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Final Report

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Hendon Investigation Area - Preliminary Vapour Risk Assessment

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ABBREVIATIONS

Abbreviation	Description
1,1-DCE	1,1-Dichloroethene
1,2-DCE	1,2-Dichloroethene
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ASC	Assessment of Site Contamination
ADWG	Australian Drinking Water Guidelines
AWQG	Australian Water Quality Guidelines
CEC	Cation Exchange Capacity
COC	Chain of Custody
COPC	Chemical of potential concern
CRC	Cooperative Research Centre
CSM	Conceptual Site Model
DEWNR	Department of Environment, Water and Natural Resources
DO	Dissolved Oxygen
EC	Electrical Conductivity
EIL	Ecological Investigation Level
EPA	Environment Protection Authority
ESA	Environmental Site Assessment
ESL	Ecological Screening Level
HIL	Health Investigation Level
HSL	Health Screening Level
IL	Investigation Level
LCS	Laboratory Control Spikes
LOR	Limits of Reporting
m AHD	metres Australian Height Datum
m BGL	metres below ground level
m BGS	metres below ground surface
NATA	National Association of Testing Authorities
NEPC	National Environment Protection Council
NEPM	National Environmental Health (Assessment of Site Contamination) Measure
PCE	Tetrachloroethene
PID	Photo Ionisation Detector
QA/QC	Quality Assurance/Quality Control
SA EPA	South Australian Environment Protection Authority
TCE	Trichloroethene
TDS	Total dissolved solids
URS	URS Australia Pty Ltd
VC	Vinyl chloride

EXECUTIVE SUMMARY

URS was engaged by the South Australian Environment Protection Authority (SA EPA) to conduct Stage IV environmental investigations within a defined Investigation Area located in Hendon, South Australia. The Investigation Area comprises land in the vicinity of a historical industrial area and consists of a number of industrial and residential properties. As a supplementary element to this work, URS was commissioned to also conduct vapour intrusion modelling and quantitative human health risk assessment works based on the outcomes of this additional environmental site assessment.

The following key conclusions were noted from the results of the 2015 intrusive investigations:

- Volatile chlorinated hydrocarbon contamination continue to be present in shallow groundwater at a depth of typically around 3.5 to 5 m below ground level within the Investigation Area associated with the Hendon industrial area.
- The nature and distribution of VCH contamination in groundwater indicates that there are a number of properties within and in the near vicinity of the Hendon industrial area that may have historically acted and may continue to be acting as sources of the reported groundwater and soil vapour impacts. This investigation and risk assessment was limited in scope to consideration of vapour intrusion. It has also been focussed on the EPA investigation area targeting principally residential zones and so does not include detailed assessment of source areas.
- A property survey has identified the presence of both concrete slab-on-ground and timber floor (crawlspace) residential construction, and notably, that underground structures (cellar/basements) are a feature of some local residential dwellings.

The objective of the vapour intrusion modelling and human health risk assessment works detailed in this report was to incorporate the updated characterisation of volatile chlorinated hydrocarbon impacts across the Investigation Area in an assessment of potential vapour inhalation risks.

Required outcomes of this assessment included:

- Assessment of potential human health risk for selected building types and occupational scenarios across the Investigation Area to the extent supported by investigation data; and
- Identification of data gaps relevant to increased confidence in the assessment of the potential presence of human health risk.

Potential vapour intrusion risks estimated on the basis of soil vapour concentrations were higher than those estimated from groundwater data. This is considered to be principally due to the use of shallow soil vapour concentrations as the use of soil vapour data as source terms potentially overestimates risks as it implicitly neglects the potentially rate-limiting step of vapours diffusing up from groundwater through moisture saturated soils. Both source scenarios (vapour and groundwater data) have been modelled.

Quantitative assessment has been based on calculation of hazard indices (HI, being modelled exposure concentrations relative to adopted exposure guidelines) assuming simple additivity of toxic effects for the key contaminants of potential concern PCE, TCE and cis 1,2 DCE.

Assessment criteria have been based on the air level response framework for TCE developed by SA Health and the EPA (TCE Action Level Response Framework). This in essence defines concentrations ranges and associated actions consistent with:

- HI < 1 *validation range* – safe, but consider if ongoing monitoring required
- 1 < HI < 10 *investigation range* – further assessment necessary

Modelling of indoor air exposure using 2015 soil vapour concentrations of PCE, TCE and DCE indicate the potential for indoor air concentrations to warrant further investigation for several exposure scenarios and at different portions of the Investigation Area, particularly:

- TCE concentrations in Zone 3 (based on the concentration of 8,400 µg/m^3 at SV04 adjacent the Hendon Childcare Centre) resulted in exceedances of the HI = 1 range for each of the residential foundation assumptions.
  - A Hazard Index of approximately 3 (equivalent to the "Investigation" classification of the Indoor Air Level Response Range Framework) for slab on ground buildings
  - A Hazard Index of 8.7 for the Residential with Basement scenario (towards the upper end of the "Investigation" classification of the Indoor Air Level Response Range Framework).
  - A Hazard Index of 1.6 for the Residential with crawl space.
- A Hazard Index for the Residential with Basement scenario for Zone 2 (comprising a residential area south-west of West Lakes Boulevard and the Industrial Area) was >1 (3.05), again within the "*Investigation*" classification. This was principally driven by the elevated DCE vapour concentrations in vapour well SV13, located on West Lakes Blvd. The HI for slab on ground construction in this area was marginally less than 1, in the *Validation* range.
- The Hazard Index for Commercial – Slab-on-Ground for Zone 1 was also only marginally <1 (0.97). This area contains a church that is understood to be used occasionally as a children's play café.
- The calculated risks due to the potential for habitable basement use exceed those for slab on ground and crawl-space homes, due to their depth/proximity to the groundwater impacts.

Some recent historical soil vapour concentrations have been notably greater than the 2015 results; however, these historical concentrations were not generally assessed to affect the classifications with respect to the Indoor Air Action Level Response Framework, other than to the extent that TCE concentrations in the northern portion of Zone 2 also warrant an *Investigation* classification for the Residential with Basement scenario.

No modelled risks exceeded the upper investigation range criteria (HI=10). The elevated concentrations of TCE identified in SV04 near the Hendon Childcare Centre and elevated DCE concentrations in SV13 provide the highest risk estimates across the four spatial zones considered in the vapour risk assessment. Better delineation of the extent of elevated soil vapour impacts and confirmation of absence or presence of and use of basements is considered warranted in these areas.

The above summary should be read in conjunction with the Limitations presented in **Section 5.2** of this report.

1 INTRODUCTION

URS was engaged by the South Australian Environment Protection Authority (SA EPA) to conduct Stage IV environmental investigations within a defined Investigation area located in Hendon, South Australia. The Investigation area comprises land in the vicinity of a historical industrial area and consists of a number of industrial and residential properties. The location of the Investigation area is shown in **Figure 1**.

As a supplementary element to this work, URS was commissioned to also conduct vapour intrusion modelling and quantitative human health risk assessment works based on the outcomes of this additional environmental site assessment.

1.1 Background and Objectives

Environmental issues including soil and groundwater contamination associated with former industrial land uses in the Hendon area have been the subject of investigations as far back as 1992. The SA EPA has been undertaking environmental assessment works in the area since 2012. While the contamination is understood to originate from one or more historical industrial sources located within the industrial area, the exact source locations have not been determined.

The most recent previous investigations, conducted by Parsons Brinckerhoff (PB) in 2014, concluded on the basis of vapour modelling to predict potential indoor air concentrations that health risks associated with inhalation of volatile chlorinated hydrocarbons (VCHs) in the residential area were acceptable. PB's reports from 2012, 2013 and 2014 identified the potential for temporal variability in vapour concentrations due to changes in soil moisturewhich as a sensitive model parameter has the potential to alter health risk assessment outcomes.

As a result, URS was commissioned to undertake additional investigations in 2014, the objective of which was to both update and refine the characterisation of volatile chlorinated hydrocarbon site contamination to soil and groundwater across the Investigation area, in conjunction with acquisition of other exposure pathway data, to support a separate assessment of the potential risks to human health. These additional investigations focused on residential areas to the south and west of the Hendon Industrial area, and a children's play café located at the corner of Philips Crescent and Circuit Drive, Hendon.

1.2 Objective

The objective of the vapour intrusion modelling and human health risk assessment works detailed in this report was to incorporate the updated characterisation of volatile chlorinated hydrocarbon site contamination across the Investigation area in an assessment of potential vapour inhalation risks.

Required outcomes of the assessment included:

- Assessment of potential human health risk for selected building types and occupational scenarios across the Investigation Area to the extent supported by investigation data; and
- Identification of data gaps relevant to increased confidence in the assessment of the potential presence of human health risk.

1.3 Scope of Works

The modelling and assessment was undertaken in general accordance with that outlined in URS's proposal '*Environmental assessment works (Stage IV), Hendon industrial area*, *SA* (Ref 03014258-1090) dated 10 April 2015. The scope of works included the following:

- Critical evaluation of site physical and chemical data, including comparison of groundwater and soil vapour VCH data, and review of current investigation data to historical results, to devise suitable model inputs.
- Vapour intrusion modelling utilising the 2004 modified J&E model and updated chlorinated solvent concentrations in groundwater and soil vapour, together with soil geophysical properties estimated from the URS Stage IV environmental investigations, for the scenarios of:
  - residential dwellings – slab on ground;
  - residential dwellings – timber floor and crawlspace;
  - residential dwellings – inclusive of basement; and
  - commercial (children's play café) building.
- A detailed modelling sensitivity analysis for key input parameters/assumptions, including consideration of historical investigation data. The model also included comparative modelling from groundwater and soil vapour to enable calibration to the soil profile.
- Preparation of this preliminary quantitative human health risk assessment (HHRA) report, limited to risks associated with vapour intrusion pathway for volatile chlorinated hydrocarbons, and based on consideration of modelled indoor air concentrations relative to the residential indoor air level framework for TCE developed by SA Health and the EPA (TCE Action Level Response Framework).

2 ENVIRONMENTAL SITE INVESTIGATIONS

2.1 Previous Investigations

Environmental site assessments at 3-5 Philips Crescent, located within the investigation area and displayed on the attached figures, by Coffey Partners in 1992 (Coffey 1992a and 1992b) identified groundwater impacts consisting of elevated concentrations of metals, boron, fluoride and VOCs including volatile chlorinated hydrocarbons (VCHs) trichloroethylene (TCE), tetrachloroethylene (PCE) and 1,2-dichlroethane (1,2-DCE) . The groundwater flow direction was inferred to be north westerly and it was concluded that VOC impacts may have included on and an off-site source to the north-east. It was noted that TCE was formerly used on the site as a solvent for cleaning circuit board panels. A soil gas survey by Coffey Partners in 1992 (Coffey 1992c) identified widespread elevated concentrations of VOCs within the soil vapour the property located at 3-5 Philips Crescent. It was noted at that time that an unacceptable health risk may have existed for site users and possibly nearby residents.

The SA EPA commenced undertaking additional environmental assessment works in the area in 2012 conducting an Environmental Site Assessment (ESA) (PB, 2013a). The works involved the sampling and extension of the groundwater and soil vapour well network into the area surrounding the 3-5 Philips Crescent property. The investigation identified elevated concentrations of PCE and TCE in groundwater in the vicinity of the Hendon Laugh'n'Learn Child Care Centre (MW07), a well adjacent on Philips Crescent (GW9) and a well adjacent to a residential area (MW14). A vapour risk assessment conducted by PB (2013b) indicated that the vapour risks were below the assessment criteria and considered to be tolerable. However the elevated result for the vapour well in the vicinity of the childcare centre triggered a soil vapour investigation at the site.

Additional investigations were conducted in 2013 and 2014 by PB (2013b, 2014b). The investigations included the extension of the groundwater and soil vapour well network, soil vapour bore monitoring and installation of passive Radiello samplers within service pits surrounding the childcare centre. Elevated concentrations of VOC's were identified in the north eastern corner of the Hendon industrial area, and up hydraulic gradient of the Philips Crescent property indicating that it was likely that there was more than one source of contamination in the Hendon industrial area. Concentrations of TCE were also detected in the passive Radiello samplers within the service pits surrounding the childcare centre. A vapour risk assessment conducted by PB (2014b) which concluded, based on available data, that risks to residential receptors including the occupants of the Hendon Child Care Centre were acceptable. A number of contaminant sources were deemed likely within the industrial area. The investigation (PB, 2014b) also identified the possibility of a deep sewer along Tapleys Hill Road acting as a preferential pathway for the migration of chlorinated hydrocarbon impacts.

PB's reports from 2013 and 2014 also identified the potential for temporal variability in vapour concentrations due to changes in soil moisture, which may alter the outcomes of the health risk assessment.

Works have been recently undertaken to the north of the Hendon industrial area by a third party (CH2MHILL, 2015) comprising the installation and sampling of three nested sets of vapour bores (SV18, SV19 and SV20) in the general vicinity of chlorinated solvent contaminated vapour bore SV10 (and its paired groundwater monitoring well MW14). It was noted that a potential TCE and PCE source area may be located up hydraulic gradient of

MW14 towards MW23; spills or leaks of solvents may have occurred from former activities in this area including a munitions factory during World War II, and an oil store, plating, chemical and printed wiring factory operated by Philips. LAI industries currently manufacture switchboards and control gear assemblies within an industrial property in this area. A human health risk assessment in this area has been undertaken to assess the chlorinated solvent vapour risks to residents and commercial occupants.

2.2 Stage IV Environmental Investigations (URS, 2015)

The objective of the Stage IV environmental investigations was to update and refine the characterisation of volatile chlorinated hydrocarbon (VCH) contamination to soil vapour and groundwater across the Investigation area, in conjunction with acquisition of other exposure pathway data, to support a separate assessment of the potential risks to human health. The investigations focused on residential areas to the south and west of the Hendon Industrial area, and the children's play café located at the corner of Philips Crescent and Circuit Drive, Hendon.

The scope of works, conducted in April and May 2015, included (refer **Figure 2**):

- monitoring of 28 existing groundwater wells to the south and west of the investigation area (the program included sampling of a further 6 groundwater wells associated with another site on the north of the industrial area);
- installation of eight new soil vapour wells (SV21-SV28) at locations designated by the SA EPA (south & west) to further delineate the contaminant plume, and at two locations around the children's play café site, followed by monitoring of 19 (previously installed and new) soil vapour wells as designated by the SA EPA; and
- conduct of a survey of properties within an area designated by the SA EPA to identify construction type, presence of basements/cellars, and groundwater use.

The following was concluded from the results of the investigation:

- Groundwater flow in the region (refer **Figure 3**) appears to be influenced by incidental extraction of groundwater by the deep sewer trunk mains, which indicates the potential for transport of VCH contaminated groundwater via the sewerage system.
- VCH contamination continues to be present in shallow groundwater at a depth of typically around 3.5 to 5 m below ground level within the Investigation area associated with the Hendon industrial area. Results are shown on **Figure 5** to **Figure 9**.
- The nature and distribution of VCH contaminationwas generally consistent with previous observations. Concentrations in a number of wells, including several along West Lakes Boulevard south of the Philips Crescent site, were the highest recorded since 2012.
- The nature and distribution of VCH contamination in groundwater indicates that there are a number of properties within and in the near vicinity of the Hendon industrial area that have historically and may continue to be acting as sources of the reported contamination.
- Soil vapour VCH contamination is also present, to a large degree reflective of groundwater impacts (refer **Figure 10** to **Figure 12** for TCE, PCE and cis-1,2-DCE).

- The property survey identified the presence of both concrete slab-on-ground and timber floor (crawlspace) residential construction, and notably, that underground structures (cellar/basements) are a feature of the local residential dwellings.

3 REFINED SITE CHARACTERISATION

3.1 Site Physical Setting

The site is located on the Adelaide Plains approximately three kilometres east of the Gulf St Vincent. The major physiographic feature of the region is the northeast to southwest trending Mt Lofty Ranges located approximately five kilometres to the east (Geological Map sheet 1:50,000 “*Adelaide*”, Department of Mines and Energy (1988)). The Adelaide Plains consist of sediments derived from the erosion of the Mt Lofty Ranges.

3.1.1 Soils

According to the “Soil Association Map of the Adelaide Region” (Department of Mines, 1972), the SA EPA’s Hendon investigation area lies predominantly within an area of the Adelaide outwash plains dominated by Red Brown Earth soil types RB6/RB7. However, in the western extent of the investigation area (west of the area encompassed by the current groundwater and soil vapour monitoring network)is likely that shallow soils comprise estuarine muds and sands associated with the low lying flats of the Port River environs.

Reference to published geological maps (Geological map sheet 1:250,000 “Adelaide”, SA Department of Mines and Energy 1969) indicates the investigation area is underlain by the Pooraka Formation, a pale red-brown sandy clay containing carbonate.

Consistent with a conceptual site model prepared by PB (Figure 7 of PB (2014)), URS’s review of borehole logs for the historical and recent groundwater and soil vapour monitoring wells indicates that although the saturated zone representative of the shallow water bearing layer comprises primarily silty clay, sandy clay and clayey sand, overlying materials in the vadose zone are predominantly sandier (comprising variably clayey sand/sandy clay, silty sand, sand, and to a lesser degree, silty clay). Based on URS’s review of borelogs, these sandy vadose zone materials are distributed widely across the investigation area, with no apparent spatial trends.

Soil physical property testing was conducted on samples collected from soil vapour wells SV21, SV22, SV25 and SV27 during the Stage IV environmental investigations. **Table 3-1** provides a summary of the results (in full in **Table 1**, attached), grouped into like materials and depths.

Table 3-1 Summary of Tested Soil Properties

Soil Type	Bore and Sample Depth Interval (mbgl)	Wet Bulk Density (t/m3)	Dry Density (t/m3)	Moisture Content (%)	Porosity
SAND	SV21: 1.5 – 2.0	1.76	1.65	6.6	36.2
Sandy CLAY	SV22: 1.5 – 2.0 SV27: 1.5 – 2.0	1.95 2.00	1.56 1.79	24.9 12.0	40.6 32.5
Sandy CLAY	SV21: 2.5 – 3.0 SV25: 2.5 – 3.0 SV27: 2.5 – 3.0	1.97 1.97 2.09	1.57 1.62 1.76	25.5 21.9 18.8	40.8 39.0 34.2

Soil Type	Bore and Sample Depth Interval (mbgl)	Wet Bulk Density (t/m3)	Dry Density (t/m3)	Moisture Content (%)	Porosity
Silty CLAY	SV22: 2.5 – 3.0	1.97	1.56	26.4	42.0

3.1.2 Groundwater

Regional Hydrogeology

Up to six thin gravel aquifers are likely present within the quaternary sediments beneath the site, and up to four tertiary aquifers exist within the tertiary sediments beneath the investigation area.

The salinity of the shallow groundwater is generally high with total dissolved solids greater than 5,000 mg/L. The greatest proportion of extracted water comes from the first tertiary aquifer due to its low salinity and high production; this tertiary aquifer is used for seasonal irrigation of golf courses and other recreational grounds.

The regional groundwater flow direction is expected to be to the west, towards the West Lakes Boating Lake and Gulf St Vincent. The West Lakes Boating Lake is located approximately 300 m to the west of the western boundary of the EPA Investigation area. The shallow man-made lake discharges to the Port River, which in turn discharges to the Barker Inlet to the north.

Groundwater Field Parameters

Field parameters measured during groundwater sampling conducted by URS as part of the Stage IV environmental investigations are summarised below.

Table 3-2 Groundwater Field Parameters

Parameter	Results and Comments
pH	pH varied from 5.34 (GW01) to 7.73 (MW09), with values typically indicative of a mildly acidic groundwater environment
Oxidation/Reduction Potential (ORP)	Field Redox potential varied from -223.3 mV (BH95) to 228.4 mV (GW01), indicative of conditions ranging from both highly oxidising to highly reducing conditions; however, the majority of bores reported reducing conditions.
Dissolved Oxygen (DO)	Dissolved oxygen (DO)[1] varied from 0.01 mg/L (BH95, MW12) to 3.85 mg/L (MW07). DO concentrations were generally low, with a mean for all bores sampled of 0.7 mg/L.
Electrical Conductivity (EC) and Calculated Total Dissolved Solids (TDS)	Electrical conductivity (EC) ranged from approximately 0.8 mS/cm (BH25) to 30 mS/cm (MW20). Total dissolved solid (TDS)[2] concentrations (estimated from electrical conductivity) ranged between approximately 500 mg/L (BH25) and 20,000 mg/L (MW20).

[1] DO measurements were carried out following the removal of a water sample from the well rather than in-situ. As a result, the measured DO may differ from the actual conditions in the aquifer due to disturbance during water retrieval.
[2] TDS = EC (mS/cm) reading x 670

Parameter	Results and Comments
Temperature	Temperature ranged from 19.8 (GW01) degrees Celsius (°C) to 23.7 °C (MW26)

Site-Specific Hydrogeology

The site-specific hydrogeology, based on observations made during the Stage IV environmental investigations and historical investigation data, is summarised in **Table 3-3**.

Table 3-3 Hydrogeological Summary

Aspect	Results
Depth to Groundwater	Standing water levels (SWL) measured during the Stage IV environmental investigations varied from approximately 3.3 metres below ground level (mBGL) to 4.7 mbgl, with an average of 3.9 mbgl. Over the period 2012 to 2015, groundwater levels have been gauged in March, April, June and September; the shallowest results to date were recorded in September 2012, at an average of 0.35 m shallower than April 2015 levels.
Groundwater Inferred Flow Direction	Groundwater elevations calculated for wells across the site varied between -0.387 m Australia Height Datum (mAHD) and 0.953 mAHD. Given the variation in salinity, URS gave consideration to applying a correction for variation in density to calculated elevations. However, the calculation (based on Pavelic and Dillon (1993)) indicated corrections typically only of up to around 6 mm, which are not significant to the overall flow direction across a site of this magnitude. For consistency with previous reports, uncorrected elevations have been used in inferring the groundwater contours that are presented graphically on **Figure 3**. From the contours, and consistent with previous investigations (historical gauging results are presented in **Table 3**), the inferred direction of groundwater appears to be towards Tapleys Hill Rd. Groundwater east and west of Tapleys Hill Rd appears to flow towards a low point centred along Tapleys Hill Rd. PB's suggestion that this is due to influence from the sewerage system appears valid, with 525 mm diameter VC (vitreous clay) sewer trunk mains running along Tapleys Hill Road and De Havilland Avenue. These mains are assumed to be gravity fed and pumped due to the low elevation of the area, providing a mechanism for localised drawdown of the water table in the event of leakage into the sewers (and effectively also a mechanism for transport of contaminated groundwater).

3.2 Residential Construction

An initial property survey was conducted on 12 May 2015 as part of the URS Stage IV environmental investigations, encompassing over 100 properties west and south of the Hendon industrial area, as shown on **Figure 13**. The two survey areas (covering selected properties within zones 2 and 4, as outlined in section 4.7.2 and displayed in Figure 14 and 15) were targeted based on inferred elevated impacts to groundwater beneath residential dwellings.

A supplementary property survey was also undertaken between 12 to 16 July 2015 based on the initial vapour modelling outcomes for properties in the vicinity of elevated soil vapour TCE contamination identified in vapour bore SV04 (within part of Zone 3) at the corner of Tapleys Hill Road and West Lakes Boulevard.

The objective of the property surveys was to assess the construction of dwellings (timber floor / concrete slab on ground), presence of below ground structures (basements, cellars) and any registered or unregistered groundwater wells. The following works were undertaken:

- Preparation and distribution of letters and survey forms by a URS employee to assess the presence and use of or intended installation of basements and/or groundwater bores.
- URS undertook a survey of selected properties. Where occupants were available, URS completed the survey at the time of the doorknock. Additionally, occupants were provided with the option of providing URS with a completed survey via post.
- A building surveyor from Rider Levett Bucknall SA Pty Ltd accompanied URS personnel during the initial property survey, to provide an opinion for each property on likely building foundation type, either in lieu of, or as a supplement to, occupant-supplied information.

The survey results, which have been provided to the EPA in a separate letter report, are summarised below:

- Of the 138 properties door knocked and surveyed, 40 occupants provided responses.
- Of the 40 responses provided, 6 residences were identified to have basements (including 4 within the southern survey area/ Zone 2 and 2 within the western survey area/ Zone 4); 3 were identified to have vehicle service pits; and 2 domestic groundwater wells were identified. It is noted that in addition to use of the basements for storage, two residents noted use of the basements as bedrooms.
- The property construction survey of 115 properties in the western and southern survey areas by Levett Bucknall SA Pty Ltd identified 39 properties likely constructed using an on-ground slab, two properties with both raised floors and on-ground slabs, and the remainder of properties likely to be constructed with raised floors and a crawlspace.
- The supplementary survey area of 23 selected properties near the corner of Tapleys Hill Road and West Lakes Boulevard (within Zone 3) identified four properties that may contain raised floor, four properties that were unable to be adequately inspected and the remainder of properties with on-ground slabs. No basements were identified in this area.

3.3 Nature and Distribution of VCH Concentrations

3.3.1 Groundwater

A total of 28 groundwater wells within the Vapour Intrusion Risk Assessment Area (outlined on **Figure 5**) were sampled between 27 and 30 April 2015 as part of the Stage IV environmental investigations. The sampled wells included GW01, GW02, GW09, BH13, BH22, BH25, MW01-MW12, MW15-MW16, MW18-MW22, MW26-MW27 and MW95.

Tabulated summary results and graphical presentations for the targeted contaminants of potential concern are presented as follows:

Figure 5: Groundwater TCE Results
Figure 6: Groundwater PCE Results
Figure 7: Groundwater 1,2 DCE Results
Figure 8: Groundwater Total VCH Results
Figure 9: Groundwater Results – Other Chlorinated Solvents

Table 4: Groundwater Results – VCH
Table 5: Groundwater Results – Natural Attenuation, Major Ions and Alkalinity
Table 6: Historical Groundwater Results – VCH

Table 3-4 provides a summary of groundwater analytical results for halogenated aliphatics, aromatics, fumigants and trihalomethanes where reported concentrations exceeded the LOR.

Table 3-4 Summary of 2015 Groundwater Analytical Results – VCHs

VCH	Units	Min result	Max result	Screening Level	Wells exceeding guidelines
Trichloroethene	µg/L	<0.05	1350	20	BH22, GW2, GW9, MW2, MW4, MW5, MW7, MW8
Tetrachloroethene	µg/L	<0.05	179	40	MW2, GW9, MW4, MW5, MW12
1,1-Dichloroethene	µg/L	<0.1	47.9	30	GW9
1,2-Dichloroethene (sum cis & trans)	µg/L	<0.1	984.6	60	GW2, GW9, MW2,MW4, MW5, MW12
Vinyl chloride	µg/L	<0.3	56.7	0.3	GW1, GW2, GW9, MW2, MW5
1,1-Dichloroethane	µg/L	<0.1	0.8	2.7*	-
1,2-Dichloroethane	µg/L	<0.1	1.5	3	-
Chloroform	µg/L	<0.1	2.44	3	-
Chlorobenzene	µg/L	<0.1	0.36	300	-
Total Trihalomethanes	µg/L	0.11	2.44	250	-

* US EPA Regional Screening Level (Residential Tapwater 1E-06 ICR)

This data summary highlights that TCE, PCE, cis-1,2-DCE and VC are the principal volatile contaminants of potential concern identified in groundwater. 1,1 DCE was identified marginally in excess of the drinking water guideline in one well (GW9; where substantially higher TCE and DCE impacts were evident), but only at trace levels and has not been considered further . All other analysed halogenated aliphatics, aromatics, fumigants and trihalomethanes were reported below the LOR.

An inspection of tabulated historical groundwater data (**Table 6**) for the key VCHs of concern (TCE, PCE, cis-1,2-DCE and VC) indicated that while there is commonly a small degree of temporal variability, the 2015 groundwater results are generally consistent with previous results. The following points are of note:

- Generally, VCH concentrations in impacted wells down-gradient of the inferred source areas are observed to be increasing (MW02, MW04, MW06, MW07, MW08) while those up-gradient of the source areas are observed to be decreasing (MW12, GW1). Concentrations in wells near the centre of impact (GW9, GW2) appear relatively steady to declining.
- TCE and cis-1,2-DCE concentrations in well MW04 located down-gradient of the highest concentration wells, on the boundary of the residential area, exhibit an apparently uniform increasing trend; PCE concentration in this well in 2015 are also the highest reported to date. TCE and PCE results for well MW05 (up-gradient from MW04) exhibit variability, but 2015 results remain within the range of historical concentrations.

3.3.2 Soil Vapour

Laboratory certificates for the analysis of VCHs from summa canister samples are presented in full in the URS Stage IV environmental investigation report. Tabulated summary results and graphical presentations of selected VCHs are presented as follows:

Figure 10: Soil Vapour TCE Results
Figure 11: Soil Vapour PCE Results
Figure 12: Soil Vapour cis-1,2-DCE Results

Table 7: Soil Vapour Results – VCHs
Table 8: Historical Soil Vapour Results – Selected VCHs

The following notes are made on the basis of an inspection of tabulated historical soil vapour data (**Table 8**) for the key VCHs of concern (TCE, PCE, cis-1,2-DCE and VC), for areas to the south and west of the industrial area:

- For both SV01 and SV02 (which correspond in location approximately to wells in which groundwater concentrations exhibit increasing trends), TCE vapour concentrations are close to the lower end of the historical range, while PCE concentrations show almost an order of magnitude reduction from 2014 results.
- An increasing trend in both TCE and cis-1,2-DCE is evident for well SV04; while TCE concentrations have increased progressively to five times the 2012 concentration, cis-1,2-DCE concentrations have increased by over an order of magnitude. (Nearby groundwater well MW07 exhibits increasing TCE concentrations but relatively stable cis-1,2-DCE concentrations).
- Soil bore SV15, located near the Hendon Child Care Centre, and approximately 20-30 m north of SV04, reported a TCE concentration of 560 µg/m^3 for April 2015, consistent with a possible decreasing trend, although representing a step down from previous results which have ranged from 1300 µg/m^3 to 1900 µg/m^3.
- SV17, located near the up-gradient edge of the investigation area, reported a TCE concentration over an order of magnitude lower than for 2014 (only two sampling events have been conducted for this well).
- Notable variability between 2015 and 2014 results (with 2015 results lower) was observed for SV06 (TCE, PCE), SV07 (TCE, PCE), which should be taken into account in assessment of potential vapour risks.

- For the remaining wells, the soil vapour measurements conducted in April 2015 were relatively consistent with historical data, where available.

3.3.3 Critical Review of Chemical Concentration Data

Relative significance of VCHs to risk assessment

Table 3-5 below presents a summary of the results of concentrations for TCE, PCE, cis-1,2-DCE and VC for sampling conducted between 19 April and 13 May 2015 (noting that the SV13 result shown is the largest of the triplicate results). Where concentrations exceed the NEPM vapour intrusion screening, the degree to which the result exceeds this guideline is shown adjacent the result in parentheses, to provide an indication of the relative magnitude of exceedance of the key VCH contaminants.

Table 3-5 Summary of Soil Vapour Analytical Results – TCE, PCE, cis-1,2-DCE, VC

Location and Depth	Trichloroethene (µg/m^3)	Tetrachloroethene (µg/m^3)	cis-1,2-Dichloroethene (µg/m^3)	Vinyl chloride (µg/m^3)
NEPM HIL Residential A/B (1m)	20	2000	80	30
Southern Investigation Area				
SV01 – 1.5m	**460 (23x)**	**5800 (2.9x)**	**95 (1.2x)**	<9.7
SV02 – 2m	**390 (20x)**	**3600 (1.8x)**	**400 (5x)**	<5.8
SV03 – 2m	**42 (2x)**	**38**	**8**	<3.3
SV06 – 2m	**410 (20x)**	**1300**	**8.8**	<3
SV07 – 1.8m	**22**	**500**	<4.6	<3
SV08 – 1.8m	**21**	**29**	<4.6	<3
SV11 – 1.8m	**17**	**10**	<4.5	<2.9
SV13 – 1.8m	**280 (14x)**	**1650**	**9480 (120x)**	<10
SV17 – 2m	**9.6**	**1200**	<4.4	<2.9
SV22 – 2m	**25,000 (1250x)**	**28,000 (14x)**	**220 (2.75x)**	<30
SV23 – 2m	**530 (27x)**	**1800**	**12**	<3
SV24 – 1.9m	**17**	**7.8**	<4.4	<2.9
SV25 – 2m	**26**	<7.8	<4.5	<2.9
SV26 – 2m	**9.4**	**32**	<4.7	<3
SV27 – 2m	**22**	**13**	<4.7	<3
SV28 – 2m	**11**	**7.9**	<4.6	<3
Western Investigation Area				
SV04 – 1m	**8400 (420x)**	<39	**280 (3.5x)**	<14
SV05 – 2m	**20**	**11**	<4.8	<3.1
SV14 – 1.8m	**20**	**3.5**	<0.86	<0.56
SV15 – 1.8m	**560 (28x)**	**6.8**	**5.7**	<1.2
SV15M (?m)	**19**	<7.8	<4.5	<2.9
SV21 – 2m	**550 (28x)**	**8.2**	<4.6	<3

The following is noted from the above comparison:

- Where elevated VCH concentrations were reported in soil vapour, the ratio of TCE to the NEPM criterion was at least an order of magnitude higher than that for PCE, from which it is evident that TCE may be considered the risk driver of these two compounds.

- Elevated cis-1,2-DCE concentrations were reported in four bores in the southern investigation area and one in the western area. In the southern area, for vapour wells SV01 and SV02, TCE concentrations were over 20 times the NEPM criterion, while cis-1,2-DCE concentrations varied between being marginally over and up to five times the NEPM criterion. Elevated TCE soil vapour concentrations are materially higher than PCE soil vapour concentrations with reference to the criterion, hence TCE would still be the principal risk driver. However, at location SV13, the reported cis-1,2-DCE concentration exceeds the NEPM criterion by a substantially greater margin than the TCE concentration, indicating that cis-1,2-DCE may drive risk assessment at this location. In the western area, the only reported exceedance of the cis-1,2-DCE screening criteria is to a much lesser degree than the corresponding TCE exceedance.

Comparison of Soil Vapour Data to Expectations from Groundwater Data

Table 3-6 below presents a comparison, for selected VCH compounds of:

- the measured soil vapour concentrations (at the depths indicated for each soil vapour bore) and the groundwater concentrations for nearby wells;
- "% Theoretical" values, as the ratio of the reported soil vapour concentration to the *theoretical maximum equilibrium soil vapour* concentrations at the groundwater/air interface (nominally 3.5 m), based on Henry's Law.

Results for March 2014 (blue cells) are shown for comparison with 2015 results (white cells).

Table 3-6 Comparison of Adjacent Groundwater and Soil Vapour Analytical Results – TCE, PCE, cis-1,2-DCE, VC

	Trichloroethene (Vapour - µg/m3) (Water - µg/L)	Tetrachloroethene (Vapour - µg/m3) (Water - µg/L)	cis-1,2-Dichloroethene (Vapour - µg/m3) (Water - µg/L)	Vinyl chloride (Vapour - µg/m3) (Water - µg/L)
Henry's Law Constant (Unitless)	0.4	0.724	0.167	1.11
Southern Investigation Area				
SV01 – 1.5m	510	21000	<200	<100
MW02	19.1	54.3	217	<0.3
% Theoretical	**6.7%**	**53.4%**	**-**	**-**
SV01 – 1.5m	460	5800	95	<9.7
MW02	56.5	179	319	0.4
% Theoretical	**2.0%**	**4.5%**	**0.2%**	**-**
SV02 – 2m	1100	26000	1800	<110
MW05	9.22	25.5	189	<0.3
% Theoretical	**29.8%**	**140.8%**	**5.7%**	**-**
SV02 – 2m	390	3600	400	<5.8
MW05	48.9	131	326	0.4
% Theoretical	**2.0%**	**3.8%**	**0.7%**	**-**

	Trichloroethene (Vapour - µg/m3) (Water - µg/L)	Tetrachloroethene (Vapour - µg/m3) (Water - µg/L)	cis-1,2-Dichloroethene (Vapour - µg/m3) (Water - µg/L)	Vinyl chloride (Vapour - µg/m3) (Water - µg/L)
SV13 – 1.8m	450	3000	12000	<110
MW12	12.3	49.8	171	<0.3
% Theoretical	**9.1%**	**8.3%**	**42.0%**	**-**
SV13 – 1.8m	280	1650	9480	<10
MW12	10.8	60.2	90.5	<0.3
% Theoretical	**6.5%**	**3.8%**	**62.7%**	**-**
SV22 – 2m	25,000	28,000	220	<30
GW9	1350	95.3	963	0.5
% Theoretical	**4.6%**	**40.6%**	**0.1%**	**-**
SV23 – 2m	530	1800	12	<3
(GW9)	1350	95.3	963	0.5
% Theoretical	**0.1%**	**2.6%**	**0.01%**	**-**
Western Investigation Area				
SV04 – 1m	5200	7.1	44	<2.3
MW07	330	0.17	57.9	<0.3
% Theoretical	**3.9%**	**5.8%**	**0.5%**	**-**
SV04 – 1m	8400	<39	280	<14
MW07	470	0.18	58.1	<0.3
% Theoretical	**4.5%**	**-**	**2.9%**	**-**
SV15 – 1.8m	1400	<29	<21	<10
(MW07)	330	0.17	57.9	<0.3
% Theoretical	**1.1%**	**-**	**-**	**-**
SV15 – 1.8m	560	6.8	5.7	<1.2
(MW07)	470	0.18	58.1	<0.3
% Theoretical	**0.3%**	**5.2%**	**0.1%**	**-**
SV21 – 2m	550	8.2	<4.6	<3
MW08	190	0.14	10.2	<0.3
% Theoretical	**0.7%**	**8.1%**	**-**	**-**

In the above tables, no value is calculated where either result is less than the laboratory LOR. A comparison of the 2014 data is not available for those locations vapour wells were installed and sampled in 2015 (i.e. as part of the Stage IV environmental investigations by URS).

From the above table it is noted that:

- Measured soil vapour concentrations are in many cases significantly lower than the theoretical maximum calculated from the measured groundwater concentrations, ranging from as low as 0.01% to close to 10%.

- In a few instances, measured soil vapour concentrations range from approximately 30% to 140% of the theoretical maximum, across TCE, PCE and cis-1,2-DCE. In relation to these instances, it is noted that:
  - In only one instance (cis-1,2-DCE for SV13/MW12) was a high proportion of the theoretical vapour concentration apparent for consecutive sampling rounds (42% for 2014, 63% for 2015). It is noted that using 2013 data for soil vapour well SV13 (6,300 µg/m^3) and groundwater monitoring well MW12 (340 µg/L) gives a value of 11%.
  - There was generally poor consistency in relation to the proportion of theoretical maximum recovered between the different VCHs at any given location. For example, at SV01 and the adjacent groundwater well MW02, the DCE groundwater concentration is approximately twice the PCE concentration, however the PCE vapour concentration is more than 50 times the DCE concentration.
  - This phenomenon is not limited to the current round of sampling, with 2014 results indicative of similar discrepancies.

The soil vapour results are considered to generally be low in comparison to theoretical maximum values, even taking into account the shallower depth of measurement (typically 1.5 m above the groundwater level). This phenomenon (lower vapour than the theoretical maximum) is consistent with literature observations. Shen *et al*[3] (2012) concluded that under certain conditions of rainfall and infiltration, a *clean water lens* may form on top of contaminated groundwater. As the diffusion coefficients for solutes such as these VOCs in groundwater is approximately 4 orders of magnitude lower than their relative diffusion coefficients in air, this clean water lens can act to greatly slow the diffusion of vapour from the groundwater source.

As such, standard groundwater sampling techniques that may effectively integrate sample concentrations across several metres of thickness of well screen may greatly over-estimate the potential vapour concentrations generated from the relatively less contaminated lens located at the groundwater-vadose zone interface. .

The US EPA also acknowledges this effect in the 2012[4] *Conceptual Model Scenarios of the Vapor Intrusion Pathway*, with Section 6.4.2 noting:

> *In locations where there is significant infiltration through the unsaturated zone, a layer of clean groundwater may build up on top of the contaminated groundwater plume and act as a barrier to VOC volatilization from the groundwater to soil gas and may decrease the soil vapor concentration distribution in the subsurface. This process has been referred to as clean water lens (Fitzpatrick and Fitzgerald, 1996) and diving plumes (Griesemer, 2001). Also, if the soil is coarse grained and there is high downwards drainage of the infiltrating water through the soil, the water may flush the contaminant from the soil gas as it infiltrates down the subsurface, which may also decrease the soil vapor concentration (Mendoza and McAlary, 1990).*

[3] R Shen, K Pennell, E Suuberg (2012) *A numerical investigation of vapour intrusion – The dynamic response of contaminants vapors to rainfall events*, School of Engineering, Brown University, Providence, USA
[4] US EPA (2012), *Conceptual Model Scenarios for the Vapor Intrusion Pathway,* EPA 530-R-10-003, Office of Solid Waste and Emergency Response, US EPA, February 2012.

However, even where this clean water lens effect is in existence, it is not clear why the relative *groundwater:soil vapour* concentration ratios for each of the contaminants would not be relatively consistent (ie. why a much greater %theoretical PCE than DCE at SV01/MW02). It may be associated with heterogeneous/stratified concentration gradients in groundwater, spatial variability in contaminants between the locations of the groundwater and vapour wells, or potentially some contribution from vadose zone sources.

4 VAPOUR INTRUSION RISK ASSESSMENT

4.1 Introduction

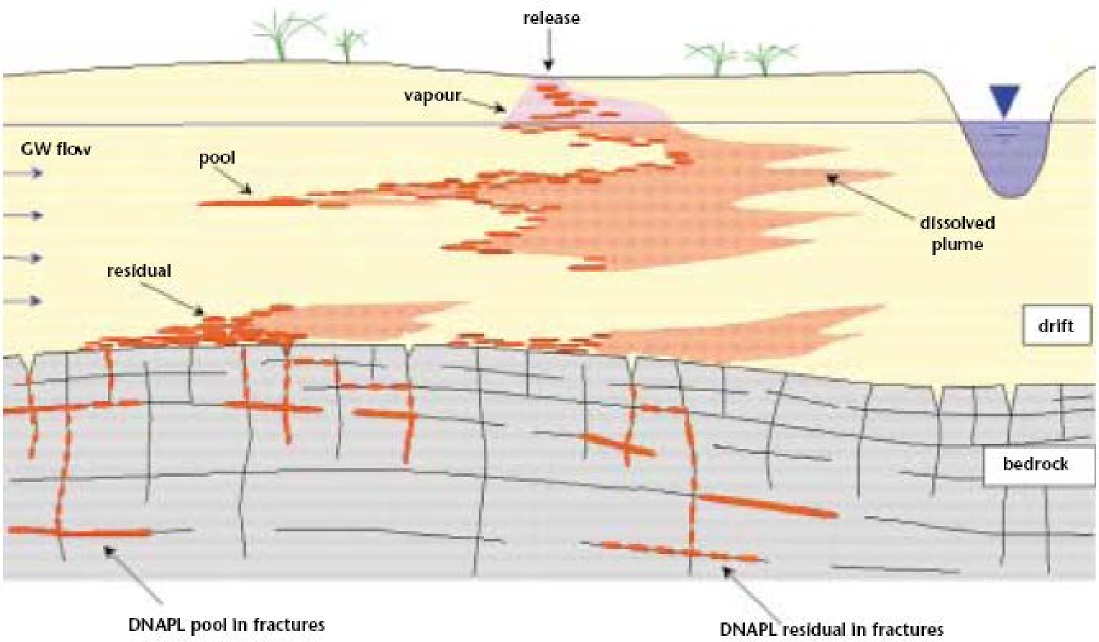
This section provides a conceptual site model focused on exposure via vapour intrusion (considering a number of potential scenarios across the investigation area), and vapour modelling to establish whether identified groundwater or soil vapour concentrations may represent unacceptable vapour risks to building occupants.

4.2 Generalised Conceptual Behaviour

4.2.1 Chlorinated Ethenes in Groundwater

PCE, TCE, DCE (3 isomers) and vinyl chloride are volatile, dense, non-aqueous phase liquids (DNAPL). If released into groundwater as DNAPL they tend to sink until they reach a low permeability layer that they cannot penetrate or until the NAPL mass is reduced (by leaving a 'trail' of residual NAPL along the path), such that there is insufficient mass for continued movement of the liquid. However, as the NAPL migrates downward it may also migrate laterally, spreading out in response to localised heterogeneities in the aquifer permeability, as illustrated in **Figure 4-1**.

Figure 4-1 Schematic Illustration of DNAPL Distribution in Unconsolidated Deposits[5]



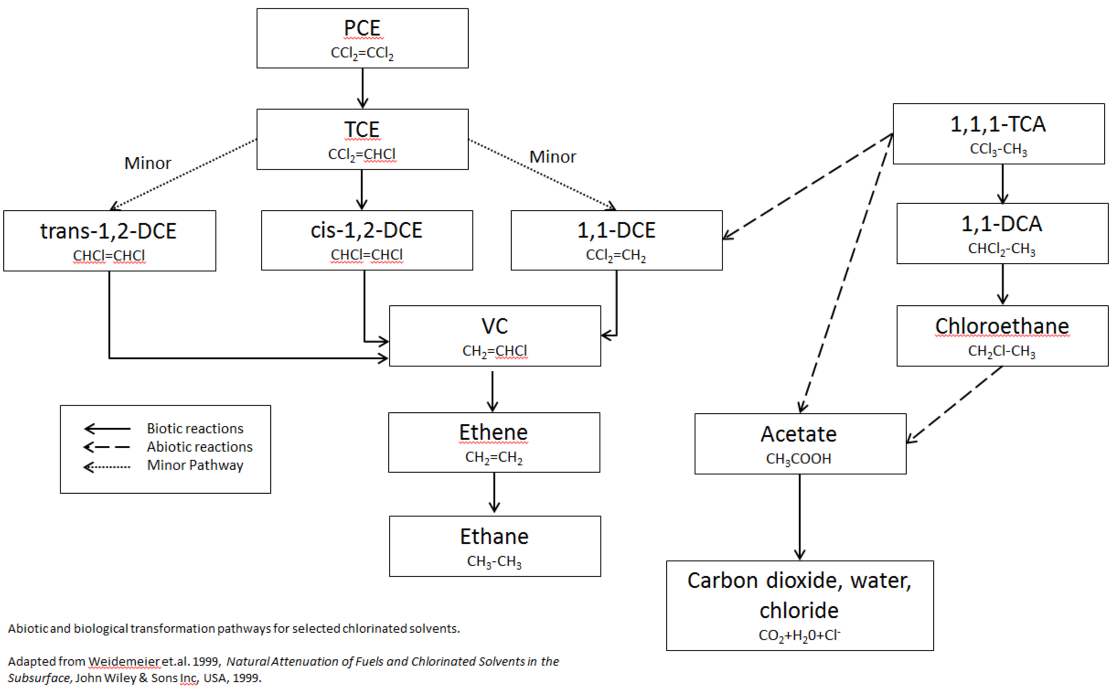
DNAPL may be mobile or present only as residual DNAPL in disconnected pore spaces, or as smearing on soil particles. When DNAPL is in contact with groundwater the contaminants gradually dissolve into the water, creating a dissolved phase 'plume' that can then migrate down-gradient with the groundwater as well as, to a lesser extent, diffuse (driven by concentration gradients) in all directions.

[5] UK Environment Agency (2003) 'An illustrated handbook of DNAPL transport and fate in the subsurface', Environment Agency R&D Publication 133

A 'rule of thumb' for assessing whether residual DNAPL may be present near a groundwater monitoring well, based on observed concentrations in the groundwater, is that dissolved concentrations above approximately 1% of the aqueous pure-phase solubility may be indicative of the local presence of DNAPL.[6] On this basis, PCE concentrations above approximately 2 mg/L could indicate the presence of DNAPL, while this is approximately 10 mg/L for TCE and 35 mg/L for DCE. In the case of the Hendon assessment area, all measured dissolved phase concentrations are well below these levels, so no DNAPL is evident. It is noted however, that this assessment has principally focussed on residential areas, rather than potential source areas.

The more highly chlorinated ethenes (PCE, TCE) are relatively biodegradation resistant (stable) in aerobic (oxygenated) environments. However, under anaerobic (reducing) conditions PCE and TCE can degrade into less-chlorinated ethenes by a process of successive dechlorination, producing daughter products as shown in **Figure 4-2**.

Figure 4-2 Abiotic and Biological Transformation Pathways



Therefore, when PCE or TCE are identified as chemicals of concern in environmental investigations, their chlorinated daughter products (DCE and VC) are also of potential concern. Commonly PCE and or TCE are likely to be the principal source chemicals where the chlorinated ethenes have originated from use as degreasing solvents. DCE and VC may then be generated via this reductive dechlorination process. Although there are three forms (isomers) of DCE (1,1-DCE, cis-1,2-DCE and trans-1,2-DCE), the main one to be formed from degradation of TCE is typically cis-1,2-DCE.

It is noted that 1,1 DCE may also be formed via abiotic (non-biological) processes from trichloroethane (TCA), so its presence (e.g. in the absence of cis 1,2 DCE) may indicate the historic use of TCA as an alternative solvent to TCE or PCE.

[6] US EPA. 1992. *Estimating Potential for Occurrence of DNAPL at Superfund Sites*. OSWER Publication 9355.4-07FS. National Technical Information Service (NTIS) Order Number PB92-963338CDH.

4.2.2 Chlorinated Ethenes in Vapour

US EPA (2012)[7] and ITRC (2007)[8] provide recent technical guidance summarising expected behaviour of volatile COPC for the *vapour intrusion pathway*. For chlorinated solvents such as PCE, TCE and cis-1,2-DCE, the following summarises the expected generalised behaviour and aids in supporting the adopted investigation approach and consequent assessment.

- Chemicals volatilise from impacted soil and/or groundwater and diffuse towards regions of lower chemical concentration (*Diffusion*).
- Soil gas can be drawn into a building due to a number of factors, including barometric pressure changes, wind load, thermal currents, or depressurization from building exhaust fans (*Advection*).
- The rate of movement of vapours into buildings is a difficult value to quantify and depends on the geology, chemical properties, building design, operation and condition, and the pressure differential.
- Advective transport is likely to be most significant in the region very close to a basement or a foundation, and soil gas velocities decrease rapidly with increasing distance from the structure. The reach of the building "zone of influence" on soil gas flow is usually less than a few feet, vertically and horizontally.

  It is noted that advection may not have a *net* effect on chronic exposure (i.e. long term), as buildings may also be over-pressurised (as opposed to under-pressurised), thereby reducing the potential for vapour intrusion part of the time. The UK Environment Agency does not recommend generic inclusion of advective flow in its CLEA model[9] due to absence of evidence of a sustained driving force for advective flow.
- PCE, TCE and cis-1,2-DCE vapours are unlikely to biodegrade to any significant degree while migrating through the vadose zone. The same is not true for vinyl chloride which can be susceptible to aerobic, vadose zone biodegradation, in a similar manner to that routinely observed for petroleum hydrocarbons.
- Soil vapour concentrations can be higher beneath sealed surfaces (such as roads, building slabs) compared to similar depths beneath open surfaces due to build-up beneath the slab.
- All else being equal, soil vapour concentrations are proportional to source concentrations and soil vapour concentrations will be higher closer to the source.
- In general, temporal variability in soil vapour concentrations (at 4 feet/ 1.2 m depth) is relatively minor, having been found to vary by up to only a factor of 2, and seasonal variations in cold (snow) climates are less than a factor of 5. Effects would be expected to be greater closer to the ground surface (ITRC).
- Infiltration from rainfall can potentially affect soil vapour concentrations by displacing soil gas, dissolving VOCs and restricting vertical migration. Generally, such soil moisture is unlikely to penetrate to any great depth and samples collected at depths greater than

[7] US EPA (2012) *Conceptual Model Scenarios for the Vapor Intrusion Pathway*, US EPA Office of Solid Waste and Emergency Response (EPA 530-R-10-003), February 2012
[8] ITRC (2007) *Vapor Intrusion Pathway: A Practical Guideline*, Technical and Regulatory Guidance, Interstate Technology and Regulatory Council Vapor Intrusion Team, January 2007
[9] UK Environment Agency (2009), *Updated Technical Background to the CLEA model*, http://www.environment-agency.gov.uk/static/documents/Research/CLEA_Report_-_final.pdf

about 3 feet/ 0.9 m (or beneath surface cover) are unlikely to be significantly affected. Due to relatively low measured soil vapour concentrations across the investigation area in comparison to groundwater concentrations, and given the relatively permeable nature of shallow soils, it is considered possible that surface infiltration has resulted in formation of a 'clean water lens' at the surface of the groundwater, lessening the resultant soil vapour concentrations in comparison to those that might be present otherwise.

4.3 Conceptual Site Model

A "conceptual site model" serves to provide a qualitative understanding of the contamination status of a site and to identify the means by which human and/or environmental receptors may be potentially exposed to the contamination. The conceptual site contamination model provided as part of this study incorporates the following elements:

- A description of the nature, extent and sources of contamination.
- Identification of chemicals of potential concern.
- A contaminant exposure pathway analysis.

It is noted with respect to the latter, that this assessment is limited specifically to potential human health risk through vapour intrusion.

This section of the report summarises the key information available (presented in more detail above) regarding the site setting, the nature, extent and sources of contamination, the identified contaminants of potential concern (COPC) and the potential receptors and exposure pathways by which the identified contamination may impact upon segments of the environment.

A summarised conceptual site model, based on that developed by PB (2014) and supplemented with the findings of the Stage IV environmental investigations conducted by URS, is presented in **Table 4-1** below.

Table 4-1 Summary Conceptual Site Model

Aspect	Current Conceptual Site Model	Impact of May 2015 Investigation Findings
Site Setting	Shallow groundwater is present at depths of approximately 3.5 m to 5.0 m below ground level, taking into account observed seasonal variations. Vadose zone soils comprise variably sand, silty sand, sandy clay/clayey sand and silty clay. The shallow groundwater lies predominantly within silty clay soils. While regional groundwater flow is expected to be to the west or north-west, local groundwater flow appears materially influenced by the action of leaking trunk sewers as groundwater sinks in the vicinity of Tapley's Hill Rd.	
Nature and Source of Dissolved Phase Contaminants	Volatile chlorinated hydrocarbons including PCE, TCE, 1,1-DCE, 1,2-DCE and VC are present in groundwater at concentrations exceeding adopted screening criteria. The primary contaminants of potential concern for this vapour risk assessment are the chlorinated solvents TCE, PCE and cis-1,2-DCE. based on their relative toxicity and the magnitude and broad distribution of impacts. Vapour sampling has found concentrations of PCE and TCE constitute approximately 40% and 48%, respectively, of the chlorinated vapours sampled and laboratory analysed. Based on the reported concentrations of specific VCHs in groundwater across the	

Aspect	Current Conceptual Site Model	Impact of May 2015 Investigation Findings
	investigation area, sources of the impacts are considered to potentially be derived from: – The former Delen Corporation industrial site at 3-5 Philips Crescent (now Hendon Paint Supplies); – One or more properties south-east of 3-5 Phillips Crescent and north of West Lakes Boulevard (PCE/TCE/1,2-DCE), including the children's play café/ church at corner of Philips Crescent and Circuit Drive (formerly an industrial property) and the Epic Storage site (formerly SABCO site) further to the south-east bounded by West Lakes Boulevard, Willowie Street and Botting Street; – An industrial property within the north-eastern portion of the industrial area, between MW14 and MW23 (PCE/TCE); – The industrial property west of well MW18 and bounded by Tapleys Hill Road; and – One or more industrial properties to the east of MW08 and Tapleys Hill Road	
Presence of DNAPL	Measured VCH concentrations are not considered indicative of the presence of DNAPL, although the presence of DNAPL is not precluded.	
Possible Transport Mechanisms	Identified possible transport mechanisms for shallow groundwater impact include: – Lateral migration within the groundwater – Vertical migration of heavier-than-water VOCs within groundwater – Diffusion of vapours into indoor and/or outdoor air and possibly service trenches and underground structures – Lateral migration of groundwater and vapour through the deep sewer and/or surrounding backfill material	
Exposure Pathways Receptors	Potential exposure pathways include contact with, or ingestion of extracted groundwater, or inhalation of vapours either arising from the subsurface or transported by sewer pipes. It is noted that the property survey has identified that below-ground structures (basements/cellars) are a feature of building construction in the locality, and this must be taken into consideration. Pathways relevant to this assessment are discussed in **Section 4.6** below.	
Soil Vapour Concentrations	The spatial distribution of vapour concentrations across the site, shown graphically in **Figures 10** to **12**, appears to generally align with that of groundwater with elevated VCH concentrations (**Figure 5** to **7**). However, soil vapour concentrations are typically lower than maximum values potentially available from reported groundwater concentrations, suggesting that rainfall and surface water infiltration may be lessening the effective source strength through formation of a clean lens above the impacted groundwater.	

4.4 Chemicals of Potential Concern

Chemicals of potential concern (COPC) are identified as those, which are known or suspected to be present at concentrations high enough to warrant inclusion in an assessment of risks to human health. The identification of COPC is based on the assessment of the nature and extent of these chemicals in the environment at the site, coupled with a comparison of analytical results for groundwater and soil vapour samples with human health based screening level guidelines.

It should be noted that the presence of chemicals at concentrations higher than the screening level guidelines does not indicate an unacceptable risk; rather it indicates that potential exposures to these chemicals should be evaluated in greater detail, taking into account site-specific pathways of exposure.

As discussed above, the COPC in relation to the vapour intrusion risk assessment across the Investigation area are PCE, TCE, cis-1,2-DCE. While VC was identified as a contaminant of concern in groundwater, vapour sampling has identified no VC above laboratory limits of reporting in soil vapour. This is consistent with the conceptual behaviour of VC, whereby it is susceptible to biodegradation in the vadose zone, while the more highly chlorinated compounds are not. As vapour intrusion is the only pathway of interest in this assessment, VC has not been further considered in the absence of measurable vapour concentrations.

4.5 Toxicity Assessment

The NEPM adopts inhalation toxicity data based on several sources for PCE, TCE, and cis-1,2-DCE. A detailed toxicity review and assessment for these chlorinated hydrocarbons is included in the ASC NEPM Schedule B7, Appendix 6, available from the Australian Government Website[10].

The adopted toxicity data is summarised in **Table 4-2** below.

Table 4-2 Chlorinated COPC Toxicity Data Summary (NEPC 2013)

Chemical of Potential Concern	Critical Effect Summary	Threshold Risk Value or Guideline	Ref
Tetrachloroethene (PCE)	Inhalation Tolerable Concentration (TC) in air based on neurotoxicological effects as the most sensitive endpoint. Based on a LOAEC of 20 mg/m^3 from a chronic occupational study with an uncertainty factor of 100.	0.2 mg/m^3	WHO 2006
Trichloroethene (carcinogenic affects – non-threshold)	Inhalation Unit Risk based on non-Hodgkin's lymphoma, renal cell carcinoma and liver tumours in humans (epidemiological), with a 4-fold adjustment for multiple tumour sites.	Unit Risk = 0.004 $(mg/m^3)^{-1}$	US EPA 2011
Trichloroethene (non-carcinogenic affects – threshold)	RfC based on route-extrapolation from, and oral studies for, the critical effects of heart malformations in rats and immunotoxicity in mice, and incorporation of uncertainty factors ranging from 10 to 100.	0.002 mg/m^3	US EPA 2011
cis-1,2-Dichloroethene	Inhalation value obtained from extrapolation from oral US EPA value. A review of genotoxicity by WHO (2011) provided unclear results. A review conducted by the US EPA (2010) suggested that overall 1,2-DCE is not genotoxic or mutagenic. On this basis, the NEPC considers the adoption of a threshold dose-response appropriate.	0.007 mg/m^3	US EPA 2010

It is noted that while TCE can be assessed for potential impacts via both carcinogenic and non-carcinogenic toxicity mechanisms, the (marginally) more sensitive endpoint is the assessment of threshold (non-carcinogenic) effects.

[10] http://www.comlaw.gov.au/Details/F2013C00288/Html/Volume_15

In assessing risks based on the adopted Threshold Risk Values (TRV), background inhalation intakes as a proportion of the TRV were adopted from the NEPM as 10% for TCE and PCE with no contribution (0%) from background sources for cis 1,2 DCE, consistent with NEPM.

4.6 Exposure Pathways and Receptors

4.6.1 Introduction

An “exposure pathway” is a means by which a population or individual (“receptor”) may be exposed to site-derived contaminants. Receptors may be either human (e.g. building occupants) or environmental (e.g. discharge to a river or lake). Potential exposure pathways are evaluated for completeness based on the existence of:

- a source of chemical contamination;
- a mechanism for release of contaminants from identified sources;
- a contaminant retention or transport medium (e.g. soil, air, groundwater etc.);
- potential receptors of contamination; and
- a mechanism for chemical intake by receptors at the point of exposure (i.e. ingestion, dermal contact or inhalation).

Whenever one or more of the exposure pathway elements is missing, the exposure pathway is incomplete that is, if there is contamination present, but no exposure route to receptors, then there no risk to human health and/or the environment.

4.6.2 Exposure Pathway Summary

As noted, this assessment *is limited specifically to the exposure pathway of vapour intrusion*; on the basis of the varied land uses across the investigation area, the following potential exposure pathways and receptors have been identified for this human health risk assessment:

- Inhalation of volatile chemicals by occupants of commercial buildings.
- Inhalation of volatile chemicals by occupants of residential dwellings.

In general, the potential for exposure to sub-surface derived volatile chemicals in *outdoor* air is materially less than in indoor air, due to lower concentrations and lower assumed duration of exposure (less time outdoors).

4.7 Quantitative Exposure Assessment

4.7.1 Introduction

This section outlines quantitative vapour intrusion modelling and sensitivity analysis undertaken to assess the potential for human health risk associated with the presence of VCH impacts in the subsurface across a portion of the EPA Hendon investigation area.

The modelling has been conducted to assess specific zones within a Vapour Intrusion Risk Assessment Area (refer **Figure 14**); a sub-region of the EPA assessment area (**Figure 1**).

This has been delineated based on the scope of URS's engagement and the extent of the groundwater well and soil vapour monitoring network.

Modelling has been undertaken using an Excel-spreadsheet-based model, using the Johnson and Ettinger algorithms, outlined in **Appendix A**. Spreadsheets incorporating the assumptions and calculations are included in **Appendix B**.

4.7.2 Scope of Modelling

Three building constructions are contemplated in modelling of vapour intrusion for this assessment:

- Slab-on-ground (typically a concrete "stiffened raft" footing or strip footings and concrete floor slab poured on the ground surface);
- Timber floor with crawlspace (where the timber floor is supported typically from concrete strip footings or stumps, such that a shallow (generally ventilated) crawlspace is present between the ground surface and the timber floor structure); and
- Basement (assumed to have a concrete foundation beneath ground level).

Additionally, based on the size of the investigation area, the spatial variability in COPC data and land use, the modelling has considered four spatial zones across the Vapour Intrusion Risk Assessment Area (refer **Figure 14**), as follows:

Zone 1: **Commercial/Industrial area to the north of West Lakes Boulevard (inclusive of the Children's Play Café)**. This area is considered separately due to the commercial rather than residential exposure scenario, a groundwater depth marginally shallower than for the investigation area generally, and high VCH concentrations associated with the source areas.

Zone 2: **Residential area south of West Lakes Boulevard and east of Tapleys Hill Road.** This area, across West Lakes Boulevard from a known source area(s), requires assessment for elevated concentrations of TCE, PCE and cis-1,2-DCE. Commercial building use is also considered for this area.

Zone 3: **Residential area near intersection of Tapleys Hill Road and West Lakes Boulevard**. Separate assessment of this area is proposed on the basis of high soil vapour concentrations reported adjacent the Hendon Childcare Centre (being assessed separately), which have the potential to represent a health risk to nearby residential areas given the relatively sparse investigation locations. Commercial building use is also considered for this area to enable comparison of modelling with results from the Hendon Childcare Centre investigation.

Zone 4: **Residential area west of Tapleys Hill Road, north of Zone 3**. This area, away from the elevated VCH concentrations reported near the Hendon Childcare Centre, is assessed on the basis of elevated TCE/PCE concentrations and a groundwater depth marginally shallower than for the investigation area generally. Commercial building use is also considered for this area.

Modelling has also been undertaken based on measured concentrations both in soil vapour and in groundwater. A number of individual model runs are required, as illustrated in **Table 4-3**.

Table 4-3 Summary of Vapour Intrusion Model Runs and Sources Considered

Structure Type	Zone 1	Zone 2	Zone 3	Zone 4
Residential Concrete Slab-on-Ground	–	✓	✓	✓
Residential Timber Floor (Crawl Space)	–	✓	✓	✓
Residential with Basement*	–	✓	✓	✓
Commercial Concrete Slab-on-Ground	✓	✓	✓	✓
Commercial Timber Floor (Crawl Space)	–	–	✓	✓

* *The presence of basements at a few properties were identified within surveys of selected properties within Zones 2 (south of Hendon industrial area) and Zone 4 (west of Hendon industrial area). Responses were received from approximately one third of such properties. No basements were identified in properties within the property survey of part section of Zone 3 in the direct vicinity of corner of Tapleys Hill Road and West Lakes Boulevard. However as responses were not provided from a few of the properties within the survey area the potential presence of basements cannot be ruled out and such modelling of such a vapour intrusion scenario was included..*

For each modelling run, relevant source concentrations were adopted as detailed in **Table 4-7**.

4.7.3 Estimating Exposure Concentrations

4.7.3.1 Introduction

In order to evaluate the risks to human health via inhalation of vapours it is necessary to estimate an exposure point concentration for each COPC. The exposure point concentration is calculated as a concentration (expressed as $\mu g/m^3$) in air within the breathing zone of the receptor. For different exposure pathways the exposure point breathing zone may be indoor air (ground floor or basement), outdoor air or within an excavation or utility pit. The exposure point concentration in the case of indoor air may be estimated via a number of different methods depending on the data available. These methods are discussed below.

From Groundwater Concentration Data

This method involves modelling indoor air concentrations using measured groundwater concentrations and information on overlying soils and relevant buildings. This modelling is typically conducted using the Johnson & Ettinger (J&E) vapour transport model (USEPA, 2003)[11] and also as documented in ASTM 1739-95 (2010)[12] and comprises the following four distinct steps (listed here in relation to a concrete slab-on-ground scenario):

[11] USEPA, 2003. User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings. June 2003.
[12] ASTM (2010), Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites E1739-95, ASTM International, Reapproved 2010

- Modelling the partitioning of the volatile contaminant between the aqueous phase in groundwater and the vapour phase immediately above the water table.
- Modelling the migration of contaminant vapours upwards through the unsaturated zone soils to beneath the concrete slab underlying the building.
- Modelling the migration of contaminant vapours through the concrete slab into the building.
- Modelling the dilution of the contaminant vapours within indoor air on the basis of the air exchange (ventilation) rates within the building.

This process involves the use of a series of assumptions and conservative simplifications of complex process at each stage of the modelling process, and consequently typically provides an overestimate of actual indoor air concentrations.

From Measured Soil Vapour Concentrations

The use of measured soil vapour concentrations from within the unsaturated zone in conjunction with the J&E model reduces the uncertainty to some extent by removing the need to model the partitioning process (Step 1 above). While the uncertainty inherent in Step 2 (migration through the unsaturated zone) can also be reduced by using soil vapour data obtained from relatively shallow depths close to the depth of the building foundation (including sub-slab data), it should be noted however, that concentrations at shallower depth are likely to be more variable over time than deeper soil vapour samples. The J&E model is used to model migration from the point of measurement to the slab, through the slab, and dilution within the building.

Direct Measurement of Indoor Air Concentrations

The final method for assessing concentrations of COPC in indoor air is via direct measurement. This can be conducted using a number of methods including adsorbent tubes and evacuated canisters. Direct measurement of indoor air concentrations has the great advantage of removing the need for mathematical modelling of partitioning, migration and dilution processes; however, there are a number of factors which make the process of obtaining a truly representative sample of indoor air problematic. These factors include:

- Temporal variations in indoor air concentrations due to variations in ventilation regimes within the building and variations in atmospheric conditions.
- Spatial variations within a given building due to the influence of preferential migration pathways such as drains and service lines.
- Non-site related sources of COPC. The principal COPC for this investigation (PCE and TCE) are used in a range of consumer products and processes such as dry-cleaning, aerosol paints, degreasers, automotive chemicals, furniture polish and cleaners that may be present in homes and workplaces. Consequently there is scope for indoor air sampling to be affected by sources present in the home, such that reported concentrations of COPC in indoor air may be unrelated to site-derived contamination.

No direct measurement of COPC concentrations in indoor air was undertaken for this investigation.

Summary

For the purposes of this assessment, exposure point breathing zone air concentrations have been estimated on the basis of two different methods:

- Modelling from groundwater COPC concentration data; and
- Modelling from vadose zone soil vapour COPC concentration data.

These different methods provide two complementary lines of evidence on which to base the assessment of risks to potentially exposed populations.

4.7.3.2 Vapour Models

Details of the vapour models used are attached as **Appendix A**. Short summaries of the models are provided below.

Residential & Commercial Buildings – Concrete Floors

The Johnson & Ettinger (J&E) vapour transport model (USEPA, 2003) has been used to estimate the potential concentrations of volatile COPC within residential and commercial buildings above impacts identified in groundwater. Parameters in the model were adjusted to characterise emissions into a building constructed on a concrete slab.

The model incorporates pressure-driven (advective) flows into the building, such as those associated with wind effects on the structure, stack effects due to heating or unbalanced mechanical ventilation. The US EPA vapour intrusion model allows the advective flow component (Q_{soil}) to be specified or calculated based on an empirical relationship between permeability, crack width in the foundation and differential pressure. Johnson (2005), however, recommends that Q_{soil} should not be used as an independent variable but should be calculated on the basis of the ratio $Q_{soil}/Q_{building}$ (where $Q_{building}$ is the building ventilation rate) and this approach has been adopted by CRC CARE (2011) in the derivation of HSLs for petroleum hydrocarbons. One limitation of this fixed ratio approach to estimating the contribution of advection is that it necessarily minimises the significance of (sensitivity of the model to) air exchange rates where advection is a material contributor. That is, for a fixed Qs:Qb, if you double the building air exchange rate (increase ventilation), you double the flux of soil vapour entering the building.

CRC CARE (2011) adopted the fixed ratio approach in the derivation of HSLs, subsequently incorporated into the NEPM, however the US EPA fixed Qsoil (per unit area) has been used for the baseline modelling here. It is noted that where migration rates are diffusion, rather than advection controlled, the difference between the two approaches is minimal.

Where a soil vapour source term has been used rather than a groundwater source, the model has been adjusted so that the measured soil vapour concentration at the relevant vapour well depth is entered as the source term, rather than using a soil vapour concentration calculated via partitioning from the groundwater source via Henry's Law. It is noted that this approach may lead to significant variation from model predictions from a groundwater source, particularly where the measured vapour concentrations are shallow and advective flows are potentially material. Shallow vapour concentrations are potentially more prone to temporal variability and the assumption of a shallow vapour source ignores the potentially rate limiting step of contaminants having to diffuse more slowly up to this depth from a deeper source.

Residential Buildings – Basements

Modelling of vapour intrusion into basements follows the same approach as modelling intrusion into slab on ground buildings, however the depth of the assumed source is reduced based on the assumed depth of the basement (2.4 m adopted).

Additionally, it has been assumed that use of a basement would not involve continuous occupation, but could involve use for up to eight hours a day, such as for bedroom use. Concentrations upstairs from a basement have been assumed to have a concentration *one-third* of that of the basement. This is consistent with guidance from CRC CARE[13] in estimating concentrations above basements in small buildings, such as single family residences.

It is noted that there are significant limitations associated with attempting to model vapour intrusion into basements using soil vapour concentrations as the source data, particularly where, as in this instance, the depth of the soil vapour data (1 -2 m bgl) is shallower than the assumed depth of basements.

While concentrations at greater depths would be expected to be higher, and therefore shallower vapour concentrations may be underestimates for this purpose, the adoption of a soil vapour concentration as a source implicitly assumes that the source of the vapours is located at that measurement depth, and this can artificially overestimate the significance of advective flows, as advection is a near-surface phenomenon.

For comparative purposes, modelling vapour intrusion into basements adopting measured concentrations as source concentrations was undertaken assuming a minimal (100 mm) thickness of clean backfill gravel immediately below the basement slab. We note that the estimated soil-vapour to indoor air attenuation factor derived via this method (approximately 275) matches reasonably well with the 50%ile sub-slab to indoor air attenuation factor (330) identified by the US EPA vapour intrusion database[14].

Residential & Commercial Buildings – Timber Floors (Crawlspace)

Included in **Appendix A** is a summary of the crawlspace vapour modelling using an approach and data derived from Robinson and Turczynowicz, (2002)[15]. The basic features of the model were reviewed by CRC CARE in 2009. Features include

- Diffusion dominates vapour transport between the source of contamination and the building zone of influence.
- All soil properties in any horizontal plane are homogeneous.
- The contaminant is homogeneously distributed within the zone of contamination.
- The aerial extent of contamination is greater than that of the building floor in contact with the soil.
- Vapour transport occurs in the absence of convective water movement within the soil column (i.e., evaporation or infiltration), and in the absence of mechanical dispersion.

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[13] CRC CARE 2013, *Petroleum hydrocarbon vapour intrusion assessment: Australian guidance*, CRC CARE Technical Report no. 23, CRC for Contamination Assessment and Remediation of the Environment, Adelaide, Australia.
[14] US EPA Vapour intrusion database, available on line at http://www.epa.gov/oswer/vaporintrusion/documents/OSWER_2010_Database_Report_03-16-2012_Final_witherratum_508.pdf
[15] Turczynowicz L., 2002. Establishing Health-Based Investigation levels for benzene, toluene, ethylbenzene, xylenes, naphthalene and aromatic and aliphatic ≤EC 16 TPH fractions. Site Contamination Technical Workshop, Adelaide 13 to 15 May 2002

- The model does not account for transformation processes (e.g., biodegradation, hydrolysis, etc.).
- The crawl-space and building ventilation rates are constant values.

While the model was initially applied to petroleum hydrocarbons and incorporated biodegradation to develop screening levels, biodegradation has not been incorporated into the Excel-based model used herein.

It is noted that there is limited data available for ventilation rates in crawl-spaces and that these may vary substantially on a site-by site basis, as well as likely being affected by environmental factors such as wind-speed and direction.

Outdoor Air and Excavations

The ASTM vapour transport model (ASTM, 2002)[16] has been used to estimate the potential concentrations of volatile COPC in the breathing zone of outdoor air. This uses a simple box model to account for some atmospheric mixing. A large 100 m by 100 m source zone has been assumed with a mixing height of 1.5 m and an average wind speed of 2.5 m/s (9 km/h).

Concentrations within shallow excavations have also been estimated using the ASTM model, however the depth to the source is adjusted to reflect to depth from the base of the excavation to the groundwater source, the dimensions of the excavation are used and the wind speed is adjusted to reflect a more confined space scenario. A typical excavation is estimated as 1 m x 10 m x 1.0 to 1.5 m depth. A wind speed considered representative of a more confined space within an excavation is 0.5 m/s (1.8 km/h).

4.7.3.3 Vapour Model Inputs

In order to estimate exposure point concentrations in air via modelling from groundwater and soil vapour data it is necessary to specify a range of input parameters to characterise the following:

- The construction type and details of existing buildings on the property where the exposure occurs (building parameters);
- The nature of the vadose (unsaturated) zone and saturated zone geology (geology parameters); and
- The contaminant source concentrations in groundwater and soil vapour (source parameters).

Building Parameters

Buildings currently located within the investigation area include:

- Residential slab-on-grade houses (concrete raft footing construction) without basements
- Residential timber floored houses (crawlspace construction) without basements
- Residential houses including basements
- Commercial buildings without basement (Children's play café)

[16] ASTM, 2002. Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum release Sites. ASTM Designation E 1739-95[E].

Despite slab-on-ground being the most common building practice for domestic construction in Adelaide, the estimate by Rider Levett Bucknall indicates that less than 35% of dwellings in the survey area for this investigation are constructed using this method, with the greater proportion likely to be timber floored (noting that this estimate is based in most cases on external appraisal only). With respect to basements in this investigation area, it is noted that interview with, or responses from occupants, were achieved for only 29 dwellings; of these, 6 (close to 20% of respondents) were identified to have basements, indicating this to represent a scenario warranting consideration from a vapour intrusion risk perspective.

The input parameters describing features of these building types relevant to the modelling of exposure point air concentrations are listed in the spreadsheet tables in **Appendix A** and summarised in **Table 4-4** below.

Table 4-4 Building Modelling Inputs

Input Parameter	Units	Value Residential	Value Commercial	Comments
Building Characteristics – Slab on ground				
Depth of Basement	m	0 / 2.4	0	Assume 2.4 m for Residential basement case
Width of Building	m	10	20	Default Assumption
Length of Building	m	10	20	Default Assumption
Area of Emission – Building Area	m^2	100	400	Assume whole building above source
Foundation/Wall Thickness	m	0.1	0.15	CRC CARE
Height of Room	m	2.4	3	CRC CARE
Air exchange rate - indoors	exch/hr	0.6	0.83	CRC CARE
Fraction of Cracks in Walls and Foundation		0.001	0.001	CRC CARE
Q_{soil}	cm^3/s	83.3	333.3	Calculated from US EPA default of 5 L/min for 100 m2 building footprint
Volumetric Water Content in foundation cracks	ml/ml	0.12	0.12	Default value ASTM 1739-95
Volumetric Air Content in foundation cracks	ml/ml	0.26	0.26	Default value ASTM 1739-95
Building Characteristics – Crawl Space				
Area of Emission – Building Area	m^2	100	312.5	CRC CARE and Turcynowicz (2002)
Air exchange rate - indoors	exch/hr	0.6	2	CRC CARE and Turcynowicz (2002)
Air exchange rate in Crawl Space	exch/hr	3	3	calibration with Hendon Child Care Centre
Air exchange rate - indoors	exch/hr	0.6	0.83	CRC CARE
Qcsd (volumetric flow: crawl-space to indoor air)	m^3/day	911	2242	Turcynowicz (2002) 911 m^3/day for 127 m^2 house footprint
Outdoor Air Characteristics				
Length of Contaminated Area	m	20	20	Site-specific assumption
Width of Contaminated Area	m	20	20	Site-specific assumption
Wind Speed Outdoors	m/s	2.5	2.5	Site-specific assumption
Height of Outdoor Mixing Zone	m	1.5	1.5	Default Value

Geological Parameters

The geological parameters used in modelling exposure point vapour concentrations from groundwater and soil vapour concentration data are presented in **Table 4-5** below. For the purposes of this modelling, on the basis of a review of former investigation area borelogs, it is assumed that the unsaturated soils consist of 2 m of sandy soils overlying sandy clays to the water table.

It is noted that the physical testing of soil cores recovered during the Stage IV environmental Investigations (URS, 2015) provides justification for the parameters adopted.

Properties for the upper sandy layer have been assigned properties based on the CRC CARE default for sand/sandy clay, as shown in the table below. These default properties are considered to be conservative with respect to the measured properties for soils in the 1.5-2.0 m range, for example:

- Moisture content: Adopted default 0.08 ml/g; measured range 0.06 - 24.9 ml/g
- Volumetric air content: Adopted default 0.257; measured range 0.017 to 0.254 ml/ml

Properties for the deeper layer, comprising silty and sandy clay, were adopted on the basis of results for the deeper samples tested. These samples showed an average specific gravity of 2.67 g/ml, and the bulk density of 1.56 was adopted on the basis of typical reported material values. The moisture content of 0.26 ml/g, within the range of reported values, was selected to give a volumetric air content of 0.01, which approximates the typical reported value for the volumetric air content for the deeper soils.

It is noted that this is a low volumetric air content (wet soil), and that this would act as something of a barrier to slow vapour migration. This is considered consistent with the observations of relatively low vapour concentrations compared to equilibrium estimates from groundwater, as discussed in **Section 3.3**.

Table 4-5 Geological Modelling Inputs

Input Parameter	Units	Value Residential	Comments
Depth of Top of Contaminated Aquifer (bgs)	m	3.5/3.1	Refer Table 4-7
Thickness of Capillary Fringe	m	0.2	Estimated for sandy clay
Thickness of Vadose Zone	m	3.3	
Average Soil Temperature	C	25	Site-specific assumption
Vadose Zone Layer 1 Characteristics	CRC CARE – Sand, Sandy Clay		
Depth of Layer 1 from Foundations	m	2	CRC CARE Default inputs for a sand/sandy clay
Moisture Content	ml/g	0.08	
Organic Carbon Fraction		0.003	
Soil Bulk Density	g/ml	1.625	
Density of Solids	g/ml	2.65	
Total Soil Porosity	ml/ml	0.39	
Volumetric Water Content	ml/ml	0.130	
Volumetric Air Content	ml/ml	0.257	

Input Parameter	Units	Value Residential	Comments
Vadose Zone Layer 2 Characteristics	Sandy Clay – Site Specific Data Summary		
Depth of Layer 2 from Foundations	m	1.3	Based on site specific measurements for the deeper sediments
Moisture Content	ml/g	0.26	
Organic Carbon Fraction		0.003	
Soil Bulk Density	g/ml	1.56	
Density of Solids	g/ml	2.67	
Total Soil Porosity	ml/ml	0.42	
Volumetric Water Content	ml/ml	0.406	
Volumetric Air Content	ml/ml	0.010	
Capillary Fringe	Sandy Clay – based on vadose zone layer 2		
Volumetric Water Content	ml/ml	0.406	Consistent with site data and CRC CARE for a clay
Volumetric Air Content	ml/ml	0.010	

Groundwater depths for modelling purposes were assessed from data from the 2012 to 2015 period. While the April 2015 data shows groundwater levels ranged typically between 3.5 m and 4 m, seasonal variations apparent from historical data suggested that maximum levels could be 0.35 m higher (shallower) than 2015 data. Accordingly, with reference to the zones discussed in **Section 4.2**, table 4-6 summarises adopted depths to water across the assessment area.

Table 4-6 Adopted Groundwater Depths for Modelling

Zone	Description	Assumed Depth to Water (m bgl)	Comments
Zone 1	Commercial	3.1 m	Depths across the commercial area close to the Children's play café are 3.5 m; allowing for seasonal variation, adopt 3.5 - 0.35
Zone 2	Southern Residential	3.5 m	Depths range between 3.9 and 4.1 m, except for 3.7 m at wells MW11 and MW27 which are outside the area of greater impact. Adopted depth for model is conservatively based on general minimum of 3.9 - 0.35 for seasonal variation.
Zone 3	Residential in vicinity of Hendon Childcare Centre	3.5 m	Groundwater in the vicinity of the Childcare Centre is measured at 3.8 m, with bores in the surrounding residential areas showing 3.9 m or greater. A depth of 3.5 m is adopted to take into account seasonal variation.
Zone 4	Western Residential	3.5 m	Recorded depths (2015) range from 3.8 to 4.1 m (other than non-network well BH22* for which a depth of 3.3 m was recorded. No information on the construction of this well is known, and this well is discounted. A depth of 3.5 m is used to reflect seasonal effects.

Source Concentrations

Modelling has been based on maximum PCE, TCE and cis-1,2-DCE concentrations for both groundwater and soil vapour in each of the zones, as summarised below.

Table 4-7 Adopted Groundwater and Soil Vapour Source Concentrations

Zone	CoPC	Groundwater Source (µg/L)	Location	Soil Vapour Source (µg/m^3)	Location
Zone 1	PCE	95.3	MW9	28000	SV22 (2m)
	TCE	1350	MW9	26000	SV22 (2m)
	DCE	963	MW9	9480	SV13 (1.8m)
Zone 2	PCE	179	MW2	6800	SV01 (1.5m)
	TCE	78.1	MW4	460	SV01 (1.5m)
	DCE	326	MW5	9480	SV13 (1.8m)
Zone 3	PCE	0.018	MW7	6.5	SV15 (1.8m)
	TCE	470	MW7	8400	SV04 (1m)
	DCE	58.1	MW7	280	SV04 (1m)
Zone 4	PCE	0.14	MW8	11	SV05 (2m)
	TCE	190	MW8	550	SV21 (2m)
	DCE	10.2	MW8	<4.8	SV06 (2m)

Exposure Parameters for Receptors

Residents

Assumptions for exposure patterns for residents have been taken from enHealth 2012.

- It is assumed that residents will spend:
  - 20 hours per day indoors
  - 3 hours per day outdoors (negligible contribution to exposure outdoors)
- Residents are assumed to be potentially exposed to site-derived impacts for 35 years.
- Basements are assumed to be occupied for 8 hours per day (such as bedroom use), with the remaining 12 hours per day indoors spent upstairs (ground level).

Commercial Worker

- It is assumed that the commercial worker may spend 240 days per year for 30 years working in areas above the contaminated groundwater (CRC CARE 2011), and the impacted groundwater is assumed to remain beneath the workplace (at the measured concentration) for the whole 30 years;
- A commercial worker may spend up to 8 hours per day indoors on the ground floor of a building and 2 hours per day outdoors.

Intrusive Worker - Shallow Excavation

- An intrusive worker may spend 20 days working in areas above the contaminated groundwater over a 1 year period;
- It is assumed that up to 10 hours (whole work day) is spent within a shallow (<1.5 m) excavation.

4.8 Risk Characterisation

4.8.1 Methods for Quantifying Risks to Human Health

Risk characterisation is the final step in a quantitative risk assessment. It involves the incorporation of the exposure assessment and toxicity assessment to provide a quantitative assessment of potential health risks. In the assessment presented, evaluation of exposures to the COPC involves an assessment of threshold and non-threshold risks.

The calculation of risks has been undertaken using an in-house spreadsheet model, RiskE (URS Australia). The equations utilised within RiskE apply risk assessment methodology as outlined in **Appendix A**, following protocols established by enHealth and USEPA. The output from this model has been incorporated into the tables presented in the text of the report and into the calculation sheets contained in **Appendix B**.

Hazard Index for Threshold Effects

The potential for adverse threshold effects resulting from inhalation exposure to an individual COPC, is evaluated by comparing an exposure concentration with the adopted guideline or Reference Concentration (RfC). The resulting ratio is referred to by the USEPA as the hazard quotient (USEPA, 1989)[17] and is derived in the following manner for inhalation exposures:

$$Hazard\ Quotient\,(inhalation) = \frac{Exposure\,Concentration\,in\,Air}{(RfC - Background)\ or\ TWA}$$

If the exposure concentration in air for the individual COPC exceeds the RfC with consideration of background intakes, (*i.e.*, if the hazard quotient exceeds one), this indicates potentially unacceptable exposures. The hazard quotient does not represent a statistical probability of an effect occurring.

To assess the overall potential for adverse health effects posed by simultaneous exposure to multiple chemicals, the hazard quotients for each chemical and exposure pathway have been summed. The resulting sum is referred to by the USEPA as the hazard index (HI). The HI approach assumes that multiple sub-threshold exposures to several chemicals could result in a cumulative adverse health effect, and exposures are summed over all intake routes.

[17] United States Environment Protection Agency (US EPA) 1989. Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual. Interim Final, Office of Emergency and Remedial Response, US EPA, Washington DC. OSWER Directive 9285.7-0/a.

Acceptable Risk

An “acceptable” risk in this assessment has been defined as a Hazard Index no greater than 1.0 (as per risk assessment industry practice, supported by protocols outlined in enHealth (2012) and USEPA guidance).

It is noted that the SA EPA and SA Health recently collaborated in development of an Indoor Air Level Response Range for the Clovelly Park / Mitchell Park area, where intrusion of TCE vapour to residences was the issue of concern (**Appendix C**). The reference concentration for TCE of 2 µg/m^3 (as per **Table 4-2**) 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 (20 µg/m^3) fell into the “Investigation” range, wherein although no immediate health concerns were considered to be associated with such levels, further assessment was required. These concentrations (2 and 20 µg/m^3) are equivalent to Hazard Indices of 1 and 10.

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

- Where the sum of Hazard Indices for the CoPC for any modelled scenario is <1, this is considered to be equivalent to results within the “Validation” range of the SA EPA/SA Health Indoor Air Level Response Range.
- Where the sum of Hazard Indices 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 SA EPA/SA Health Indoor Air Level Response Range
- Where the sum of Hazard Indices 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 SA EPA/SA Health Indoor Air Level Response Range, indicative of a potential health risk and warranting further action.

Non-Threshold Carcinogenic Risks

The potential for unacceptable non-threshold carcinogenic risks associated with exposure to COPC has been evaluated using US EPA methodology.

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 is calculated as follows for inhalation exposures:

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 for each pathway.

Acceptable Risk

The adopted acceptable risk is defined as no more than to 1 x 10^{-5} incremental lifetime risk of cancer, consistent with enHealth (2012) and the 1999 ASC NEPM (as amended 2013).

For the COPC at the site, TCE is the only potentially carcinogenic contaminant. As noted in **Section 4.5**, the critical toxicological effect for TCE is associated with threshold (non-carcinogenic) effects. As such, this quantitative assessment has focussed on threshold effects only.

4.9 Modelled Exposure Point Vapour Concentrations and Hazard Indices

The results of modelled indoor air VCH concentrations, expressed as Hazard Indices, are summarised in **Table 4-8**, (Groundwater Source) and **Table 4-9** (Soil Vapour Source) below, based on the input parameters above. Modelling spreadsheets are included in **Appendix B**.

Table 4-8 Calculated Hazard Indices for Vapour Intrusion – Groundwater Source

Structure Type	Foundation	COPC	Groundwater Source			
			Zone 1	Zone 2	Zone 3	Zone 4
Residential	Slab-on-Ground	PCE	-	0.0003	3.4E-07	2.7E-07
		TCE	-	0.018	0.11	0.04
		DCE	-	0.021	0.004	0.0007
		Sum	-	0.039	0.110	0.044
	Crawl Space	PCE	-	0.0001	1.0E-07	7.9E-08
		TCE	-	0.006	0.04	0.01
		DCE	-	0.007	0.001	0.0002
		Sum	-	0.013	0.036	0.014
	Basement	0	-	0.0005	5.5E-07	4.3E-07
		0	-	0.03	0.17	0.07
		0	-	0.03	0.01	0.001
		Sum	-	0.063	0.177	0.070
Commercial	Slab-on-Ground	PCE	0.00004	0.00005	5.2E-08	4.06E-08
		TCE	0.0635	0.0027	0.016	0.007
		DCE	0.0128	0.0032	0.0006	0.0001
		Sum	0.076	0.006	0.017	0.007
	Crawl Space	PCE	-	-	2.3E-08	1.82E-08
		TCE	-	-	0.008	0.003
		DCE	-	-	0.0003	0.0001
		Sum	-	-	0.008	0.003

Modelling of indoor air exposure using 2015 groundwater concentrations of PCE, TCE and DCE as the vapour source did not indicate an unacceptable health risk for any of the exposure pathways considered. For scenarios other than dwellings inclusive of basements, the greatest risk scenario was Residential slab-on-ground construction in Zone 3 (based on groundwater TCE concentration of 470 µg/L adjacent the Hendon Childcare Centre), and for this scenario, modelled vapour concentrations are approximately an order of magnitude below the reference concentration. While there are higher TCE concentrations present in Zone 1, this area is commercial, rather than residential use and calculated risks are therefore lower.

Table 4-9 Calculated Hazard Indices for Vapour Intrusion – Soil Vapour Source

Structure Type	Foundation	COPC	Soil Vapour Source			
			Zone 1	Zone 2	Zone 3	Zone 4
Residential	Slab-on-Ground	PCE	-	0.013	1.7E-05	1.7E-05
		TCE	-	0.126	**3.02**	0.12
		DCE	-	0.628	0.028	0.0003
		Sum	-	0.767	**3.04**	0.122
	Crawl Space	PCE	-	0.004	7.3E-06	6.1E-06
		TCE	-	0.05	**1.58**	0.05
		DCE	-	0.29	0.0175	0.0001
		Sum	-	0.346	**1.60**	0.052
	Basement	PCE	-	0.061	0.0001	0.0001
		TCE	-	*0.47*	**8.60**	*0.56*
		DCE	-	**2.52**	0.07	0.001
		Sum	-	**3.05**	**8.68**	*0.565*
Commercial	Slab-on-Ground	PCE	0.007	0.002	1.5E-06	2.60E-06
		TCE	*0.872*	0.019	0.46	0.02
		DCE	0.085	0.096	0.004	0.00004
		Sum	*0.965*	0.117	0.463	0.019
	Crawl Space	PCE	-	-	1.4E-06	1.18E-06
		TCE	-	-	0.30	0.01
		DCE	-	-	0.003	0.00003
		Sum	-	-	0.308	0.010

Modelling of indoor air exposure using 2015 soil vapour concentrations of PCE, TCE and DCE as the vapour source indicate a Hazard Index of close to or greater than 1 for several exposure scenarios:

- TCE concentrations in Zone 3 (based on the concentration of 8,400 µg/m^3 at SV04 adjacent the Hendon Childcare Centre) resulted in exceedances of the HI = 1 range for each of the residential foundation assumptions.
  - A Hazard Index of approximately 3 (equivalent to the “Investigation” classification of the Indoor Air Level Response Range) for slab on ground buildings
  - A Hazard Index of 8.7 for the Residential with Basement scenario (towards the upper end of the “Investigation” classification of the Indoor Air Level Response Range)[18].
  - A Hazard Index of 1.6 for the Residential with crawl space.
- The Hazard Index for the Residential with Basement scenario for Zone 2 was >1 (3.05), again within the “further investigation” classification. This was principally driven by the elevated DCE concentrations in this area.
- The Hazard Index for Commercial – Slab-on-Ground for Zone 1 was only marginally <1 (0.97).

The elevated concentrations of TCE identified in SV04 near the Hendon Childcare Centre and elevated DCE concentrations in SV13 provide the higher risk estimates in this assessment

[18] No basements were identified in properties within part section of Zone 3 in the direct vicinity of corner of Tapleys Hill Road and West Lakes Boulevard (near vapour bore SV04). However as responses were not provided from a few of the properties within the survey area the potential presence of basements cannot be ruled out and such modelling of such a vapour intrusion scenario was included.

area. The calculated risks due to habitable basement use exceed those for slab on ground and crawl-space homes, due to their depth/proximity to the groundwater impacts.

4.9.1 Review in Context of Historical Results

Groundwater Concentrations

While some temporal variability in groundwater concentrations for TCE, PCE and DCE is evident, there are no instances where historical monitoring results indicate the likelihood of temporal variations of an order of magnitude that would be necessary for such variation to result in modelled indoor vapour concentrations to represent a risk.

The only instance where reported concentrations for the 2015 monitoring period are approximately an order of magnitude lower than the maximum measured groundwater concentrations is for well GW1 (TCE of 3.72 µg/L (2015) compared to 37.5 µg/L (2013); cis-1,2-DCE of 18.2 µg/L (2014) compared to 196 µg/L (2013). These 2013 concentrations are well below those used for modelling for Zone 1 and are not assessed to pose unacceptable risk, and a decreasing trend rather than temporal variability is apparent for GW1.

Soil Vapour Concentrations

A number of instances of historically elevated soil vapour concentrations for soil vapour wells within the Vapour Intrusion Risk Assessment Area are evident from the summary presented below in **Table 4-10**.

Table 4-10 Historical Variations in Soil Vapour Concentrations within Vapour Intrusion Risk Assessment Area

Zone	Location	2015 Result ($\mu g/m^3$)	Historical Range ($\mu g/m^3$)	Modelling Input ($\mu g/m^3$)
1	SV11	PCE 10	PCE <5.1-160	PCE 28,000
2	SV01	TCE 460 PCE 5,800 DCE 95	**TCE 510-1400** **PCE 12,000-23,000** DCE <76-200	TCE 460 PCE 6800 DCE 8480
2	SV02	TCE 390 PCE 3,600 DCE 400	**TCE 310-1100** **PCE 12,000-26,000** DCE 42-1800	TCE 460 PCE 6800 DCE 8480
2	SV06	TCE 410 PCE 1300	**TCE 430-780** PCE 1800-2700	TCE 460 PCE 6800
2	SV07	TCE 22 PCE 500	TCE 39-72 PCE 830-1600	TCE 460 PCE 6800
2	SV08	PCE 29	PCE 56-85	PCE 6800
2	SV13	TCE 280 PCE 1650 DCE 9480	TCE 200-450 PCE 1200-3000 **DCE 6300-12,000**	TCE 460 PCE 6800 DCE 8480
2	SV17	TCE 9.6 PCE 1200	TCE 200 PCE 2900	TCE 460 PCE 6800
3	SV14	PCE 3.5	**PCE 8.2-17**	PCE 6.5
3	SV15	TCE 560	TCE 1300-1900	TCE 8400

The bold ranges shown in the above table indicate where historical results exceed concentrations used as input for the vapour intrusion modelling.

Based on the tabulated data:

- Historical TCE and PCE soil vapour concentrations in Zone 2 have been recorded up to 3x and 4x the recently measured concentrations used for modelling (historical maxima for TCE 1,400 µg/m^3, PCE 26,000 µg/m^3 in SV01 and SV02). It is noted that these elevated TCE and PCE results (in SV01 and SV02) are not co-located with the elevated DCE concentrations driving the risk at SV13.

  Review of the calculated hazard quotients in Table 4-9 shows that the hazard quotient for TCE for a basement setting (0.47) would exceed 1 were concentrations to increase to the historically highest concentrations. As such, the presence of basements and temporal variability of TCE should be considered in the broader Zone 2 area, in the vicinity of West Lakes Blvd in the area of SV01 and SV02.
- Historical cis-1,2-DCE results at SV13, also in Zone 2, were as high as 12,000 µg/m^3; approximately 1.4x the concentration used for modelling. Such an increase would not affect modelled outcomes.
- Historical PCE results at SV14 in Zone 3 were approximately 2.6x the concentration used for modelling. PCE has a negligible concentration to the Hazard Indices for any of the modelled scenarios for Zone 3 (TCE is the risk driver), such that allowing for this historical variation does not materially change the risk assessment outcome.

Given the variability identified in soil vapour concentrations, it is considered that further monitoring would be of value in establishing the appropriateness of the most recently measured concentrations as the basis for estimating exposure.

4.10 Sensitivity Analysis of Key Risk Modelling Inputs

4.10.1 Introduction

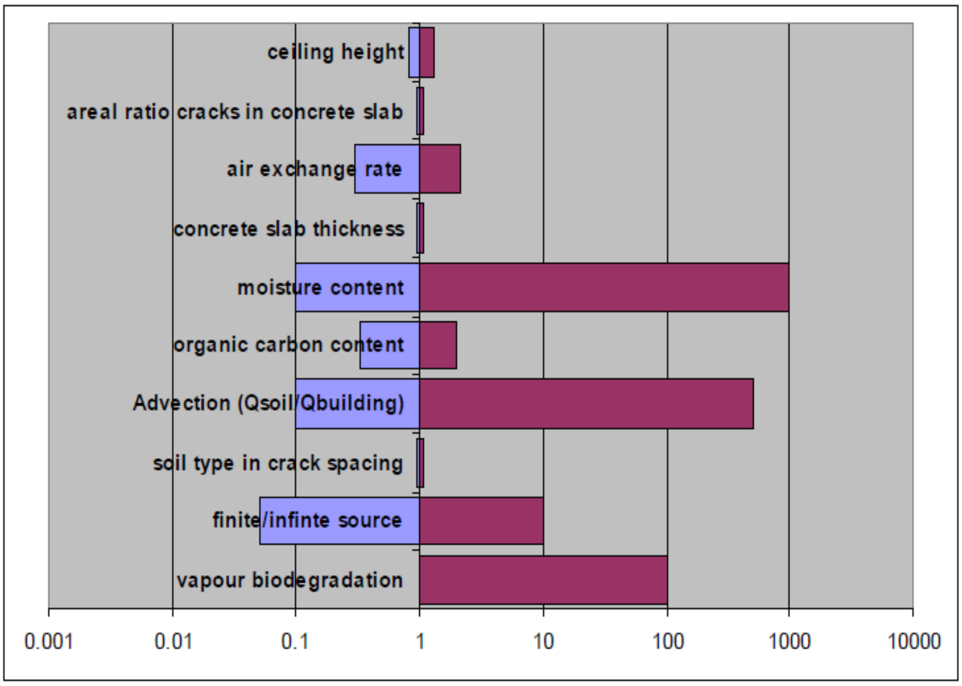
CRC CARE Technical Report 10 derived Health Screening Levels for petroleum hydrocarbons using the Johnson and Ettinger model. As part of the sensitivity analysis document (Part 3), a summary of the key input parameters was included (refer to **Figure 4-3**).

This CRC CARE assessment found the key parameters that the modelling was sensitive to were:

- Moisture content;
- The advection (pressure driven flow) rate;
- *Vapour biodegradation* (*not considered applicable to TCE*);
- Source life for soils (finite/infinite source) – not considered applicable for groundwater sources;
- Organic carbon content (relevant for modelling from a soil source only); and
- The indoor air exchange rate.

Other parameters were found to be relatively insensitive. A quantitative comparison has been undertaken for key parameters and is detailed below.

Figure 4-3 CRC CARE Technical Report 10, Part 3 Sensitivity Analysis Summary (Figure 4)



4.10.2 Volumetric Air Content, Moisture Content and Soil Bulk Density

The volumetric air content, moisture content and soil bulk density are related parameters as far as the J&E model are concerned, in that they affect the air-filled pore space, through which the models assumes the majority of vapour transport occurs.

Increasing the soil bulk density decreases the available soil pore space and thereby reduces vapour transport (all else being equal). Increases in moisture content similarly reduce the available air-filled porosity as the moisture takes up more of the available pore space, thereby reducing vapour migration.

While CRC CARE TR10 incorporates default soil properties for three classes of soil (sand, silt and clay) in the derivation of the HSLs, site-specific soil testing has also been undertaken (Section 3.1.1).

On this basis, the vapour intrusion modelling has been undertaken with a *base-case* scenario incorporating two soil layers:

1. Surface soils comprising sand/sandy clay with parameters consistent with the CRC CARE TR10 defaults for sandy clay
2. Site specific data for deeper soils (2.5-3 m) which can be categorised as wet, sandy and silty clay soils, with the following adopted parameters.
   - soil bulk density of 1.56 t/m^3.
   - a moisture content of 26 wt% (0.26 mL/g)
   - a volumetric air content of 0.01 mL/mL.

Table 4-11 summarises the measured soil volumetric air content data for deeper soils at the site. As Table 1 (attached) shows, these soils were wet, with moisture contents all greater than 90% of total porosity and above 97% for three of the four samples.

Table 4-11 Soil Sample Volumetric Air Content Data

Sandy CLAY	Silty CLAY	Sandy CLAY	Sandy CLAY
SV21, 2.5-3.0 m	SV22, 2.5-3.0	SV25, 2.5-3.0	SV27, 2.5-3.0
0.0084	0.00943	0.03667	0.01068

This data has been used in a Monte Carlo (probabilistic) simulation with the volumetric air content defined via a log normal distribution (**Figure 4-4**) with a mean volumetric air content of 1.63 mL/mL and assumed standard deviation of half the mean. It is noted that the adopted mean air content (average of the above results) is higher than 3 of the 4 relevant measured samples.

Figure 4-4 Lognormal distribution assumption for Volumetric Air Content

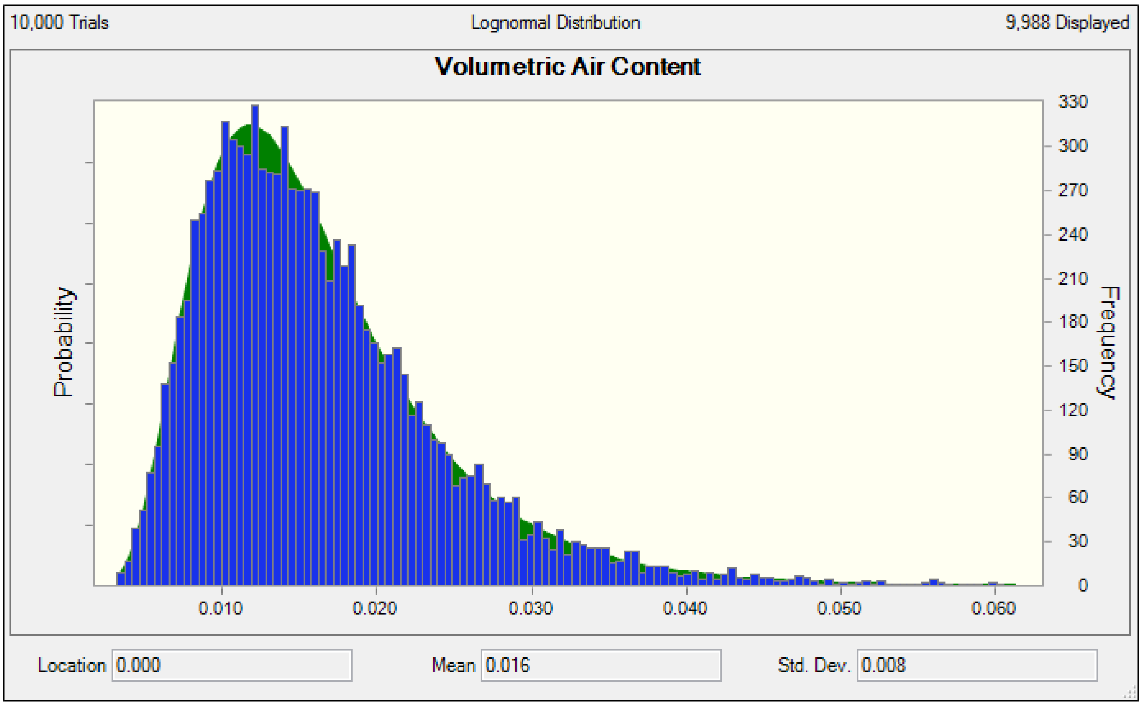
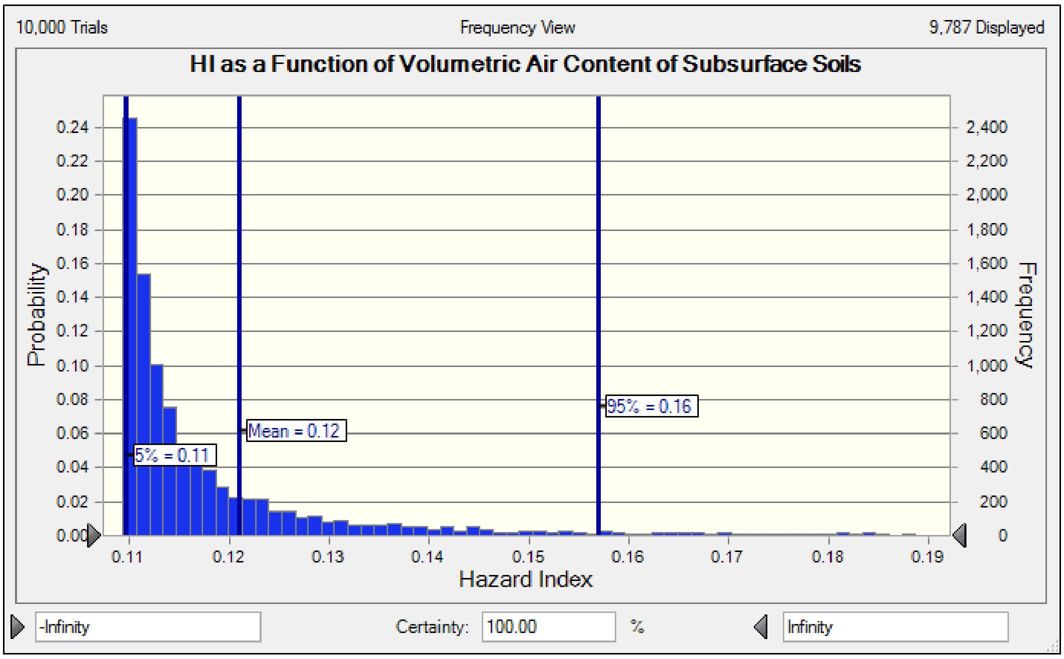


Figure 4-5 below, provides a distribution of hazard indices, based on the above distribution assumptions for volumetritc air content in subsurface soils at the site. This data is based on the example scenario for residential, slab on ground, groundwater source in Zone 3.

Based on the range of moisture contents and related porosity parameters at the site, the variation in HI is relatively minor, with the median probabalistic result for the HI (0.12), consistent with the determistic result of 0.11 for this scenario (**Table 4-8**).

Figure 4-5 Monte Carlo estimates of Hazard Index as a Function of Volumetric Air Content



4.10.3 Indoor Air Exchange Rate (AER)

Figure 4-6 shows the assumed probabilistic distribution of indoor air exchange rates, with a median of 0.6 exchanges per hour (enHealth 2012), a minimum of 0.2 exch/hr and a gamma distribution to give an upper 95%ile indoor air exchange rate of 1.33 exch/hr.

Figure 4-6 Distribution assumption for Indoor Air Exchange Rate – Median of 0.6 exch/hr

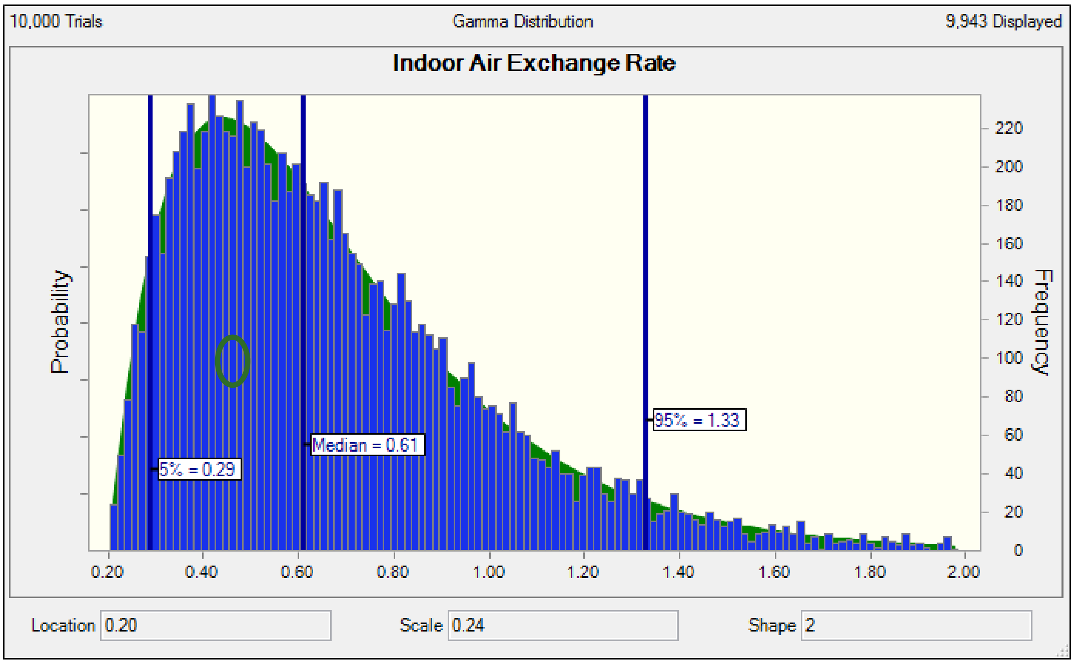
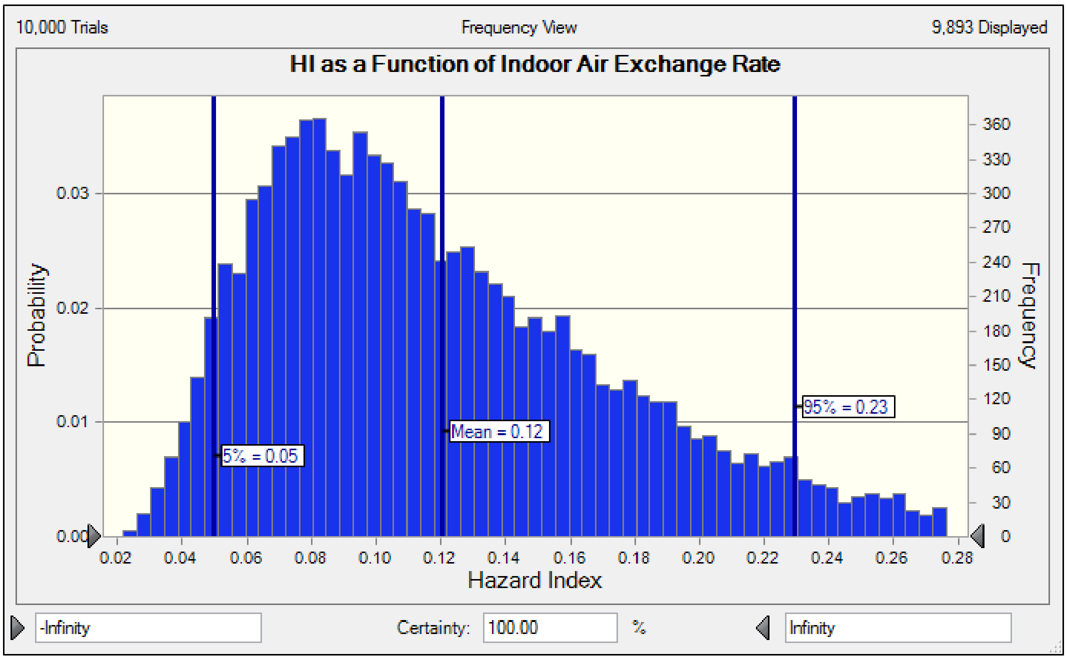


Figure 4-7, provides a distribution of hazard indices, based on the above distribution assumptions for indoor air exchange rate. This data is again based on the scenario for residential, slab on ground, groundwater source in Zone 3.

This shows a deviation from the mean of approximately two-fold for the 5% and 95%ile HI estimates.

Figure 4-7 Monte Carlo estimates of Hazard Index as a Function of Indoor Air Exchange Rate



4.10.4 Soil Vapour Advection Rate

Introduction

From a technical perspective, not all jurisdictions approach the need and methodology for incorporation of advection in vapour intrusion modelling for the assessment of chronic health risks in the same way. There are three main approaches:

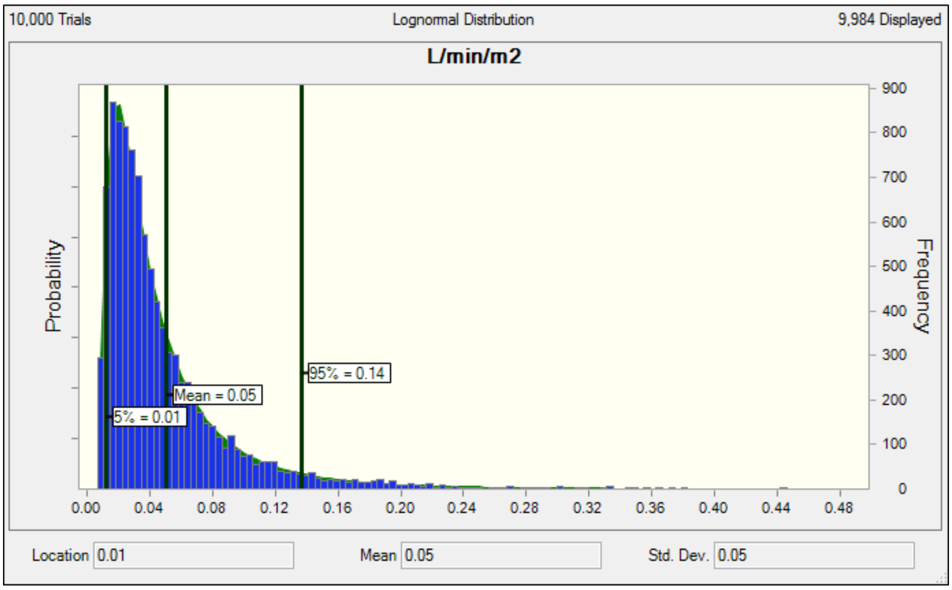
- CRC CARE has established the soil advection rate (Qs) to the building ventilation rate (Qb) with a default value of the Qs/Qb ratio of 0.005 (1 in 200 attenuation), based on the US EPA database of paired indoor air and subsurface samples.
  - Nadebaum and Friebel note in CRC CARE TR10 that the impact on HSLs of changing the soil advection rate (Qs/Qb ratio) "is mainly limited to surface soil vapour sources. Other source types (soil and groundwater) and depths 1 m and greater are not significantly affected by increasing Qsoil/Qbuilding above the selected value of 0.005."

    That is, the influence of advection is a relatively near surface phenomenon. With deeper sources, the vapour must first diffuse up to the near-surface advective zone, where they may be more rapidly swept into buildings, depending upon the (positive or negative) pressure gradients.
- The US EPA J&E vapor intrusion spreadsheet model uses a fixed value of Qsoil (recommending 5 L/min as a default) for a given (100 m^2) residential building footprint.

- The UK Environment Agency doesn't recommend incorporation of advection in its Technical CLEA[19] guidance, noting that:
  - *"On balance, the inclusion of advective flow in soil transport modelling is not recommended at this time, because there is a need for stronger evidence that the driving force for such flow exists and that any observed difference could be sustained long enough to have an effect*."

Modelling has been undertaken for this project using the US EPA approach, as incorporation of advection will result in estimation of higher concentrations (risks) than exclusion of advection. **Figure 4-8** shows the assumed probabilistic distribution for advection rate as a lognormal distribution with a mean equal to the US EPA default assumption of 0.05 L/min/m2 (5L/min for 100 m2 building footprint), one order of magnitude either side of the default assumption of 0.005 (CRC CARE 2010).

Figure 4-8 Distribution assumption for Advection Rate



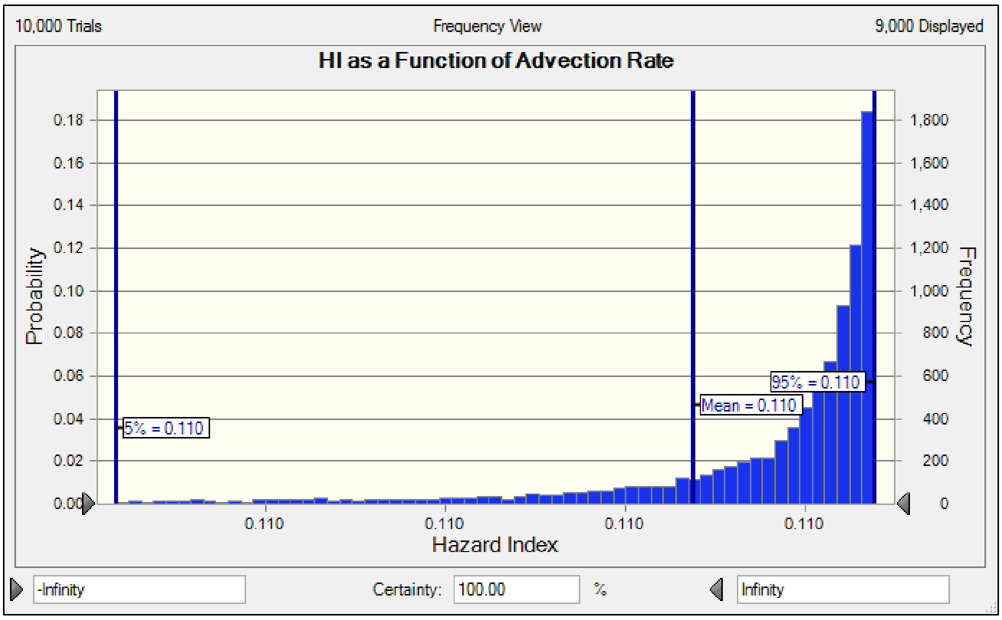
Groundwater Source

Figure 4-9 provides a plot of modelled indoor air concentration from deep groundwater as a function of advection rate. In essence, changes in assumed advection rate have negligible effect from a groundwater source (no difference in mean and 95%ile results). That is, due to the nature of the soils at the site, the rate of vapour migration is controlled by slow diffusion through the moist clayey soils.

This data is again based on the scenario for residential, slab on ground, groundwater source in Zone 3.

[19] UK Environment Agency (2009), Updated Technical Background to the CLEA Model, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291014/scho0508bnqw-e-e.pdf

Figure 4-9 Monte Carlo estimates of Hazard Index as a Function of Advection Rate-Groundwater Source

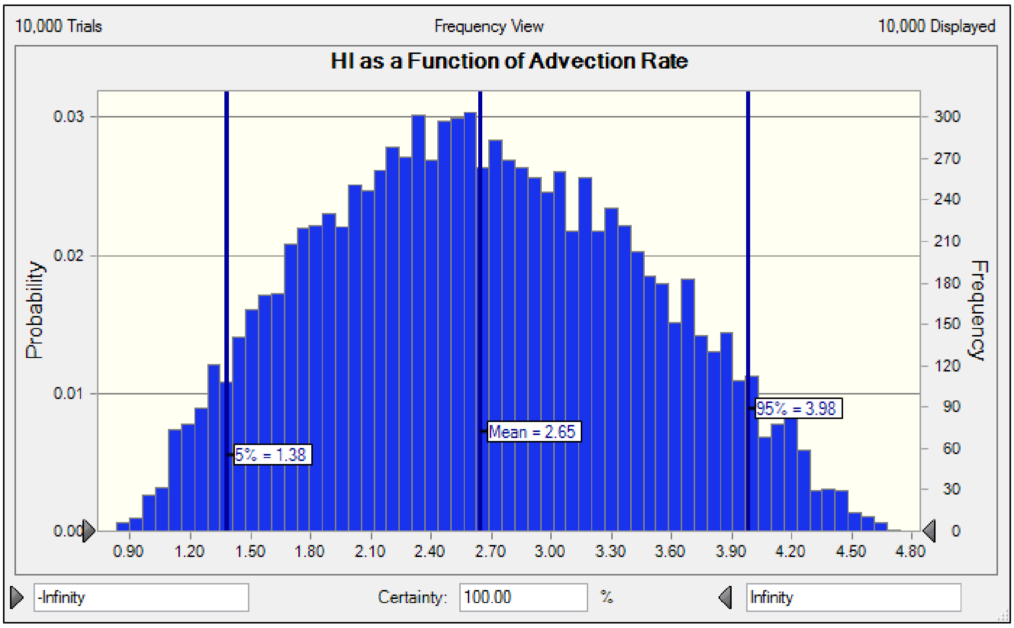


Soil Vapour Source

In contrast, the assumption of a shallow soil source of vapour (as measured in SV04 (Zone 3) at 1 m depth) implicitly assumes shallow impacts at this depth giving off vapours continuously (rather than having to diffuse to this depth from groundwater). This results in the modelled indoor vapour concentration being significantly more sensitive to the advection rate.

This assumed distribution of advection rates resulted (**Figure 4-10**) in a mean HI of 2.65, with a range from 1.38 to 3.98 for the 5% and 95%ile HI estimates. This compares with the deterministic result of 3.04 for this scenario (**Table 4-9**).

Figure 4-10 Monte Carlo estimates of Hazard Index as a Function of Advection Rate - Soil Vapour Source



4.10.5 Crawl Space Air Exchange Rate

There is relatively limited data available on crawl space exchange rates. Data summarised by Turcynowicz (2002) referred to data from studies undertaken on six homes in Melbourne where rate varies from 201.6 to 585.6 per day for brick veneer and 556.8 to 2085.6 per day for well ventilated weatherboard (Delsante et al, 1998[20]).

Studies on the Hendon Child Care Centre were used to estimate a crawl space air exchange rate of 3 per hour (72 per day). This is a relatively conservative value in relation to the data of Delsante, and the sensitivity of risk estimates has been considered based on assuming air exchange rates between 0.6 per hour and 10 per hour are equally probable (**Figure 4-11**).

Figure 4-11 Distribution assumption for Crawl Space Air Exchange Rate

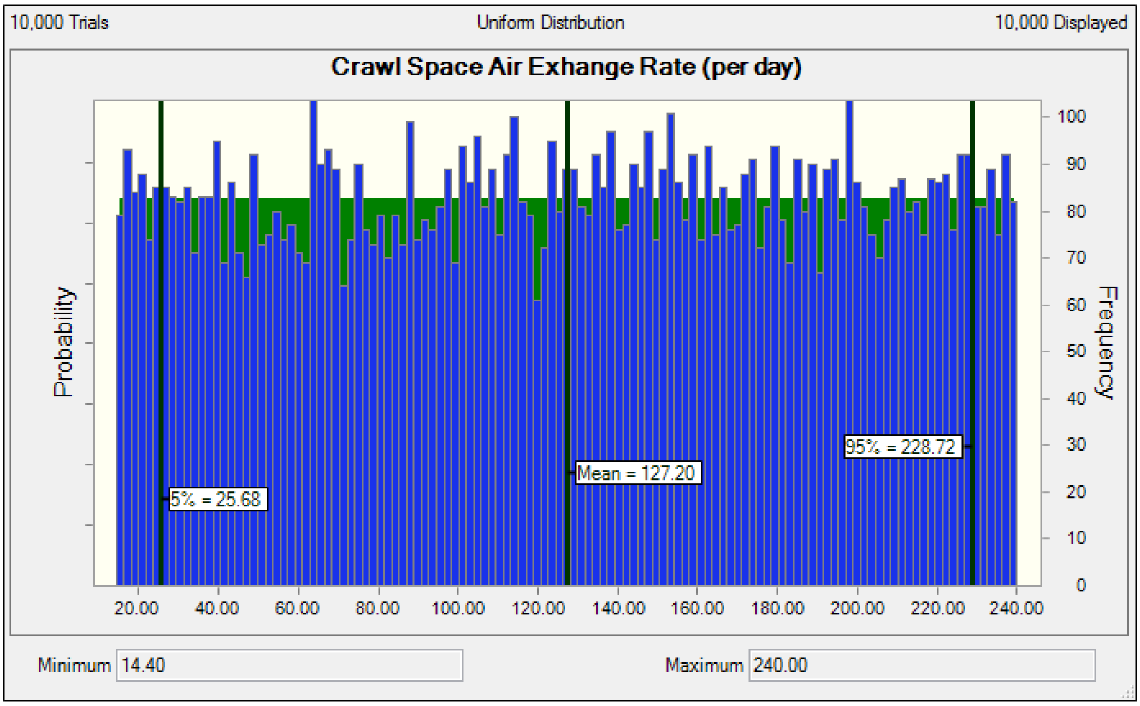
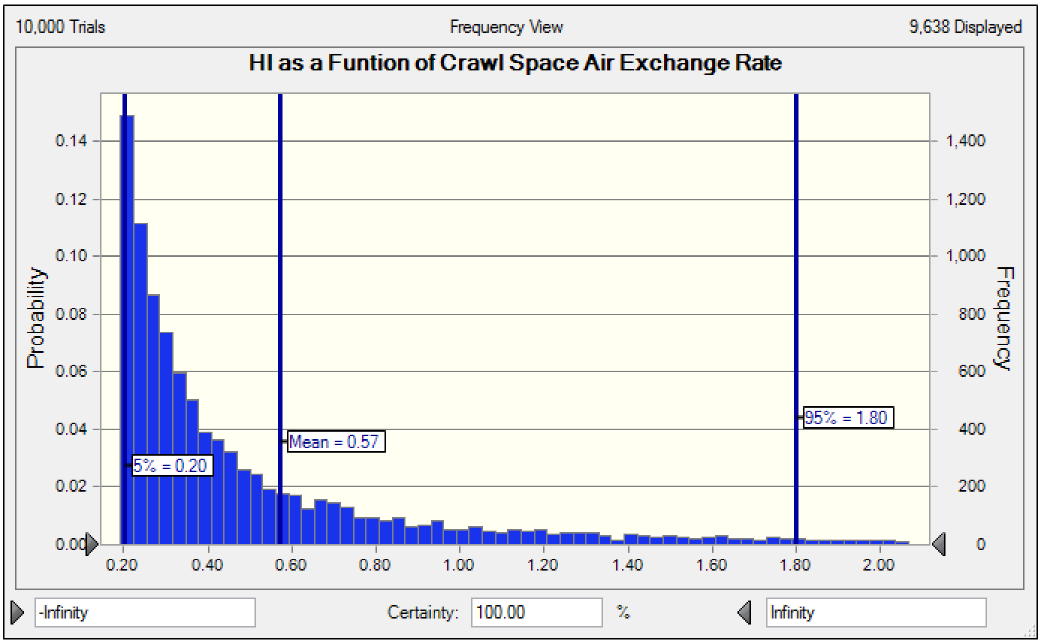


Figure 4-12 shows the distribution of hazard indices estimated on the basis of this crawl space air exchange distribution. This assumed distribution resulted in a mean HI of 0.57, with a range from 0.2 to 1.8 for the 5% and 95%ile HI estimates. This compares with the deterministic result of 0.67 for this scenario (**Table 4-9**). At the upper end, indoor air concentrations marginally exceed the target HI of 1, but are well within the further investigation range.

[20] Delsante A., Chan C. Threlfall G., Williamson T and Olweny M., 1998. Further measurements of Ventilation Rates in the Sub-Floor Spaces of Houses with Suspended Timber Floors. Environmentally Responsible Housing for Australia, Proceedings of the ARC/NAFI Research Seminar.
Delsante A., Chan C. Threlfall G., Williamson T and Olweny M., 1998. A Progress Report on the Measurement of Ventilation Rates in Sub-floor Spaces of Houses with Suspended Timber Floors. Environmentally Responsible Housing for Australia, Proceedings of the ARC/NAFI Research Seminar

Figure 4-12 Monte Carlo estimates of Hazard Index as a Function of Crawl Space Air Exchange Rate



5 CONCLUSIONS AND LIMITATIONS

5.1 Conclusions

URS conducted environmental assessment works in the Hendon investigation area in April/May 2015. The following was concluded from the results of this investigation:

- Volatile chlorinated hydrocarbon contamination remains present in shallow groundwater at a depth of typically around 3.5 to 5 m below ground level within the Investigation Area associated with the Hendon industrial area.
- The nature and distribution of VCH contamination in groundwater indicates that there are a number of properties within and in the near vicinity of the Hendon industrial area that may have historically and may continue to be acting as sources of the reported groundwater and soil vapour contamination. This investigation and risk assessment was limited in scope to consideration of vapour intrusion. It has also been focussed on the EPA investigation area targeting principally residential zones and so does not include detailed assessment of source areas.
- A property survey has identified the presence of both concrete slab-on-ground and timber floor (crawlspace) residential construction, and notably, that underground structures (cellar/basements) are a feature of some local residential dwellings.

The objective of the vapour intrusion modelling and human health risk assessment works detailed in this report was to incorporate the updated characterisation of volatile chlorinated hydrocarbon impacts across the Investigation Area in an assessment of potential vapour inhalation risks.

Required outcomes of this assessment included:

- Assessment of potential human health risk for selected building types and occupational scenarios across the Investigation Area to the extent supported by investigation data; and
- Identification of data gaps relevant to increased confidence in the assessment of the potential presence of human health risk.

Potential vapour intrusion risks estimated on the basis of soil vapour concentrations were higher than those estimated from groundwater data. This is considered to be principally due to the use of shallow soil vapour concentrations as source terms potentially overestimates risks as it implicitly neglects the potentially rate-limiting step of vapours diffusing up from groundwater through moisture saturated soils. Both source scenarios have been modelled to ensure elevated vapour concentrations are considered.

Assessment has been based on calculation of hazard indices assuming simple additivity of toxic effects for the key contaminants of potential concern PCE, TCE and cis 1,2 DCE. Assessment criteria are based on the residential indoor air level response framework for TCE developed by SA Health and the EPA (TCE Action Level Response Framework). This in essence defines concentrations ranges and associated actions consistent with:

- Hazard Index < 1 *validation range* - safe, but consider if ongoing monitoring required
- 1 < HI < 10 *investigation range* – further assessment necessary

Modelling of indoor air exposure using 2015 soil vapour concentrations of PCE, TCE and DCE indicate the potential for indoor air concentrations to warrant further investigation for several exposure scenarios and at different portions of the Investigation Area, particularly:

- TCE concentrations in Zone 3 (based on the concentration of 8,400 µg/m^3 at SV04 adjacent the Hendon Childcare Centre) resulted in exceedances of the HI = 1 range for each of the residential foundation assumptions.
  - A Hazard Index of approximately 3 (equivalent to the "Investigation" classification of the Indoor Air Level Response Range Framework) for slab on ground buildings
  - A Hazard Index of 8.7 for the Residential with Basement scenario (towards the upper end of the "Investigation" classification of the Indoor Air Level Response Range Framework).
  - A Hazard Index of 1.6 for the Residential with crawl space.
- A Hazard Index for the Residential with Basement scenario for Zone 2 (comprising a residential area south-west of West Lakes Boulevard and the Industrial Area) was >1 (3.05), again within the "*Investigation*" classification. This was principally driven by the elevated DCE vapour concentrations in vapour well SV13, located on West Lakes Blvd. The HI for slab on ground construction in this area was marginally less than 1, in the *Validation* range.
- The Hazard Index for Commercial – Slab-on-Ground for Zone 1 was also only marginally <1 (0.97). This area contains a church that is understood to be used occasionally as a children's play café.
- The calculated risks due to the potential for habitable basement use exceed those for slab on ground and crawl-space homes, due to their depth/proximity to the groundwater impacts.

Some recent historical soil vapour concentrations have been notably greater than the 2015 results; however, these historical concentrations were not generally assessed to affect the classifications with respect to the Indoor Air Level Response Framework, other than to the extent that TCE concentrations in the northern portion of Zone 2 also warrant an *Investigation* classification for the Residential with Basement scenario.

No modelled risks exceeded the upper investigation range criteria (HI=10). The elevated concentrations of TCE identified in SV04 near the Hendon Childcare Centre and elevated DCE concentrations in SV13 provide the highest risk estimates across the four spatial zones considered in the vapour risk assessment. Better delineation of the extent of elevated soil vapour impacts and confirmation of absence or presence of and use of basements is considered warranted in these areas (Figure 15).

5.2 Limitations

This conclusion and all information in this Report are provided strictly in accordance with and subject to the following limitations and recommendations:

a) This Report has been prepared for the benefit of the SA EPA.

b) Except as required by law, no third party may use or rely on, this Report unless otherwise agreed by URS in writing. Where such agreement is provided, URS will provide a letter of reliance to the agreed third party in the form required by URS.

c) This Report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by URS for use of any part of this Report in any other context.

d) This conclusion is based solely on the information and findings contained in this Report.

e) This conclusion is based solely on the scope of work agreed between URS and the EPA and described in section *1.3* ("Scope of Works") of this Report.

f) This Report is dated 31 July 2015 and is based on the conditions encountered during the site investigations conducted, and information reviewed, from 10 April to 31 July 2015. URS accepts no responsibility for any events arising from any changes in site conditions or in the information reviewed that have occurred after the completion of the site investigations.

g) The investigations carried out for the purposes of the Report have been undertaken, and the Report has been prepared, in accordance with normal prudent practice and by reference to applicable environmental regulatory authority and industry standards, guidelines and assessment criteria in existence at the date of this Report.

h) Where this Report indicates that information has been provided to URS by third parties, URS has made no independent verification of this information except as expressly stated in the Report. URS assumes no liability for any inaccuracies in or omissions to that information.

i) URS has tested only for those chemicals specifically referred to in this Report. URS makes no statement or representation as to the existence (or otherwise) of any other chemicals.

j) Except as otherwise specifically stated in this Report, URS makes no warranty or representation as to the presence or otherwise of asbestos and/or asbestos containing materials ("ACM") on the site. If fill has been imported on to the site at any time, or if any buildings constructed prior to 1970 have been demolished on the site or materials from such buildings disposed of on the site, the site may contain asbestos or ACM. Without limiting the generality of sub-clauses (h) and (m), even if asbestos was tested for and those test results did not reveal the presence of asbestos at specific points of sampling, asbestos may still be present at the site if fill has been imported at any time, or if any buildings constructed prior to 1970 have been demolished on the site or materials from such buildings disposed of on the site.

k) Investigations undertaken in respect of this Report are constrained by the particular site conditions, such as the location of buildings, services and vegetation. As a result, not all relevant site features and contamination may have been identified in this Report.

l) Subsurface conditions can vary across a particular site and cannot be exhaustively defined by the investigations described in this Report. It is unlikely therefore that the results and estimations expressed in this Report will represent conditions at any location removed from the specific points of sampling.

m) A site which appears to be unaffected by contamination at the time the Report was prepared may later, due to natural phenomena or human intervention, become contaminated.

n) Except as specifically stated above, URS makes no warranty, statement or representation of any kind concerning the suitability of the site for any purpose or the permissibility of any use, development or re-development of the site.

o) Use, development or re-development of the site for any purpose may require planning and other approvals and, in some cases, environmental regulatory authority approval. URS offers no opinion as to whether the current use has any or all approvals required, is operating in accordance with any approvals, the likelihood of obtaining any approvals for development or redevelopment of the site, or the conditions and obligations which such approvals may impose, which may include the requirement for additional environmental works.

p) URS makes no determination or recommendation regarding a decision to provide or not to provide financing with respect to the site.

q) The ongoing use of the site and/or the use of the site for any different purpose may require the owner/user to manage and/or remediate site conditions, such as contamination and other conditions, including but not limited to conditions referred to in this Report.

r) To the extent permitted by law, URS expressly disclaims and excludes liability for any loss, damage, cost or expenses suffered by any third party relating to or resulting from the use of, or reliance on, any information contained in this Report. URS does not admit that any action, liability or claim may exist or be available to any third party.

s) Except as specifically stated in this section, URS does not authorise the use of this Report by any third party.

t) It is the responsibility of third parties to independently make inquiries or seek advice in relation to their particular requirements and proposed use of the site.

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