factor α (unitless)	Indoor Air Concentration, C_{ia}, ($\mu g/m^3$)	Inhalation Reference Conc, RfC ($\mu g/m^3$)	SA EPA Action Level for TCE ($\mu g/m^3$) *
							- No Action (ND) - Validation (0 - 2) - Investigation (2 - <20) - Intervention (>20)
Commercial/Retail - Zone 1							
Commercial/Retail - Slab on Grade							
SV22	2	PCE	25,000	1.1×10^{-6}	0.03	40	-
		TCE	19,000	2×10^{-6}	0.04	2	Validation*
		Cis-DCE	<100	6.2×10^{-6}	<0.0006	7	-
SV31	1.5	PCE	14,000	7.7×10^{-4}	11	40	-
		TCE	1,000	8.45×10^{-4}	0.85	2	Validation*
		Cis-DCE	310	7.9×10^{-4}	0.24	7	-
Commercial/Retail – Crawl Space							
SV22	2	PCE	25,000	1.1×10^{-6}	0.03	40	-
		TCE	19,000	2×10^{-6}	0.04	2	Validation*

Location	Depth, m	COPC	Soil Vapour, C_{source} (µg/m^3)	Attenuation Factor α (unitless)	Indoor Air Concentration, C_{ia}, (µg/m^3)	Inhalation Reference Conc, RfC (µg/m^3)	SA EPA Action Level for TCE (µg/m^3) * - No Action (ND) - Validation (0 - 2) - Investigation (2 - <20) - Intervention (>20)
		Cis-DCE	<100	6.2 x 10^{-6}	<0.0006	7	-
SV31	1.5	PCE	14,000	7.4 x 10^{-4}	9.6	40	-
		TCE	1,000	8.1 x 10^{-4}	0.81	2	Validation*
		Cis-DCE	310	7.5 x 10^{-4}	0.23	7	-
Residential – Zones 2 - 4							
Residential - Slab on Grade							
SV01 (Zone 2)	1.5	PCE	13,700	3.2x 10^{-5}	0.40	40	-
		TCE	428	3.5 x 10^{-5}	0.01	2	Validation
		Cis-DCE	<20	3.3 x 10^{-5}	<0.001	7	-
SV13 (Zone 2)	1.8	PCE	770	3 x 10^{-5}	0.024	40	-
		TCE	160	3.4 x 10^{-5}	0.005	2	Validation
		Cis-DCE	3,300	3 x 10^{-5}	0.11	7	-
SV04 (Zone 3)	1.1	PCE	<340	4.4 x 10^{-4}	<0.2	40	-
		TCE	3,200	5.2 x 10^{-4}	1.7	2	Validation
		Cis-DCE	26	4.9 x 10^{-4}	0.01	7	-
SV21 (Zone 4)	2	PCE	<340	1.4 x 10^{-6}	<0.0005	40	-
		TCE	1,640	1.9 x 10^{-6}	0.003	2	Validation
		Cis-DCE	<20	3.2 x 10^{-6}	<0.0001	7	-
Residential – Crawl Space							
SV01 (Zone 2)	1.5	PCE	13,700	3 x 10^{-5}	0.4	40	-
		TCE	280	3.3 x 10^{-5}	0.01	2	Validation
		Cis-DCE	<20	3 x 10^{-5}	<0.001	7	-
SV13 (Zone 2)	1.8	PCE	770	2.9 x 10^{-5}	0.02	40	-
		TCE	160	3.2 x 10^{-5}	0.005	2	Validation
		Cis-DCE	3,300	3 x 10^{-5}	0.10	7	-
SV04 (Zone 3)	1.1	PCE	<340	4.4 x 10^{-4}	<0.2	40	-
		TCE	3,200	4.8 x 10^{-4}	1.55	2	Validation
		Cis-DCE	26	4.5 x 10^{-4}	0.01	7	-
SV21 (Zone 4)	2	PCE	<340	1.3 x 10^{-6}	<0.0004	40	-
		TCE	1,640	1.7 x 10^{-6}	0.003	2	Validation
		Cis-DCE	<20	3.2 x 10^{-6}	<0.0001	7	-

* The SA EPA Action Level ranges for TCE have been derived for sensitive land uses. Therefore for Zone 1 (Commercial/Retail), to allow comparison to the SA EPA Action Level ranges (No Action, Validation, Investigation etc), the calculated Hazard Indices described in Section 13.7.2 (both <1) were adopted. This is due to the fact that a hazard Index of <1 is equivalent to results within the 'Validation' range of the SA EPA Action Levels (refer Section 13.7.1).

It can be seen that the attenuation factors for slab on grade construction and crawl space construction are very similar and provide a calculated Indoor Air Concentration that is essentially the same for either construction scenario.

The remainder of the vapour intrusion assessments in this VIRA update will be undertaken using only the slab on grade construction type only for all houses without basements. A separate model will be used for basement constructions.

13.6 Indoor Air Inhalation Exposure Assessment

Assessment of potential inhalation exposure was conducted for residents and commercial workers inhabiting homes or businesses in the various zones, using the calculated indoor air concentrations from Table 23 and Table 25.

Exposure parameters for residents are outlined in Table 26. Other exposure characteristics are listed in Table 20.

Table 26 – Exposure parameters for quantifying inhalation exposures – Residential Setting

Exposure Parameter	Value	Comment
ET = Exposure Time [hours/day]	24	Assume residents at home all day [4]
FI = Fraction inhaled from contaminated source [unitless]	1	Assume all vapour inhalation is derived from the site
EF = Exposure frequency [days/year]	365	enHealth 2012
ED = Exposure Duration [days]	35 years	Enhealth 2012
AT(t) = Averaging Time (threshold), for chronic threshold risks/non-cancer [hours]	ED X EF x 24 hrs = 30660 hrs	enHealth 2012
AT(nt) = Averaging Time (non-threshold) for non-threshold risks / carcinogens [hours]	70 yrs x 365 days x 24 hrs = 613200 hrs	J&E, USEPA 2004; USEPA 2009; enHealth 2012

Overall, the residential exposure values used are considered to be very conservative and protective of sensitive populations including children.

Inhalation exposure concentrations can be calculated from the following:

$$\text{Inhalation Exposure Concentration, } EC_{inh}\ (mg/m^3) = C_{ia} \times (ET \times EF \times ED \times FI) / AT$$

Multipliers for various exposure parameters can be calculated as shown for the following scenarios:

On-site exposure: Residential 24-hr exposure:

$EC_{inh} = C_{ia}$ x (24hr x 365 days/year x 35 years x 1) / 35 years (Threshold effects)
$= C_{ia}$ x (8760 hours/year x 35 years) / 306,600 hours $= C_{ia}$ x 1 mg/m^3
$EC_{inh} = C_{ia}$ x (24 hr x 365 days/year) x 35 years x 1) / 70 years (Non-threshold)
$= C_{ia}$ x (8760 hours/year x 35 years) / 613,200 hrs $= C_{ia}$ x 0.5 mg/m^3

20-hr exposure:

$EC_{inh} = C_{ia}$ x (20 hr x 365 days/year x 35 years x 1) / 35 years (Threshold effects)
$= C_{ia}$ x (7300 hours/year x 35 years) / 306,600 hours $= C_{ia}$ x 0.83 mg/m^3
$EC_{inh} = C_{ia}$ x (20 hr x 365 days/year) x 35 years x 1) / 70 years (Non-threshold)
$= C_{ia}$ x (7300 hours/year x 35 years) / 613,200 hrs $= C_{ia}$ x 0.42 mg/m^3

Commercial Worker exposure:

$EC_{inh} = C_{ia}$ x (8hr x 240 days/year x 30 years x 1) / 35 years (Threshold effects)
$= C_{ia}$ x (1920 hours/year x 30 years) / 306,600 hours $= C_{ia}$ x 0.2 mg/m^3
$EC_{inh} = C_{ia}$ x (8 hr x 240 days/year) x 30 years x 1) / 70 years (Non-threshold)
$= C_{ia}$ x (1920 hours/year x 30 years) / 613,200 hrs $= C_{ia}$ x 0.1 mg/m^3

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[4] More conservative than enHealth (2012) which recommends 20 hours/day as default exposure scenario.

13.7 Risk Characterisation

13.7.1 Quantitative Assessment of Risk

Approach

Risk characterisation is the final step in a quantitative risk assessment, incorporating the exposure and toxicity assessments to provide a quantitative assessment of risks. Risk is characterised separately for threshold and carcinogenic/non-threshold effects as follows.

Assessment of Threshold Effects

For chemicals where a threshold dose-response approach is appropriate, the potential exposure and health risks are quantified by comparing the estimated intake (or exposure concentration) with the threshold values adopted that represent a tolerable intake (or concentration), with consideration for background intakes. The potential for adverse threshold effects resulting from inhalation exposure to an individual COPC was evaluated by comparing an exposure concentration with the adopted guideline or Reference Concentration (RfC).

The calculated ratio is termed a Hazard Index (HI), which is the sum of all ratios (termed Hazard Quotients [HQ]) over all relevant pathways of exposure. These are calculated using the following equations:

- *Hazard Quotient (HQ) (oral or dermal) = Daily Chemical Intake / [(ADI, TDI, RfD) – Background]*
- *Hazard Quotient (HQ) (inhalation) = Exposure Concentration in Air / [(TC, RfC) – Background]*
- *Hazard Index (HI) = Σ HQ (All pathways)*

Where:

ADI = Acceptable Daily Intake
TDI = Tolerable Daily Intake
RfD = Reference Dose
TC = Tolerable Concentration

Interpretation of an acceptable HQ or HI requires acknowledgement of the inherent conservatism that is built into the establishment of appropriate guideline (threshold) values (using many uncertainty factors) and the exposure assessment (as noted in Section 13.6). Hence, in reviewing and interpreting the calculated HQ/HI the following is noted:

- A HQ/HI less than or equal to a value of 1 (where intake or exposure is less than or equal to the relevant threshold value) represents no cause for concern (as per risk assessment industry practice, supported by protocols outlined in enHealth 2012 and the amended NEPM) and has been adopted in this assessment to indicate acceptable levels of risk.
- A HQ/HI in excess of 1 does not necessarily indicate that adverse health effects have occurred, or will occur. Rather, this indicates the need to further review the magnitude of the exceedance in relation to the underlying exposure assumptions (and level of conservatism) and toxicological information.

It is noted that the EPA and SA Health have collaborated in development of an Indoor Air Level Response Range which can be used in assessing TCE vapour intrusion to residences. The reference concentration for TCE of 2 $\mu g/m^3$ was adopted as the upper end of the 'Validation' range, where concentrations are deemed safe, but ongoing monitoring may be appropriate. TCE results up to one order of magnitude above this concentration (up to 20 $\mu g/m^3$) fall into the 'Investigation' range, wherein although no immediate health concerns were considered to be associated with such levels, further assessment is required. These concentrations (2 and 20 $\mu g/m^3$) are equivalent to Hazard Indices of 1 and 10 respectively.

A Hazard Index of <1 indicates that the exposure point concentration falls below the reference concentration for that chemical. For each exposure scenario, Hazard Quotients for each of the three chemicals of potential concern (PCE, TCE, cis-1,2-DCE) are summed to provide a Hazard Index. This approach (simple additivity) is consistent with a screening level approach recommended in enHealth (2012). Accordingly:

- Where the Hazard Index for the COPC for any modelled scenario is <1, this is considered to be equivalent to results within the 'Validation' range of the EPA/SA Health Indoor Air Level Response Range.

- Where the Hazard Index for the COPC for any modelled scenario is >1 but <10, this is considered to be equivalent to results within the 'Investigation' range of the EPA/SA Health Indoor Air Level Response Range.
- Where the Hazard Index for the COPC for any modelled scenario is >10 but <100, this might be considered to be equivalent to results within the 'Intervention' range of the EPA/SA Health Indoor Air Level Response Range, indicative of a potential health risk and warranting further action.

Assessment of Non-Threshold (Carcinogenic) Effects

Non-threshold carcinogenic risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to a potential non-threshold carcinogen. The numerical estimate of excess lifetime cancer risk due to exposure is calculated as follows for oral/dermal and inhalation exposures:

Carcinogenic Risk (oral or dermal) = [Daily Chemical Intake] X [Cancer Slope Factor]

Carcinogenic Risk (inhalation) = [Exposure Concentration in Air] X [Inhalation Unit Risk]

The total non-threshold carcinogenic risk is the sum of the risk for each chemical and for each pathway.

For assessment of contaminated sites, the following points outline the level of non-threshold carcinogenic risk that is considered to be acceptable, as presented in the NEPM (1999 amended 2013).

- Calculated incremental risks below 1×10^{-6} would be considered to be effectively zero.
- Calculated incremental risks $\leq 1 \times 10^{-5}$ are considered to be acceptable.
- Calculated risks greater than 1×10^{-5} would be considered to warrant some form of action, which may involve further evaluation of the risks to reduce uncertainties and determine whether action is required to reduce the risks.

On this basis, a total Target Risk value of $>1 \times 10^{-5}$ has been adopted as indicating conditions that would warrant further assessment. Carcinogenic risk values $\leq 1 \times 10^{-5}$ are considered to be representative of acceptable risks.

Toxicity Reference Values

Table 27 shows the toxicity reference values that were adopted for use in the risk assessment.

Table 27: Toxicity Reference Values for VCH

Chemical	Inhalation Reference Concentration, RfC µg/m³ Threshold Concentration; Chronic non-cancer risk	Inhalation Unit Risk $(\mu g/m^3)^{-1}$ Non-threshold risk; Carcinogenic risk
TCE (USEPA 2011)	2	4.8E-06 (Includes Age-adjusted adjustment factor, ADAF, to account for potential for kidney damage in early-life exposure)
PCE (USEPA 2012)	0.04	2.6E-07
Cis-DCE (USEPA 2010)	0.007 TRV (Toxicity Reference Value) Note: No RfC has been formally derived. However an inhalation TRV has been derived by route-to-route extrapolation from the USEPA oral TRV for cis-DCE, based on a 70-kg adult inhaling 20 m³ air daily.	- (Unit Risk has not been established; insufficient evidence)

The SA EPA Indoor Air "Validation Level" is set at the same value as the TCE inhalation Reference Concentration of 2 µg/m³. This is interpreted as being an acceptable level. SA EPA guidance indicates that indoor air levels between 2 – 20 µg/m³ are considered to be "Investigation Levels", requiring further assessment. Indoor air levels greater than 20 µg/m³ are considered to be "Intervention Levels".

13.7.2 Calculated Risks

Table 28 presents a summary of the threshold risks (HQ/HI) and the non-threshold risks (ILCR, Incremental Lifetime Cancer Risk) for the adopted COPCs, based on the maximum calculated indoor air concentrations of the identified VCH (TC, PCE, DCE) in the four zones. The highest indoor air concentration calculated from soil vapour for slab on grade or crawl space construction was used for each scenario.

The values presented (and all other risk calculations) are rounded to 1 or 2 significant figures reflecting the level of uncertainty inherent in risk calculations. The JEM outcomes for TCE risks for a range of construction types and exposure scenarios in Zones 1, 3 and 4 are included in Appendix AA. The included spreadsheets illustrate the methodology and inputs used for all scenarios; these specific examples also illustrate the elevated risks modelled for these scenarios.

Table 28 – Calculated Vapour Intrusion Risks in Slab on Grade Buildings and Residential Basements - Maximum Calculated Indoor Air Concentrations from Groundwater and/or Soil Vapour

VCH Scenario	Attenuation Factor α	Indoor Air Concentration, C_{ia}, µg/m^{3}	Threshold Risk - Hazard Index	Non-Threshold Risk - ILCR
Zone 1 – Commercial				
Slab on Grade OR Crawl Space				
Groundwater – GW09				
TCE (Gw 480 µg/L	6.1 x 10^{-7}	0.1	0.01	5 x 10^{-8}
PCE (Gw 26 µg/L)	3.5 x 10^{-7}	0.006	0.00003	1.4 x 10^{-10}
DCE (Gw 325 µg/L	1.7 x 10^{-6}	0.08	0.0004	n/a
Sum			*HI = Σ HQ = 0.01*	*ILCR = 5 X 10^{-8}*
Soil Vapour - SV31				
TCE (SV 1,000 µg/m^{3})	8.4 x 10^{-4}	0.84	0.08	3.8 x 10^{-7}
PCE (SV 14,000 µg/m^{3}	7.7 x 10^{-4}	11	0.05	2.6 x 10^{-7}
DCE (SV 310 µg/m^{3})	7.9 x 10^{-4}	0.24	0.007	n/a
Sum			*HI = Σ HQ = 0.14*	*ILCR = 6.4 X 10^{-7}*
Zone 2 – Residential				
Slab on Grade OR Crawl Space				
Groundwater – MW05				
TCE (Gw 73 µg/L)	4.4 x 10^{-6}	0.12	0.06	2.8 x 10^{-7}
PCE (Gw 78 µg/L)	2.4 x 10^{-6}	0.12	0.003	1.6 x 10^{-8}
DCE (Gw 120 µg/L)	1 x 10^{-5}	0.18	0.005	n/a
Sum			*HI = Σ HQ = 0.06*	*3 X 10^{-7}*
Soil Vapour – SV01				
TCE (SV 428 µg/m^{3})	3.5 x 10^{-5}	0.015	0.007	3.6 x 10^{-8}
PCE (SV 13,700 µg/m^{3})	3.2 x 10^{-5}	0.4	0.01	5.6 x 10^{-8}
DCE (SV <200 µg/m^{3})	3.3 x 10^{-6}	<0.007	0.001	n/a
Sum			*HI= Σ HQ = 0.02*	*ILCR = 9 X 10^{-8}*
Soil Vapour – SV13				
TCE (SV 160 µg/m^{3})	3.4 x 10^{-5}	0.005	0.003	1.3 x 10^{-8}
PCE (SV 770 µg/m^{3})	3.1 x 10^{-5}	0.024	0.0006	3 x 10^{-9}
DCE (SV 3,300 µg/m^{3})	3.3 x 10^{-5}	0.11	0.015	n/a
Sum			*HI = Σ HQ = 0.02*	*ILCR = 1.6 X 10^{-8}*
Basement				
Groundwater – MW05				
TCE (Gw 73 µg/L)	9.1 x 10^{-6}	0.24	0.12	5.8 x 10^{-7}
PCE (Gw 78 µg/L)	4.7 x 10^{-6}	0.24	0.006	3.1 x 10^{-8}
DCE (Gw 120 µg/L)	2.7 x 10^{-5}	0.5	0.014	n/a
Sum			*HI = Σ HQ = 0.14*	*6 X 10^{-7}*
Zone 3 – Residential				
Slab on Grade OR Crawl Space				

VCH Scenario	Attenuation Factor α	Indoor Air Concentration, C_{ia}, µg/m^3	Threshold Risk - Hazard Index	Non-Threshold Risk - ILCR
Groundwater – MW07				
TCE (Gw 780 µg/L)	3.4 x 10^{-5}	9.7	4.8	2.3 x 10^{-5}
PCE (Gw <20 µg/L)	3 x 10^{-5}	0.4	0.01	5 x 10^{-8}
DCE (Gw 53 µg/L)	3.6 x 10^{-5}	0.3	0.008	n/a
Sum			*HI = Σ HQ = 4.8*	*2.3 X 10^{-5}*
Soil Vapour – SV04				
TCE (SV 3200 µg/m^3)	5.2 x 10^{-4}	1.7	0.84	4 x 10^{-6}
PCE (SV <340 µg/m^3)	4.8 x 10^{-4}	<0.2	0.004	2 x 10^{-8}
DCE (SV 26 µg/m^3)	4.9 x 10^{-4}	0.01	0.001	n/a
Sum			*HI = Σ HQ = 0.84*	*ILCR = 4 X 10^{-6}*
Basement				
Groundwater – MW07				
TCE (Gw 780 µg/L)	7.5 x 10^{-5}	21.4	10.7	5.1 x 10^{-5}
PCE (Gw <20 µg/L)	6.6 x 10^{-5}	0.85	0.02	1.1 x 10^{-7}
DCE (Gw 53 µg/L)	8.1 x 10^{-5}	0.63	0.018	n/a
Sum			*HI = Σ HQ = 10.7*	*5.1 X 10^{-5}*
Zone 4 – Residential				
Slab on Grade OR Crawl Space				
Groundwater – MW08				
TCE (Gw 380 µg/L)	1.4 x 10^{-6}	0.2	0.1	5 x 10^{-7}
PCE (Gw 8 µg/L)	1.1 x 10^{-6}	0.006	0.0001	7 x 10^{-10}
CDCE (Gw 15 µg/L)	2.6 x 10^{-6}	0.006	0.0002	n/a
Sum			*HI = Σ HQ = 0.1*	*5 X 10^{-7}*
Soil Vapour – SV21				
TCE (SV 1,640 µg/m^3)	1.9 x 10^{-6}	0.003	0.001	7 x 10^{-9}
PCE (SV <340 µg/m^3)	1.4 x 10^{-6}	<0.0005	0.00001	6 x 10^{-11}
DCE (SV <20 µg/m^3)	3.2 x 10^{-6}	<0.00006	0.000001	n/a
Sum			*HI = Σ HQ = 0.001*	*ILCR = 7 X 10^{-9}*
Basement				
Groundwater – MW08				
TCE (Gw 380 µg/L)	1.2 x 10^{-5}	1.64	0.68	3.3 x 10^{-6}
PCE (Gw 8 µg/L)	7.6 x 10^{-6}	0.05	0.001	5 x 10^{-9}
DCE (Gw 15 µg/L)	3 x 10^{-5}	0.06	0.002	n/a
Sum			*HI = Σ HQ = 0.69*	*3.3 X 10^{-6}*

* Highest C_{ia} calculated for slab on grade or crawl space was used to calculate the risks.

Note: Red font is used where target risk exceedances are calculated and the HI puts the scenario into a similar category as the SA EPA Intervention Range.

13.8 Exposure for Maintenance/Trench Workers

There are various methods for calculating exposure to volatile contaminants within a trench. This assessment considered firstly the potential exposure in a trench as a simulated building and calculated the predicted air concentrations using the JEM, and the risks associated with expected exposure patterns for maintenance workers working intermittently in a trench or excavation.

The highest potential for vapour intrusion risk in a trench scenario is in narrow trenches, where the width is narrower than the depth. Broad-area excavations of 2 m width or more have a greater potential for vapour diffusion and dilution and hence have limited potential for vapour buildup. This assessment considered trenches of 1 – 1.5 m depth and width of 1 m.

<u>Input parameters included:</u>

Trench dimension: Area = 10 m x 1 m

Height: 1 m or 1.5 m	(Most underground services are installed within these depths)
Air Exchange Rate: 2/hour	(CCME 2011: "Based on urban canyon studies and consultation with United States Environmental Protection Agency (US EPA) Region III, an air exchange rate of 2/h is used when the trench depth is greater than the trench width (relative to the wind direction), to reflect circulation cells within the trench limiting gas exchange with the atmosphere. When trench width exceeds the trench depth, air exchange between the trench and atmosphere is considered unrestricted and an air exchange rate of 360/h is used based on the ratio of trench depth to average wind speed." Review of Approaches for Modelling Vapour Migration into Trenches and Excavations by Meridian Environmental for CCME 2011. http://www.ccme.ca/files/Resources/supporting_scientific_documents/pn1455_n_hexane.pdf
Exposure Frequency and duration:	12 working days per year (one per month) for 30 years, ie 8 hours x 12 days = 96 hours. (Assumes whole time spent inside the trench breathing in the calculated concentration. In reality, workers would be expected to spend at least half of that time breathing air above the trench, which would rapidly dissipate the COPC concentrations)
Receptor: Adults	(The IUR for TCE is adjusted to remove the Age adjusted safety factor (ADAF) that is added to TCE to protect against early-life exposure. This takes the IUR form 4.8 x 10^{-6} (with ADAF, for general population) back to 4 x 10^{-6} (adults only)

Exposures and inhalation risks to trench workers were modelled in the zones with the highest COPC concentrations in the environment and/or highest predicted indoor air exposures (Zone 1, Zone 2 and Zone 3), and the results are shown in Table 29.

The JEM does not include an option to model for potential vapour migration laterally through the trench walls. In general, the highest VCH concentrations are found in the deeper soil levels and we would expect lower concentrations in the top half-metre; however this does not account for potential preferential pathway migration or other disturbances in the soil profile and therefore it cannot be guaranteed that some higher than expected vapour concentrations may migrate laterally through a trench wall. This possibility can be offset by the over-estimate of exposure by assuming a worker spends all day within the trench breathing in the calculated vapour concentration; in reality, workers would generally spend less than a full working day (eight hours) in a trench and during that time they would spend a proportion of time standing upright and breathing in air outside the trench.

Note: Risks to trench workers were considered to be primarily inhalation risks. There is little evidence of likely ingestion or dermal contact with the COPC, as they were not reported to be present in the soil and so there would be minimal exposure opportunities through dust contact or ingestion. Direct contact with groundwater is not envisaged in this trench scenario, as the water table is approximately 2 metres below the assumed trench floor. If deeper trenching is required (to 2 m or more), a more complete OHS assessment would be required to cover all potential hazards of confined space entry.

Table 29 – Calculated Vapour Intrusion Risks for Workers in Trenches – Trench Air Concentrations calculated from Soil Vapour and/or Groundwater

VCH Scenario	Attenuation Factor α	Indoor Air Concentration, C_{ia}, µg/m^3	Threshold Risk - Hazard Index	Non-Threshold Risk - ILCR
Zone 1 – Commercial				
Soil Vapour - SV31 - 1m trench				
TCE (SV 1,000 µg/m^3)	9.6 x 10^{-3}	9.6	0.04	1.8 x 10^{-7}
PCE (SV 14,000 µg/m^3)	8.8 x 10^{-3}	123	0.03	1.5 x 10^{-7}
DCE (SV 310 µg/m^3)	9 x 10^{-3}	2.8	0.004	n/a
Sum			*HI = Σ HQ = 0.07*	*ILCR = 3.3 X 10^{-7}*
Soil Vapour - SV31 – 1.5m trench				
TCE (SV 1,000 µg/m^3)	3 x 10^{-1}	303	1.4	6 x 10^{-6}
PCE (SV 14,000 µg/m^3)	2.8 x 10^{-1}	397	0.1	4.5 x 10^{-7}
DCE (SV 310 µg/m^3)	2.9 x 10^{-1}	89	0.1	n/a
Sum			*HI = Σ HQ = 1.6*	*ILCR = 6.5 X 10^{-6}*
Soil Vapour – SV22 – 1.5m trench				
TCE (SV 19,000 µg/m^3)	7.7 x 10^{-6}	0.15	0.0007	2.7 x 10^{-9}
PCE (SV 25,000 µg/m^3)	4.4 x 10^{-6}	0.11	0.00002	1.3 x 10^{-10}
DCE (SV 100 µg/m^3)	2.2 x 10^{-5}	0.002	0.000006	n/a
Sum			*HI = Σ HQ = 0.001*	*ILCR = 2.8 X 10^{-9}*
Zone 2 – Residential				
Soil Vapour – SV01 – 1.5 m trench				
TCE (SV 428 µg/m^3)	1 x 10^{-2}	4.3	0.02	9.6 x 10^{-8}
PCE (SV 13,700 µg/m^3)	9 x 10^{-3}	124	0.03	1.5 x 10^{-7}
DCE (SV <200 µg/m^3)	1 x 10^{-2}	1.9	0.0003	n/a
Sum			*HI= Σ HQ = 0.05*	*ILCR = 2.5 X 10^{-7}*
Soil Vapour – SV13 – 1.5 m trench				
TCE (SV 160 µg/m^3)	4 x 10^{-3}	0.66	0.003	1.5 x 10^{-8}
PCE (SV 770 µg/m^3)	3.8 x 10^{-3}	2.9	0.0007	3.5 x 10^{-9}
DCE (SV 3,300 µg/m^3)	3.9 x 10^{-3}	127	0.02	n/a
Sum			*HI = Σ HQ = 0.02*	*ILCR = 2 X 10^{-8}*
Zone 3 – Residential				
Groundwater – MW07 – 1.5 m trench				
TCE (Gw 780 µg/L)	7.8 x 10^{-5}	22	0.1	5 x 10^{-7}
PCE (Gw <20 µg/L)	6.9 x 10^{-5}	0.9	0.0002	1 x 10^{-9}
DCE (Gw 53 µg/L)	8.5 x 10^{-5}	0.6	0.0002	n/a
Sum			*HI = Σ HQ = 0.1*	*5 X 10^{-7}*
Soil Vapour – SV04 – 1.5 m trench				
TCE (SV 3200 µg/m^3)	9.9 x 10^{-2}	318	1.49	6 x 10^{-6}
PCE (SV 30 µg/m^3)	9.1 x 10^{-2}	2.74	0.0006	3 x 10^{-9}
DCE (SV 26 µg/m^3)	9.3 x 10^{-2}	2.4	0.003	n/a
Sum			*HI = Σ HQ = 1.5*	*ILCR = 6 X 10^{-6}*
Soil Vapour – SV04 – 1 m trench				
TCE (SV 3200 µg/m^3)	2.45 x 10^{-3}	7.9	0.04	1.5 x 10^{-7}
PCE (SV 30 µg/m^3)	2.2 x 10^{-3}	0.07	0.00002	8 x 10^{-11}
DCE (SV 26 µg/m^3)	2.3 x 10^{-3}	0.06	0.00008	n/a
Sum			*HI = Σ HQ = 0.4*	*ILCR = 1.5 X 10^{-7}*

Table 29 shows that the only trench scenarios that had a Hazard Index >1, and potentially entering the SA EPA Investigation Range, was for a 1.5 m trench in the Zone 1 Commercial area in the vicinity of SV31, and in Residential Zone 3 in the vicinity of SV04[1]. A 1 m trench in these areas shows an acceptable risk for intermittent entry.

Additional modelling (not shown here) shows that a trench at SV31 to a depth of up to 1.45 m (ie, with 5 cm of soil above the measured vapour concentrations to allow some attenuation) would be in the acceptable range, with HI of 0.45 and ILCR of 1.6×10^{-6}. For SV04, a trench could be modelled with an acceptable risk down to 1.05 m, ie with 5 cm of soil able the measured vapour concentrations. The soil vapour concentrations below 1.1 m are unknown and trenches below 1.05 m were not modelled. Using groundwater concentrations in this area indicates an acceptable risk.

All other trench scenarios across all zones indicated an acceptable risk, based on a low exposure frequency of 1 day per month for 30 years, two half-days per month or any variation of 96 hours per year. A worker working on intrusive maintenance activities for a shorter period could enter a trench more frequently, eg, 3 days per month for 10 years.

It should be noted that all modelled trench air concentrations were orders of magnitude below the Workplace Exposure Standards (Safe Work Australia 2013), which are intended to cause no significant adverse health impacts to workers (adults). The relevant Exposure Standards are shown in Table 30.

Table 30 – Workplace Exposure Standards for Airborne Contaminants (Safe Work Australia 2013)

Chemical	Occupational Exposure Standard, TWA µg/m³	Occupational Exposure Standard, STEL µg/m³
TCE	54,000	216,000
PCE	340,000	1020,000
1,2-DCE	793,000	-

TWA = Time Weighted Average over a 40 hour working week.

STEL = Short Term Exposure Limits, for up to 15 minutes at a time. The STELS should be offset by periods of lower exposure so that the TWA is not exceeded overall.

There are several reasons for the difference between 'acceptable exposure levels' in the workplace and Reference Concentrations or similar guidelines for protection of public health. These include consideration of the type of receptor, the type of exposure, and the safety factors applied to the primary toxicological data. In the case of workers in excavation and trenches, it is expected that the exposure would be only to adults (no or minimal impact on development); exposure would be intermittent (with time for the body to recover from each exposure event); and the workers would be generally regarded as healthy. Additional safety factors are included in deriving public protective guidelines than are used for occupational exposure standards, including factors to account for developmental protection and for protection of vulnerable or sensitive populations such as people with compromised immune systems. Such safety factors are typically of the order of 3-10; removing a safety factor of 3 for assessment of the exposure in a 1.5 m trench would reduce the Hazard Index proportionally, to give HI <1 for all trench scenarios.

These results indicate that overall, excavation and trenching works should not pose a significant health risk to adult workers for intermittent exposure, of the order of 1 day per month (12 days or 24 half-days per year).

13.9 Discussion

Current Vapour Intrusion Risks

As shown in Table 28, all modelled risks in indoor air are at or within the EPA 'Validation Range' (TCE indoor air concentrations equal 0 – 2 µg/m³ or combined vapour exposures show a Hazard Index <1), and are considered to be safe, apart from the modelled risk in Zone 3 associated with TCE in groundwater at MW07 (see further discussion below). A TCE indoor air concentration of below 2 µg/m³ is at the lower end of the 'Investigation' range of the SA EPA/SA Health Indoor Air Level Response Range (i.e. no immediate health concerns are considered to be associated with measured levels, but further assessment is warranted).

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[1] Note that no soil vapour data is available for depths below 1.1 m for SV04; the trench risks were modelled as if the measured concentration was present at 1.5 m. In reality, it may be a higher concentration.

Trenches to a depth of 1.5 metres were modelled for maintenance works up to one day per month or 12 days per year. The VCH concentrations and exposure risks were considered to be in the acceptable range for adult workers with intermittent exposure.

Zone 3

All modelled risks in Zone 3 based on soil vapour data were within the EPA Validation Range and are considered to be safe. The maximum calculated vapour risks in Zone 3, based on the assumptions and input parameters used and the maximum VCH concentrations reported, showed a maximum Hazard Index of 10.7 in a theoretical basement dwelling, using TCE groundwater concentrations in MW07 (the maximum TCE in groundwater reported across the wider HAA). This well MW07 is in the vicinity of soil vapour bore SV04, which reported the maximum TCE concentrations in the residential zones; there appears to be consistency between groundwater concentrations and soil vapour concentrations and indicates that groundwater is the likely source of the soil vapour concentrations.

The soil vapour concentrations in SV04 translated into a Hazard Index < 1 and is generally considered to be in the acceptable range. Fate and transport modelling from groundwater into soil vapour and subsequent migration is less reliable than modelling from soil vapour alone, and may have overestimated the risks in this soil profile. The risks calculated for a slab on grade or crawl space house based on maximum TCE in soil vapour reported in that vicinity (from SV04) showed risks were approximately five times lower than when MW07 groundwater data was used (HI = 0.84 based on soil vapour vs HI = 4.9 based on groundwater; ratio = 0.84/4.9 = 0.17). If the slab on grade risks based on soil vapour are used as a basis to calculate the basement risks, the basement risks would be multiplied by a factor of 0.17 to give a TCE indoor air concentration of 3.6 µg/m3 and a HI of 1.86; this would place the risk in a habitable basement to the EPA Investigation Range.

It is noted that the risk assessment for all scenarios was based on very conservative exposure parameters of 24 hours per day, 365 days per week for 35 years. This is an unlikely and overly conservative assumption used in the initial modelling.

Using the enHealth 2012 exposure guideline (20 hours per day in a standard dwelling) for modeling from groundwater well MW07 into slab on grade or crawl space reduced the Hazard Index modelled from groundwater from 4.8 to 4.0 and the ILCR from 2.3 x 10^{-5} to 1.8 x 10^{-5}.

The Basement scenario for MW07 was modelled using the most conservative exposure assumptions, including continuous residence in the basement for 24 hours per day, 365 days per week for 35 years. This is an unlikely and overly conservative assumption used in the initial modelling, particularly for a basement. A more likely scenario would be use of the basement for shorter periods such as a home office or cinema or store room or possibly a bedroom; if exposure is assumed to occur for up to 10 hours per day, the Hazard Index modelled from groundwater is reduced from 10.7 to 4.5 and the ILCR from 5.1 x 10^{-5} to 2.1 x 10^{-5}.

However, as noted above, modelling vapour risks from dissolved groundwater concentrations is less reliable than predicting migration of measured soil vapour through the soil column; the groundwater model is likely to have overestimated the risks in this scenario and the risks predicted form the measured soil vapour concentrations should be used in preference.

In summary, the reported vapour intrusion risk modelled from groundwater MW07 may be overestimated and may not be representative of the risks in the Zone 3 residential area. This is indicated when considering all the data overall, including:

- the soil vapour data in this area (SV04) reported risks within the EPA Validation Range, which is considered to be safe;
- The AECOM 2016 report stated that the soil vapour data collected through passive Waterloo samplers as well as the permanent soil vapour wells in zone 3 indicated that the highly elevated TCE soil vapour concentration observed in bore SV04 was not representative of concentrations in the surrounding residential area (ie, it was higher than the surrounding area);
- the results of the Greencap sampling rounds in 2016 and 2017 showing the other seven soil vapour samples in Zone 3 with TCE concentrations an order of magnitude less than reported in SV04 (ranged from <LOR to a maximum of 280 µg/m^3; compared with 3,200 µg/m^3 in SV04);
- Considering the next highest reported concentration of TCE in Zone 3 (160 µg/m3 at 1.5 m, SV34), vapour intrusion modelling indicates an Indoor Air Concentration of 0.06 µg/m3 with a Hazard Quotient of 0.03 and ILCR of 1.5 x 10^{-7}).

- Separate work undertaken in the child care centre with similar soil vapour results to those reported in SV04 has shown no TCE concentrations of concern in indoor air.

Trends in Vapour Intrusion Risk since AECOM, 2016

Risks associated with Soil Vapour

Overall, Greencap notes that the risks associated with maximum VCHs in soil vapour have decreased since the AECOM (2016) VIRA, as the soil vapour concentrations have all decreased since the AECOM/URS soil vapour monitoring program in 2015 and 2016.

There is an encouraging overall trend across the site, where the Greencap sampling results indicate that VCH soil vapour concentrations have reduced or remained stable since the previous round of monitoring. This was particularly apparent in the vapour bores that had the highest historical vapour concentrations (eg, SV01, SV02, SV04, SV22); these have all decreased significantly, as have the associated vapour intrusion risks.

However some vapour bores with previously low vapour concentrations reported some increases in the Greencap monitoring rounds (Nov 2016 and Jan 2017). In particular, the TCE concentrations at SV07, SV08, SV26 (Zone 2) and SV33 (Zone 4) have increased since the AECOM VIRA, as shown in Table 31.

Table 31 – Vapour bores with increased TCE concentrations in November 2016 or January 2017

	SV07	SV08	SV26	SV33
Sample depth, m	1.8	1.7	2.0	1.5
TCE				
Historical maximum reported conc^n (pre-Nov 2016)	72	21	9	43
Feb 2016 results (AECOM)	8	< 7	<6.8	43
Nov 2016	5	<3	<3	120
Jan 2017	32	140	130	95

Note: all results in µg/m^3

Predictive modelling was undertaken on the *maximum increased* TCE soil vapour concentrations, in SV08, SV26 and SV33, using the JEM (USEPA 2004) to assess likely or potential health risks. The modelling indicates that the risk is currently acceptable but further assessment may be needed to monitor the potential for increasing soil vapour concentrations with time.

The model predicts that, for a slab on grade residential dwelling built on sand, and with TCE measured at 140 µg/m^3 at 1.5 m depth, the indoor air concentrations are approximately 0.1 µg/m^3, with a HQ of 0.05 and ILCR of 2×10^{-7} for full-time residents on site for 35 years. This is below the adopted target risk levels of HI < 1 and ILCR of 1×10^{-5}.

However, it is noted that SV08 and SV26 appear to have increased by a factor of 10 or more over the last year and to be at their historical highest concentrations. The trends in these bores should be monitored to determine if this is likely to be an ongoing increase or to stabilise. If the concentrations do not increase significantly, the vapour intrusion risk in these areas appears to be within the target risk levels and would be considered acceptable.

Based on conservative inputs for soil profile and exposure parameters, including use of higher Q_{soil} of 108 L/min (based on 95th % AF of 0.3) indicative TCE concentrations in soil vapour have been calculated for indicative screening levels, as shown in Table 32.

Table 32 – Indicative TCE Screening Values at various depths in Sand – For slab on grade construction

	Soil Vapour Concentration	
Soil Vapour depth (m)	Maximum Concentration for "Acceptable Risk" in SAND	Indicative Screening Value (half Acceptable Risk value, allowing for potential additional contaminants)
1	1450	725
1.5	2200	1100
2	3000	1500

Two values are suggested: one showing the concentration equalling the Acceptable Risk value (HQ=1) assuming no other contaminants are present. The second value is half of the 'Acceptable Risk' value, to allow for other potential contaminants and to still have a Hazard Index HI < 1.

Risks associated with groundwater
As vapour intrusion risks are directly related to the concentrations of volatile components in soil and/or groundwater, the risks will increase or decrease in relation to the trends in the groundwater plume. In general, the only increased vapour intrusion risks related to groundwater concentrations appear to be associated with MW07 (Zone 3, near the childcare centre) and MW08 (Zone 4). Both of these monitoring wells reported significantly higher concentrations of TCE compared with the 2015 results used in the AECOM VIRA, as shown in Table 33.

Table 33 – Groundwater Wells with increased TCE concentrations in November 2016 or January 2017, compared with historical results (2015)

TCE	MW07	MW08
	µg/L	µg/L
Apr 2015 results (URS/AECOM)	470	190
Nov 2016	400	380
March 2017	780	310

Table 33 shows that TCE concentrations have increased approximately 40-50% in these 2 wells (MW07 and MW08) compared with the results considered in the URS and AECOM 2016 VIRA.

However the highest groundwater concentration (MW07) indicates a similar vapour intrusion risk from groundwater as for soil vapour in the area (from SV04). This is lower than the previous risks for this area, based on higher soil vapour concentrations, and indicates that the risks have not increased on the site since the AECOM VIRA update in 2016. AECOM considered that this area was not representative of the wider Zone 3 residential area. It is noted that several rounds of environmental and indoor air quality sampling in this area have shown that it is not impacted by VHCs in the environment and is safe.

13.10 Sensitivity Analysis

A sensitivity analysis generally involves varying assumed input parameters to establish which parameters have the greatest effect on model results.

Most of the input variables are already considered to be conservative and were not changed, such as the residence time and exposure time in the proposed future buildings, which were set at the maximum feasible.

In reality, it is not expected that residents would be likely to reside full time (i.e. 24 hours per day) in the modelled scenarios, especially a basement, for the total assumed duration (35 years); however this input variable was not changed in the sensitivity analysis. If residents resided for less time in the habitable spaces than was calculated, the potential vapour intrusion health risks would decrease. Overall the exposure parameters were considered to be very conservative and protective.

The input variables that were changed as part of the sensitivity analysis were those that may indicate a higher potential risk. These included more conservative parameters for groundwater temperature and soil profile (for groundwater risks); building air exchange rate (AER) for the groundwater and soil vapour risks. These parameters are considered to be sensitive in predicting the attenuation factor and final indoor air concentration, and hence the potential health risk.

Groundwater Temperature Increase: For the basement construction scenario, the vapour intrusion risk was re-calculated for a basement above MW08 (the scenario with the next highest risk from groundwater, after MW07) with a higher average groundwater temperature. The initial model assumed a groundwater temperature of 22^{0}C (based on the average recorded groundwater temperature across the site and on annual average ambient temperatures reported for Adelaide); this was increased to 25°C as a potential worst case average temperature. This change increased the risks marginally, by approx. 10%. For example, considering the TCE risk (which was the highest reported vapour inhalation risk in all scenarios and considered to be the risk driver), the indoor air concentration increased from 0.20 to 0.22 $\mu g/m^3$, the Threshold Risk (Hazard Quotient) increased by 10% from 0.1 to 0.11 for resident on site for 365 days per year for 35 years.

More Conservative Soil Profile: The soil profile was amended by changing the surface layer to sand with default or published geotechnical parameters instead of the zone-specific collected data (ie, sand down to 1.5 m, with published values for total porosity of 0.387 and soil moisture of 8% instead of the sandy clay layer used in the model with total porosity of 0.34 and soil moisture of 16%). This change increased the risks significantly. For example, considering the TCE risk (which was the highest reported vapour inhalation risk in all scenarios), the indoor air concentration increased four-fold from 0.2 to 0.9 $\mu g/m^3$ with the change in soil moisture.

Indoor Air Exchange Rate (AER): The indoor air exchange rate for the residential scenario, initially modelled at the assumed residential house AER value of 0.6 changes/hour, was halved to 0.3/hour, to account for potential reduced air flow in an energy-efficient household. (Q_{soil} was amended to reflect the AER change.) This increased the predicted indoor air concentration above MW08 fourfold, from 0.2 to 0.9 $\mu g/m^3$, and the risks also increased (Hazard Quotient increased from 0.1 to 0.4)

This assessment indicates that the primary sensitivity and potential for increased risks above those predicted is the amount of ventilation and indoor air exchange rate, and the soil moisture. In cases of prolonged drought, where the surface soil may become drier, or if energy changes lead to a reduction in indoor air exchange, the concentrations of volatile contaminants in the subsurface environment may pose an increased risk of vapour intrusion.

13.11 Uncertainties and Limitations

Uncertainty in any assessment refers to a lack of knowledge (that could be refined through the collection of additional data or conduct of additional studies) and is an important aspect of the risk assessment process. An assessment of uncertainty is a qualitative process relating to the selection and rejection of specific data, estimates or scenarios within the risk assessment. In general, to compensate for uncertainty, conservative assumptions are often made that result in an overestimate rather than an underestimate of risks.

In general, the uncertainties and limitations of the risk assessment can be classified into the following categories:

Sampling and Analysis:
The available data relating to contamination in soil and groundwater was based on samples collected using a gridded and targeted approach. While these data may be reasonably representative of concentrations that may be present beneath the site, concentrations outside the sample locations are not known and can only be inferred. The sampling locations were chosen to target the assumed locations with maximum potential to detect chlorinated solvents and the sampling results are generally consistent with the expected spatial and temporal trends. However any sampling strategy can only provide limited data. Soil vapour data provides a more robust estimate for use in vapour intrusion modelling than modelling from soil or groundwater data alone.

As well as uncertainties in the contaminant sampling analyses, there are many uncertainties in the selection of the geotechnical inputs used in the modelling. The geotechnical data for each zone is not homogenous within the zone and judgement was required to select geotechnical data to represent a range of soil conditions, including ranges of particle size and moisture content which both have a significant influence on vapour intrusion modelling. Soil composition and moisture content is most variable spatially and can vary significantly within a few metres of the exact sampling location. There may also be some seasonal variation in soil moisture in the surface layer (usually the top metre is most affected by surface rainfall; the deeper soil layers are less affected). Changes in soil moisture can have a significant impact on the vapour intrusion risk.

Toxicological Assessment:
In general, the available scientific information is insufficient to provide a thorough understanding of all of the potential toxic properties of chemicals to which humans may be exposed. It is necessary to extrapolate these properties from data obtained under other exposure conditions and involving different species. The majority of the toxicological knowledge of chemicals comes from experiments with laboratory animals, which generally show interspecies differences in chemical absorption, metabolism, excretion and toxic response. There may also be uncertainties concerning the relevance of animal studies using exposure routes that differ from human exposure routes (e.g. oral or gavage to inhalation). In addition, the necessity to extrapolate results of short-term or sub-chronic animal studies to humans exposed over a lifetime has inherent uncertainty; as does the use of data from occupational studies of higher-dose exposures.

If assessment of short-duration exposures (acute or sub-chronic) is required (e.g. for intrusive trench workers), the use of chronic values for the assessment of such short duration exposures is expected to be conservative and result in an overestimate of actual risk.

Exposure Assessment:
The quantification of exposure has adopted a number of conservative assumptions. Modelling has assumed that maximum concentrations in soil vapour and groundwater are present beneath the whole of the areas that may be occupied, and it has been assumed that these concentrations do not change over the 35 years of assumed exposure. For the initial assessment, it has been assumed that residents may spend their whole time in the dwelling and may spend their whole childhood and many years of adulthood inside the dwelling (35 years in total). The risk assessment did not have access to enough data on the population and building characteristics to tailor the exposure assessment further. These various assumptions are expected to overestimate chronic risks.

In addition, the values adopted for the purpose of quantifying exposure are point values that are derived from a wide range of physiological or behavioural values that are better defined using a distribution or range. It is overly complex to present the assessment based on distributions hence the point values identified are considered to provide a reasonable approximation of average exposure and reasonable maximum exposure (RME). However the overall approach is expected to result in an overestimate of actual exposure. With additional data, some of these assumptions may be able to be refined.

Building Characteristics:

The building characteristics used in the assessment were based on published default values for residential scenarios and commercial scenarios. The same values were adopted as were used in the CRC CARE HSL development for building size and ventilation rate. The building footprint is not a significant contributor to changes in risk, but ceiling height and ventilation rate makes a major contribution. If the ceiling height increases, the risks will decrease; if the ventilation rate decreases, the risks will increase. The assessment must make use of general assumptions on these important input variables.

Overall:
A number of conservative approaches and assumptions have been adopted for exposure scenarios, which are expected to overestimate health risks. Such approaches and assumptions include:

- Residents living on the site as children and adults for 35 years (conservative default value); and
- Concentrations remain unchanged beneath the buildings for the duration of occupancy (i.e. no dilution, degradation or mass depletion over time).
- The toxicity reference values adopted are generally conservative and protective of public health, with several safety factors built in.

However other assumptions were less conservative and based on measured geotechnical data, which included measured soil moisture at higher than the default moisture and other assumptions used in initial modelling.

13.12 VIRA Summary

The human health risk assessment considered the presence of VHC compounds PCE, TCE and DCE in soil vapour and groundwater across four separate Zones in the HAA, and the potential for vapours to move into residential and commercial buildings.

For the purpose of this assessment the contamination was assumed to be present beneath buildings at the maximum concentration reported during the recent Greencap assessment works (2 groundwater monitoring events and 2 soil vapour monitoring events between October 2016 and March 2017) with no consideration of long-term source depletion or attenuation (e.g. metabolism, degradation, dilution and volatilisation).

The risk assessment considered the vapour impacts on various construction types including residential slab on grade, crawl space and basement buildings, using the maximum reported contaminant concentrations from each of the zones. An assessment was also undertaken into risks associated with maintenance/trench workers, discussed further below.

Based on the available data, and with consideration of the uncertainties identified, the following conclusions were made regarding potential risks to human health across the HAA:

- The risks overall have decreased across the HAA, along with the soil vapour concentrations that were the risk drivers in the previous assessments. The maximum risks identified are associated with dwellings above MW07, which may not be an accurate reflection of the risks to non-basement dwellings in this area; the soil vapour risks should be a more accurate reflection of vapour intrusion risks than groundwater modelling. The risks calculated from the soil vapour sampling in that area (SV04) show a reduction over time and are lower than the risks associated with previous soil vapour concentrations in SV04. The soil vapour concentrations have decreased by approximately 50% since February 2016, from 6,900 µg/m^3 to 3,200 µg/m^3, with a commensurate decrease in risk.
- Zone 1 Commercial workers: Inhalation risks to retail/commercial workers were below the target risk levels of 1 x 10^{-5} (non-threshold risks) and Hazard Index of 1 (for threshold risks), and are in a similar category to the SA EPA 'Validation Range' which is considered to be 'safe'. It is noted that the source concentrations here are decreasing over time, and are expected to continue to decrease.

  Zone 2 Residents: Inhalation risks to residents (adult and child) for all construction types were considerably less than the target risk levels of 1 x 10^{-5} (non-threshold risks) and Hazard Quotient of 1 (for threshold risks) and were within the SA EPA 'Validation Range' which is considered to be safe.
- Zone 3 Residents: The maximum inhalation risks to residents (adult and child) calculated for all construction types from TCE concentrations in groundwater in MW07 were above the SA EPA Validation Range and generally accepted target risk levels of 1 x 10^{-5} (non-threshold risks) and Hazard Quotient of 1 (for threshold risks). However, vapour intrusion risks modelled from groundwater data is less reliable than soil vapour data, and soil vapour data should take precedence for all areas where feasible (in this case, all construction types apart from basements where soil vapour data was not available). The risks calculated for a slab on grade or crawl space house based on maximum TCE in soil vapour reported in that vicinity (from SV04) showed risks were approximately five times lower than when MW07 groundwater data was used (HI = 0.84 based on soil vapour vs HI = 4.9 based on groundwater, ratio = 0.84/4.9 = 0.17). If the slab on grade risks based on soil vapour are used as a basis to calculate the basement risks, the basement risks would be multiplied by a factor of 0.17 to give a TCE indoor air concentration of 3.6 µg/m3 and a HI of 1.86; this would place the risk in a habitable basement to the EPA Investigation Range. Greencap soil vapour monitoring in surrounding wells in Zone 3, plus previous assessments including widespread passive sampling (AECOM 2016) indicate that the maximum VCH concentrations measured in this area (in SV04) was not representative of the wider residential area in Zone 3 and that these results (SV04 and MW07 vicinity) should not be included in the residential risk assessment. Seven other soil vapour samples in Zone 3 showed TCE concentrations an order of magnitude lower than those found in SV04. The predicted vapour intrusion risks from groundwater in Zone 3 are likely to be significantly overestimated and other environmental investigation programs in this area, including indoor air assessments, show that the area is safe.
- Zone 4 Residents: Inhalation risks to residents (adult and child) for all construction types were less than the target risk levels of 1 x 10^{-5} (non-threshold risks) and Hazard Quotient of 1 (for threshold risks), and are considered to be in the SA EPA Validation Range and to be safe.
- Inhalation risks to occasional visitors will be lower than the risks to residents or workers due to lower exposure frequencies and durations, and are considered to be safe.

Inhalation risks to construction and maintenance workers in shallow trenches (less than 1.5 m deep) were considered to be low and acceptable, due to the low exposure frequencies and durations expected for maintenance and excavation work and to the open air nature of the work which inhibits vapour accumulation. The potential vapour concentrations soon dissipate in shallow or wide excavations but may accumulate in deep or narrow trenches. The calculated vapour concentrations in theoretical trenches of 1.5 m in Zone 1 (near SV31) were marginally higher than the SA EPA Investigation Range and may need some additional assessment if regular entry is required. Vapour concentrations for all VHC in all trenches were an order of magnitude below the relevant Safe Work Australia Workplace Exposure Standards for Airborne Contaminants. Vapour concentrations in all trenches at 1 m deep were within the SA EPA Validation Range.

14.0 CONCLUSIONS

Greencap has conducted additional (Stage 3) groundwater and soil vapour monitoring across the HAA to obtain additional seasonal data with respect to the distribution of VCH identified in groundwater and soil vapour. In addition, the work has included groundwater fate and transport modelling to inform the boundaries of a potential GPA and updating a previously developed human health / vapour intrusion risk assessment, based on the findings of the abovementioned monitoring. It is noted that the central and northern portions of the HIA (including the Childcare Centre west of the Tapleys Hill Road / West Lakes Boulevard intersection) are subject to separate environmental assessment works and were not assessed as part of the Stage 3 investigation work.

Groundwater and Soil Vapour Monitoring

The groundwater investigations comprised the gauging, sampling and analysis of 31 groundwater monitoring wells (on two occasions) across the HAA using predominantly low flow (micro-purge) sampling techniques. The soil vapour investigations comprised the sampling and analysis of 28 soil vapour points (on two occasions) across the HAA using summa canisters.

All groundwater and soil vapour samples were analysed for VCH including PCE, TCE, DCE and VC (main COPC). Ten selected groundwater monitoring wells were also analysed for natural attenuation parameters and major cations and anions per groundwater monitoring event.

Groundwater analytical results were compared to potable, recreational and irrigation criteria to maintain consistency with the previous assessment work completed across the HAA, while soil vapour results were compared to interim soil vapour HILs as stipulated in the NEPM.

A number of elevated VCH concentrations were reported in groundwater above the adopted groundwater criteria with the most significant TCE, PCE or 1,2-DCE concentrations reported from monitoring wells GW09, MW02, MW04, MW05, MW07 and MW08. The elevated TCE concentrations ranged from 32µg/L (MW02) to 780µg/L (MW07) while the elevated PCE concentrations ranged from 52µg/L (MW02) to 78µg/L (MW05). Elevated 1,2-DCE concentrations ranged from 62µg/L (MW07) to 252µg/L (GW09). Trend analysis was undertaken for a number of groundwater wells using the Mann Kendall tool (where sufficient data was available), which indicated the majority of concentration trends displayed stable, probably decreasing or decreasing trends. Some increasing trends were identified within monitoring wells MW04, MW06, MW07 and MW08 indicating that the VCH contaminated plumes have not reached steady state conditions and may still be migrating to these locations from the up hydraulic gradient sources. In terms of groundwater chemistry, the majority of the groundwater was described as sodium chloride dominated within the HAA (and was generally saline). Some groundwater wells exhibited groundwater chemistry typical of freshwater recharge, predominantly within the north western portion of the HAA.

A number of TCE concentrations were reported to exceed the adopted NEPM HIL criteria over both sampling events with the most significant TCE concentrations reported from soil vapour point locations SV04, SV21 and SV22 (within and west of the HIA). The elevated TCE concentrations ranged from 29µg/m^3 (SV30) to 19,000µg/m^3 (SV22))). In addition, some elevated PCE and cis-1,2-DCE soil vapour concentrations were reported exceeding the adopted NEPM HILs with the most significant PCE and 1,2-DCE concentrations reported from soil vapour point locations SV22 and SV13 respectively (within and south of the HIA). The elevated concentrations in soil vapour generally coincided with elevated concentrations of similar chemicals in nearby groundwater monitoring wells. Trend analysis was also undertaken for a number of soil vapour points using the Mann-Kendall tool (where sufficient data was available) which indicated that decreasing trends were evident at all soil vapour point locations. This indicates that VCH in soil vapour may potentially undergo some natural degradation or volatalisation.

Conceptual Site Model

A summary of the CSM is provided as follows:

- The geological setting of the HAA is complex. Significant variations in the subsurface material does not enable the boundaries of geological units such as clays and sands to be confidently determined across the HAA. As a result, this could not be confidently replicated within the 3D model domain.
- The groundwater flow across the eastern portion of HAA generally occurs to the north west.
- Groundwater in the western portion of HAA generally occurs to the south west.

- The groundwater contour pattern is influenced by low groundwater levels measured in MW07 and MW25; both potentially influenced by some groundwater discharge into the deep sewer main located in the vicinity.
- There was a shallow, assessed to be 'perched', aquifer identified within the vicinity of a former service station in Royal Park (north western portion of the HAA).
- This perched aquifer was characterised by higher groundwater levels in comparison with the deeper (likely regional uppermost) aquifer.
- The groundwater flow direction in the perched aquifer was assessed to be to the south west (Coffey, 2011) and groundwater in the deeper regional uppermost aquifer was assessed to be to the north west (Coffey, 2011) (i.e. similar to the groundwater flow direction assessed for the south eastern portion of the HAA).
- Hydraulic conductivity estimates during previous investigations were only conducted for a limited number of wells located to the south-east of Tapleys Hill Road. This indicates that the coverage of these values is not sufficient to enable confident delineation of different hydraulic conductivity zones in the model.
- The exact location(s) of the potential sources of groundwater impacts and their dimensions have not been defined sufficiently to enable accurate replication within the numerical model.
- The VCH compounds identified as the primary chemicals of concern are unlikely to undergo significant degradation/de-chlorination and the overall distribution of the parent and daughter products in groundwater is further complicated by the presence of multiple sources/plumes.

Groundwater Fate and Transport Modelling

The primary objective of the numerical modelling is to assist the EPA in defining a boundary for a proposed GPA, based on the EPA's intention to 'to ensure that the pathway of direct exposure to contaminated groundwater is not realised' between the contaminated plumes and local residents. A summary of the numerical 3D modelling is provided as follows:

- The model extent covers an area approximately 5.5 km east-west and 4 km north-south.
- A two layer model was constructed. The base of layer 1 was positioned to include the screened intervals of all shallow wells. The base of the layer 2 was assigned to include the screened intervals of the deep wells (MW21 and MW22).
- The Flow Model boundary conditions included:
    - Constant head boundaries positioned along the eastern and western extents of the model domain.
    - The default 'no-flow' boundaries along the northern and southern edges of the model.
    - Drain boundary conditions positioned at the locations of the deep mains identified in previous reports prepared by PB, URS and AECOM.
- The flow model was calibrated and used as the basis for the transport model.
- The transport model was constructed based on the following assumptions:
    - The sources of contamination have been conservatively set to be constant and assigned with maximum concentrations reported in the groundwater wells since 1992.
    - The MT3DMS has been used for the simulation of advection and dispersion of contaminants in groundwater systems. No chemical sorption and no reactive transport (degradation PCE and TCE into DCE and VC) has been simulated.
- During the transport model calibration, the source locations/dimensions were varied to achieve a reasonable match between the mapped and simulated plume configurations, extensions and concentrations.
- After the calibration, the transport model was run until the simulated VCH concentrations in groundwater reach steady state conditions (i.e. the plumes reached their maximum extents and concentrations under the modelled conditions).
- The modelling results indicate that the groundwater contamination potentially occurred at around 1950 and there are multiple plumes emerging from different sources.
- Modelling results also indicate that the deep sewer mains are influencing the plume migration by acting as a hydraulic "sink".

- A number of uncertainties and data gaps have been identified for the flow and transport model and included:
    - Ø The role, if any, of the perched groundwater system.
    - Ø The hydraulic conductivities of the uppermost regional and perched aquifers.
    - Ø The extents of the sewer mains influences on groundwater flow and contaminant transport.
    - Ø The actual locations and dimensions of groundwater sources and concentrations of VCH at the inferred sources.
- The above and other identified uncertainties and data gaps were considered to be critical to the outcomes of the modelling. Additional work focused on the reduction of the identified uncertainties would be required to construct a more realistic groundwater flow and transport model for the site.
- Although a suggestive extent of the GPA was included in the report it is concluded that the GPA may be defined more confidently if the data gaps are addressed and information incorporated into the updated groundwater flow and transport model for the HAA.

Vapour Intrusion Risk Assessment

An update to the previous VIRA conducted by AECOM in April 2016 was undertaken using additional data sourced from two recent soil vapour and two groundwater sampling events (including site specific geotechnical data). To be consistent with previous risk assessments, the investigation area was broken into four zones. The following conclusions were made regarding potential risks to human health via the inhalation pathway:

- Zone 1 Commercial workers: Inhalation risks to retail/commercial workers were less than the target risk levels and are in a similar category to the SA EPA 'Validation Range' which is considered to be safe. It is noted that the source concentrations here are decreasing over time, and are expected to continue to decrease.
- Zone 2 Residents: Inhalation risks to residents (adult and child) for all construction types were considerably less than the target risk levels and were in the SA EPA 'Validation Range' which are considered to be safe.
- Zone 3 Residents: The maximum inhalation risks to residents (adult and child) calculated for all construction types from TCE concentrations in groundwater in MW07 were above the SA EPA Validation Range and generally accepted target risk levels of 1 x 10^{-5} (non-threshold risks) and Hazard Quotient of 1 (for threshold risks). However, vapour intrusion risks modelled from groundwater data is less reliable than soil vapour data, and soil vapour data should take precedence for all areas where feasible (in this case, all construction types apart from basements where soil vapour data was not available). The risks calculated for a slab on grade or crawl space house based on maximum TCE in soil vapour reported in that vicinity (from SV04) showed risks were approximately five times lower than when MW07 groundwater data was used (HI = 0.85 based on soil vapour vs HI = 4.9 based on groundwater, ratio = 0.85/4.9 = 0.17). If the slab on grade risks based on soil vapour are used as a basis to calculate the basement risks, the basement risks would be multiplied by a factor of 0.17 to give a TCE indoor air concentration of 3.6 µg/m3 and a HI of 1.86; this would place the risk in a habitable basement to the EPA 'Investigation Range'. Greencap soil vapour monitoring in surrounding wells in Zone 3, plus previous assessments including widespread passive sampling (AECOM 2016) indicate that the maximum VCH concentrations measured in this area (in SV04) was not representative of the wider residential area in Zone 3 and that these results (SV04 and MW07 vicinity) should not be included in the residential risk assessment. Seven other soil vapour samples in Zone 3 showed TCE concentrations an order of magnitude lower than those found in SV04. The predicted vapour intrusion risks from groundwater in Zone 3 are likely to be significantly overestimated and other environmental investigation programs in this area, including indoor air assessments, show that the area is safe.
- Zone 4 Residents: Inhalation risks to residents (adult and child) for all construction types were less than the target risk levels and are within the SA EPA 'Validation Range' which are considered to be safe.
- Inhalation risks to maintenance/trench workers in shallow trenches (less than 1.5 m deep) are considered to be low and acceptable (i.e safe), due to the lower exposure frequencies and durations expected for maintenance and excavation work and to the open air nature of the work which inhibits vapour accumulation. The potential vapour concentrations soon dissipate in shallow or wide excavations but may accumulate in deep or narrow trenches. The calculated vapour concentrations in theoretical trenches of 1.5 m in Zone 1 (near SV31) were marginally higher than the SA EPA Investigation Range and

may need some additional assessment if regular entry is required. Vapour concentrations for all VHC in all trenches were an order of magnitude below the relevant Safe Work Australia Workplace Exposure Standards for Airborne Contaminants. Vapour concentrations in all trenches at 1 m deep were within the SA EPA Validation Range which is considered to be safe.

- Inhalation risks to occasional visitors will be lower than the risks to residents or other occupiers due to lower exposure frequencies and durations, and are considered to be safe.
- Greencap notes that the risks associated with maximum VCH results in soil vapour have generally decreased since the completion of the previous VIRA update as the maximum soil vapour concentrations have decreased.

15.0 LIMITATIONS OF THIS REPORT

This report has been prepared in accordance with the agreement between the South Australian Environment Protection Authority and Greencap. This report is solely for the use of the South Australian Environment Protection Authority.

This report has been prepared in accordance with industry recognised standards and procedures at the time of the work using a degree of skill and care ordinarily exercised by members of its profession and consulting practice. The report presents the results of the assessment based on the quoted scope of works (unless otherwise agreed in writing) for the specific purposes of the commission. No warranties expressed or implied are offered to any third parties and no liability will be accepted for use of this report by any third parties.

Information provided by third parties has been assumed to be correct and complete. Greencap does not assume any liability for misrepresentation of information by third parties or for matters not visible, accessible or present on the subject property during any site inspections conducted during the time of the work.

The first stage in the site assessment process generally involves site history research and/or a site inspection. This stage is intended to establish whether there is a likelihood of site contamination. Depending on the location of the site and surrounding land use, there could be contamination present which could not have been identified by preliminary investigation of this nature - for example, if there had been dumping of waste liquids which has left no visual evidence and past owners were not aware of. If recommendations have been made on whether or not to conduct further investigation, these have been based on the likelihood of site contamination, and are generally based on the sensitivity of the proposed future use of the site. A more conservative approach is generally adopted for a sensitive future use such as residential or a child care centre. Subsequent stages of soil or groundwater investigation may follow. The site assessment process is often ongoing, with additional stages of investigation being required to resolve issues raised in previous stages of the investigation. In cases where sampling and analysis of soil and/or groundwater has been conducted, then the following standard limitations apply:-

- The results presented in the report apply only to the specific locations and the time the sampling was conducted. The nature and extent of contaminants present on a site can change due to physical disturbance or removal, chemical or biological transformation, or due to the migration of the contaminants to different areas.
- The borehole or test pit logs indicate the approximate subsurface conditions only at the specified test locations. Soil and rock formations are variable, and conditions in areas not sampled may differ from those at the actual sampling locations due to natural subsurface variation.
- The precision with which subsurface conditions are indicated depends largely on the frequency and method of sampling and investigation, and the degree of subsurface variation. There can be no complete guarantee that contaminants are not present at significant concentrations in some areas, even with the most thorough site assessment.
- Any conclusions or recommendations are based solely on the land use assumptions stated in the report. These conclusions or recommendations do not apply to any other land use for the site.

This report should be read in full, shall only be presented in full and may not be used to support any other objective than those set out in the report, except where written approval with comments are provided by Greencap. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. Opinions and judgements expressed herein are based on Greencap’s understanding of current regulatory standards and should not be construed as legal opinions.

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