CONCEPTUAL SITE MODEL
ORICA BOTANY
DOCUMENT CONTROL

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Conceptual Site Model – Orica Botany, 2017

DOCUMENT CONTRIBUTORS

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</table>

VERSION

Version: Rev2, Issued 20 September 2017
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td><strong>SOLID PHASE INTERACTIONS</strong></td>
<td>51</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Key Mechanisms</td>
<td>51</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Solid-Phase CHC Distribution</td>
<td>52</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Evolution</td>
<td>52</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Other Areas</td>
<td>52</td>
</tr>
<tr>
<td>4.6</td>
<td><strong>VAPOUR PHASE INTERACTIONS</strong></td>
<td>53</td>
</tr>
<tr>
<td>4.7</td>
<td><strong>17C MODEL</strong></td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td><strong>CONTAMINANT PLUMES</strong></td>
<td>57</td>
</tr>
<tr>
<td>5.1</td>
<td><strong>GENERAL</strong></td>
<td>57</td>
</tr>
<tr>
<td>5.2</td>
<td><strong>GROUNDWATER – CHC DISTRIBUTIONS</strong></td>
<td>57</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Southern Plumes</td>
<td>58</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Central Plume</td>
<td>58</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Northern Plumes</td>
<td>59</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Temporal Changes</td>
<td>60</td>
</tr>
<tr>
<td>5.2.5</td>
<td>Other Compounds</td>
<td>63</td>
</tr>
<tr>
<td>5.2.6</td>
<td>Uncertainties</td>
<td>63</td>
</tr>
<tr>
<td>5.3</td>
<td><strong>AQUEOUS PHASE PROCESSES</strong></td>
<td>64</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Advective/Dispersive Migration</td>
<td>64</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Degradation</td>
<td>65</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Plume Volume</td>
<td>67</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Plume Mass</td>
<td>68</td>
</tr>
<tr>
<td>5.3.5</td>
<td>GTP Abstraction</td>
<td>68</td>
</tr>
<tr>
<td>5.3.6</td>
<td>Modelling</td>
<td>70</td>
</tr>
<tr>
<td>5.3.7</td>
<td>Interactions with Surface Water Receptors</td>
<td>70</td>
</tr>
<tr>
<td>5.4</td>
<td><strong>VAPOUR PHASE INTERACTIONS</strong></td>
<td>71</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Soil Vapour</td>
<td>71</td>
</tr>
<tr>
<td>5.4.2</td>
<td>Surface Flux</td>
<td>71</td>
</tr>
<tr>
<td>5.4.3</td>
<td>Temporal Changes</td>
<td>72</td>
</tr>
<tr>
<td>5.5</td>
<td><strong>SOLID PHASE INTERACTIONS</strong></td>
<td>72</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Mechanisms</td>
<td>72</td>
</tr>
<tr>
<td>5.5.2</td>
<td>Sorption / Matrix Diffusion</td>
<td>74</td>
</tr>
<tr>
<td>5.5.3</td>
<td>Desorption / Back-Diffusion</td>
<td>74</td>
</tr>
<tr>
<td>5.5.4</td>
<td>Sorbed Mass</td>
<td>75</td>
</tr>
<tr>
<td>5.6</td>
<td><strong>BULK PLUME BEHAVIOUR</strong></td>
<td>75</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Phase Partitioning</td>
<td>75</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Mass Balance</td>
<td>75</td>
</tr>
</tbody>
</table>
APPENDICES

Appendix A: Site Industrial History
Appendix B: Properties of Chemicals, Wastes and DNAPLs
Appendix C: Selected CHC Distributions
Appendix D: Key Monitoring Programs
Appendix E: Modelling Works Summary
Appendix F: Glossary
1 INTRODUCTION

1.1 INTRODUCTION

This document presents an updated Conceptual Site Model (CSM) for the Botany Groundwater Cleanup (BGC) Project, and other current contamination projects at the Botany Industrial Park (BIP) and surrounds (the ‘Model Area’ or ‘site’). Previous versions of the CSM have been presented in 2007 (URS, 2007e) and 2010 (Golder, 2011a). This CSM incorporates the information gained from work conducted since late-2010 and aims to support ongoing groundwater contamination management and remediation planning by Orica Australia Pty Ltd (Orica).

1.2 CONTEXT

1.2.1 Botany Industrial Park

BIP is an industrial chemical complex formerly owned by Orica and now occupied by a number of individual chemical manufacturing companies, including Orica. The BIP site has a long industrial history (since the early 1940s), and was formerly owned and operated by Orica’s predecessor company, ICI Australia Ltd (ICIA). Historical operations at BIP have resulted in soil and groundwater contamination on and adjacent to the site. This contamination has been the focus of detailed and extensive investigations since 1989. Investigation and remediation of contamination at the site is ongoing, with a number of technologies being implemented and trialled to address soil and groundwater contamination.

1.2.2 Botany Groundwater Cleanup

The BGC Project addresses BIP-related chlorinated hydrocarbon (CHC) contamination issues. The overall remediation strategy, as required by various regulatory mechanisms, has been a risk-based approach to:

- Protect human health and environmental receptors via hydraulic containment of the CHC plumes and source areas and administrative measures.
- Monitor the nature and extent of contamination to identify potential exposure pathways that require management.
- Investigate potential technologies to remediate CHC source zones and plumes. However, periodic independent reviews have not identified practicable remediation alternatives.

1.2.3 Conceptual Site Model

Periodic revision of the CSM for the BGC Project by Orica is required as additional information is generated and the understanding of contamination conditions and behaviour develops. Since the 2010 CSM was prepared, significant additional information has been collected, remediation works have been completed addressing some legacy issues and the understanding of plume behaviour has developed. The key changes include, but are not limited to:

- Remediation works have been completed (or almost completed) for former Car Park Waste Encapsulation (CPWE) and former Chlor Alkali Plant (FCAP) (largely ancillary to the BGC Project).
- Operation of the hydraulic containment system and groundwater treatment plant (collectively referred to as the ‘GTP system’) has continued with a significant volume of groundwater and mass of CHCs removed from the environment and treated.
- Redevelopment of Southlands, property formerly owned by Orica, downgradient of BIP.
- Significant changes to dissolved-phase CHC plumes have been observed, including more significant decreases in concentrations than expected in some areas.
- Additional groundwater flow and solute transport modelling has been completed indicating there may be significant biodegradation and/or sorption mechanisms occurring.
- The understanding of fate and transport of CHCs has been further developed.
- The understanding of aquifer microbiology has been further developed.
While operation of the GTP system has successfully met the primary objective of the BGC Project, with progression of the BGC Project and observed CHC plume changes, increasing focus on the natural processes controlling residual contamination in the environment is warranted to help support long-term remediation planning. This will require a greater understanding of the fate and transport mechanisms (e.g. biodegradation, partitioning, matrix diffusion), which have previously been subject to relatively little specific assessment.

1.3 OBJECTIVES

Existing CSM documents, reflecting the focus of previous investigations and remediation on the primary BGC Project objective to protect human health and environment, have provided a comprehensive repository of available site information at the time, and detailed description of site history, natural setting, contamination sources, plumes, receptors and quantified risks. However, the CSMs do not reflect the changes that have occurred since commencement of GTP operation, or the up-to-date understanding of source behaviour and plume fate and transport (i.e. ‘pathways’). For these reasons, the primary objectives of this CSM are to clearly and concisely present:

- Overview of site industrial and natural setting.
- Current understanding of fate and transport mechanisms of CHC contaminants.
- Current nature of CHC contamination in different phases in source areas, plumes and receiving environments.

1.4 SCOPE

The CSM focusses on the principal contamination and remediation issues at, and beyond, BIP relating to the BGC Project (i.e. CHCs) and primarily on those processes affecting CHC fate in the aquifer (i.e. CHC behaviour in source zones and groundwater plumes).

Contamination issues, whether potential or identified, not relating to CHCs in the aquifer from former industrial operations at BIP are not addressed within this CSM.

1.5 CSM STRUCTURE

Regulatory guidance (NEPC, 2013) defines a CSM as a representation of site-related information regarding contamination sources, receptors and exposure pathways, with the interrelations between these illustrated in Diagram 1-1 (below). This CSM is mainly focussed on the ‘pathway’ components.

Diagram 1-1: CSM Framework
The structure of the CSM is broadly based on the different components in the ‘17C Model’ in Diagram 1-2 (below) as adapted from the ‘14 compartment model’ (Vanderkooy et al 2014). The model provides a framework to consider interactions between different contaminant phases (Dense Non-Aqueous Phase Liquid (DNAPL), aqueous, sorbed and vapour) in two different physical zones (high transmissivity sandy zones and low-permeability peaty/clay units) encountered at the site. Addition of components within the receiving environment has been provided (i.e. a ‘17 compartment model’). Degradation within phases is not easily captured within the model structure.

**Diagram 1-2: 17 Compartment Model Framework**

The CSM is divided into the following sections:

<table>
<thead>
<tr>
<th>SECTION</th>
<th>OBJECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction Provide scope, objectives and overall context of this CSM.</td>
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<tr>
<td>2</td>
<td>Site Background Provide an overview of site industrial history, contaminating activities and regulatory context to support discussion in Sections 4 – 6.</td>
</tr>
<tr>
<td>3</td>
<td>Environmental Setting Provide an overview of natural site setting (e.g. hydrology, geology, hydrogeology, geochemistry) to support discussion in Sections 4 – 6.</td>
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<tr>
<td>4</td>
<td>Contaminant Source Zones Describe CHC sources and processes/interactions affecting contaminant behaviour within vapour, aqueous and solid phases using the framework of the ‘17C model’.</td>
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<tr>
<td>5</td>
<td>Contaminant Plumes Describe CHC plumes and processes/interactions affecting contaminant behaviour within vapour, aqueous and solid phases using the framework of the ‘17C model’.</td>
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</table>
| 6       | Receiving Environment Describe receiving environments (air, surface water) and process affecting CHC behaviour in these using the framework of the ‘17C model’.

A glossary describing abbreviations and key terms is provided in Appendix F.

### 1.6 AUTHORSHIP

A number of parties have developed understandings of aspects of the BGC Project. As such, this CSM has been developed with contribution from a range of parties with previous and/or ongoing involvement in the BGC Project.

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2 SITE BACKGROUND

2.1 LOCATION AND LAND USES

2.1.1 Botany Industrial Park

BIP is a 73 hectare site located within an industrial and residential area approximately 12 km south of the Sydney Central Business District, New South Wales, Australia (Figure 1). BIP was subdivided by Orica in 1998–1999, and Orica currently owns and occupies only minor portions of the BIP.

BIP currently consists of a number of manufacturing plants. The GTP is in operation in the central portion of BIP. Groundwater extraction bores linked to the GTP are located along the southwestern boundary of BIP, on First and Second Streets.

In addition to the manufacturing operations, there are various shared services activities within BIP, as well as areas that are currently unoccupied and/or unused (following decommissioning and/or demolition of historical plants). Areas within northern BIP fronting Denison Street have been divested from BIP and are subject to redevelopment.

Figure 2 presents general layout of BIP, Southlands and key surrounding features.

2.1.2 Southlands

Southlands is located southwest of BIP and the Sydenham–Botany goods railway corridor. Southlands comprises Block 1 and Block 2 fronting onto McPherson Street, Banksmeadow, as well as a narrow block of land – a services corridor – on the opposite side of McPherson Street. Orica previously owned the whole of Southlands, which has recently been redeveloped for commercial use (warehousing and distribution). A large portion of the eastern area (Block 1) is retained as open space for flood detention and a portion of land is retained as easements containing GTP system infrastructure including extraction bores, monitoring bores, piping and the horizontal ‘under-bores’ to BIP and Secondary Containment Area (SCA).

2.1.3 Surrounding Areas

Details of land uses surrounding BIP and Southlands were presented in the 2010 CSM (Golder, 2011a), but are broadly summarised as:

- **Commercial/Industrial**: the Botany area is one of Sydney’s main industrial hubs. A range of industrial sites located in the vicinity of BIP have been used in the food, tobacco, paper, chemicals and materials manufacturing, fuel storage, warehousing, distribution and commercial sectors. There has been a general trend in recent years towards lighter industrial use, warehousing, distribution and freight logistics associated with Port Botany, and commercial uses. Commercial/retail developments have recently occurred fronting Denison Street to the east of BIP.

- **Infrastructure**: major infrastructure in the vicinity of BIP include the Sydenham–Botany goods railway line, which forms the southwestern boundary of BIP and northeastern boundary of Southlands, Port Botany located 1.5 km to the south of BIP and Sydney International Airport located 3 km west of BIP. Port Botany expansion project commenced circa 2010 and was completed in 2014.

- **Residential**: the closest residential areas to BIP include Matraville, Hillsdale and Eastgardens to the east. Residential areas in Banksmeadow, Botany and Pagewood are to the west and north of BIP. Urban renewal has resulted in an increasing number of medium density residential redevelopments, including in Pagewood to the north.

- **Open space**: there are a number of parks, reserves and golf courses surrounding BIP, including Hensley Athletic Field adjacent to the northeastern corner of BIP.

- **Schools**: Pagewood, Matraville and Banksmeadow Primary schools are located in the vicinity of BIP.
2.2 INDUSTRIAL HISTORY

2.2.1 Botany Industrial Park

Manufacturing began at the southern end of what is now known as the BIP in 1942, during World War II. The range of products manufactured increased during early post-war years. Statutory controls for effluent management, treatment and disposal were minimal. In the 1960s, larger manufacturing plants were constructed and BIP became predominantly a petrochemical complex. The development extended toward the northern end of BIP and the area was progressively developed as manufacturing plants were modernised, replaced or closed. Manufacturing operations that have since closed include:

- Trichloroethene (TCE) and ammonia/urea plants in the 1970s;
- Olefines I plant in the 1980s;
- Sodium silicates plants in the 1990s; and
- Chlorinated solvents (carbon tetrachloride (CTC), tetrachloroethylene (PCE) and 1,2-dichloroethane (EDC)) in the 1990s (the EDC Plant shut down in 2001; the other parts of the Vinlys Plant shut down in the 1990s).

The then Orica site was subdivided in 1998-1999 to create BIP. The principal plants currently operating on BIP include:

- Qenos1 Olefines II, Alkathene and Alkatuff Plants – ethylene, propylene, polyethylene, propane, quench oil and pygas;
- Huntsman2 Surfactants Plant – ethylene oxide, glycols, glycol ethers, non-ionic surfactants;
- Ixom3 ChlorAlkali Plant – chlorine, hydrogen, caustic soda, hydrochloric acid, ferric chloride and sodium hypochlorite;
- ALA4 – liquified nitrogen, oxygen and carbon dioxide;
- Qenos operated Site Utilities – steam, demineralised water, instrument air and other water supplies; and
- Orica GTP – treated water.

Whilst there is considerable knowledge about BIP in the earlier years, particularly with regard to the basic manufacturing processes, raw materials and the location of plants, detailed information is not always available, and is often anecdotal.

Prior to 1958, effluent was discharged to Springvale Drain via a stormwater pipe; disposal to unlined pits and stormwater drains may have also occurred. In 1958, discharge of process effluent (trade waste) to the then Water Board sewer commenced, and an effluent treatment plant was operating in that year at BIP (Woodward-Clyde, 1996f). However, untreated discharges to Springvale Drain may have continued until 1976, and uncontrolled discharge of effluent to the northern area of Southlands was occurring at least into the early 1960s. The Effluent Treatment Plant (ETP) at Eighth Avenue was built in 1976 and remains in service.

Sydney Water’s Southern and Western Suburbs Ocean Outfall Sewer 1 (SWSOOS) runs through BIP, as shown on figures in Appendix A.

The locations of the key current and historical industries that operated at BIP are shown in the figures attached to Appendix A.

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1 Qenos Pty Ltd, now a subsidiary of ChemChina Bluestar
2 Huntsman Corporation Australia Pty Ltd
3 Ixom Operation Pty Ltd was a new company created in 2015 following the sale Orica’s chloralkali business.
4 Air Liquide Australia Limited
2.2.2 Southlands

Southlands occupies part of an area once known as Veterans Swamp, which was itself part of the broader Botany Swamps that formed part of Sydney’s water supply in the 1830s and 1840s. As groundwater was drawn from the northwest of the Botany Swamps area, peat lenses were exposed, and peat cutting and sand extraction were carried out on a commercial basis into the mid-20th century.

In the 1950s Southlands was acquired by Australian Paper Manufacturers (APM). Some of the ponds and pits (now removed as part of Southlands redevelopment) were used for discharge of paper waste slurries, and dumping of bottom end furnace ash from coal-fired boilers used by industry in the area, including Bunnerong Power Station. Subsequent in-filling occurred, including use of building rubble, possibly until 1991 when the site was fenced.

Additional details are provided in Appendix A.

2.2.3 Surrounding Areas

Industry was first established in the East Botany area near the turn of the 19th century. The first industries were mainly tanneries, fellmongers, wool scourers and a paper mill. Several major industries were established in the 1920s and 1930s, including Davis Gelatine, Kellogg’s and Johnson & Johnson. Many of the chemical industries, including ICI Australia and New Zealand (ICIANZ, subsequently ICIA and now Orica) were established in the 1940s.

During the period from 1956 to 1966, several bulk fuel depots located immediately to the north and west of BIP, and further chemical manufacturing facilities were established. Reclamation works for Port Botany commenced in the mid-1970s, with further expansion works from 2010-2014. Davis Gelatine, historically a major groundwater user in the area, ceased manufacturing operations in about 1991.

Further details and locations of the various historical industries in the vicinity of the BIP are shown in Appendix A.

2.3 REGULATORY FRAMEWORK AND ENVIRONMENT

The programs of investigation and management of contamination originating from BIP have had input, direction, and regulation from various New South Wales State Government authorities. The 2010 CSM provided an overview of historical regulation of the site, which should be referred to for more detailed information.

The NSW Environment Protection Authority (EPA)\(^5\) has assessment, adjudication and enforcement duties under the principal legislation relating to contaminated land in NSW, namely the Protection of the Environment Operations Act (1997) and the Contaminated Land Management Act (1997). NSW EPA also acts as the principal regulatory reviewer of the technical material produced as part of the investigation and remediation projects.

The NSW EPA issued Orica with Notice of Clean Up Action (NCUA) No. 1030236 on 26 September 2003, under the POEO Act 1997. Following effective completion of the principal NCUA actions, and consultation with the community and Orica, the NSW EPA determined that the project would be best managed by a Voluntary Management Proposal (VMP) under the CLM Act 1997. An initial VMP was approved on 5 November 2010 (Approval No. 20101714), which was subsequently revised on 13 August 2015 (Approval No. 20151711). The VMP is the current regulatory tool requiring effective operation of the GTP hydraulic containment system, monitoring and reporting, community consultation, and source area management.

A revised Groundwater Remediation and Management Plan (GRAMP) was submitted as an attachment to the VMP; it outlines surface water and groundwater monitoring requirements.

Other government bodies or regulatory stakeholders relating to investigation and management of contamination at the site include:

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\(^5\) There are various former entities as described in the 2010 CSM (Golder, 2011a).
• WaterNSW\textsuperscript{6}: regulates groundwater extraction and injection wells/bores within NSW, including those of the GTP system.
• NSW Health: primary reviewer of human health risk assessment reports.
• Department of Planning\textsuperscript{7}: consent authority for significant development projects, including those associated with the construction and operation of large-scale remediation systems, including the GTP system.
• City of Botany Bay\textsuperscript{8}: consent authority for minor remediation works under the Local Environment Plan.

Apart from the state regulatory authorities, all stages of the investigations have also been subject to review and comment by various independent and community committees, including Technical Steering and Advisory Committees, Community Liaison Committee, Independent Management Committee.

The model area is located within the WaterNSW declared Groundwater Extraction Exclusion Area (GEEA)\textsuperscript{9}, which was created on 22 August 2003 to allow management of potential human exposure issues associated with groundwater contamination from the BIP. In this area, extraction and use of groundwater is prohibited. The GEEA was extended to the north, east and west on 11 July 2005.

The GTP system operates under EPA Environment Protection Licence (EPL) No. 2148.

2.4 ENVIRONMENTAL INVESTIGATIONS

A high-level overview of previous environmental investigations is provided in Table 2-1 (below). The scale and extent (in terms of spatial and complexity) of previous programs is very large, with many 100,000s pieces of environmental data collected since the 1990s. The 2010 CSM should be referred to for a more detailed summary, and references to key relevant components of these former works have been provided in ‘Further Reading’ sections throughout this CSM.

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<tr>
<th>STAGE</th>
<th>SCOPE OF WORKS</th>
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<td>Stage 1 – Preliminary Investigations</td>
<td>The Stage 1 Investigation (AGEE, 1990) was initiated by the then State Pollution Control Commission (SPCC) after concern was raised by the public regarding contamination migrating from the BIP into the surrounding environment. The program investigated soil gas, shallow soils, groundwater and surface water at and downgradient of BIP. Identified sources of the on- and offsite CHC contamination included the Solvents Plant, TCE and Vinyl Chloride Plants, and associated effluent management systems practices. Peak CHC concentrations in most of these media were detected within Southlands. Some CHCs were detected in bores up to 1 km west of the BIP. HCB, mercury and chromium were detected in biota within Penrhyn Estuary, however, volatile CHCs were not detected in biota samples.</td>
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<td>Stage 2 – Detailed Investigations</td>
<td>The Stage 2 Detailed Investigation was a very large program, from which more than 15,000 pieces of environmental data from various media were collected and analysed over a two-year period (July 1993 - July 1995). The works were broken into six ‘contracts’ – each assessing different components as reported by Woodward-Clyde (1996a-e): • Springvale Drain (C1) • Soil and groundwater – stratigraphy, hydrogeology and hydrology (C2) • Soil and groundwater – contamination (C3) • Biota within Penryn Estuary and botany Bay (C4) • Human health risk (C5) An overview report (Contract 6) consolidated the findings of C1-C5 works (Woodward-Clyde, 1996f) and is a key reference to this CSM.</td>
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\textsuperscript{6} There are various former entities as described in the 2010 CSM (Golder, 2011a).
\textsuperscript{7} Now known as the Department of Planning and Environment (DPE).
\textsuperscript{8} Now merged with Rockdale City Council to form Bayside Council.
Stage 2 works formed the basis of the general understanding of the site natural setting and processes, source history and contamination conditions, and gave direction to subsequent contamination assessment and management approaches.

Stage 3 – Remediation

Stage 3 investigation and remediation works included a range of investigations, remediation desktop studies, design and field trials, and remediation programs targeting reducing contaminant flux into and along Springvale Drain, and contaminant mass removal from the aquifer. Key works included:

- DNAPL source area investigations.
- Further surface water and groundwater assessment – focussing on delineation and monitoring.
- Monitoring of surface air emissions.
- Feasibility assessment and design of a bioremediation trial at Southlands.
- A pilot-scale reactive iron barrier (PSRIB) trial at Southlands.
- Temporary realignment, removal of contaminated sediments and re-lining of Springvale Drain (which occurred in 2003).
- Repair of the underground stormwater line connecting BIP with Springvale Drain.

Stage 4 - Remediation

The Stage 4 program, which followed on from works conducted in Stage 3, comprised significant programs of investigation and remediation, notionally commenced in December 2001. Stage 4 works have largely been under the framework of various regulatory tools (e.g. NCUA and VMP), and plans prepared under these including the Groundwater Cleanup Plan (GCP), Groundwater Treatment Plant (GTP) Groundwater and Surface Water Monitoring Program. Current works under the current VMP are part of Stage 4.

Key works have included:

- Development of remediation strategies. These evolved from the early-2000s (as part of the normal process of assessment and driven by regulatory tools) to the current remediation strategy.
- Design, consent, construction and operation of the GTP hydraulic containment system as part of the BGC Project.
- Groundwater flow and solute transport modelling and further investigations to support GTP system design and long-term remediation planning.
- Assessment of DNAPL source zone remediation technologies – including a study tour, desktop studies, and laboratory and field feasibility assessments of in situ chemical oxidation (ISCO), direct thermal treatment, hydraulic flushing and direct recovery. ISCO, thermal, flushing and recovery technologies were subsequently determined to not be feasible due to uncertainty in environmental benefits and impracticability.
- Trial of in situ bioremediation and PSRIB at Southlands.
- Additional DNAPL source area investigations.
- Revised human health risk assessments.
- Ongoing periodic air emission (soil vapour, surface flux and ambient air) monitoring (see Appendix D).
- Quarterly program of surface water and groundwater monitoring (hydraulic and chemical) (see Appendix D).
- Residential bore sampling (see Appendix D).

Reviews of the remediation strategy, with supporting studies, are conducted every three years (2007, 2011, 2014, 2017), as described below (Section 2.5.1.3).

Other Programs: Other works (including contamination investigation and remediation) not directly considered, but which provide information indirectly relevant, to this CSM include:

- Former Chlor Alkali Plant (FCAP) – assessment and remediation works to address mercury contamination issues (Section 2.5.2).
- HCB/HCBD in Soil and Waste – Car Park Waste Encapsulation (CPWE) remediation and Hexachlorobenzene (HCB) waste re-packaging (Section 2.5.3).
- Southlands redevelopment – works to support development (and divestment) of Southlands for commercial land use.

2.5 REMEDIATION STATUS

2.5.1 BGC Program

Orica’s overall strategy for remediation of BIP-related contamination currently comprises:
• Containment of dissolved phase CHC plumes on and off site to ensure risks to human health and the environment remain acceptable.

• Continual optimisation of operation of the hydraulic containment lines and GTP system for protection of critical human health and environmental exposures and for gradual cleanup of contamination in areas.

• Improvements to the hydraulic containment system and GTP to further reduce impacts on Springvale Drain and Penrhyn Estuary/Botany Bay.

• Ongoing review of developments in remediation technologies and experience for DNAPL, soil and groundwater phase CHCs, and their practical application to the BGC Project.

This approach is consistent with the requirements of the NCUA (September 2003) and its subsequent variation notices, and the VMP.

2.5.1.1 CHC Contaminant Plumes

The BGC Project includes containment of dissolved phase CHC plumes on and off site achieved by:

• Groundwater extraction (with ex situ treatment) from the Botany Sands aquifer along the southwestern boundary of BIP (originally referred to as the DNAPL Containment Line, but now the BIP Containment Line), the southern boundary of Southlands along McPherson Street (Primary Containment Area (PCA)) and along Foreshore Road (SCA). Extraction occurs from a total of 109 locations, with wells targeting ‘shallow’ and ‘deep’ aquifers at BIP and SCA, and the deep aquifer at PCA.

• The groundwater extracted from these groundwater containment lines is pumped to a purpose-built Groundwater Treatment Plant (GTP) located on BIP (see Figure 2.2). Treated water is reused for industrial purposes within BIP and surrounding industry, or discharged.

• Performance monitoring at the GTP and of water levels and water quality within the aquifer is conducted in a series of daily, weekly, monthly and quarterly programs (see Appendix D). Settlement monitoring (for potential subsidence) and ecological receptor monitoring was also undertaken.

• The Groundwater Injection and Recovery (GIR) system (Golder, 2011c, 2012d, 2014a) was constructed at BIP and trialled during 2010-2013 as a contingency to maintain hydraulic containment in critical areas in the case that the GTP was shut down for an extended period of time.

This system is often collectively referred to as the ‘GTP system’ or ‘hydraulic containment system’. The effectiveness of hydraulic containment is reviewed on a quarterly basis as part of compliance monitoring under the GTP monitoring program (see Appendix D for references).

Design and approvals of the BGC Project (comprising the groundwater extraction systems, transfer piping from extraction wells to the GTP, the GTP, and distribution systems for treated water and wastewater from the GTP) commenced in 2003, with an environmental impact statement (EIS) (URS, 2004i) prepared to obtain consent for the construction and operation of the system.

Limited groundwater extraction commenced at the SCA in October 2004 (0.6 ML/day) to an interim treatment system, with full-scale operation of the system commencing in 2006 (circa 6 ML/day). Various compliance monitoring programs are required as part of operating conditions under the EPL and VMP. Operation of the GTP system has been assessed to have resulted in effective hydraulic containment (JBS, 2012), with review of system performance every quarter.

Other groundwater contaminant remediation works have included:

• Enhanced In-Situ Bioremediation (EISB) trial at Southlands: Bioremediation trials in 2004 and 2005 (GeoSyntec, 2000/2006b) were partially successful, but did not provide unequivocal evidence that bioremediation would contain and treat all CHC contaminants (in particular EDC) at PCA and SCA at that time. More recent small-scale field trials by University of NSW (UNSW) (UNSW, 2010) have involved bioaugmentation using enrichment cultures developed from the original bioremediation trial area and colonies in the PSRIB.

• Pilot-Scale Reactive Iron Barrier (PSRIB) trial at Southlands (URS, 2001, 2004c, 2007h): The PSRIB was initially relatively ineffective in treating EDC and would be difficult to install at depth. Subsequent investigations of the PSRIB found that EDC was being degraded by indigenous microorganisms that had colonised the iron barrier (see Section 5.3.2).
• **Nano-Scale Zero Valent Iron**: Orica has worked with UNSW to develop a method to produce commercially viable grades and quantities of nano-scale zero valent iron (nZVI).

### 2.5.1.2 DNAPL Source Areas

On the basis of review of potential DNAPL remedial options (Orica, 2005) and more recent progress in areas of research and development, the following approaches were selected for further review and trialling:

- **In situ** chemical oxidation (ISCO) using activated sodium persulphate - laboratory-scale trials were conducted but the subsequent interpretation of results did not achieve consensus. Malcolm Pirnie (2008) considered that full-scale implementation of ISCO to treat DNAPL source zones using activated persulphate would not be practicable.

- **Direct thermal treatment** (steam injection coupled with thermal conductive heating) – concept design of a pilot-trial system was conducted, but not implemented. Direct thermal treatment was not considered practicable for full-scale implementation due to access constraints and uncertainty in benefits of source area treatment (in terms of reducing downgradient CHC concentrations and remediation timeframe).

- **Hydraulic flushing or flooding** - GeoSyntec (2006a) conducted a desktop assessment of feasibility of hydraulic flushing of DNAPL source areas. Hydraulic displacement is not currently considered by Orica to have significant application at BIP or Southlands and no further work has been conducted.

- **Direct pumping** – trials of direct recovery of DNAPL at wells located on Southlands (WG82D), the rail corridor separating Southlands and BIP (WG67D) (Woodward-Clyde, 1997b) and BIP (MWD16D in 2006 and 2010) (URS, 2006f) removed minimal volumes of product and is not considered practicable.

Research studies to assess applicability of using electrokinetics to transport oxidants into heterogeneous and low-permeability layers have also been conducted in conjunction with the University of Western Australia. The electrokinetic research work was undertaken between mid-2007 and 2009.

Excavation is a potentially viable option for removal of DNAPL from the vadose zone in areas such as:

- Former Vinlys Plant and EDC Storage Tanks (C1 Source Area).
- Former TCE Plant (S3 Source Area).

Further assessment of excavation has not been undertaken.

### 2.5.1.3 Strategy Reviews

Reviews of the CHC contamination management and remediation strategy have been conducted periodically (every three years) as required under the VMP. Technical workshops (attended by international DNAPL and groundwater experts, local consultants, representatives of NSW EPA and Orica environmental specialists and managers) were held in December 2007 (Orica, 2008), February 2011 (Orica, 2011), February 2014 (Orica, 2014) and February 2017 (Orica, 2017).

The review outcomes have recognised the large scale of the remediation project, broadly endorsed the current remediation approach and concluded that current DNAPL depletion technology is not practicable (e.g. Malcolm Pirnie, 2008) in delivering significant additional near-term reductions to human health and ecological risks, or a meaningful reduction in overall clean-up duration.

Various recommendations have been made for further assessment to aid long-term contamination management.

### 2.5.2 Former Chlor Alkali Plant

Orica used elemental mercury at their Former Chlor Alkali Plant (FCAP) at BIP in an electrolytic process which operated from 1944 until 2002, after which it was replaced with a membrane cell electrolytic plant (the process used to produce chlorine at the current plant).

Environmental investigations completed between 2004 and 2009 identified significant concentrations of mercury in soil and groundwater at, and downgradient of, the FCAP. Groundwater was also locally impacted by alkalis and acids, and there is a zone of high chloride concentrations due to dissolution of the salt stockpile extending to the southwest of FCAP. Golder (2012b/e) summarised previous environmental assessments associated with the FCAP.
Orica proposed to remediate areas of the FCAP impacted with mercury. A soil washing process was trialled and operated but was unable to meet Orica’s remediation objectives. Following further risk assessments (EnRiskS, 2013a), modelling (Laase, 2010a) and an extensive evaluation of four technology options (Golder 2012a), the preferred option was considered to be on-site containment employing low-permeability cut-off walls and capping with a vapour and liquid-tight concrete slab (Golder, 2012b/e). Excavation and consolidation or off-site disposal of minor volumes of mercury impacted shallow soils also occurred.

Construction of the cut-off walls and cap commenced in 2013 and was completed in 2016. Ongoing remediation validation and groundwater monitoring (Golder, 2013) is required. The most recent published groundwater monitoring results were presented by Golder (2016a).

2.5.3 HCB/HCBD in Soil and Waste

Hexachlorobutadiene (HCBD) and hexachlorobenzene (HCB) and other ‘heavy-end’ semi-volatile CHCs were produced as a waste by-product in former solvent and plastic manufacturing plants at BIP in Australia between 1963 and 1991.

Drummed HCB/HCBD wastes have been stored in various locations around BIP. Destruction / disposal options have been investigated, but the drummed wastes have not been able to be destroyed in accordance with requirements under the Environmentally Hazardous Chemicals (EHC) Act 1985 Licence No. 26. Repackaging of drummed wastes occurred in a specially built plant from May 2007 to mid-2010. As part of the repackaging exercise an Environmental Assessment (EA) (Orica, 2006), a human health risk assessment (URS, 2006g) and an air quality assessment (PAE, 2006) were completed.

The former Car Park Waste Encapsulation (CPWE) was created when approximately 45,000 m³ of contaminated sand and coal ash was relocated from areas previously used for storage of drummed ‘heavy end’ wastes in 1980 to a purpose-built engineered facility covered by a car park at the northeastern end of BIP on Corish Circle, Banksmeadow. The soil in the CPWE was contaminated with elevated concentrations of HCB, HCB and PCE (tetrachloroethene).

Remediation of the CPWE commenced in June 2010. As part of the Environmental Assessment prepared for the remediation project (AECOM, 2007), a Remedial Action Plan (AECOM, 2009), air quality impact assessment (PAE, 2007) and human health risk assessment (since revised by EnRiskS, 2010) were completed. Remediation works included excavation of contaminated soils with subsequent screening and treating using directly-heated thermal desorption technology. Remediation works were completed in 2013 and in 2015 Orica sold the former CPWE area and adjacent land for a commercial development.

Research into biodegradation of HCB in soils at BIP has been conducted (e.g. Manefield, 2008).

2.5.4 Southlands

Staged remediation of Southlands was undertaken during 2014 to 2016 in accordance with the Southlands Remediation Action Plan (RAP) (URS, 2008b; JBS&G, 2014/2015a) as part of the approved development project. The EA for the project contained numerous environmental assessments (including hydrology, ecological, contamination) (URS, 2009c), with EnRiskS (2013b) further assessing risks. As part of remediation works, a layer of clean fill was placed overlying the site and a flood detention basin at Block 1 Southlands constructed. These works, in conjunction with subsequent development with warehouses and paved surfaces, affects local hydrology and hydrogeology relevant to this CSM.

2.5.5 Other Contaminants

Other known contaminant plumes which originate from under BIP include:

- Ammonia – from the former Ammonia/Urea Plants, and potentially the SWSOOS.
- Benzene, toluene, ethyl benzene, xylenes (BTEX) / Total Petroleum Hydrocarbons (TPH) – primarily related to the former Ampol and/or BP depots, and the Qenos Olefines II Plant.
- Mercury from FCAP, and salt, acid and alkaline plumes from the FCAP and potentially current CAP footprints.
- Carbon disulphide from former CTC Plant.

The status of the BTEX and ammonia plumes is uncertain and have not been investigated in detail due to the greater potential for risk to human and environmental health presented by the CHC plumes. Regardless,
given the inferred location of the ammonia and BTEX plumes, it would be contained by the three groundwater containment lines and treated by the GTP.
3 ENVIRONMENTAL SETTING

3.1 CLIMATE

The site’s climate is temperate, with mild winter (June-August) and warm to hot summer (December to February) periods. Rainfall is spread evenly through the year as shown in Diagram 3-3 (below), with a mean annual rainfall of approximately 1,100 mm. The long-term patterns in rainfall (as indicated by the trends in monthly rainfall residuals in Diagram 3-4), show extended periods of below average rainfall (e.g. 1940s, late-1970s / early-1980s and early 2000s) and above average rainfall (e.g. 1950s, early-1970s and late-1980s).

Dominant wind directions range from northeast and south in summer, and west and southwest in winter.

3.2 TOPOGRAPHY

The site lies within the Botany Basin – a natural topographical basin surrounding Botany Bay. The Botany Basin is formed in a shallow depression in the sandstone bedrock which has filled with coastal sand dunes and estuarine sediments. The ground elevations rise from less than 5 m AHD around the foreshore of Botany Bay and swampy areas to between 15 and 25 m AHD in the sand dunes, and reaching a maximum elevation of 35 to 40 m AHD at the Basin edges (Figure 3).

Major topographical features of the model area include:
- An extensive low lying area (less than 5 m AHD) to the southeast of BIP, which was a former swamp (Veterans Swamp), has been largely reclaimed through drainage. Southlands is situated within this area.
- Dunes form the higher ground extending under most of BIP and to the east, north and northwest of the site.
- Dunes form the ridge of higher ground under Stephen Road.

3.3 HYDROLOGY

3.3.1 Model Area

Natural drainage patterns have been extensively modified through industrial and commercial development. In the sand dune areas there are few natural water courses and most drainage is inferred to occur through infiltration into permeable sands. The major surface water features include:
- A series of interconnected man-made lakes, where the groundwater table intersects the ground surface, called Lachlan Lakes, which are located to the north of BIP.

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10 Residual between total monthly rainfall and the long-term historical mean monthly rainfall. The graph represents the cumulative residual from 1929 for Sydney Airport weather station – i.e. a decreasing trend is indicative of below average rainfall, whereas an increasing trend represents above average rainfall.
• Surface drainage to the east of the site is via a series of lined or piped canals and drains through the Matraville area.

• Near the BIP and towards Botany Bay, surface drainage of Banksmeadow and Matraville catchments via Floodvale Drain and Springvale Drain. Shallow groundwater ingress in some sections of the drains results in drain baseflow. Floodvale and Springvale Drains originate near Page Street and Heffron Road, respectively, and were excavated in the 1870s to assist with drainage of Veterans Swamp. Both drains are piped at their northern ends. Springvale Drain is an open channel at BIP, and both drains are open channels at Southlands. Floodvale Drain is piped under Botany Golf Course and Foreshore Road, whilst Springvale Drain is piped through parts of Discovery Cove Industrial Estate and under Foreshore Road. Floodvale Drain and Springvale Drain enter Botany Bay via Penrhyn Estuary.

The location of Lachlan Lakes and Springvale and Floodvale Drains are shown on Figure 3.

Relatively small surface water features (ponds or basins) are present at Botany Council Golf Course and were formerly present at Southlands Block 1 (‘paper waste ponds’). At Southlands, the former paper waste ponds were formed from infilling with paper waste, with surface water temporarily present depending on recharge from rainfall and shallow groundwater discharge. These were removed as part of the Southlands development. A flood retention basin was constructed as part of the Southlands development within the southern portion of Block 1.

3.3.2 Springvale Drain

Water flow within Springvale Drain is closely related to rainfall, with rapid increases following rainfall events and a decrease in drain levels after rainfall events, initially rapid, representing the recession of high peak flows associated with surface runoff. The peaks are then followed by a relatively slow decline in water levels that may be representative of base flow generated by groundwater discharge to the drain.

There may also be possible industrial discharges to the drain.

Flow measurements of Springvale Drain from January to August 2007 showed a base flow of approximately 0.1 ML/d at McPherson Street (southern boundary of Southlands), with short periods of increased flow (up to 12 ML/d) following rainfall events and possible industrial discharges to the drain.

Groundwater discharge to the drain at Southlands is likely to have decreased following re-lining of the BIP stormwater drains in the early-2000s, and is inferred to have decreased since steady operation of the GTP containment system commenced circa 2007 based on observations of lower shallow groundwater levels, reduced baseflow rates and reduced CHC concentrations in surface water.

3.3.3 BIP

Surface runoff on the southern half of the BIP (i.e. south of Twelfth Avenue) flows via stormwater management systems within each plant area to two main stormwater first-flush interceptor pits (IP1 adjacent to the Eighth Avenue ETP and IP2 behind the Qenos cooling towers), with overflow discharging to Springvale Drain by gravity flow through two underground stormwater pipes that traverse the northern boundary of Southlands Block. (Relining of these stormwater pipes to prevent groundwater ingress through unsealed butt joints and consequential short-circuiting of groundwater flow into Springvale Drain occurred in the early 2000s). The discharge point is adjacent to the northern end of the Qenos Nant Street Tank Farm.

Baseflows captured at IP1 and UP2 are transferred to the BIP effluent system (for eventual disposal to Sydney Water sewer under a trade waste licence).

Surface water from non-process areas north of Twelfth Avenue and surface water overflowing first-flush systems from process areas at the Olefines II and Alkatuff Plants discharge directly to Springvale Drain at

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1 Flow measurements taken in Springvale Drain at McPherson Street (southern boundary of Southlands) show that base flow was approximately 0.42 ML/day in 2005 (prior to consistent GTP operation) and approximately 0.1 ML/day from January to August 2007 during consistent GTP operation (Golder, 2011a).

12 Some runoff from southern BIP roads and rooftops drains to stormwater drains in Beauchamp Road and Denison Street.
various locations. It is also noted that a portion of surface runoff passing through BIP is runoff from Denison Street (near the Gate 3 entrance).

### 3.3.4 Penrhyn Estuary

Penrhyn Estuary was formed as part of the development of Port Botany in the late 1970s. The estuary has since been modified as part of the Port Botany expansion that commenced in 2010.

The estuary is characterised by intertidal sand/mud flats with two channels from Springvale and Floodvale Drains that discharge stormwater after rainfall and baseflow (a result of groundwater ingress).

### 3.4 GEOLGY

#### 3.4.1 Botany Basin

The Botany Basin occupies an area of approximately 80 square kilometres and lies to the south of the City of Sydney. The areal extent of the basin is bounded by Centennial Park in the north, Randwick and Matraville in the east, Alexandria and Rockdale to the west, the Kurnell Peninsula and the northern part of the Sutherland Shire to the south.

The Botany Basin occupies an erosional depression formed in the Triassic Hawkesbury Sandstone. Erosion during the Tertiary period incised three valleys (paleochannels) in the sandstone (Griffin, 1963). Palaeodrainage features have been delineated by Griffin (1963) (terrestrial) and Albani (1981) (Botany Bay). During the Quaternary period, these valleys were filled with unconsolidated to semi-consolidated sands, silts, clays and peats, which form the Botany Sands aquifer (Acworth and Jankowski, 1993).

The Lakes Valley is one of these paleochannels, which runs from Centennial Park in the north to Botany Bay at Banksmeadow, with its position inferred from geophysics and confirmed by subsurface investigations in the Stage 2 Survey and Stage 4 works (Figure 4).

The sedimentary sequence overlying Hawkesbury Sandstone bedrock is up to 80 m thick, though generally shallower, within the Botany Basin and has been broadly simplified into the following stratigraphic units (see Diagram 3-5 below), summarised as:

- **Basal units** - fluvial and marine sands, estuarine muds and peats (Qps) fill the Lakes Valley at thicknesses of 0 m to 45 m overlying sandstone bedrock.
- **Aeolian and littoral dune and beach sands** (Qpb) that reach a maximum thickness of 30 m. Discontinuous lenses and bands of inter-dunal peat and clay are present. This unit is referred to as ‘Botany Sands’ and is most relevant to this CSM. Hard, iron cemented, sand layers locally referred to as “Waterloo Rock” are common in the upper portion of this unit and are postulated to be due to sub-areal weathering (Roy, 1983).
- **Upper unit** is represented by Holocene aeolian sands (Qhs). These are most common in proximity to Botany Bay and exist close to present day land surface.

In the past century, filling and drainage of the low-lying and coastal areas in and around the Botany Bay area has increased the land surface area. This includes much of the area south of Botany Road in Banksmeadow and for development of Port Botany and Sydney Airport. Filling involved the ‘dray and scoop’ or ‘dredging and hydraulic placement’ of Botany Sands (dune sands) materials over these areas, with some 50 million tonnes of Botany Sands estimated to have been dredged from Botany Bay and placed on the low-lying and coastal areas around the bay (Hatley, 2004).

#### 3.4.2 Bedrock

The inferred topographical surface of the Hawkesbury Sandstone is presented in Figure 4\(^{13}\). The bedrock surface deepens to the north and west away from the BIP and shows a variety of erosional features in the Hawkesbury Sandstone basement from north to south, with key features including:

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\(^{13}\) Inferred from borehole data, CPT data and geophysical surveys conducted as part of the Stage 2 investigations (Woodward-Clyde, 1996b) and preliminary plans by Griffin (Griffin, 1963).
- A broad basement valley at the northern end of the BIP which extends from Denison Street in a westerly direction beneath the Olefines II and former Polypropylene Plants, and merges into the Lakes Valley Palaeochannel which extends in a southerly direction into Botany Bay.
- A westerly trending basement ridge extending approximately along Second Street under the southern portion of the BIP.

There has been limited investigation of sandstone bedrock in the model area. Drilling works to install the GTP wells and geotechnical investigations as part of the FCAP remediation project at BIP have found a thin zone of low-permeability residual sandy clay (rather than Quaternary sedimentary deposits) overlying sandstone. The sandstone is highly weathered and low-strength in the upper zone (up to 1 m thick at BIP), with minimal weathering and medium to high strength below.

**Diagram 3-5: Conceptual schematic of Botany Basin sediments (Hatley, 2004)**

### 3.4.3 Site Stratigraphy

Based on the results of previous studies (e.g. Albani (1981), Roy (1983), Griffin (1963) and Smart (1974)) and more recent investigations by Woodward-Clyde (e.g. Woodward-Clyde, 1996b/c) and URS, a three-layer model has been developed for the Botany Sands Aquifer. This division has been based on consideration of geological and hydrogeological characteristics. Table 3-2 (below) outlines the broad division and reference names for the three layers. **Diagram 3-6** (below) presents a geological cross-section running southwest from BIP to Botany Road. A conceptual schematic of the lithology in the vicinity of BIP (noting the absence / limited presence of Layer 3) is presented in **Diagram 3-7** (below).

Various geological interpretations have been presented for the site, with key references listed at the end of this section. The quality of geological information available is variable and dependent on the investigation method, and care needs to be taken when interpreting bore logs. For example:

- Earlier investigations (e.g. Stage 2 work) used methods including Cone Penetrometer Testing (CPT), down-hole logging, seismic refraction survey and electromagnetic survey. However, the density of investigation locations was relatively sparse.
- Subsequent intrusive investigations as part of Stage 4 works were more intensive, however, have used methods of variable accuracy in terms of defining site geology. Many existing geological interpretations rely on logs from rotary mud drilling (e.g. installation of GTP wells) or hollow flight augers. More reliable methods (e.g. direct push or sonic drilling) were used relatively infrequently; for example, as part DNAPL source area investigations, GIR system installation and FCAP remedial investigations.
### Table 3-2: Model Area Stratigraphy

<table>
<thead>
<tr>
<th>LAYER</th>
<th>DESCRIPTION</th>
<th>TYPICAL THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td><strong>Upper Sand Zone</strong>&lt;br&gt;Holocene aeolian sands and fill.&lt;br&gt;Sands are typically brown to grey/white, loose to medium dense, fine to medium grained, sub-angular to sub-rounded, poorly to moderately sorted, quartzose with minor fine heavy minerals. Few peat/silt layers are present.&lt;br&gt;Fill presence and characteristics are variable, but are typically of greatest thickness at Southlands (where peat was removed and the excavations filled), southwest BIP and near drains.</td>
<td>0 to 6 m&lt;br&gt;Thickest along Stephen Road to the west and north of BIP.</td>
</tr>
<tr>
<td>Layer 2</td>
<td><strong>Middle Sand Zone</strong>&lt;br&gt;Pleistocene aeolian and littoral dune/beach sands.&lt;br&gt;Sands are typically brown to grey/white, dense, fine to medium grained, sub-angular to sub-rounded, poorly to well sorted, with minor fine grained heavy minerals.&lt;br&gt;Thin and laterally discontinuous low-permeability layers or seams variously comprised of peat, peaty sands, silty/clayey sands, organic silts, and clay are present, likely reflecting the local depositional environment (e.g. inter-dunal versus swampy depressions). These layers or seams are typically thin (up to 10s of centimetres), with many available bore logs / cross-sections now inferred to over-estimate the thickness and continuity of these layers. Often what may have been recorded as peat or peaty layers may comprise organic-rich sediments. Maximum ‘peat’ development occurs to the northwest of BIP.&lt;br&gt;Sand density is higher and/or porosity lower than in Layer 1. Sands often become very dense at depth and overlying peat/clay layers (sufficient to often cause refusal of CPT and direct-push drilling methods at depths of 10 to 20 m).&lt;br&gt;The distribution of dune sands closely follows the 10 m AHD contour.&lt;br&gt;The inferred surface of the top of Layer 2 dips from approximately 20 m AHD on the eastern margin of the Botany Basin to -6.0 m AHD at Port Botany.</td>
<td>10 to 20 m&lt;br&gt;Thicker at the northern end of BIP and Lakes Valley paleochannel.</td>
</tr>
<tr>
<td>Layer 3</td>
<td><strong>Basal Zone</strong>&lt;br&gt;Pleistocene interbedded fluvial and marine sands, clays, estuarine muds and peats. Sands are fine to coarse, clays are medium to high plasticity and often grey.&lt;br&gt;The lithology of this layer is variable and reflects the varying depositional environments. The top of Layer 3 is commonly characterised by the presence of organic-rich layers which are commonly clayey and appear to be relatively continuous across the Botany area.&lt;br&gt;While the sediments would have been deposited in horizontal layers, consolidation due to overlying deposits has resulted in layer topography controlled by bedrock topography.&lt;br&gt;Beneath Southlands, Layer 3 is thin (approximately 2 to 4 m), and is largely absent from the eastern part of the model area (e.g. Second Street at BIP) as the bedrock surface rises. To the west of the model area, where bedrock deepens, Layer 3 thickens and contains clayey layers with sand lenses.&lt;br&gt;Whilst generally incorporated into Layer 3, there is also a deeper (fourth) unit of interbedded marine and estuarine shelly clays. Within the palaeochannels the sand and clays are underlain with a basal sand, with some gravel of fluvial origin.</td>
<td>2 to 10 m*&lt;br&gt;Exceeds 30 m in Lakes Valley paleochannel.</td>
</tr>
</tbody>
</table>

* May be thicker in palaeochannels
Diagram 3-6: Geological Cross-Section (Woodward-Clyde 1996f)
Diagram 3-7: Conceptual Lithological Schematic and Example Cores
3.5 HYDROGEOLOGY

3.5.1 General

The Botany Sands contain a system of interconnected unconfined and semi-confined aquifers that are collectively referred to as the Botany Sands aquifer, which cover an area of about 18,300 hectares. Groundwater generally flows in a southwest direction from the main recharge areas in the north to discharge into a series of wetlands (Lachlan Lakes) and Botany Bay in the south. The water table elevations range from 35 m AHD at Centennial Park at the northern end of the basin to approximately 0 m AHD at Botany Bay. The typical depth to shallow groundwater in the model areas ranges from 1 to 5 m below ground level (BGL).

The Botany Sands aquifer was one of the early sources of water for Sydney and an important source of industrial water in the Botany area.

There has been significant previous work assessing the hydrogeology of Botany Sands aquifer within the model area and more broadly (see key references at the end of this section for additional details). Groundwater flow modelling within the model area has been undertaken, primarily for GTP system design purposes and as part of solute transport modelling, with the most recent model developed in 2014 (Laase, 2014).

3.5.2 Hydrostratigraphy

The hydrostratigraphy of the Botany Sands aquifer within the model area is consistent with the lithological facies described in Section 3.4.3. These are described in Table 3-3 (below).

Hydraulic models developed to simulate groundwater flow (Merrick, 2004; Laase, 2005/2010b) and the GTP system use a five layer system (Layer 1 to 5), which corresponds to Layer 1, Layer 2 and Layer 3. Layers 2A, 2B and 2C are largely an artificial construct (although do have a hydrogeological basis on the general
sequence of low-permeability layers) to aid modelling. Further discussion of modelling is provided in Appendix E.

**Table 3-3: Hydrostratigraphy**

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>Unconfined aquifer in Botany Sands. This unit extends vertically from the water table to various low-permeability layers/seams (peats, organic-rich fine sediments or finer/dense sands) that are typically encountered at nominal depths of up to 6 m below ground surface. Layer 1 is commonly referred to as the ‘shallow’ aquifer.</td>
</tr>
<tr>
<td>Layer 2 (2A, 2B and 2C sub-units)</td>
<td>Unconfined to semi-confined aquifer in Botany Sands. The aquifer is mainly semi-confined as low-permeability layers/seams (e.g. Waterloo rock, peats, organic sediments or finer/dense sands) create locally confined conditions. The sequence of Layers 2A/2B/2C broadly corresponds to the presence of low-permeability layers/seams (peats, organic-rich fine sediments or finer/dense sands) that provide hydraulic separation in some areas. However, these are not clearly defined across the model area. The sand Layers are considered interconnected vertically via leakage through the semi-confining peat and/or clay/silt-rich sediment layers and laterally by the discontinuous geometry of most of the semi-confining units. Layer 2 is commonly referred to as the ‘deep’ aquifer.</td>
</tr>
<tr>
<td>Layer 3</td>
<td>Semi-confined aquifer in fluvial and marine sands, clays, estuarine muds and peats. Groundwater flow may occur in sandy zones. Peats, clays and silts are inferred to act as discontinuous aquitards (with leakage occurring) and are not water bearing.</td>
</tr>
</tbody>
</table>

While sands within each stratigraphic Layer may appear relatively uniform and homogenous on a macroscale (i.e. model area, 100s metres), on a micro-scale (i.e. several metres or centimetres) there is inferred to be subtle variations that have considerable effects on hydrogeology. For example, at BIP within the area from Second Street to GIR wells, a feature appears to cause hydraulic separation between Layer 1 and Layer 2. The nature and distribution of this feature is not well understood (although hydraulic effects are well defined), but based on the absence of obvious peats, clays or significant silts in logs, may be related to finer or denser sands and/or possible cementation.

### 3.5.3 Recharge and Discharge

The main recharge and discharge components to/from the Botany Sands aquifer are summarised in **Table 3-4** (below). Groundwater flow models have simulated the various recharge and discharge flow components for the model area (see Laase, 2005/2010b/2014 and Appendix E). Groundwater levels are broadly controlled by Alexandra Canal, the Lachlan Lakes and Swamps, Cooks River and Botany Bay. In the vicinity of Southlands, the water table has also been historically controlled by Springvale and Floodvale Drains (Merrick, 2004). GTP extraction currently controls groundwater levels in the model area.

**Table 3-4: Recharge and Discharge Components**

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>RECHARGE</th>
<th>DISCHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>Rainfall infiltration is the largest recharge component to the Botany Basin. Between 6 and 37 % precipitation recharges the aquifer, though rates of recharge from rainfall infiltration approaching 100% have been inferred at the Botany Golf Course (URS, 2007b). Rainfall falling on surrounding impermeable areas drains into the top of Lachlan Ponds and Centennial Park systems.</td>
<td></td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Upper Lachlan Lakes and Centennial Park ponds</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Leakage from upper Lachlan Lakes and Centennial Park surface water features occurs.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Discharge of shallow groundwater to lower Lachlan Lakes occurs.</td>
<td></td>
</tr>
</tbody>
</table>

14 Based on observed significant vertical hydraulic gradients between wells screened within Layer 1 and Layer 2, and aquifer response to pumping from deep GTP extraction bores – e.g. see recent monitoring data in Golder (2015).
Leakage from drains occurs following rainfall events, and when shallow groundwater elevations are lowered (e.g. due to dry climate conditions or during GTP system operation).

Discharge of shallow groundwater to the drains occurred prior to GTP system operation.

The discharge zone has been historically altered, with significant changes in the 1940-50s (due to land reclamation south of Botany Road), 1970s (due to Port Botany development) and 2011-2014 (due to Port Botany expansion).

The groundwater flow regime in the 1950s/1960s (with areas to the northwest of BIP with water table elevation less than 0 mAH) suggests some inflow from Botany Bay would have occurred.

Operation of the SCA has resulted in some inflow from Botany Bay towards the containment line (as based on increasing salinity at some wells). This would be limited in extent to the SCA.

3.5.3.1 Historical Groundwater Extraction

Groundwater from the Botany Sands aquifer has historically been used for domestic, industrial and irrigation purposes from the 1830s, with extractions peaking in the late 1960s and early 1970s with increased industrial usage. Historical groundwater flow regimes are discussed below in Section 3.5.4.

Estimates of groundwater extraction from the Botany Sands aquifer have previously been presented (Acworth, 2006; Merrick, 1994; URS, 2004i) and were summarised in the 2010 CSM. These range from in the order of 50 ML/day in the 1960s/1970s to 20 ML/day (excluding GTP extraction) in the 2000s, and likely further reductions since, within the Botany Basin.

3.5.3.2 GTP Extraction

Groundwater extraction for hydraulic containment commenced at SCA in late 2004, and at PCA and BIP in 2005, although the system was not fully commissioned until early 2007. GTP extraction rates have varied since commissioning, generally ranging from 5.5 to 6.2 ML/day (excluding periods for maintenance shutdowns). Typical extraction rates from each containment line are 3.8 ML/day (BIP), 0.9 ML/day (PCA) and 1.3 ML/day (SCA).

3.5.4 Groundwater Flow

The historical groundwater flow regime is a key aspect that controlled the development of current distributions of contamination in soil and groundwater.

There have been substantial temporal variations in groundwater flow regimes within the Botany Sands aquifer, particularly in the East Botany area, due to changes in the locations and rates of groundwater extraction, natural variations in rainfall over the last 50 years, and land reclamation works along the northern shoreline of Botany Bay. More recently, groundwater extraction by the GTP system controls the groundwater flow regime in the model area.

An extensive evaluation of the historical (pre-1996) groundwater levels and flow directions was reported in the Stage 1 Survey (AGEE, 1990), Stage 2 Survey (Woodward-Clyde, 1996c) and more recently reviewed by Acworth (2006). These interpretations were based on relatively few data points or variable reliability (e.g. often relied on extraction licence conditions rather than actual measured rates). The 2010 CSM presented more recent evaluations of recent groundwater levels and flow regimes pre- and post- consistent GTP operation circa 2007.

Discussion of previously interpreted historical flow regimes within the model area is presented in Table 3-5 (below).
Table 3-5: Historical Groundwater Flow Regimes

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>CONCEPTUAL GROUNDWATER FLOW REGIME</th>
</tr>
</thead>
</table>

**1940s**
Groundwater flow prior to the 1950s is inferred to have been broadly to the southwest.
There may have been extraction for domestic, gardening or industrial purposes, which would have locally altered flow directions. Changes in rainfall (e.g. dry and wet periods) would have altered groundwater elevations.
Shallow groundwater would have discharged to (what is now) Springvale Drain.
The schematic to the right presents conceptual groundwater flow regime in 1942.

Note: The aerial image is from 1942

**Circa 1950s to 1980**
Historical water levels were altered during periods of heavy pumping of the aquifer directly to the north and northwest of BIP throughout the period from 1950 to 1980.
As an example, the effect of the heavy pumping, and several periods of below average rainfall, caused an alteration of the water table causing a cone of depression (less than 0 m AHD) centred around the Davis Gelatine wellfield, and local groundwater to flow towards the north and northwest.
Changes in rainfall (e.g. dry and wet periods) and pumping from other locations in the aquifer (e.g. heavy pumping also occurred at BIP and elsewhere to the north at times) would have altered groundwater flow regimes.
Flow to Springvale and Floodvale Drain would have been limited due to the lowered water table.
The schematic to the right presents a conceptual groundwater flow regime in 1969 with drawdown inferred due to pumping centred around the Davis Gelatine wellfield. Pumping from other areas may have temporally altered groundwater flow directions.
In-filling south of Botany Road and as part of Port Botany development (which commenced in 1971) may have commenced (see Bay shoreline in the schematic for mid-1980s to 2004 below).

Note: The aerial image is from 1965
Mid-1980s to 2004 (pre-GTP operation)
Reduced extraction for industrial purposes from the mid-1908s in the northwest is inferred to have resulted in return to an overall southwest groundwater flow direction towards Botany Bay. Shallow groundwater discharged to Floodvale and Springvale Drains. Discharge may have been reduced due to re-lining the drain at Southlands in the early 2000s. Groundwater extraction near the Hensley Athletic Field in the northeast corner of BIP occurred for industrial purposes. This extraction resulted in an inferred groundwater divide.
Changes in rainfall conditions (e.g. dry and wet periods) altered groundwater elevations. The vertical hydraulic gradient between shallow (Layer 1) and deep (Layer 2) groundwater is slightly downwards in the northern model area and progressively moves to an upward direction beyond Southlands as it approaches the discharge zone at Penrhyn Estuary and Botany Bay.
The schematic to the right presents conceptual groundwater flow regime in mid-1980s. The presented elevations are low compared to the latter part of this period, which may be related to dry period in the early 1980s and/or cessation in large-scale industrial extraction to the northwest of BIP.

2007-current (GTP operation)
The regional groundwater flow direction in the model area remains towards the southwest. Due to hydraulic containment, this natural flow regime has been significantly altered in the areas near the PCA, SCA and BIP containment lines, with radial flow towards the extraction lines to effect hydraulic containment.
Effective hydraulic containment is evident in the shallow (Layer 1) and deep (Layer 2) aquifers at BIP, PCA and SCA during GTP operation.
Changes in rainfall (e.g. dry and wet periods) alter groundwater elevations.
Shallow groundwater discharge to Floodvale and Springvale Drains has been reduced because of lowered water table and reduced infiltration due to industrial development of Southlands and nearby areas.
Other key groundwater flow effects resulting from extraction at the containment lines include:
• The vertical hydraulic gradient between shallow (Layer 1) and deep (Layer 2) groundwater has changed, with a more strongly downward vertical gradient within the model area due to pumping from the deep aquifer.
• Groundwater discharge to Penrhyn Estuary is limited to rainfall that infiltrates into the dunes and mixes with groundwater that was present between Foreshore Road and the Estuary before hydraulic containment commenced.
• Regional effects from operation of PCA and SCA containment lines have been observed in the deep aquifer at distances of >500 m.

A large and extensive zone of low hydraulic gradients has developed between the PCA and SCA. This changes slowly depending on rainfall, GTP system operation and drainage of the unconfined aquifer.
Port Botany expansion (circa 2011) has resulted in alteration of the discharge zone at Penrhyn Estuary.
Previous work (Griffin, 1963; Smart, 1974; AGEE, 1990) indicate that there is considerable variation in the groundwater yield of the aquifer, suggesting that there are discrete high yielding layers, or aquifers, within the sequence.

Analysis of the aquifer response to operation of GTP extraction wells (e.g. URS, 2009a) shows evidence of the variability and discontinuous nature of confining layers. Some zones of the deep aquifer at SCA and PCA show a semi-confined aquifer response to pumping, while others show largely confined responses. In addition, considerable leakage from the shallow aquifer through the confining layers into the deep aquifer, where groundwater extraction is occurring, is evident at the PCA and SCA. However, pumping tests conducted at EWD01 in early 2007 and GIR injection wells in 2010 show that there is little hydraulic connection between the shallow aquifer and deep aquifer in the vicinity of the former Solvents and Vinlys Plants (see also discussion in Section 3.5.2).

3.5.5 Aquifer Properties

On a model-area scale, the sand aquifer parameters appear relatively homogenous. However, there is considerable variation on a smaller scale and, with consideration of low-permeability layers, there is an overall range of over four orders of magnitude (OoM) in many aquifer properties.

3.5.5.1 Hydraulic Conductivity / Transmissivity

Typical bulk hydraulic conductivity and transmissivity values are presented in Table 3-6. These values are variously estimated from slug tests at monitoring wells, pumping tests at extraction wells and laboratory measurement, and simulated by numerical modelling. A hydraulic conductivity value of 20 m/day for sand is commonly used for contaminant hydrogeological interpretations.

Vertical hydraulic conductivities have been measured at 0.012 m/day (Layer 3) (Woodward-Clyde, 1996f; Hatley, 2004). No measurements are available near the BIP, but a value of 0.01 to 0.1 m/day (at least one or two orders of magnitude lower than horizontal conductivity) is considered representative. Aquifer responses from pumping tests at BIP also support vertical anisotropy.

Transmissivity (and hydraulic conductivity) follow a lognormal distribution (Woodward-Clyde, 1996c), with transmissivity varying by four orders of magnitude (i.e. with peats, clays and silts being low and sand being high). The vertical variability in hydraulic conductivity of the aquifer is significant and is highly influenced by the presence of clay and peat confining units, or finer sediments within sand units. Bedrock and residual clays underlying sands have low hydraulic conductivity, though there are limited data within the model area.

Areal variability in hydraulic conductivity has been simulated by the calibrated model (Laase, 2005/2010b).

<table>
<thead>
<tr>
<th>STRATIGRAPHIC LAYER/UNIT</th>
<th>HYDRAULIC CONDUCTIVITY RANGE</th>
<th>TRANSMISSIVITY RANGE (m²/day)</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>10-18 m/day</td>
<td>-</td>
<td>Woodward-Clyde (1996f) (lognormal mean)</td>
</tr>
<tr>
<td></td>
<td>At BIP containment line – 28 m/day</td>
<td>-</td>
<td>GTP extraction well commissioning</td>
</tr>
<tr>
<td>Layer 2 (A, B &amp; C)</td>
<td>13-26 m/day</td>
<td>0.02 – 160 m²/day</td>
<td>Woodward-Clyde (1996f) (lognormal mean)</td>
</tr>
<tr>
<td></td>
<td>At BIP containment line – 16 m/day</td>
<td>280 – 380 m²/day</td>
<td>GTP extraction well commissioning</td>
</tr>
<tr>
<td></td>
<td>(Layer 2A), 21 m/day (Layer 2B/2C)</td>
<td>-</td>
<td>Golder (2012d,2014a)</td>
</tr>
<tr>
<td></td>
<td>13-37 m/day at BIP (Second Street and GIR)</td>
<td>280 – 320 m²/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20-85 m/day</td>
<td>-</td>
<td>Laboratory measurements of Botany Sands (Hatley, 2004).</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1-12 m/day</td>
<td>10⁴ to 10⁵ m³/day</td>
<td>Woodward-Clyde (1996f) (lognormal mean)</td>
</tr>
<tr>
<td></td>
<td>10⁴ to 10⁵ m³/day</td>
<td>-</td>
<td>Golder (2012c)</td>
</tr>
<tr>
<td>Bedrock (sandstone)</td>
<td>10⁻¹ to 10⁻² m³/day</td>
<td>-</td>
<td>Golder (2012c)</td>
</tr>
<tr>
<td>Low-permeability layers</td>
<td>1.3 m/day</td>
<td>10⁻³ m³/day</td>
<td>Modelled calibrated value (Laase, 2005)</td>
</tr>
<tr>
<td>(e.g. peats, organic silts)</td>
<td>10⁻³ m³/day</td>
<td>-</td>
<td>Interpretation of grain-size analysis of silty sand seam core (Acworth, 2000)</td>
</tr>
</tbody>
</table>

3.5.5.2 Hydraulic Gradients

Hydraulic gradients are typically in the order of 1:120, though vary spatially (and temporally) depending on proximity to groundwater extraction locations (e.g. GTP containment lines or historical industrial water supply
bores). In some areas located downgradient of the GTP containment lines, zones of stagnation are inferred to exist where hydraulic gradients approach zero.

### 3.5.5.3 Flow Velocities

Based on inferred hydraulic gradients and estimates of the hydraulic conductivity, the groundwater velocities (seepage velocities) within sands in the model area are estimated to be in the range 80 to 260 m/year. An average groundwater seepage velocity of 120 m/year is commonly used for simple contaminant hydrogeological interpretations at distance from GTP containment lines.

Groundwater velocities in areas where relatively flat hydraulic gradients have formed due to groundwater extraction at GTP containment lines (e.g. between PCA and SCA, and at Southlands) are expected to be significantly less.

### 3.5.5.4 Storage

The storativity of the confined aquifer (Layer 2 and Layer 3) has been estimated to range from 0.001 to 0.003 (Woodward-Clyde, 1996f). Storativity of the confined aquifer (Layer 2) in the vicinity of BIP containment line was determined to range from 0.002 to 0.005.

The specific yield of the shallow unconfined aquifer (Layer 1) is estimated to be between 0.20 and 0.28.

### 3.5.5.5 Porosity

Total porosity of sandy units is estimated to typically be in the range of 0.30 to 0.36, though has been reported in the range of 0.25 to 0.44 (AGEE, 1990; Smart, 1974; Woodward-Clyde, 1996f). Layer 1 and Layer 2 sands were estimated to have an average total porosity of 0.37 and 0.30, respectively (Woodward-Clyde, 1996f).

### 3.5.5.6 Particle Size

Limited grain size analysis has been conducted on aquifer materials within the model area. Particle size analysis of core samples from locations on Southlands (BP45 to BP49) showed that Botany Sands encountered were of relatively uniform size distribution with D10 of approximately 0.1-0.2 mm and D60 of approximately 0.3-0.4 mm. Particle size distribution of Layer 1 materials (fill, sandy/silty gravels) were less uniform.

Particle size analyses have also been conducted on sand and silt/clay samples collected at FCAP (Golder, 2012c).

### 3.5.6 Hydrogeochemistry

The regional water quality in the Botany Aquifer has been reported by several authors (e.g. Griffin, 1963; Smart, 1974; Acworth and Jankowski 1993), and has been divided into several hydrogeochemical facies, as illustrated in Diagram 3-10 (below), with the southern zone most relevant to the model area.

The apparent general trend in water composition from inland to Botany Bay is summarised as follows:

- Increasing salinity in the deep aquifer.
- Change in composition from Na/Ca and Mg dominance to Na dominance.
- Decrease in relative proportion of sulphate to the total salinity with a corresponding increase in proportion of chloride for shallow groundwater. Bicarbonate remains approximately the same proportion relative to salinity.
- Bicarbonate dominant water changes to chloride dominated water in the deep aquifer, with sulphate remaining approximately the same proportion.
Within the model area, groundwater is typically characterised by slightly acidic, slightly reducing and mildly anaerobic conditions that are likely to favour nitrate, sulphate, manganese and iron reduction, and formation of organic acids. Uncontaminated groundwater away from Botany Bay is fresh, with low but variable concentrations of nutrients, major ions (though iron and sulphate are elevated) and organic carbon. Groundwater is nutrient-limited, especially for phosphate, for aerobic microbial activity.

Historical contamination and saline intrusion influence alter the hydrogeochemical composition within CHC plumes (e.g. higher salinity and chloride, lower pH from EDC hydrolysis, fermentation of volatile fatty acids and possibly lower nitrate), downgradient of FCAP (high and low pH, high salinity, Na, Cl), at Southlands (variable composition, increased sulphide, organic carbon and acids) and along Foreshore Road (increased Na, Cl, organic carbon and acids). The SWSOOS is a potential source of nutrients and organic carbon.

The hydrogeochemistry of the model area was assessed in Stage 2 works (Woodward-Clyde, 1996c/f), as part of GTP design and maintenance works (2003/2004, data not published), GIR system commissioning (Golder, 2014a), FCAP remediation (Section 2.5.5), post-remediation monitoring at Southlands (AECOM, 2015). Golder (2011b) presents major anion and cation concentration data available for all monitoring locations and GTP extraction wells sampled in September 2011. Pore water chemistry in two CHC impacted soil cores from northern Southlands area was assessed on a micro-scale (Acworth et al (1995), attached to the Stage 2 C6 report; Acworth, 2000). Published historical data were summarised by Geosyntec (2016).

A summary of key hydrogeochemical conditions relevant to CHC fate and transport from these studies is provided in Table 3-7.

**Table 3-7: Indicative Summary of Botany Aquifer Hydrogeochemistry**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MAXIMUM</th>
<th>MINIMUM</th>
<th>MEAN</th>
<th>MEDIAN</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved oxygen (DO) (mg/L)</td>
<td>12</td>
<td>-0.5</td>
<td>2.0</td>
<td>1.6</td>
<td>In the order of 30% of locations having strongly anaerobic conditions (i.e., DO &lt; 1 mg/L)</td>
</tr>
<tr>
<td>Oxidation-reduction potential (ORP) (mV)</td>
<td>728</td>
<td>-473</td>
<td>-35</td>
<td>-39</td>
<td>In the order of 60% of locations have reducing conditions (ORP &lt; 0 mV).</td>
</tr>
<tr>
<td>pH</td>
<td>11</td>
<td>2.3</td>
<td>5.8</td>
<td>5.8</td>
<td>In the order of 40% of locations having neutral pH (6 &lt; pH &lt; 8).</td>
</tr>
<tr>
<td>Specific conductivity (µS/cm)</td>
<td>90,400</td>
<td>0.7</td>
<td>10,342</td>
<td>1,945</td>
<td>Typically of low salinity, although salinity increases at depth with proximity to Botany Bay.</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>32</td>
<td>9</td>
<td>20</td>
<td>19</td>
<td>Varies seasonally.</td>
</tr>
<tr>
<td>PARAMETER</td>
<td>MAXIMUM</td>
<td>MINIMUM</td>
<td>MEAN</td>
<td>MEDIAN</td>
<td>COMMENTS</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------</td>
<td>---------</td>
<td>-------</td>
<td>--------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Iron (mg/L)</td>
<td>28</td>
<td>1.5</td>
<td>8.0</td>
<td>0.0</td>
<td>Mean value for extracted water by GTP system</td>
</tr>
<tr>
<td>Ferrous iron (mg/L)</td>
<td>590</td>
<td>0.1</td>
<td>104</td>
<td>0.40</td>
<td>Few data available</td>
</tr>
<tr>
<td>Manganese (mg/L)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Typically &lt;1.0 mg/L</td>
</tr>
<tr>
<td>Nitrate as N (mg/L)</td>
<td>5.9</td>
<td>0</td>
<td>1.3</td>
<td>0.10</td>
<td>Higher concentrations have been reported (Griffin, 1963; Smart 1974).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Concentrations may be higher outside of the CHC plume extents, suggesting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nitrate reduction may be occurring within the plumes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Expected GTP feedwater composition of approximately 0.05 mg/L (URS, 2004i).</td>
</tr>
<tr>
<td>Phosphate (mg/L)</td>
<td>0.49</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>Typically &lt;0.03 mg/L</td>
</tr>
<tr>
<td>Sulphate as SO4 (mg/L)</td>
<td>6,470</td>
<td>0.3</td>
<td>527</td>
<td>201</td>
<td>In the order of 85% of locations have concentrations &gt;100 mg/L. This</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>may be related to groundwater flow through pyritic peaty beds and lenses.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sulphate concentrations are generally higher in shallow groundwater than</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>deeper groundwater.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Approximately proportional to bicarbonate.</td>
</tr>
<tr>
<td>Sulphide (mg/L)</td>
<td>79</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>Highest beneath Southlands and downgradient of McPherson Street.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>May be resultant of sulphate reduction and peaty beds.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Expected GTP feedwater composition of approximately 5.5 mg/L (URS, 2004i).</td>
</tr>
<tr>
<td>Bicarbonate (mg/L)</td>
<td>334</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>Expected GTP feedwater (URS, 2004i).</td>
</tr>
<tr>
<td>Total Alkalinity (as CaCO3)</td>
<td>-</td>
<td>-</td>
<td>57</td>
<td>-</td>
<td>Expected GTP feedwater (URS, 2004i).</td>
</tr>
<tr>
<td>Total Hardness (as CaCO3)</td>
<td>-</td>
<td>-</td>
<td>194</td>
<td>-</td>
<td>Expected GTP feedwater (URS, 2004i).</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>25,500</td>
<td>8.0</td>
<td>1,805</td>
<td>370</td>
<td>Distribution varies significantly.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The highest concentrations are in a zone extending from the FCAP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>downgradient to Botany Bay related to the FCAP, and Foreshore Road area</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>due to saline intrusion.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>There is some evidence of chloride enrichment due to CHC degradation.</td>
</tr>
<tr>
<td>Total Organic Carbon (mg/L)</td>
<td>146</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Highest at Southlands and SCA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Organic carbon is generally degraded from sources other than Orica</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(i.e. paper waste material and other organic wastes on Southlands) or</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>organic-rich waters associated with the historic swamp environment and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sequences of peat.</td>
</tr>
<tr>
<td>Volatile fatty acids</td>
<td>&gt;100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Detected at Foreshore Road, BIP and Southlands (URS, 2004f).</td>
</tr>
<tr>
<td>(mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Expected GTP feedwater composition of approximately 60 mg/L, mostly as</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>acetic acid (URS, 2004i).</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Acetate concentrations in GTP feed water is typically in the range of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>30-40 mg/L.</td>
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</table>

There is significant and broad range of hydrogeochemical data (though unpublished) for feed water to the GTP collected to facilitate GTP system operation.

Acworth (2000) assessed small-scale (decimetre) vertical changes in pore water quality at two bore locations at Southlands with DNAPL present. Acworth (2000) showed systematic changes on a decimetre scale in water quality through sections containing silts (and DNAPL), especially with pH, iron and Na:Cl ratios (likely related to DNAPL degradation).

3.5.7 Groundwater-Surface Water Interactions

Interactions between groundwater and surface water most relevant to the fate of CHC contaminants within the model area are at Springvale Drain (and Floodvale Drain to a lesser extent) at, and downstream, of
Southlands, and Penrhyn Estuary (Botany Bay). These have been assessed at Springvale Drain during Stage 2 investigations (Woodward-Clyde, 1996c/f), Stage 3 investigations (Woodward-Clyde, 1997a), URS (2008a), and summarised by EnRiskS (2012, 2013b).

3.5.7.1 **Springvale and Floodvale Drains**

In general, when shallow groundwater levels are higher than the invert of Springvale Drain (or Floodvale Drain), shallow groundwater discharges to the drain (base flow). This has been assessed to have historically occurred at Southlands, and likely occurs downstream of Southlands where the drains are piped.

Shallow groundwater discharge to Springvale Drain was in the range of 40 to 210 m$^3$/day (Woodward-Clyde, 1996a), but is likely to have decreased following drain re-lining in early-2000s and significantly decreased or ceased since steady operation of the GTP containment system commenced circa 2007 based on observations of lower shallow groundwater levels, reduced baseflow rates and reduced CHC concentrations in surface water. These discharge estimates are consistent with flow measurements of Springvale Drain from January to August 2007 that showed a base flow of approximately 0.1 ML/d at McPherson Street (southern boundary of Southlands).

Conceptual interactions between groundwater and the drains are presented in [Diagram 3-11](#) and discussed following:

- The water level in Springvale Drain is closely related to rainfall with rapid increases (within days) following rainfall events (**Scenario A, Diagram 3-11**). Water within the drain may discharge to groundwater during this period. The decrease in drain level after rainfall events is initially rapid, representing the recession of high peak flows associated with surface runoff.

- The peaks are then followed by a relatively slow decline (typically over weeks or months) in water levels that may be representative of baseflow generated by groundwater discharge (due to the relative increasing groundwater levels from infiltration) to the drain (**Scenario B, Diagram 3-11**). A shallow water table divide (i.e. the ‘capture zone’) was estimated to be 20-50 m to the west of the drain and 2-5 mBGL in the 1990s. Discharge was pervasive or occurred via discrete seepages. This scenario likely represented ‘normal’ flow conditions during periods of low or no groundwater extraction in the model area (e.g. pre-GTP operation or large-scale industrial extraction in the 1960s-1980).

- During periods of consistent GTP operation (since circa 2007) and/or periods of below-average rainfall (**Scenario C/D, Diagram 3-11**) shallow groundwater elevations have been lowered to levels close to, or
below, the drain invert due to extraction of groundwater at BIP and PCA\(^\text{15}\) containment lines. Since Southlands development there is reduced local infiltration (Scenario D, Diagram 3-11). There may be minor discharge from the drain to groundwater. However, the increase in shallow groundwater levels following rainfall is still more rapid than the decrease in levels caused by hydraulic containment and there is ongoing potential for groundwater discharge to the drain after significant rainfall events or extended periods (weeks or months) when the GTP system is not operating.

\[\text{Diagram 3-12: Conceptual Penrhyn Estuary Interactions (after Heiss and Michael, 2014)}\]

\(^{15}\) Monitoring has shown that extraction in the deep aquifer can cause drawdown and containment of shallow groundwater at PCA (Golder, 2010c).
3.5.7.2 Penrhyn Estuary and Botany Bay

Surface water from Springvale Drain and Floodvale Drain, and groundwater, discharge to Botany Bay at Penrhyn Estuary, as conceptualised in Diagram 3-12 (above).

Groundwater is discharged along the saltwater interface – an intertidal seawater/terrestrial groundwater mixing zone – which forms due to the density differential between groundwater and seawater, wave and tidal actions. Monitoring of groundwater at Penrhyn Estuary has confirmed that fresh groundwater is not discharged directly into the estuary but is mixed with saline water in a zone of diffusion approximately 2 m below the intertidal ground surface (URS, 2004a, 2007a).

Diagram 3-13 presents conceptualised salinity at monitoring locations at Penrhyn Estuary in September 2006.

Diagram 3-13: Penrhyn Estuary Pore Water Salinity

In common with estuaries elsewhere, the discharge of groundwater to Penrhyn Estuary is also influenced by pressures exerted during the tidal movement of marine water in the estuary (i.e. tidal pumping) and wave action. Tidal pumping is the reversing flow of groundwater in coastal environments resulting from the changing tides – at high tide, the pressure exerted from estuarine water slows, stops or reverses the discharge of groundwater to the estuary; while at low tide, the reduced pressure of overlying estuarine water allows groundwater to discharge.

Surface waters flowing into Penrhyn Estuary from the drains are relatively fresh and can cause a fresh water lens during high flow events, and have historically carried sediments.

The volume of fresh groundwater entering the mixing zone beneath the estuary has been reduced by hydraulic containment occurring at the SCA (Diagram 3-12, B), and is now largely limited to rainfall that infiltrates into the dunes and mixes with groundwater that was present between Foreshore Road and the estuary before hydraulic containment commenced.

It is noted that the Port Botany expansion project has significantly altered the geometry of Penrhyn Estuary downgradient of the SCA. Recent observations of water levels during low groundwater extraction rates indicate that these changes have resulted in decreased water levels at the western end of the SCA.

3.6 MICROBIOLOGY

Microbiology is the study of microscopic organisms encompassing viruses, protozoa, fungi, bacteria and archaea. The microbiology of the Botany Sands Aquifer has been under investigation for over a decade with a principal focus on the bacteria present because this is the most abundant group of microorganisms and the major contributor to ecosystem services such as contaminant degradation. Bacteria are present in the Botany Sands Aquifer on average at 1 million cells per millilitre (ranging from 10,000 to 10,000,000 cells/mL). These abundances are comparable at different depths (5 and 15 m below ground surface). The closer the groundwater pH is to neutral (pH 7) the more abundant the bacteria are (Munro et al, 2016).

Using various contemporary techniques for describing the different species of bacteria present (microbial community composition) it has been shown that the dominant bacterial phyla present are the Firmicutes, Chloroflexi, Spirochaetes, Synergistetes, Bacteroidetes and the Proteobacteria. Other bacterial phyla observed are the Armimonadetes, Actinobacteria, Spirochaetae, Elusimicrobia. Genera observed include the Dehalococcoides, Sedimentibacter, Desulfovibrio, Dehalobacter, Azospira, Acidovorax, Dechlorosoma, Desulfotibacterium, Geobacter, Pseudomonas, Petrimonas, Oscillibacter, Clostridium and Desulfosporosinus.
DNAPL samples extracted from the aquifer were accompanied by spore forming (hardy) bacteria including *Paenibacillus*, *Clostridium* and *Bacillus* species. Some of these bacteria (*Dehalococcoides*, *Dehalobacter*, *Geobacter* and *Desulfitococcus*) are known to degrade the organochlorines contaminating the aquifer. The others are known for breaking down (fermenting) natural organic matter and releasing acetate and hydrogen. Archaeal genera observed include *Methanosaeta*, *Methanosarcina* and *Methanoregula*, which can use acetate and hydrogen to produce methane gas.

Comparisons between the microbial communities in the vicinity of the Botany Industrial Park and elsewhere in the Botany Sands Aquifer have revealed the impact of the contaminant profile (e.g. Stephenson et al., 2013). The microbial community has adapted to exploit the contaminants for growth.

Further discussion of bioremediation related research is provided in Sections 2.5.1.1 and 5.3.2.

**FURTHER READING**

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSM (2009).</td>
<td>PSM reviewed existing geology and hydrogeology information to assess potential model area settlement due to operation of the GTP system. PSM re-interpreted site stratigraphy, and included various geological cross-sections and plans.</td>
</tr>
<tr>
<td>Smart J.V. (1974)</td>
<td></td>
</tr>
<tr>
<td>Roy P.S. (1983)</td>
<td></td>
</tr>
<tr>
<td>URS (2004e, 2005b, 2006a/c/e)</td>
<td>Geological cross-sections, cored bores, bedrock/Layer 3 topography as part of DNAPL source area investigations.</td>
</tr>
<tr>
<td>Golder (2011c)</td>
<td>Sonic core logs, well pumping tests, infiltration tests as part of works for the GIR.</td>
</tr>
<tr>
<td>Golder (2012c)</td>
<td>Geotechnical investigation at FCAP (BIP) – includes triaxial permeability, strength, CPT, SPT, sonic and rotary core logs, core photos.</td>
</tr>
<tr>
<td>Acworth (2000)</td>
<td>Core (direct push) log, discrete-interval pore water quality, CPT (northern Block 1 Southlands)</td>
</tr>
<tr>
<td>Acworth (2006)</td>
<td>Historical groundwater flow regimes for Botany Aquifer</td>
</tr>
<tr>
<td>URS (2009c)</td>
<td>Review of Springvale Drain hydrology as part of the Southlands development project</td>
</tr>
<tr>
<td>URS (2008a)</td>
<td></td>
</tr>
</tbody>
</table>
4 CONTAMINANT SOURCE ZONES

4.1 CONTAMINANT TYPES AND PHASES

Contaminants of potential concern (COPC) in the model area include:

- Volatile and semi-volatile chlorinated hydrocarbons (CHCs).
- Mercury and chromium.
- Ammonia.
- TPH and BTEX.

Only CHCs are discussed further herein. Key documents presenting information in relation to mercury are discussed in Section 2.5.2. Key documents presenting information in relation to other COPC are included in Section 5.2.5.

As discussed in Section 2.1, historical industrial operations at BIP since the early 1940s have resulted in CHC contamination in the subsurface on- and off-BIP. Historical releases of process, product or waste fluids or solids to the subsurface have occurred, resulting in the formation of CHC source areas or zones. Other potential sources of CHCs not considered further include historical and current stack emissions as their contribution to source zones is considered insignificant in the context of the model area.

CHCs within the subsurface are distributed between several phases, including:

- Dense non-aqueous phase liquid (DNAPL) either as:
  - Residual DNAPL: disconnected single and multi-pore zones of DNAPL within the pore spaces; or
  - Pooled DNAPL: accumulation of DNAPL in interconnected zones where pore spaces are filled with DNAPL (typically in depressions in the upper surface of aquitards).
- Adsorbed or diffused into particles of the aquifer matrix (including peat/clay/silt layers and sands).
- Dissolved in groundwater (including dissolved contaminants in sand and diffused into pores of low-permeability materials).
- A gas phase in soil vapour within the vadose (unsaturated) zone (and possibly in the saturated zone due to CHC degradation processes).

Each phase can exist in either transmissive (i.e. sand) or low-permeability (i.e. peat/clay/silt seams) media present in source zones. Interactions between these phases and zones (transmissive or low-permeability) within source areas and plumes will occur, and will change over time. For example, while the geometry of low-permeability units controlled DNAPL distribution within source areas, DNAPL dissolution and dissolved CHC migration in the transmissive zones ( sands) have been the dominant processes controlling the movement and distribution (and associated risks) up until recently (when processes such as matrix diffusion and desorption are inferred to have become increasingly important).

Most of the CHCs under investigation form DNAPLs when present as pure product – i.e. they have a specific gravity greater than water, do not readily mix with water (immiscible), and generally have a low viscosity and a low solubility. Some historical product releases were in the dissolved phase.
4.2 SOURCE AREAS

4.2.1 General Description

Areas or zones of the subsurface containing DNAPL are considered ‘source areas’. A description of these source areas within the model area, and the processes and interactions between the different CHC phases within these areas (as illustrated by the 17C Model), are described below. It is noted that there is overlap in discussion of dissolved-phase CHCs within source areas and downgradient plumes.

Assessments (URS, 2000, 2004e, 2005b/e, 2006a/b/c/e/f) of DNAPL source areas have identified nine main inferred source areas extending from the southern portion of the plant site to the northern boundary which can broadly be grouped into Northern Plumes (N1 to N5), Central Plume (C1) and Southern Plumes (S1 to S3) Source Areas, which are shown on Figure 5. The CPWE represented a source of sorbed phase CHCs (mostly heavy-end compounds), but has recently been remediated (Section 2.5.3).

The main chemicals of concern were either process products or waste streams. A summary of the physicochemical properties of the main CHCs of concern (PCE, TCE, CTC, EDC, VC and HCB) detected in the model area is provided in Appendix B — which also contains a more comprehensive list of properties of selected volatile and semi-volatile CHCs (Table B10). Stening (2010) assessed effective solubilities from a DNAPL (recovered from MWD16 within S2 Source Area), which suggests pure phase solubilities of CHC components within groundwater (see Appendix B) at the site are different to literature values.

The general properties and composition of the primary process products and wastes handled on BIP, and theoretical dissolved plume composition are presented in Appendix B and summarised in Table 4-8 (below).

Table 4-8: Primary Source Materials

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>APPROXIMATE MOLAR COMPOSITION</th>
<th>RELEVANT SOURCE AREAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTC, PCE and TCE</td>
<td>CTC, PCE and TCE (manufactured products)</td>
<td>S1, S2, S3, N4</td>
</tr>
<tr>
<td>‘Pure EDC’</td>
<td>EDC (99%)</td>
<td>C1</td>
</tr>
<tr>
<td>‘Crude EDC’</td>
<td>EDC (95%), 1,1,2-TCA and CFM</td>
<td>C1</td>
</tr>
<tr>
<td>‘EDC Lights’</td>
<td>EDC (50%), CFM (40%)</td>
<td>S2, S1, C1 (minor), N1 (minor)</td>
</tr>
<tr>
<td>‘EDC Heavies’</td>
<td>1,1,2-TCA (80%), EDC (15%), 1,1,2,2-TeCA (5%)</td>
<td>S2, S1, C1 (minor), N1/N2/N3 (minor)</td>
</tr>
<tr>
<td>‘EDC Tars’</td>
<td>1,1,2-TCA (30%), CFM and 1,1,2,2-TeCA</td>
<td>S2, S1, C1 (minor)</td>
</tr>
<tr>
<td>1,1,2,2-TeCA</td>
<td>1,1,2,2-TeCA (intermediate product in manufacture of TCE)</td>
<td>S3</td>
</tr>
<tr>
<td>‘Heavy Ends’</td>
<td>HCB, HCBD, HCE and, post-1978, octachlorostyrene (OCS) - by-products of the production of CTC and PCE at the former Solvents Plant</td>
<td>S2, S3, N1/2/3 (minor)</td>
</tr>
</tbody>
</table>

Percentages are approximate molar composition based on observed dissolved phase composition within source areas.

4.2.2 Heavy Ends

As discussed in Section 2.5.3, sorbed-phase ‘heavy end’ semi-volatile CHCs formerly at the CPWE and Denison Street stockpile represent an historical source of CHCs.

The soil in the CPWE was contaminated with elevated concentrations of HCBD (1,360 – 2,580 mg/kg), HCE (290 – 620 mg/kg), HCB (55 – 265 mg/kg) and PCE (URS, 2007g). Woodward-Clyde (1998) reported mean values for HCBD (3,225 mg/kg), octachlorostyrene (OCS, 230 mg/kg), HCB (90 mg/kg) and PCE (65 mg/kg) for encapsulated material. The CPWE has since been remediated (Section 2.5.3), though localised residual groundwater contamination is reported (Section 4.4.5).

The Denison Street landscaping mound is located to the south of Gate 3 along the eastern boundary of the BIP (Figure 5). The mound consists of material removed during the remediation of the former drum storage area (current Olefines 2 location) that contained low levels of CHC contamination. The stockpile has been capped with topsoil and revegetated with trees and shrubs. Characterisation of the contaminated soil by URS (URS, 2007g) reported concentrations of HCBD concentrations ranging from 17.9 mg/kg to 74.3 mg/kg. More recent investigations reported very low concentrations of chlorinated benzenes in soils in the landscaping mound (Golder, 2011d).

4.2.3 CHC Mass Estimate

An estimate of CHC mass in DNAPL, soil and groundwater phases within the model area was conducted by URS (2007f). Based on the simplifications, assumptions and calculations described by URS (2007f), the total mass of the selected CHCs (EDC, PCE, TCE, CTC, VC and CFM) in the model area is shown in Diagram 4-
14. Vapour phase and other CHCs were not considered but may still be significant (e.g. cis-1,2-DCE or 1,1,2-TCA).

URS (2007f) conducted a sensitivity analysis showing that the estimated mass of the selected CHCs in the aquifer would most likely be between 9,600 tonnes and 19,400 tonnes, with the level of certainty in estimated masses decreasing from dissolved phase >>> sorbed phase >> DNAPL. The mass estimate relied on data collected in 2004/2005. The cumulative CHC mass within the subsurface over time (i.e. from the 1940s - 2004/2005) would be higher than the sum of these components (i.e. DNAPL + solid phase + aqueous phase masses) estimated in 2005 as CHCs that have degraded, volatilised or migrated from the model area were not accounted for.

If potential sources were present for 40 years and a product density of 1.6 kg/L is assumed, then this mass estimate value equates to approximately 400 - 800 L per day of product release (excluding degradation).

Based on the conceptual understanding of contaminant geochemistry and behaviour, the mass ratio between the three phases is considered reasonable (i.e. it is likely that the DNAPL phase mass could be expected to be up to an order of magnitude higher than contaminant mass in the dissolved phase).

More details of mass estimates in terms of CHC phases are discussed in relevant sections below.

4.2.4 Uncertainties

The level of certainty in inferred distributions and estimated masses/fluxes of CHCs is considered to vary depending on the CHC phase, with certainty increasing from most certain to least certain dissolved phase >>> vapour phase, sorbed phase >>> DNAPL phase. The level of certainty reflects the historical focus of investigations on phases/pathways that represent the greatest potential risk to receptors (i.e. groundwater, surface water and ambient air), and practicalities and technologies for investigations available at the time.

The level of certainty also depends on scale – with model-area scale attributes reasonably well understood, but micro-scale characteristics (e.g. 10s centimetres) much less so.

**Dissolved Phase**

On the model-area scale, the distribution and mass balance of dissolved-phase CHCs is considered reasonably well understood. There are significant spatial and temporal information relevant to this phase as a large portion of previous investigations have focussed on CHC phases and pathways that represent the greatest risk to receptors – namely, model-scale hydrogeology, CHCs in groundwater and surface water (and ambient air). More recent work involved in implementing, operating and monitoring the GTP hydraulic containment system, has increased certainty in dissolved-phase CHC characteristics. Further discussion of uncertainties in the aqueous phase are presented in Section 5.2.

**Sorbed Phase**

While there has been significant characterisation of model-area scale geology and sorbed-phase CHCs within inferred source areas, the quality of these data is variable (i.e. there are limited cored locations, samples comprised bulk samples collected below the water table) and there is limited understanding of some
key attributes on a micro-scale, such as physical and geochemical properties of low-permeability layers/seams and sands across the model area.

Sorbed phase mass estimates (URS, 2007f) were calculated (rather than based on field or laboratory measurements) based on interpreted dissolved phase distributions, literature partitioning coefficients, relatively few measurements of organic carbon content and gross assumptions on physical characteristics of the aquifer (e.g. portion as peat/organic-rich sediments).

**DNAPL**

The distribution and mass of DNAPL in the subsurface is considered very difficult to estimate with any reasonable degree of certainty due to uncertainty in distribution, highly variable DNAPL properties, discontinuous nature of many lithological and geological features, uncertainty in release history, and difficulty in detecting DNAPL in the subsurface.

DNAPL has only been positively identified at relatively few locations (<20) on BIP and Southlands. DNAPL distributions have been inferred from industrial history, visual confirmation in soil bores/pits, hydrophobic dye tests, dissolved phase groundwater concentrations, CPT conductivity logs and neutron geophysical borehole logs. Thus, the maximum lateral extent of inferred DNAPL zones previously presented (e.g. Figure 4.1 in the 2010 CSM) is considered generally speculative and based largely on dissolved phase concentrations and plume geometry. For this reason, more generalised Source Areas have been presented in Figure 5.

Indeed, typical ‘rules of thumb’ methods (e.g. Kueper et al, 2003, Feenstra et al., 1991) based on percentage of pure phase solubility cannot be used to make assumptions about proximity of the DNAPL source area to the groundwater sampling point. The use of dissolved phase data to assess the distribution of DNAPL in the subsurface at BIP is complicated by the nature of DNAPL releases (i.e. continual chronic spills/leaks or fewer but larger acute spills), the significant mass of CHCs within the subsurface that is inferred to have exceeded the assimilation capacity of the aquifer in some areas, potentially complex lateral and vertical migration pathways, and variety of sources with different composition and physicochemical characteristics. For example, there are concentrations exceeding 10% of pure phase solubility of EDC that are 100s metres downgradient of the source area in the C1 Plume). Stening (2010) suggests effective solubilities are different to literature values.

Other identification and characterisation techniques such as membrane interface probes (MIPs) and ribbon-samplers were not available for use in Australia at the times of historical investigations. Geophysical techniques including ground penetrating radar (GPR), electromagnetic resistivity, Lund 3D resistivity have also been used, but with limited success.

**Orders of Magnitude**

Due to the range in CHC concentrations (e.g. <0.01 to >1,000 mg/L) and scale of CHC masses in various phases (i.e. in 100s or 1,000s tonnes), and the variable levels of certainty, consideration of relative values or OoM is appropriate within this CSM. OoM are also relevant to hydrogeological features, for example hydraulic conductivity has been shown to follow a log-normal statistical distribution, and vary from $10^{-5}$ to 10 m/day (six OoM).

4.3 DNAPL PHASE

4.3.1 DNAPL Behaviour

The nature and behaviour of DNAPLs (and CHCs) in the subsurface have been the subject of extensive investigation by various researchers (e.g. Barbee, 1994; Cohen et al, 1993; Feenstra et al, 1991; Gerhard et al, 2007; Guilbeault et al 2005; Imhoff et al, 1993; Kueper and McWhorter, 1991, Kueper et al, 2003; Pankow and Cherry, 1996; Poulsen and Kueper, 1992; UK Environment Agency, 2003). Sale and Newell (2011) provide a high-level summary of processes affecting DNAPL behaviour.

A summary of the key processes relevant to DNAPL in source areas within the model area based on the above literature follows. A schematic diagram of DNAPL behaviour in the subsurface is presented in Diagram 4.15.

- Driven by gravity and capillary forces, DNAPL released at the surface migrates downward through the subsurface (fill and sands). Capillary forces reflect the tendency of wetting fluids to be drawn into porous media due to liquid-liquid attraction or liquid-solid attraction (e.g., water being drawn into a dry sponge) (Sale and Newell, 2011).
• Above the water table, DNAPL displaces air and typically occurs as a wetting phase. DNAPL behaviour in the vadose zone is complex due to the interaction of the DNAPL, air and water within the soil pores. If only a small amount of DNAPL is released, it may be insufficient to overcome capillary forces and be retained within the unsaturated zone.

• For a larger spill or a continuous leak, there may be sufficient DNAPL to enable migration below the capillary fringe and water table where DNAPL displaces water and typically occurs as a non-wetting phase.

• For DNAPL to displace water, the DNAPL pressure must exceed the pore water pressure (termed the displacement pressure). The displacement pressure is related to DNAPL properties and size of the pore (larger pores have lower DNAPL displacement pressures), hence, the most influential parameters governing migration of DNAPL are intrinsic permeability of the aquifer, and the density and viscosity of the DNAPL (Gerhard et. al., 2007).

• This means that DNAPL in saturated media preferentially moves within zones of the largest pores (e.g. the most permeable sand units), with zones of smaller pores (e.g. low-permeability silty seams/layers and fine or cemented sands – termed capillary barriers) inhibiting DNAPL movement. This leads to DNAPL distributions primarily being controlled by macro- and micro-scale lithology features in thin pools (lateral DNAPL zones overlying low-permeability units) and vertical fingers (narrow interconnected pathways). Investigations in the model area suggest that the discontinuous low-permeability layers within the Botany Sands aquifer strongly influenced the lateral and vertical migration of DNAPL in the subsurface.

• Initially, following release, the portion of the pore space filled with DNAPL (DNAPL saturation) is sufficient to allow connection between these pools and fingers. DNAPL spreads laterally as a thin layer following the topography of the capillary barrier (e.g. seams of peat / organic-rich silts and clays), accumulating within depressions, until it reached residual saturation or drains through fractures or permeable weaknesses.

• Large spills (e.g. release from EDC Storage Tank prior to 1973) tend to give rise to greater lateral spreading and longer migration times than small-scale chronic releases (e.g. leaks/spills from Solvents Plant) which tend to promote greater vertical penetration and stop once the primary source ceases. Higher density and lower viscosity DNAPLs (e.g. EDC, PCE or TCE) have a greater propensity for vertical migration than low density/high viscosity DNAPLs (e.g. coal tars). DNAPL pool depths on non-wetting peat layers, such as likely present at BIP, may range from 100 to 200 mm.

• Over time, DNAPL is depleted due to dissolution and volatilisation (in the vadose zone) leaving residual DNAPL as ganglia (disconnected pockets or blobs with DNAPL occupying a small portion of pore spaces – residual saturation) that are immobile. Depletion is initially faster as the most volatile, soluble and accessible DNAPLs (e.g. fingers and ganglia in transmissive sands) are mobilised, and progressively slows as pooled DNAPL (which have a relatively small contact area with the flowing groundwater) or ganglia in hydraulically isolated zones become increasingly dominant. Source zone depletion within the model area varies with area, but is expected to be in the order of many decades.

• Residual and pooled DNAPL saturations in the subsurface can be approximated based on DNAPL properties and subsurface properties. Literature values for residual DNAPL saturation for PCE and TCE in sands presented by Cohen et al (1993) range from 10% to 20%, while lower residual saturation of between 1% and 15% has been reported for PCE in sands (Kueper et. al., 2003). However, the limited positive results obtained when using hydrophobic dyes on soils in DNAPL investigations at BIP and Southlands (anecdotal evidence suggests only respond to DNAPL saturations exceeding approximately 5%) suggest that residual saturations are typically less than 5% (most likely much less in sand units). The wettability of the low-permeability layers (clays/peats/silts) has not been determined.

• The potential presence of surfactants and/or co-solvents (e.g. near the former Huntsman plants at BIP) may significantly alter some of the chemical properties of DNAPLs – in particular, the effective solubility and reduced interfacial tension of DNAPL. There is also some evidence that EDC (from dissolution of Central Source Area) partitions into DNAPL within the Southern Source Areas (Stening, 2010).

In summary, the key factors controlling the architecture of DNAPL within the subsurface within the model area include:

• Geology – the intrinsic permeability of the aquifer and geometry of capillary barriers (layers of peats/silts/clays, fine grained or cemented sands).
- DNAPL release – the rate and volume (i.e. small-scale chronic leaks versus a large spill) and age.
- DNAPL properties - density and viscosity, interfacial tension, wettability and vapour pressure (and will be dependent on DNAPL composition). A summary of the main chemical properties of the principal DNAPL components is provided in Appendix B.

Diagram 4-15: Conceptual DNAPL Model (Woodward-Clyde, 1996f)

4.3.2 Central Source Area

The conceptual model of DNAPL within the Central Source Area is provided in Table 4-9 (below).

The historical extent of the inferred source area (see Figure 5) is approximately 200 m wide and can be inferred to extend down-dip (southwest) for approximately 130 m. The eastern and northern boundaries of the C1 source area is difficult to establish. The inferred source area distribution is based on:

- Understanding of industrial process/plant (primary source history).
- Dissolved-phase concentrations - concentrations of EDC in excess of pure-phase solubilities have been reported in the vicinity of the former EDC Storage Tanks (and still remain at depth at BP91) and exceeding 100 mg/L in groundwater along the northern end of Second Street, confirming that the DNAPL source area has historically likely extended approximately 200 m wide in the upper 20 m of the aquifer (URS, 2005b).
- Sorbed phase concentrations - concentrations of CHCs in the soil strata are variable, with discrete zones of high concentrations (exceeding 2,000 mg/kg) (URS, 2005b), which are likely to be associated with low-permeability layers.
Table 4-9: Conceptual Model – Central Source Area

**Central Source Area: circa 1966-1990s**

**DNAPL Sources**

- Chronic leaks/spills of Pure EDC and/or Crude EDC from EDC Storage Tanks from 1966-1997. Prior to this, the tanks were used to store ethanol.
- A major loss of containment from one of these tanks prior to 1973.
- Chronic losses of EDC and EDC wastes from discontinuous paved surfaces and/or effluent systems at the EDC Storage Tank area and/or former Vinyls Plant.
- Leaks/spills of dissolved-phase VC from two former Vinyl Chloride spheres, which were emptied of VC then washed-out with water (much of which drained to ground) to conduct annual maintenance prior to 1988.

DNAPL within the C1 source area is predominantly comprised of EDC (inferred from aqueous-phase concentrations). **Section 4.1** discusses the composition of Pure EDC, Crude EDC and EDC wastes.

The historical composition of groundwater within the C1 source area has not changed significantly over the period from early-1990s (Woodward-Clyde, 1996c/f) to 2013 (Golder, 2014b) (although CHC molarity and distribution has changed) – the relative proportion of EDC has remained stable (typically exceeding 90%), with minor proportions (<10% molar fraction) of PCE, TCE, cis-1,2-DCE and VC – indicating that there have been no significant changes in DNAPL composition within the C1 source area.

**Source Area Evolution**

- DNAPL entry to subsurface with significant retention as pooled DNAPL in vadose zone and upper aquifer by peaty/silty lower-permeability seams at approximately 4-8 mBGL (2-6 mAHDL).
- These upper lower-permeability layers inhibited vertical DNAPL migration. Lateral DNAPL migration controlled by topography of these lower-permeability seams/layers down-dip towards the west and northwest. This is supported by residual DNAPL encountered in the shallow aquifer (<5 mBGL) approximately 40 m downgradient of the former EDC Storage Tanks (URS, 2000/ 2004e).
- Minor DNAPL likely leaked slowly through fractures or weaknesses, or overflowed discontinuous upper lower-permeability layers.
- Dissolution of DNAPL retained in the upper aquifer within sand units resulted in formation of the ‘Central Plume’ (primarily EDC in the 10s-100s mg/L) prior to development of the C1 Plume (see below) towards the southwest and spread northwest (during periods of industrial groundwater extraction to the northwest of BIP – **Section 3.5.4**). A portion of the Northern Plumes (in particular N3/N5) are likely related to this northwest migration.
- Volatilisation of volatile DNAPL components in vadose zone (and resultant aqueous-phase CHCs).
- Sorption to organic material within sands (minor) and lower-permeability seams within source area.
- Matrix diffusion into saturated low-permeability units.
Central Source Area: mid-1990s to circa 2007

DNAPL Sources

Primary DNAPL sources are inferred to have largely ceased with cessation of EDC manufacture for export and closure of the Vinyls Plant in 1998.

Source Area Evolution

- Significant vertical mobilisation of pooled DNAPL from the upper aquifer (Layer 1) to lower units (Layer 2 and 3) likely due to intrusive investigations within the C1 Source Area in 1994/1995 (Woodward-Clyde, 1996c) and near the former EDC Storage Tanks and the former Vinyls Plant in 2005 (URS, 2005b) that penetrated lower-permeability layers at 4 mBGL and 12 mBGL.
- It is unlikely that intrusive investigations completely drained all pooled DNAPL from the upper lower-permeability layer and that there are other topographic low-point accumulations on this layer.
- Significant amounts of DNAPL may have come to rest above low-permeability layers at depths between approximately −14 and −18 mAHD (24 and 28 mBGL), with pooled DNAPL possibly present above a thick clay/sandy-clay layer at a depth of approximately −18 mAHD.
- Further lateral migration of DNAPL in lower aquifer controlled by topography of lower-permeability layers at -14 mAHD and Layer 3 clays / bedrock towards the north and northwest – this may contribute to the N3/N5 source areas. The sandstone bedrock ‘ridge’ that runs southeast-northwest underlying Second Street would have prevented further migration to the southwest at depths greater than -10 mAHD.
- Decreasing DNAPL mass flux in groundwater within the shallow aquifer due to preferential dissolution of readily hydraulically accessible ganglia, leaving pooled DNAPL.
- The DNAPL mobilisation likely resulted in increased dissolution mass flux (as the DNAPL became more hydraulically accessible through the aquifer) in the deeper aquifer and formation of the C1 Plume ‘slug’ (where aqueous concentrations exceed 1000 mg/L) and possible overlap with the Northern Plumes (N3/N5).
- Reduced volatilisation of DNAPL in vadose zone and additional volatilisation from dissolved-phase.
- Increased sorption to organic matter in low-permeability seams within, and downgradient of, source area within lower aquifer.
- Increased matrix diffusion into low-permeability units within the lower aquifer.

URS (2007f) estimated the CHC mass in DNAPL within the Central Source Area ranged between 950 and 2,600 tonnes (based on data collected in the early-2000s).
Central Source Area: post-2007

DNAPL Sources

No primary DNAPL sources.

Source Area Evolution

- No further DNAPL migration.
- Ongoing preferential dissolution of high solubility DNAPL components from residual DNAPL in high permeability sand units. DNAPL as ganglia and pooled DNAPL remains in increasingly hydraulically inaccessible portions.
- In the upper aquifer and at the former Vinyls Plant, there is relatively low dissolution of DNAPL as residual DNAPL is depleted and the downgradient groundwater has increasingly become controlled by desorption and matrix diffusion of CHCs from organic-rich low-permeability seams (and possibly sands). This is supported by decreasing and low (>OoM decrease) EDC concentrations at the BIP containment line in shallow wells and wells south of Tenth Avenue.
- Significant ongoing (but reducing) DNAPL depletion in sands in the lower aquifer at the former EDC Storage Tanks due to dissolution of readily dissolved DNAPLs. Increasing influence of desorption and matrix diffusion of CHCs from organic-rich low-permeability seams (and possibly sands). This is supported by persistent (>100 mg/L) but decreasing EDC concentrations at the BIP containment line north of Tenth Avenue.
- Preferential dissolution of EDC is observed with dissolved-phase CHC composition at BP91 (near the former EDC Storage Tanks) in the deeper aquifer where DNAPL is inferred to be present (EDC concentrations exceeding 1,000 mg/L dominated by EDC (typically >95% molar fraction), with a lower proportion (EDC circa 50% molar fraction) in the upper aquifer.
- Reducing volatilisation of DNAPL in the vadose zone and from dissolved-phase CHCs.
- Capture of dissolved-phase CHCs at the downgradient BIP containment line.

Based on persistent and elevated dissolved phase concentrations over the past 10 years the C1 Source is inferred to contain residual DNAPL.
4.3.3 Southern Source Areas

The conceptual model of DNAPL within the Southern Source Areas is provided in Table 4-10 (below).

Table 4-10: Conceptual Model – Southern Source Areas

<table>
<thead>
<tr>
<th>S2 &amp; S3 Source Areas</th>
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<tr>
<td>DNAPL Sources</td>
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- The Solvents Plant produced CTC and PCE, and used EDC wastes from the Vinyls Plant as supplementary feedstock. By-products included Heavy Ends waste which was drummed and stored in the northern part of the BIP prior to 1978. From 1978 a Heavy Ends treatment plant processed this waste to fully chlorinate the wastes and separate the solid phase (HCB crystals) and liquids (HCBD, HCE and OCS).
- Floor drains (vitreous clay pipes) around the boundary of the Solvents Plant collected CTC and PCE which was transferred to an interceptor pit ('Save All Pit') prior to delivery to the Effluent Treatment Plant. The vitreous clay pipes were reported to have had unsealed joints, and therefore may have leaked. Pits and tanks may have overflowed. Aggressive (e.g. acidic) process conditions also created the potential for chemical degradation of floor drains and pits.
- The most likely sources of Heavy Ends compounds include DNAPL leaked/spilled from process equipment, process equipment drainage for maintenance, leaks/spills from temporarily stored equipment, leaks/spills from temporarily stored drummed Heavy Ends waste and/or related to spillage of sludge dewatering solids.
- PCE and CTC appear to be major components of inferred DNAPL located under and to the north of the former Solvents Plant. Elevated concentrations of HCB and HCE have been detected in some cases. Section 4.1 discusses the composition of DNAPL sampled at S2 Source Area, EDC Wastes and Heavy Ends waste.
- Stening (2010) suggests that partitioning of aqueous phase CHCs from the Central Source (primarily EDC) into DNAPL may have altered the composition.

**Former TCE Plant** - operational 1948-1976; decommissioned 1976; demolished 1994:
- The TCE Plant produced TCE and PCE using 1,1,2,2-TeCA and pentachloroethane as intermediate products.
- DNAPL in the S3 Source Area is likely to have entered the subsurface because of leaks, equipment drainage and spills at multiple locations at the former TCE Plant including the former TCE and PCE storage tanks and drains.
- TCE and PCE are likely to be major components in inferred DNAPL located beneath the former TCE Plant. Other compounds including PeCA, 1,1,2,2-TeCA and Heavy Ends compounds are also likely to be a component of DNAPL at this location. Elevated concentrations of HCB and HCE have been detected in some cases.

**Former CTC Plant** - operational 1945-1952:
- The original CTC Plant was located upgradient of the former TCE Plant and produced CTC by reaction of carbon disulphide and chlorine.
- Spills and leaks of CTC may have occurred.

**Source Area Distribution and Evolution**
- The inferred maximum areal distribution of DNAPL in the Southern Source Areas is presented in Figure 5. The eastern boundary (Second Street) and the zone extending north along Second Street towards Tenth Avenue (where pooled DNAPL has been observed) is difficult to establish.
- Dissolved CHC concentrations reported at high percentage solubilities (URS, 2004e, 2005b/e, 2006a/e/f) indicate that a significant mass of DNAPL is likely to exist primarily as residual DNAPL beneath the former Solvents Plant, former TCE Plant, possibly the Botany rail corridor and the northern portion of Block 1 Southlands. Pooled DNAPL has been observed at various locations to the west (e.g. BP105 and WG67) and north (e.g. MWD16) of the former Solvents Plant. DNAPL was recovered from cores in northern Block 1 Southlands (Acworth, 2000). DNAPL properties are presented in Appendix B.
- Often, reported concentrations of heavy-end compounds that have very low solubilities (such as HCB and HCE) and likely partition into DNAPL have been used to infer the presence of DNAPL. These heavy-end compounds will likely be very persistent.
- CHC concentrations in the soil strata (URS, 2005e), and work by Acworth (2000), suggest DNAPL is present in discrete zones, often associated with layers of organic-rich sediments.
- DNAPL at MWD16 appears to be related to the former Solvents Plant, either through subsurface migration or leaks/spills, but the mechanism under which DNAPL reached MWD16 (approximately 100 m to the north of the former Solvents Plant) is not known.
URS (2007f) estimated CHC mass in DNAPL at S2 (2,300 – 7,500 tonnes) and S3 (400 and 1,200 tonnes) (based on data collected early-2000s). The mass estimate did not consider some CHCs (e.g. 1,1,2,2-TeCA, 1,1,2-TCA and heavy ends) that may be significant in DNAPL at S2/S3.

The topography and geometry of low-permeability seams/layers (peaty and organic-rich sediments) likely controlled DNAPL migration in the subsurface either via directing lateral migration or retarding vertical movement. Beneath the former Solvents Plant and former TCE Plant key low-permeability layers are observed at 1 and -14 mAHD. These layers appear to have a significant dip toward the west, with gradients as steep as 1 in 10, while a bedrock ridge also runs along Second Street (on the eastern side of the former Solvents and TCE Plants) at about 10 mAHD. DNAPL appears to be associated with these layers – either acting as capillary barriers, as indicated by observations of pooled and residual DNAPL or inferred from soil and groundwater concentrations.

Marine clays of Layer 3 and weathered sandstone, which are encountered at depths ranging from –4 m AHD in the southeast corner of the former TCE Plant to -17 m AHD along the railway corridor, are also inferred to have controlled DNAPL migration. Compounds indicative of contamination from the former Solvents Plant and former TCE Plant have been reported near weathered sandstone bedrock underneath, and to the west of, the rail corridor indicating DNAPL migration in a westerly direction along the top of the weathered sandstone layer.

Given the age of the source (decades), it is likely that a significant mass of residual DNAPL in the highly permeable zones of the aquifer has dissolved into the Southern Plumes. However, the strong sorption characteristics, relatively low solubility in groundwater of PCE and CTC and relatively steady state of the Southern Plumes, suggests that a significant proportion of total CHC mass remains as DNAPL and/or is adsorbed to aquifer materials within the source areas.

**S1 Source Area**

**DNAPL Sources**

Former liquid trade waste overflow area - operation suspected between 1945 and 1958:

- Effluent overflow is likely to have been a source of DNAPL on the Rail Corridor and Block 1 Southlands.
- Prior to 1958 – 1972: trade waste water was discharged to Springvale Drain in what is understood to have been an open unsealed channel (noting the railway was constructed circa 1920s and would have to have had a underlying drain) that travelled west from the BIP across the northern portion of Block 1 Southlands (refer Figure 5), or was disposed of in soak-away ponds situated across an area roughly northeast of the former liquid trade waste overflow area. Surface runoff and/or effluent (primarily comprising dissolved-phase, but possibly also free-phase, contaminants) from the original CTC Plant, Solvents Plant and TCE Plant (and other non-CHC plants operational at the time) mixed in the open or subsurface drainage systems and may have entered the ground along the drain.
- In 1958, the Eighth Avenue effluent treatment plant was established, and continues to operate to date. Trade waste collected at this point was (and still is) pumped to the discharge point to sewer at what is now Fourteenth Avenue.

The composition of DNAPL from sources such as the trade waste overflow, the former Solvents Plant effluent collection system and ‘Save All’ pits is likely to be highly variable.

**Source Area Distribution and Evolution**

The exact mechanism under which DNAPL reached the S1 source area is not known. Some possible scenarios include:

- Surface runoff and/or effluent from the original CTC Plant, the Solvents Plant and TCE Plant was mixed in open or subsurface drainage systems and entered the ground at a common point (possibly along a drain that travelled west from the BIP across the northern portion of Block 1 Southlands). The shallow low-permeability layers at 1 and -14 mAHD likely retarded vertical migration and facilitated lateral migration. The presence of Heavy Ends compounds in DNAPL in the S1 source area indicates that a portion of DNAPL originated from the former Solvents Plant.
- DNAPL from both the Solvents Plant and TCE Plant entered the subsurface at different locations but accumulated in similar locations due to topography of subsurface capillary barriers and low-permeability layers.

URS (2007f) estimated CHC mass in DNAPL at S1 ranged between 650 and 2,700 tonnes (based on data collected early-2000s). The mass estimate did not consider some CHCs (e.g. 1,1,2,2-TeCA, 1,1,2-TCA and heavy ends) that may be significant in DNAPL at S1.
Based on persistent and elevated dissolved phase concentrations (PCE, CTC) over the past 10 years, the S1 Source is inferred to contain residual DNAPL.

4.3.4 Northern Source Areas

The conceptual model of DNAPL within the Northern Source Areas is provided in Table 4-11 (below).

There is significant uncertainty in the understanding of primary sources and DNAPL distribution within the Northern Source Areas. However, overall, there is inferred to be a small DNAPL mass within Northern Source Areas. The source of CHCs within the Northern Source Areas is likely related to local DNAPL releases, DNAPL migration from the Central Source area (at N5), and/or northerly migration of dissolved phase CHCs from the Central Source Area. The hypothesis that a significant portion of CHCs present in sorbed and dissolved-phases possibly related to historical migration of dissolved-phase CHCs from the Central Source Area during historical periods of intensive groundwater extraction north of BIP from the 1960s-1970s is supported by few indicators of shallow DNAPL sources and the presence of VC in the N2 Source Area, which could have been drawn across from the former VC Spheres’ area.

The DNAPL mass estimates by URS (2007f) are considered conservative as they were largely based on aqueous phase concentrations that may have been partially related to desorption/back-diffusion rather than DNAPL dissolution, and do not take into account potential contribution from migration of dissolved phase impacts from the C1 Source.

Table 4-11: Conceptual Model – Northern Source Areas

N1, N2, N3 Source Areas

DNAPL Sources

- Leaks/spills from drummed EDC wastes from the former Vinyls Plant and drummed Heavy Ends waste from the former Solvents Plant.
  - N2: Press's Lane area – drummed waste was stored from approximately 1964 to 1972. Orica (then ICI) stored the re-drummed HCB from March 1979 to 1980. However, there is limited evidence for surface sources in the area (DNAPL has either depleted in the upper aquifer or is related to historical migration of dissolved-phase CHCs from the Central Source Area).
  - N3: Near the former HCB Drum Store (1975 to 1979) where drummed Heavy Ends wastes produced at the former Solvents Plant were stored. Re-drumming activities were also undertaken in this area in the early 1980s.
  - The former Open Area Drum Store (upgradient of N3 at the current location of the Olefines II Plant) (1967 to 1975) was a potential minor EDC source, though EDC was not a predominant contaminant in shallow materials excavated as part of construction of the Olefines II Plant (and placed in the CPWE).

Source Area Distribution

It is not possible to accurately define the N1, N2 and N3 source areas, or locations where DNAPL may have entered the subsurface. The distribution in Figure 5 is inferred from historical drum storage activities, some anecdotal observations of CHC odours during construction works at Anderson Street carpark, and historical dissolved CHCs at depth within the N1, N2 and N3 Plumes. Groundwater concentrations indicate that EDC is the most pervasive CHC, with lower portions of PCE, TCE, VC and CFM. Extensive groundwater monitoring along the western site boundary has not identified evidence of DNAPL in shallow parts of the aquifer.

As DNAPLs were likely derived from the leakage of poorly stored waste material, and not from manufacturing or bulk storage of chemicals, the sources are considered to be diffuse and of limited area, which may explain the lower concentration of contaminants in comparison with the Central EDC Plume and the Southern Plumes.

URS (2007f) considered the DNAPL mass currently within N1 and N2 insignificant, and estimated that the CHC mass in DNAPL at N3 ranged between 130 and 1,374 tonnes. These estimates are considered highly uncertain (due to the potential influence of historical dissolved-phase CHCs associated with the Central Source Area), depth of impact and assumptions used in the estimate.

It is considered unlikely that significant DNAPL existed, or if it did has since depleted, within the source areas. If present, the DNAPL would be within disconnected and localised pockets at low residual concentrations. This is supported by:
• Relatively uniform distribution of dissolved CHCs at depth (which comprise 80-95% EDC) that have decreased from being typically less than 1 to 2% of the aqueous solubility of the CHC (prior to early 2000s) to typically <1 mg/L (as indicated by CHC concentrations at the northern end of First Street).

• The highest concentrations of volatile CHCs in soil and groundwater are generally detected in deeper parts of the soil profile, particularly in a zone between –14 and –27 m AHD.

• Concentrations of CHCs in soil strata were typically low (<10 mg/kg), though can exceed 100 mg/kg (URS, 2005b).

Source Area Evolution

• **1960s to 1970s**: Potential spillage/leaks from stored drums to the subsurface. DNAPL is likely to have been retained in the shallower aquifer, with localised areas of deeper vertical migration. The Northern Plumes are formed via:
  - Depletion of DNAPL via dissolution.
  - Dissolution of EDC (and minor portion of other CHCs) from the Central Source Area and migration in the deeper aquifer to the north during periods of intensive industrial groundwater extraction to the north of BIP. Matrix diffusion and sorption of CHCs to layers of peat / organic-rich sediments, and sorption to sands.

• **Post-1980s**: No further identified significant sources. Migration from the Central Source Area to the north ceases. Depletion of residual DNAPL sources (if present) continues and diffusion and desorption, primarily from layers of peat / organic-rich sediments, occurs.

• **Post-2007**: The dissolved phase CHC contamination in the N1, N2 and N3 Plumes is now being captured by the GTP hydraulic containment system.

N4 Source Area

**DNAPL Sources**

• Leakage/spills of CTC (and possibly PCE) from the former CTC/PCE Storage Tanks (located where the Alkatuff Plant is now located). CTC and PCE stored in the former storage tanks were finished product and, as such, for simplification could each be regarded as being a single component DNAPL. Both CTC and PCE were transported between the former Solvents Plant and the tank farm by road tanker. Small leaks/spills could have occurred during transfers between tanks and road tankers, and during transfer hose disconnection.

• In the early 1980s, anecdotal evidence shows that during a routine operational check one of the tanks indicated that it had slowly leaked an unknown quantity of CTC.

Source Area Distribution and Evolution

• The N4 Source Area is partially located under the Alkatuff Plant and is inferred to be confined to the upper aquifer. There is some overlap with sources of Heavy Ends and EDC from the Central Source Area.

• No detailed investigations have been conducted within the immediate area of the former CTC/PCE storage tanks. However, dissolved-phase CHC data indicates that the depth of DNAPL migration may have been limited.

• Prior to construction of the Alkatuff Plant in 1990/1991, air sparging of the vadose zone was undertaken to address CTC contamination. No validation testing was known to be carried out when the sparging was stopped.

• URS (2007f) estimated that the CHC mass in DNAPL at N4 ranged between 60 and 260 tonnes. However, it is now considered unlikely that significant DNAPL currently exists within the saturated zone (due to depletion via dissolution).

N5 Source Area

**DNAPL Sources**

• Limited evidence for primary DNAPL sources at N5 - elevated dissolved-phase EDC concentrations at depth are likely to be associated with the C1 Plume (via migration of dissolved-phase CHCs) or DNAPL (if present) associated with the Central Source Area.

• Possible minor contribution from leakage/spill from drummed EDC wastes stored adjacent to the HCB Drum Store.
Source Area Distribution and Evolution

URS (2007f) estimated that the CHC mass in DNAPL at N5 ranged between 140 and 450 tonnes. Results from the 2005 DNAPL investigation (URS, 2005b) and baseline monitoring of the GTP hydraulic containment wells (URS, 2005c) indicated that the elevated EDC concentrations in the inferred N5 Source Area were likely to be associated with the C1 Plume. The presence of high concentrations of EDC at depth at all bundle piezometers upgradient of the HCB Drum Store also supports this contention.

4.4 AQUEOUS PHASE INTERACTIONS

The nature and distribution of CHCs in groundwater plumes within the model areas are discussed in detail in Section 5.2, with distributions discussed for the principal plume groups containing one or more overlapping contaminant plumes, known as the Southern Plumes, Central Plume and Northern Plumes. As the inferred source areas were largely defined based on concentrations of aqueous phase CHCs, the distribution of CHCs in groundwater within source areas is described in Section 4.3. The following section focusses on the contribution of source zones to downgradient plumes (e.g. dissolution of DNAPL and temporal changes within source areas).

The principal aqueous phase CHC contaminants within source areas are EDC, PCE, TCE, VC, CTC and CFM. However, a wide range of other volatile CHCs are found either due to their presence as minor constituents in DNAPL sources or from in-situ transformation of primary CHCs. Semi-volatile CHCs (‘heavy ends’) are also present.

The summary of contaminant distribution presented in the following sections is largely inferred from DNAPL source investigations, GCP and GTP monitoring programs, and monitoring of BIP (and PCA to a lesser extent) containment lines.

4.4.1 Key Mechanisms

The key aqueous phase interaction within source areas is the dissolution of CHCs in DNAPL (see also Section 4.3) and subsequent migration away from the source area. As groundwater passes through a portion of the aquifer containing residual DNAPL or pooled DNAPL, partitioning of CHCs will occur until equilibrium is reached (the effective solubility). Partitioning into pore water within the vadose zone will also occur.

The effective solubility for each CHC compound is mostly dependent on the DNAPL composition (molar fraction) and pure phase solubility (Raoult's Law). In this way, DNAPL composition has been estimated based on groundwater concentrations in the Central and Southern Source Areas, and vice versa. However, it should be noted that the calculated pore water solubilities are theoretical as the calculations are based on pure component solubility and do not take into account effects of such factors as temperature, salinity, volatilisation, differential sorption/desorption behaviour to aquifer materials, differential dissolution (more soluble components will dissolve faster), co-solvency, biotransformation and abiotic transformation. Dissolution of multi-component DNAPL samples (from MWD16 within S2 Source Area) in groundwater (SGS, 2007; Stening, 2010) suggest pure phase solubilities of CHC components within groundwater (see Appendix B) at the site are different to literature values under laboratory conditions.

Over time, migration (advection, dispersion, diffusion), degradation (abiotic and biological), differential sorption/matrix diffusion (Section 4.5) and volatilisation (Section 4.6) result in depletion of aqueous phase CHCs in source areas, thereby driving further dissolution of DNAPL. Ultimately, the rate of DNAPL dissolution is governed either by the local rate at which constituents can partition into groundwater, or by the rate at which dissolved phase constituents migrate away from the DNAPL (Sale and Newell, 2011). The mass flux of CHCs in groundwater emanating from source areas, which change over time, is a key metric in understanding source area behaviour.

While aqueous phase interactions in transmissive zones (sand) are dominant, CHCs will also migrate into lower-permeability layers. On the basis that the hydraulic conductivity and transmissivity of these layers is at least several OoM lower than for sands within the model area, the key CHC migration mechanism in these layers is inferred to be matrix diffusion, which is discussed in Section 4.5.

Dissolution rates change over time by:
• Mass transfer mechanisms – i.e. preferential dissolution of DNAPL in the most hydraulically accessible zones and with geometry (i.e. highest surface area perpendicular to groundwater flow) most amenable to dissolution (e.g. ganglia). This changes according to distribution of DNAPL within the subsurface.

• Preferential dissolution of high solubility components – e.g. EDC will dissolve more readily (by a factor of 50) than PCE, with the proportion of the latter increasing with time. This changes the DNAPL composition over time.

4.4.2 Central Source

The nature and distribution of aqueous phase CHCs within the Central Source was assessed as part of 2004/2005 DNAPL investigations, with monitoring of few locations within the source area (BP91) since. Periodic monitoring of numerous downgradient locations (BIP containment line) has occurred since 2005.

Dissolved phase concentrations of CHCs in excess of 3,000 mg/L and pure-phase solubilities have historically been reported in the vicinity of the former EDC Storage Tanks through the entire thickness of the aquifer, and still remain at BP91 (below 18 mBGL) indicating that significant dissolution of DNAPL occurs in the deeper aquifer. CHC composition is dominated by EDC (generally more than 90%) in the deeper aquifer (below 18 mBGL). In the vicinity of the former Vinyls Plant, there are lower CHC concentrations with a higher proportion of CFM and chlorinated ethenes.

The OoM of CHC concentrations has decreased significantly in the shallow aquifer (6-14 mBGL) at BP91 from *circa* 100 mg/L in early 2000s to <10 mg/L, with a decreasing proportion of EDC (<50%), and increasing portions of 1,1,2-TCA, 1,1,2,2-TeCA, PCE, TCE, CFM and VC (which are less soluble than EDC).

The C1 Plume is inferred to co-mingle with the N4 and N5 Source Areas, and Southern Sources (prior to 2007 when hydraulic containment at Second Street BIP commenced).

As described in Section 4.3.2, aqueous phase interactions have changed temporally as the source evolved:

• During *early times* (*circa* 1966-1990s) of source evolution, increasing dissolution of DNAPL in the upper aquifer would have occurred as DNAPL entered and migrated within the subsurface. Substantial DNAPL accumulated overlying shallow peaty layers. Vertical DNAPL migration into the deeper aquifer, with subsequent increasing dissolution, is inferred to have formed the ‘low level’ C1 Plume (as indicated by elevated EDC concentrations with an OoM of 10-100 mg/L reported at northern Southlands in 1994/1995) and likely contributed to CHCs within the Northern Source Areas. Possible variations in source releases would have resulted in temporal variability in dissolution. Significant sorption and matrix diffusion within source areas would have attenuated plume development (Section 4.5).

• In the *mid-1990s* and 2004/2005, vertical mobilisation of a portion of shallow DNAPL from the upper aquifer is likely to have resulted in accumulation of DNAPI overlying deeper peaty layers and a significant increase in DNAPL dissolution flux through the deeper aquifer. This is inferred to have generated the C1 Plume ‘slug’ (where aqueous concentrations exceed 1,000 mg/L) that had reached downgradient of Botany Road by the mid-2000s, and possibly a second smaller ‘slug’ that has since been captured by the BIP containment line. This is also likely to have further contributed to EDC in the Northern Sources (N3/N5). The mass of CHCs released to the aqueous phase exceeded the attenuation capacity of the aquifer within the source zone (as indicated by evidence of limited retardation of the C1 Plume ‘slug’).

• At *later times* of source evolution (*post-2007*), further contribution to the C1 Plume ceases with hydraulic containment at First and Second Streets. Dissolution of DNAPL in the upper aquifer and in the vicinity of the former Vinyls Plant has decreased, as indicated by relatively low (1-10 mg/L) CHC concentrations at BP91 and downgradient south of Tenth Avenue, with aqueous phase CHC concentrations inferred to be increasingly controlled by desorption and back-diffusion from matrix storage.

Relatively stable and high EDC concentrations (*circa* 3,000 mg/L) in the deep aquifer at the former EDC Storage Tanks (upgradient of BP91) suggest significant residual DNAPL mass remains and that CHC concentrations are largely controlled by ongoing dissolution. Decreasing downgradient CHC concentrations in the deep aquifer north of Tenth Avenue to N4/N5 Source Areas suggest a slowly decreasing dissolution flux (assuming no change in attenuation mechanisms) – consistent with source decay via preferential dissolution.
4.4.3 Northern Sources

The nature and distribution of aqueous phase CHCs within the Northern Sources was assessed as part of 2004/2005 DNAPL investigations. There are relatively few locations regularly monitored within inferred source areas, though periodic downgradient groundwater monitoring has occurred at BIP Containment Line.

Aqueous phase CHCs within the Northern Source Areas are characterised by:

- Organic contaminants were reported in production bores north of BIP in the late 1960s (AGEE 1990), likely indicative of the start of the Northern Plumes. EDC concentrations exceeding 100 mg/L reported in the northern BIP area (e.g. WG84) and north of Southlands (at WG86) in the deep aquifer in 1994/1995 may be related to dissolution from northern DNAPL sources and migration north (and then southwest) from the Central Source Area.

- Relatively uniform distribution of dissolved CHCs at depth (which comprise 80-95% EDC) that have decreased from being typically less than 1% of the aqueous solubility of the CHC (prior to early 2000s) to typically <1 mg/L (as indicated by CHC concentrations at BIP containment line extraction wells along First Street).

- The highest concentrations of volatile CHCs in soil and groundwater are generally detected in deeper parts of the soil profile, particularly in a zone between −14 and −27 m AHD. EDC is the most pervasive volatile CHC and at the highest concentrations. Other volatile CHCs detected at elevated concentrations include PCE, TCE, VC and CFM.

- Extensive groundwater monitoring along the western site boundary has not identified evidence of DNAPL in shallow parts of the aquifer.

As discussed in Section 4.3.4, aqueous phase interactions have conceptually changed temporally as the source evolved:

- During early times (1960s to 1970s) of source evolution, dissolution of DNAPL retained in shallower aquifer and localised areas of deeper DNAPL likely occurred. Aqueous phase CHCs (primarily EDC) are thought to have also migrated from the Central Source Area in the deeper aquifer during periods of intensive industrial groundwater extraction to the north of BIP. These are likely to have formed the start of the Northern Plumes in the 1960s. Significant sorption and matrix diffusion within source areas, particularly due to increasing aquifer depth and areas of significant peat development in northern BIP (Section 3.4.3), act as a significant sink and would have attenuated plume development.

- During intermediate times (post-1980s), CHC migration from the Central Source Area to N1/N2 likely ceased, though vertical mobilisation of DNAPL at the Central Source in mid-1990s and 2004/2005 likely resulted in increased dissolution and CHC concentrations at N5 and possibly N3. CHC mass removal via soil excavation at the former Open Drum Storage Area and gradual depletion of residual DNAPL sources (if present) would have also occurred via dissolution (and other mechanisms). As aqueous phase CHC concentrations slowly decreased, desorption and back-diffusion from matrix storage become dominant mechanisms.

- During later time (post-2007), further contribution to the Northern Plumes ceased with hydraulic containment at First and Second Streets. The persistent (but low – typically <1 mg/L) CHC concentrations in the northern portion of BIP containment line at First Street are likely related to desorption and back-diffusion from matrix storage. The persistent (and high – typically circa 100 mg/L) EDC concentrations at depth at the N3/N5 area are likely related to the Central Source Area.

4.4.4 Southern Sources

Dissolved CHC concentrations have historically been reported at high percentage, indicative of significant mass of DNAPL. Often, reported concentrations of heavy end compounds that have very low solubilities (such as HCB and HCE) and likely partition into DNAPL have been used to infer the presence of DNAPL. However, there has been limited groundwater investigation or monitoring within the Southern Source Areas since these DNAPL investigations.

Compositions of dissolved CHCs are subtly different within each source area, consistent with the composition of inferred primary sources (Appendix B), though overlap considerably:
• **S2 Source Area:** Historically high concentrations (>100 mg/L) of CTC and PCE, which are the principal components, generally in excess of 50% and 30% of total CHC mass respectively. Some DNAPLs contain higher components of heavy-end CHCs, and co-mingling of DNAPLs has occurred.

• **S3 Source Area:** Generally differentiated by lower concentrations (<10 mg/L) of volatile CHCs, the absence of CTC and high proportion of PCE, TCE and 1,1,2,2-TeCA.

• **S1 Source Area:** Concentrations of CTC, PCE and TCE are generally less than observed in the overlapping S2 Plume. Elevated EDC concentrations (>100 mg/L) are present, though are likely to be primarily associated with the C1 Plume.

• Aqueous phase CHCs from the Central Source Area (primarily EDC) co-mingle with Southern Plumes (particularly S1 and S2), and Stening (2010) suggests that partitioning of aqueous phase EDC from the Central Source Area into DNAPL may have occurred.

As discussed in Section 4.3.3, aqueous phase interactions have conceptually changed temporally as the source evolved:

• **During early times (circa 1948-1991)** of source evolution, releases and increasing dissolution of DNAPL underlying the former Solvents Plant, former TCE Plant and trade waste discharge area would have occurred. Reports of organic contaminants in production bores at Block 1 Southlands in the 1960s and elevated CHCs in the order of 100 mg/L (particularly EDC, TCE, cis-1,2-DCE) within shallow aquifer in 1981 at Block 1 Southlands (AGEE, 1990), suggest plume development occurred early during this period. Potential discharge of aqueous phase CHCs and dissolution of DNAPL related to the unlined drain within the S1 Source Area may have resulted in aqueous phase CHCs further to the west. Vertical DNAPL migration into the deeper aquifer, with subsequent dissolution, is inferred to have formed the Southern Plumes within the deeper aquifer. Significant sorption and matrix diffusion within source areas would have attenuated plume development (Section 4.5). Temporal and spatial variations in source releases would have resulted in temporal variability in dissolution and plume development. Significant sorption and matrix diffusion within source areas, particularly due to significant clays of Layer 3 present at depth in these areas (Section 3.4.3), acted as a significant sink and would have attenuated plume development.

• **During intermediate times (post-1990s)** primary sources ceased and preferential dissolution of CHCs from DNAPLs likely resulted in changing plume compositions, and gradually decreased. Persistent elevated CHC concentrations are consistent with dissolution of residual DNAPLs in discrete aquifer intervals. However, as aqueous phase CHC concentrations slowly decreased, desorption and back-diffusion from matrix storage starts to become increasingly important. There is increased intermingling of EDC from the C1 Plume ‘slug’, and potential partitioning into residual DNAPL.

• **At later times** of source evolution (post-2005) commencement of extraction of deep groundwater at Block 2 Southlands in 2004, and hydraulic containment at the PCA and SCA, resulted in changing flow regimes and potential changes in dissolution within source areas. Decreasing but persistent CHC concentrations within and downgradient of source areas suggests decreasing dissolution rates. Lower but persistent aqueous phase CHC concentrations since circa 2010 are indicative of increasing control by desorption and back-diffusion from matrix storage. There is uncertainty in current CHC concentrations within S3 and southern S2 source areas.

### 4.4.5 Other Areas

As discussed in Section 2.5.3, ‘heavy end’ semi-volatile CHCs formerly at the CPWE and Denison Street stockpile represent a historical source of CHCs. Historically, volatile CHC concentrations generally less than 1 mg/L, and HCB ranging up to 0.228 mg/L were present in a localised zone near the former CPWE. The former CPWE has since been remediated, with very low CHC concentrations currently reported (Golder, 2016b).

### 4.4.6 Degradation

Degradation or transformation of aqueous phase (or DNAPL) CHCs within source zones may occur via biotic and abiotic pathways:

• Abiotic degradation of chlorinated ethanes via hydrolysis. Examples include in the Southern Source Areas where hydrolysis of 1,1,1-TCA and 1,1,2,2-TeCA to EDC may be occurring, and hydrolysis of
EDC to VC (and aqueous HCl) in the Central Source Area. Dehydrohalogenation is another possible abiotic transformation mechanism. Abiotic degradation has not been quantified within source zones.

- Biodegradation of CHCs within source zones has not been quantified at the site. Microbiology of the aquifer (Section 3.6) and CHC biodegradation within plumes (Section 5.3.2) has been assessed.

Discussion of degradation within the plumes is included in Section 5.3.2.

4.4.7 CHC Mass Discharge

Dissolved phase mass estimates (URS, 2007f) were estimated based on interpreted dissolved phase distributions for the plume as a whole, and have not been estimated within individual source areas.

The term source decay is used to describe the various processes (dissolution, volatilisation, sorption, diffusion and degradation) that result in decrease in DNAPL mass and CHC contribution to the surrounding phases (solid, aqueous, vapour). Source decay is a key attribute to understand and facilitate prediction of plume behaviour. The key component of source decay within high-permeability sand aquifers is mass flux or discharge from the source zone.

Central and Northern Sources

While there are few monitoring locations within source areas, since there has been hydraulic containment of plumes emanating from Central and Northern Source Areas since circa 2007, consideration of estimated or measured CHC concentrations at the BIP containment line (at extraction and monitoring wells) (Table 4-12) has been used as a proxy estimate of the lower limit mass discharge of aqueous phase CHCs emanating from these sources (Golder, 2014b). These estimates suggest that EDC discharge from source areas upgradient of the BIP containment line has decreased significantly between 2005 and 2013 (assuming attenuation rates have remained constant).

Solute transport modelling has assumed constant EDC source terms, with a modelled cumulative EDC source flux (1,761 tonnes) over the period 2005 to September 2013 (Laase, 2014) equating to an average rate of EDC dissolution of approximately 555 kg/day. While this is similar to the EDC mass discharge from the Central Source in 2005 estimated by Geosyntec (2006a) (450 kg/day) and at the BIP containment line in 2005 in Table 4-12 (474 kg/day), it is more than the estimated discharge at the BIP containment line in 2013.

JBS&G (2015b) presented estimates of EDC discharge at the BIP containment line using a slightly different approach (see Table 4-12). JBS&G (2015b) also considered potential chloride enrichment (assuming degradation of EDC only and no other sources of chloride) to semi-quantitively estimate possible EDC discharge from the source areas upgradient of the BIP containment line (in the order of 520 kg/day in 2005 and 480 kg/day in 2013). However, these estimates are considered of low reliability, and are sensitive to the calculations for First Street. Semi-quantitative estimates of EDC discharge upgradient of Second Street (i.e. discharge from the Central Source Area) were reported to be in the order of 260 kg/day in 2005 and 160 kg/day in 2013 (JBS&G, 2015b).

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16 Noting the CHCs emanating from source areas will be subject to attenuation prior to reaching the BIP containment line.
17 Based on measured concentrations and estimated extraction rates (using a ratio of theoretical pump curves and measured total line flow rate) for individual wells (noting the BIP containment line was not operational in 2005).
18 Background chloride concentrations were estimated to be circa 35 mg/L, with typical chloride concentrations of 75, 109 and 120 mg/L at the BIP containment line downgradient of N1/N2/N3, N4/N5 and C1, respectively. Estimated chloride enrichment was used to calculate the additional EDC discharge that may have been degraded between source area and the BIP containment line.
19 As indicated by the apparent increase in calculated CHC discharge at First Street (Table 4-12). This is likely a function of differences in the wells sampled in 2005 and 2013.
Table 4-12: Estimated CHC Mass Discharge at the BIP Containment Line

<table>
<thead>
<tr>
<th></th>
<th>Estimated CHC Concentration (Golder, 2014b) (mg/L)</th>
<th>Calculated CHC Mass Load (kg/day)</th>
<th>Calculated CHC Mass Load (kg/day)</th>
<th>Calculated CHC Mass Load (kg/day)</th>
<th>Calculated CHC Mass Load (JBS&amp;G, 2015b) (kg/day)</th>
<th>Average Measured CHC Concentration (Inflow to GTP) (mg/L)</th>
<th>Average Calculated CHC Mass Load (Inflow to GTP) (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Street</strong></td>
<td>53</td>
<td>109</td>
<td>27</td>
<td>15</td>
<td>30</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td><strong>Second Street</strong></td>
<td>461</td>
<td>365</td>
<td>214</td>
<td>71</td>
<td>56</td>
<td>61</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total BIP</strong></td>
<td>166</td>
<td>474</td>
<td>279</td>
<td>30</td>
<td>86</td>
<td>116</td>
<td>34 (range 24-54 mg/L)</td>
</tr>
</tbody>
</table>

Note: Second Street load is attributable to C1 Source. A portion of First Street is attributable to the Northern Sources. First Street includes some locations at the southern end that are inferred to be influenced by the C1 Source Area – i.e. a portion of the CHC load for First Street is attributable to the C1 Source.

While there is considerable uncertainty in these estimates, they suggest that CHC discharge from the Central Source Area has decreased by a factor of up to 1.6 to 3 times over the period 2005 to 2013, while there is more uncertainty in the decrease from the Northern Source Areas. This decrease in mass discharge is consistent with tailing of decreasing CHC concentrations (Section 4.4.2), and is inferred to be indicative of reduced DNAPL dissolution and the increasing importance of desorption/back-diffusion. Historical EDC discharge likely varied (e.g. may have been significantly higher during late-1990s).

It is noted that while CHC concentrations of GTP feed (combined flow from BIP, PCA and SCA) containment lines has been routinely sampled as part of plant operation, routine sampling of individual lines commenced in November 2013, and estimates of mass discharge at each line prior to this time were based on monitoring of individual extraction and monitoring wells (see Appendix D for references). There are limited reliable flow data available for individual extraction wells, but reliable flow data for combined flows from each line.

**Southern Sources**

There are few monitoring locations currently within Southern Source Areas. While CHCs currently emanating from Southern Source Areas will be captured by the PCA, the significant downgradient distance (and likely significant plume attenuation and intermingling with C1 Plume) means it is difficult to reasonably estimate the mass discharge of CHCs from DNAPL sources based on available PCA data. Decreasing mass discharge and concentrations at the eastern end of the PCA since 2005, which appeared to be approaching an asymptote, suggest decreasing dissolution from Southern Source Areas.

Modelling (Laase, 2014) predicts an EDC discharge from S1/S2/S3 in the order of 20 kg/day in 2005 and 10 kg/day in 2013.

### 4.5 SOLID PHASE INTERACTIONS

#### 4.5.1 Key Mechanisms

Within source areas, dissolution of DNAPL and partitioning between aqueous-phase CHCs and soils, and diffusion of aqueous-phase CHCs into low-permeability layers, will occur. These processes represent a reversible sink of CHCs termed ‘sorption capacity’ and ‘matrix storage’, respectively. While matrix diffusion is technically a mechanism of the aqueous phase, it is strongly related to low-permeability layers and sorption and is discussed in this section.

Sorption/desorption and diffusion/back-diffusion process occur concurrently. Desorption and back-diffusion are slower than the sorption and initial inward diffusion process, meaning that they can sustain plumes for extended periods even after all DNAPL is depleted (Sale and Newell, 2011).

Description of sorption and matrix diffusion is provided with reference to plumes in Section 5.5.1.
4.5.2 Solid-Phase CHC Distribution

As discussed, in Section 4.2.4, there is a lower level of understanding of solid-phase interactions within source areas relative to those in the aqueous phase, reflecting the focus and practicalities of historical investigations and relatively few reliable solid-phase data.

Solid-phase CHCs within source areas are characterised by:

- Generally low concentrations (<10 mg/kg) with discrete zones of high concentrations (>100 mg/kg), often associated with seams/layers of organic-rich sediments and peats.
- **Central Source Area**: Concentrations of CHCs in the soil strata are variable, with discrete zones of high concentrations (exceeding 2,000 mg/kg), which are likely to be associated with low-permeability layers. There is likely significant CHC mass sorbed or retained within the matrix of low-permeability layers and sands (to a lesser extent).
- **N1, N2 and N3 Source Areas**: Concentrations of CHCs in soil strata are typically low (<10 mg/kg) though can exceed 100 mg/kg. Apparent greater peat development in the northern BIP area (e.g. see Section 3.4.3 and borelog for BP69), suggest there is significant potential for sorption of CHCs.
- **S1, S2 and S3 Source Areas**: CHC concentrations in the soil strata are often low (<10 mg/kg) with discrete zones of high concentrations (>500 mg/kg). The higher total CHC concentrations (up to a maximum of approximately 2,500 mg/kg) tend to be associated with aquifer materials with an apparently high organic content. Strong CHC odours were typically noted within, or in close proximity to, low-permeability layers within the soil strata. Inferred significant DNAPL overlying significant clay layers at depth, suggest matrix storage will be significant.

Sorbed phase mass estimates (URS, 2007f) were calculated (rather than based on field or laboratory measurements) based on interpreted dissolved phase distributions, literature partitioning coefficients, relatively few measurements of organic carbon content and assumed physical characteristics (bulk density and thickness of sand and peat/silt layers). The mass estimates were not generated for each source area, rather for the plume as a whole, and separately considered sand and low-permeability layers.

4.5.3 Evolution

Solid phase interactions have likely temporally varied during the evolution of source areas, as discussed in Section 4.3.2 to Section 4.3.4, and conceptually summarised as follows:

- **During early times** of source evolution, dissolution of DNAPL and sorption of dissolved CHCs to the aquifer matrix has the effect of retarding the movement of the plumes, i.e. dissolved CHC compounds will travel more slowly than the average groundwater velocity. Diffusion of CHCs into low-permeability layers will occur. For CHCs in source areas the most significant process is adsorption to organic carbon in organic-rich sediment layers and (to a lesser extent) the sand aquifer matrix. This scenario was likely dominant during the 1960s to 1980s in source areas.
- **At intermediate times** of source evolution (i.e. stable DNAPL), partitioning between sorbed and other phases is at equilibrium within the source area (i.e. there is limited additional sorption capacity near the source). Matrix diffusion will also slow (depending on geometry of low-permeability media and time), with the thicker clays in Layer 3 likely a significant matrix storage. This scenario is considered currently significant within the lower aquifer at the Central Source Area and Southern Source Areas.
- **At late times** of source evolution, DNAPL is depleted and aqueous phase concentrations decrease. This causes desorption and matrix back-diffusion from low-permeability layers into the aqueous phase resulting in sustained downgradient aqueous phase concentrations (i.e. a ‘tailing’ effect). This scenario is considered currently dominant in the Northern Source Areas and upper aquifer at the Central Source Area.

4.5.4 Other Areas

CHCs have been reported in soils outside DNAPL source areas, and these represent a potential historical source via dissolution to groundwater or volatilisation into soil gas.

Earlier Stage 1 soil investigations sampled locations throughout BIP and Southlands (AGEE, 1990), whilst Stage 2 soil investigations focused on shallow soils at Southlands (Woodward-Clyde, 1996c). Subsequent soil investigations focused on DNAPL source areas.
Soil formerly contaminated with HCB, HCBD and other chlorinated and non-chlorinated compounds are located in various parts of the BIP, including within the:

- Former CPWE area (remediated in 2013);
- Denison Street landscaping mound; and
- Shallow soils where HCB and HCBD were previously drummed and stored.

The locations of the former CPWE and Denison Street landscaping mound are illustrated in Figure 5.

Extensive shallow soil (<1.5 m) sampling was conducted on Southlands during Stage 2 investigations (Woodward-Clyde, 1996c). Significant additional soil data have been collected as part of the Southland development, with historical data summarised in the Remediation Action Plan (JBS&G, 2014/2015a) and subsequent validation.

### 4.6 VAPOUR PHASE INTERACTIONS

Vapour phase CHCs occur from volatilisation of CHCs in DNAPL and pore water within the vadose zone, and groundwater. DNAPL properties, water content, matrix properties and surface cover (pavements, infrastructure) will affect volatilisation. Air emissions from the ground surface and vapour transport within the vadose zone will occur.

Vapour phase CHC transport will occur via:

- **Gas-phase diffusion** – this is the primary transport process under natural conditions. This reflects the volatility of CHCs (i.e. causes concentration gradients from at the water table to ground surface) and large gas-phase diffusion coefficients (potentially four orders of magnitude greater than aqueous phase diffusion coefficients) (Sale and Newell, 2011). The effective diffusion coefficient is strongly dependent on water content. As water content increases, the cross-sectional area available for vapour phase transport decreases and the tortuosity of the flow paths increases. Higher water content leads to a reduced effective diffusion coefficient.

- **Advection** - density-driven advective flow of vapor phase CHCs can be caused by volatilisation of DNAPL, changes in atmospheric pressure, engineered systems (e.g., soil vapour extraction) and negative pressure in buildings (Sale and Newell, 2011). Advective flow will preferentially occur in transmissive media (e.g. sands rather than peats/clay). Effects such as dispersion and mixing during advective flow will result in dilution of vapours in soil gas.

- **Partitioning** into soils (organic-rich sediments and sands) and pore water will occur as vapour plumes expand, retarding vapour migration. As source depletion occurs and volatilisation decreases, desorption will occur.

- **Degradation** of most CHCs is limited under aerobic conditions typical of the vadose zone, with the exception of VC, DCM and CM which readily degrade under aerobic conditions. This is demonstrated by assessment of soil gas at the Botany Golf Course overlying the C1 Plume showing significant and rapid VC degradation in the vadose zone (URS, 2007i).

Volatilisation and vapour transport within source areas has likely changed over time:

- Rates of volatilisation of CHCs from source areas were likely highest as DNAPLs were first released and retained with the vadose zone (particularly during the 1960s and 1970s), with decreasing volatilisation over time as primary sources ceased and DNAPL ganglia depleted.

- Preferential volatilisation of the most abundant and volatile CHCs will occur, with volatilisation decreasing over time as these components are depleted.

- Temporal changes in infiltration and GTP operation - infiltration is thought to form a clean water ‘lens’ at the water table, with increased downward vertical hydraulic gradients caused by GTP operation promoting formation of this lens and reduced volatilisation rates.

There has been limited assessment of soil gas or air emissions overlying source areas at the site, though assessment of ambient air, soil vapour and surface flux emissions overlying plumes off-BIP and Southlands was conducted in the mid-1990s and is currently routinely conducted to facilitate risk quantification (see EnRiskS, 2010; AECOM, 2016) (Section 5.4).

Recent work in progress (GSI, 2016) included in initial assessment of surface flux emissions overlying the Central Source Area. Preliminary results indicated there were minimal vapour emissions overlying the
Central Source Area and downgradient plume at BIP, with reported concentrations of volatile CHCs and degradation end-products (ethane/ethene) in surface air emissions less than reporting limits, with the exception of low concentrations of PCE. Ethanol and isopropyl alcohol were also reported in surface flux emissions, possibly related to former use of EDC Storage Tanks for ethanol storage prior to 1966. As surface flux emissions are influenced by attenuation and lateral migration of vapours within the vadose zone, the volatilisation flux is likely to be higher than surface emissions.

Vapour phase CHCs have not been considered in previous mass or flux estimates. However, as an example, consideration of historical average CHC concentrations reported in surface flux emission samples collected near the S2 Source Area (AS09) (AECOM, 2016) suggest historical CHC surface emissions within the S2 Source Area may have been of an OoM of 1 kg per day\(^2\), and may have been at least an OoM less since 2011. Volatilisation flux of CHCs from residual DNAPL and the water table is likely to be higher than surface emission flux.

4.7 17C MODEL

The following provides an OoM semi-quantitative balance of CHC masses for each phase (where known), and key interactions between these phases within source areas.

**Central Source Area**

\[\begin{array}{|c|c|}
\hline
\text{Source Zone} & \text{C1 Source Zone} \\
\hline
\text{Vapour} & \text{Feat./Clay} \\
\hline
\text{DNAPL} & \text{Botany South} \\
\hline
\text{Aqueous} & 950-2,600 tonnes \\
\hline
\text{Sorbed} & \\
\hline
\end{array}\]

**Phase Interactions:**

1. **CHC volatilisation** flux from DNAPL, sorbed or aqueous phases, and migration in the vadose zone, has not been quantified. The OoM of historical maximum CHC air emissions within source zones is uncertain. However, recent work at the Central Source Area suggests the magnitude of these processes is currently very low relative to that for fluxes in groundwater. Degradation of CHCs has also occurred.

2. Mass transfer from DNAPL to aqueous phase has not been quantified within the source area. However, this will be similar to, or less than, that for downgradient flux in groundwater from mature sources, which has been quantified (see Note 4. below).

3. Differential sorption and matrix diffusion fluxes are uncertain as they cannot be easily differentiated from dissolution and effects of degradation etc. However, decreasing CHC concentrations suggest ongoing sorption and matrix diffusion are minimal. Decreasing and ‘tailing’ of downgradient CHC concentrations (OoM 1-10 mg/L in the shallow aquifer and OoM 100-1,000 mg/L in the deep aquifer) and fluxes in groundwater suggest desorption and back-diffusion are becoming increasingly significant.

4. The mass discharge of EDC emanating from the Central (and Northern Source Areas) in groundwater has been estimated to be in excess of the order of 260-500 kg/day in 2005 and has decreased to in excess of the order of 100-160 kg/day in 2013. Modelled mass discharge of EDC from Southern Source Areas is in the range of 10-20 kg/day.

Degradation and sorption/diffusion mechanisms mean actual flux from the source may be higher. The mass flux has likely varied over time (e.g. higher during the late 1990s and early 2000s).

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\(^2\) Calculated based on average historical air emission rates of total CHCs at AS09 as presented by AECOM (2016) and S2 Source Area presented by URS (2007f). These may not be representative of actual emissions that will be influenced by spatial and temporal variability in emissions due to changes in local climate, surface conditions, groundwater and vadose zone conditions, but are considered to provide a relative OoM value for comparative purposes.
Southern Source Areas

CHC Phase Balance:

- **Vapour**: CHC mass in soil gas overlying the Southern Source Areas has not been quantified but is likely to be at least several OoM less than that of DNAPL.
- **DNAPL**: 3,350 – 11,400 tonnes (circa 2005), predominantly in the deeper aquifer. The aquifer response (shrinking plumes) suggests the lower-end estimate of residual mass is more likely.
- **Aqueous**: Aqueous CHC mass has only been considered in broader plume. The aqueous phase CHC mass is likely to be significantly less than that for DNAPL. Degradation of CHCs, including to the vapour-phase, has not been distinguished from other processes (e.g. dissolution).
- **Sorbed**: CHC mass in the solid phase has only been considered in the broader plumes. Based on local stratigraphy, downgradient plume concentrations and tailing, solid phase CHC mass is likely to be most significant in the deeper aquifer.

Phase Interactions:

1. **CHC volatilisation** flux from DNAPL or aqueous phases, and migration in the vadose zone, has not been quantified. The OoM of historical maximum CHC air emissions within source zones is uncertain, though based on flux emissions measured at AS09 may have historically been with an OoM of 1 kg per day and at least an OoM less since 2011. Degradation of CHCs has also occurred.

2. Mass transfer from DNAPL to aqueous phase has not been quantified within the source area. However, this will be similar to, or less than, that for downgradient flux in groundwater from mature sources, which has been semi-quantified (see Note 4. below).

3. **Desorption and back-diffusion** fluxes are uncertain as they cannot be easily differentiated from dissolution and effects of degradation etc. However, decreasing CHC concentrations suggest ongoing sorption and matrix diffusion are minimal. Decreasing and ‘tailing’ of CHC concentrations (OoM 1 mg/L in the shallow aquifer and OoM 10-100 mg/L in the deep aquifer) and CHC mass fluxes at the PCA suggest desorption and back-diffusion are becoming increasingly significant.

4. The **mass flux** from the source areas in groundwater has not been quantified. The EDC mass flux was modelled to be in the range of 10 – 20 kg/day.

Northern Source Areas

CHC Phase Balance:

- **Vapour**: CHC mass in soil gas overlying the Northern Source Areas has not been quantified, but is likely to be insignificant compared to other phases based on source age and very low CHC concentrations in groundwater.
- **DNAPL**: 330 – 2,084 tonnes (circa 2005), predominantly in the deeper aquifer. This estimate is considered conservative as it was based on aqueous

Phase Interactions:

1. **CHC volatilisation** flux from DNAPL or aqueous phases, and migration in the vadose zone, has not been quantified. The OoM of historical maximum CHC air emissions within source zones is uncertain. Degradation of CHCs has also occurred.

2. Mass transfer from DNAPL to aqueous phase has not been quantified within the source areas but is considered to be low as residual DNAPL mass is inferred to be minimal and/or in hydraulically inaccessible zones.

3. **Differential sorption and matrix diffusion** fluxes are uncertain as they cannot be easily differentiated from dissolution and effects of degradation etc. However, decreasing CHC concentrations suggest ongoing sorption and matrix diffusion is minimal. Decreasing and ‘tailing’ of downgradient CHC concentrations (OoM 0.1 mg/L in the shallow aquifer and OoM 1-10 mg/L in the deep aquifer) suggest desorption and back-diffusion are significant. This will be similar to, or less than, that for downgradient flux in groundwater, which has been quantified (see Note 4. below).
phase concentrations that may have been partially related to desorption/back-diffusion rather than DNAPL dissolution.

- **Aqueous**: Aqueous CHC mass has only been considered in the broader plumes. The aqueous phase CHC mass is likely to be less than that for sorbed and DNAPL phases. Degradation of CHCs, including to the vapour-phase, has not been distinguished from other processes (e.g. dissolution).

- **Sorbed**: CHC mass in solid phase has only been considered in the broader plumes. Based on downgradient plume concentrations, solid phase CHC mass is likely to be most significant in the deeper aquifer.

4. The **mass flux** emanating from the source area in groundwater was discussed for the Central Source Area though is inferred to have remained reasonably consistent or decreased between 2005 and 2013. This is inferred to be largely related to increasing importance of desorption/back-diffusion.

**FURTHER READING**

- **URS (2000, 2004e, 2005b/e, 2006a/b/c/e)**
  Series of intrusive investigations in early 2000s to characterise and delineate DNAPL source areas – test pitting, geophysics, soil cores, monitoring wells, DNAPL samples, soil and groundwater sampling, analyses. Interpretation of DNAPL distribution, percent solubilities in groundwater, review of primary sources and DNAPL composition.

- **Woodward-Clyde Pty Ltd (1996b/c)**
  Stage 2 investigation in 1990s – described primary source history, soil and groundwater investigation in source areas, initial DNAPL conceptual model.

- **Laase (2007, 2014)**
  Solute transport modelling of EDC ad CTC. Included review of source history, literature fate and transport parameters

- **Golder (2014b), JBS&G (2015b)**
  Review of lines of evident for attenuation mechanisms – plume composition, chloride enrichment, plume migration/retardation, GTP mass removal.
  Estimation of CHC discharge at BIP containment line and from DNAPL sources.

- **URS (2007f)**
  Estimate of CHC mass in DNAPL, solid and aqueous phases.

- **Golder (2012b)**
  Consolidated information and references in relation to mercury impacts, hydrogeochemistry and geochemical conceptual model in relation to the FCAP.
5 CONTAMINANT PLUMES

5.1 GENERAL

Dissolution of DNAPL and desorption/back-diffusion within source areas has resulted in formation of the dissolved phase plumes. Within the plume area, CHCs are distributed between the following phases:

- Dissolved in groundwater (including dissolved contaminants in sand and diffused into pores of low-permeability materials).
- Adsorbed to the aquifer matrix (including peat/clay/silt layers and sands).
- Gas phase in soil vapour within the vadose (unsaturated) zone (and possibly in the saturated zone due to CHC degradation processes).

Each phase can exist in either transmissive (i.e. sand) or low-permeability (i.e. peat/clay/silt seams) media present in source zones. Interactions between these phases and zones (transmissive or low-permeability) within plumes occur, and change over time. Within the model area, CHC migration from source areas is dominated by advective flow in the sands; however, degradation and differential sorption/matrix diffusion are significant.

This section considers the nature and distribution of CHCs in groundwater plumes (Section 5.2) as a reference phase, with processes within the aqueous phase (Section 5.3). Interactions with vapour (Section 5.4) and solid (Section 5.5) phases are considered. Degradation, which does not neatly fit within the 17C model, is addressed in Section 5.3.2.

5.2 GROUNDWATER – CHC DISTRIBUTIONS

Dissolved phase groundwater contamination of various CHCs is distributed over a wide area in the aquifer (Figure 6) from inferred sources at BIP/Southlands towards Penrhyn Estuary and Botany Bay. The principal contaminants are EDC, PCE, TCE, VC, CTC and CFM. However, a wide range of other volatile chlorinated compounds are found either due to their presence as minor constituents in DNAPL sources or from in-situ transformation of primary CHCs, with increasing fractions of some like cis-1,2-DCE and 1,1,2-TCA.

Assessment of the groundwater contamination in the model area has identified three principal plume groups containing one or more overlapping contaminant plumes, known as the Southern Plumes, Central Plume and Northern Plumes. The boundaries of the various plumes are not readily distinguishable, partly because:

- Plumes overlap and their breadth varies with depth. This overlap has increased since GTP containment system operation commenced.
- Many compounds are present in multiple plumes.
- Degradation daughter products may also be present in primary sources.
- Interpretations of CHC distributions as part of GCP/GTP programs (see Appendix D) considered maximum CHC concentration at any depth (providing highly conservative distributions). Examples of vertical distribution of CHCs at transects south of Southlands presented by Golder (2015) are included in Appendix C.

A comprehensive review of the contaminant plume composition, sources and distribution for the whole model area prior to GTP containment system operation was presented in the March 2004 GCP Report (URS, 2004d). Distributions were based on historical assessments from Stage 2 and Stage 3 works, DNAPL investigations (Section 4.2), and investigations of other areas (URS, 2004b, 2005f, 2007c). Distributions of principal CHCs are updated on a quarterly basis (see Appendix D for references), with less frequent presentation of vertical distribution via cross-sections. Since operation progressively commenced from late-
2004 to 2007, significant changes in CHC distributions have occurred, with recent interpretations of areal and vertical cross-sectional distributions of principal CHCs presented by Golder (2015).

Appendix C presents inferred areal distributions (based on maximum concentration at any depth) of EDC, PCE, CFM and VC (principal CHCs considered to represent a reasonable range of the extent and behaviours of CHCs within the model area) in 2005 (at the commencement of GTP containment system operation) and 2015.

Modelling efforts (Laase, 2007, 2014; Geosyntec, 2016) have also presented interpolated distributions for EDC and CTC for different time periods and aquifer layers. However, consideration of uncertainties in these interpolated distributions is required (see Section 5.2.6). Alternate distributions of EDC within different model aquifer layers in 2005 and 2013 were interpreted by JBS&G (2015b) (Appendix C).

5.2.1 Southern Plumes

The Southern Plumes comprise three separate (but overlapping) plumes - S1, S2 and S3. CTC, PCE, TCE, cis-1,2-DCE and VC are the dominant contaminants in terms of concentration and distribution. The plumes have historically discharged (in some instances) to Penrhyn Estuary in a zone between Floodvale and Springvale Drains at the eastern end of the estuary. However, most of the Southern Plumes are currently being contained by the PCA and SCA. Contamination currently discharging to Penrhyn Estuary is largely comprised of CHCs that had already passed the SCA containment line before its operation commenced.

- The S2 Plume is inferred to be derived from the former Solvents Plant. The S2 Plume is readily discernible by historically high concentrations (>100 mg/L) of CTC and PCE, which were the principal components (50% and 30% of total CHC mass, respectively. Since 2007 there has been a decreasing trend in concentrations and an increasing portion (albeit at lower overall concentrations) of cis-1,2-DCE and TCE, with the highest concentrations (in the range of 10-100 mg/L) currently inferred to be confined to the vicinity of the source area.
- The S3 Plume is generally differentiated from the overlapping S2 Plume by the lower concentration (<10 mg/L) of volatile CHCs, the absence of CTC and high proportion of PCE, TCE and 1,1,2,2-TeCA.
- The S1 Plume is inferred to be derived from DNAPL present in the northern part of Block 1 Southlands. Concentrations of CTC, PCE and TCE are generally less than observed in the overlapping S2 Plume. Elevated EDC concentrations (>100 mg/L) are present in the S1 Plume and are primarily associated with the C1 Plume.
- At McPherson Street on Southlands, and near the SCA containment line at Foreshore Road, there has been significant overlap of the Southern Plumes, and with the S1 and C1 Plumes due to changing groundwater flow regimes from abstraction at the PCA and SCA, respectively. The overlap varies with depth.
- Differential retardation of CHC components has occurred, as shown by greater migration distance of CFM compared to CTC (which has not been reported at Penrhyn Estuary).
- Degradation of parent compounds has contributed to the distribution of CFM (from CTC), cis-1,2-DCE and VC (from PCE/TCE and EDC), and EDC (from 1,1,2-TCA) to a lesser extent.
- CHCs have historically been generally pervasive through all depths of the aquifer, with the highest concentrations (historically >100 mg/L) generally occurring within the deep aquifer. Currently, the highest concentrations of CHCs are encountered in a more defined zone within the deep aquifer from approximately -5 to -20 m AHD.
- While high concentrations (>100 mg/L) of CTC and PCE (and lower concentrations of associated CHCs) have historically been observed in the shallow aquifer beneath the rail corridor and Southlands, concentrations within the shallow aquifer are currently low (typically <1 mg/L).

5.2.2 Central Plume

The Central (C1) Plume consists predominantly of EDC, with concentrations historically exceeding 3,000 mg/L in the core of the plume, and varying concentrations of 100 to 1,000 mg/L at the leading edge of the
plume. The front of the plume core (where EDC concentrations are close to or exceed 1,000 mg/L) has migrated in a southwesterly direction at a rate of approximately 100 m/year, and is currently north of Foreshore Road. The Central Plume has been progressively captured by BIP, PCA and SCA containment lines since 2005.

- The dissolved C1 Plume is comprised predominantly of EDC (generally in excess of 90% w/w), with minor components of various chlorinated ethenes and ethanes. The boundaries of the C1 Plume are readily discernible by the very high concentrations of EDC, often in excess of 100-1,000 mg/L.
- The C1 Plume is inferred to co-mingle with the S1 Plume at, and south of Southlands, and the N3/N4/N5 Plumes.
- Immediately downgradient of the C1 Source Area, concentrations of dissolved CHCs (predominantly EDC) have typically exceeded 1,000 mg/L through the entire thickness of the aquifer. CHC concentrations have decreased since 2007, but still exceed 1,000 mg/L at BP91 and 100 mg/L in the deep part of the aquifer north of Tenth Avenue and at the southern end of the First Street containment line. Lower CHC concentrations (<1 to 10 mg/L) and a higher proportion of CFM and chlorinated ethenes are present south of Tenth Avenue.
- At Southlands, the highest concentrations of CHCs are generally encountered between 8 and 20 mBGL, and have historically exceeded 3,000 mg/L. Current concentrations likely exceed 100 mg/L in discrete zones.
- Concentrations within the shallow aquifer are currently low (typically <1 mg/L).
- The migration of the C1 Plume can be observed by the movement of a ‘slug’ (where concentrations of EDC exceed 1,000 mg/L) that has progressed from Southlands circa 2000, McPherson Street in mid-2000s, Botany Road in 2010, and is currently located north of Foreshore Road. The position of this ‘slug’ approximately corresponds (considering advective solute transport and retardation due to sorption to aquifer materials) to potential mobilisations of DNAPL during intrusive investigations in the C1 Source Area in 1994/1995. Migration at the front of this slug south of Southlands has occurred primarily in distinct zones – 8-12 mBGL and <20 mBGL.
- Another ‘slug’ of EDC upgradient of First Street BIP approximately corresponds (considering advective solute transport and retardation due to sorption to the aquifer) to the potential mobilisation of DNAPL during intrusive investigations in the C1 Source Area in 2005.
- The C1 Plume overlaps the S1 Plume on Southlands and McPherson Street, but can be distinguished by the absence of CTC. The concentrations of volatile CHCs detected in SCA monitoring wells on Foreshore Road show intermingling between the Central Plume and the Northern Plumes (at MWF04 to MWF06) and Southern Plumes (near MWF11).
- Significant concentrations (>100 mg/L) of VC have been historically detected in the Central Plume, and concentrations are highly spatially and temporally variable. While dissolved VC may be related to the C1 Source Area (the VC Spheres were flooded with water and drained prior to maintenance), variable VC concentrations may also be related to plume co-mingling, degradation of TCE (predominantly via the cis-1,2-DCE pathway), and abiotic degradation (hydrolysis) of EDC to VC under alkaline conditions.

### 5.2.3 Northern Plumes

The Northern Plumes are comprised of a series of smaller, overlapping plumes (N1, N2, N3, N4 and N5), consisting predominantly of EDC (historical maximum concentrations between 100 mg/L and 200 mg/L) and minor concentrations of chlorinated ethenes (e.g. TCE, cis-1,2-DCE and VC). Plume N4 comprises predominantly CTC and is inferred to be derived from the CTC/PCE storage tanks. The overlapping plumes are diffuse and decrease in concentrations with distance downgradient from BIP.

- The N1, N2, N3 and N5 Plumes are inferred to be derived from drummed wastes from the former Vinyls Plant, and/or CHCs that historically migrated at depth north from the Central Source Area during periods of intensive groundwater extraction in the 1960s-1970s, and show similar composition. EDC present at depth within the N4/N5 and possibly N3 Source Areas may be related to the C1 Plume. This hypothesis is strengthened by the presence of VC in the N2 Source Area, which could have been drawn across from the former VC Spheres.
- The dissolved phase contamination is predominantly comprised of EDC (generally in excess of 80%), with minor components of various chlorinated ethenes and ethanes and a general absence of chlorinated methanes.
• The highest concentrations (>10 mg/L total volatile CHCs) are largely restricted to discrete zones in the lower part of the aquifer. Volatile CHCs are not present throughout large portions of the aquifer, particularly the shallow aquifer.
• The N4 Plume is comprised predominantly of CTC near the source area and its degradation product CFM at downgradient locations. The presence of CTC from the N4 Plume is generally restricted to the upper portion of the aquifer.
• Co-mingling between N4 and N5 Plumes, and C1 Plume occurs.
• While concentration trends increase and decrease depending on location and depth, in general the Northern Plumes appear to be stable. However, a zone of elevated (approximately 100 mg/L) CHCs (predominantly EDC) is inferred to have migrated at depth from the N1/N2 source area to under Nuplex (by the mid-2000s), and is migrating towards the southwest to the SCA at decreasing CHC concentrations (in the order of 10 mg/L) suggestive of some attenuation.
• EDC (and TCE and VC) detected in the deep aquifer along the western half of the SCA along Foreshore Road is likely to be related to the Northern Plumes. VC is likely derived from the degradation of EDC and/or degradation of TCE.
• Variable concentrations of CHCs at some locations in the vicinity of Dent Street (see Figure 6) may be related to changes in groundwater flow since cessation of groundwater extraction from upgradient areas in 2003. A bore (BMC-1) located on Herford Street (see Figure 6) was used for irrigation of Botany Golf Course (until it was shutdown due to CHC contamination in 2003).

5.2.4 Temporal Changes

Evolution of the dissolved phase plumes is closely related to source history (described for each Source Area in Section 4.3), changes in the groundwater flow regime over time and fate and transport mechanisms (i.e. interactions between solid and vapour phases, and degradation). Diagram 5-16 (below) presents examples of EDC plume development over time. Conceptually, the key periods of plume evolution include:

• During early times (circa 1966-1980s) active primary DNAPL sources and migration within the subsurface resulted in increased dissolution and initial formation of the plumes. Highly soluble components of shallow plumes likely evolved first, with lower solubility and deeper impacts forming as source areas evolved. During periods of intensive groundwater extraction to the north of BIP, migration of CHCs from the Central Source and Northern Sources likely contributed to the diffuse zone of CHCs in the deep aquifer in the Northern Plumes. Variable industrial groundwater pumping may have resulted in other plume flow directions at times. The nature and timing of plume evolution during this period is unclear, but AGEE (1990) and the Stage 2 (Woodward-Clyde, 1996c) provide some historical context of CHCs in production bores in this area.
• Post-1980s, the groundwater flow regime returned to natural conditions with flow generally to the southwest and interception of shallow groundwater in the C1 and Southern Plumes by Springvale Drain.
• In the mid-1990s and 2004/2005, vertical mobilisation of DNAPL from the upper aquifer resulted in a C1 Plume ‘slug’ (where aqueous concentrations exceed 1,000 mg/L that had reached downgradient of Botany Road by the mid-2000s), and possibly a second smaller ‘slug’ that has since been captured by the BIP containment line.
• Hydraulic containment was progressively achieved at the SCA, PCA and BIP from late-2004 to 2007. Operation of the GTP hydraulic containment system has caused cut-off of plumes at these locations, and significant changes in the groundwater flow regime and distribution of CHCs within the aquifer. Significant CHC mass was removed from the aquifer by the GTP system, and plume extent and CHC concentrations have decreased significantly. The broad-scale effects in groundwater flow and contaminant distribution following hydraulic containment have been summarised by URS (2009a) and Geosyntec (2016). Differences in EDC, PCE, CTC and VC distributions from 2005 to 2015 are presented in Appendix C.
1950s-1970s: conceptual plume development

1990: total CHCs (light blue <10 mg/L, dark blue >10 mg/L) (AGEE, 1990)

1994: EDC (dotted line >100 mg/L; dashed line >1000 mg/L) (Woodward-Clyde, 1996c/f)

1999: EDC (dotted line >100 mg/L; dashed line >1000 mg/L) (Woodward-Clyde, 2000)

2005: EDC (Appendix C) (dotted line >100 mg/L; dashed line >1000 mg/L)

2015: EDC (Appendix C) (dotted line >100 mg/L)

Diagram 5-16: Examples of inferred EDC distributions over time
Key changes in CHC distributions and behaviour between 2005 (commencement of GTP hydraulic containment) and 2015 broadly comprise:

- The hydraulic containment system has removed a significant volume of groundwater and mass of CHCs from the aquifer. Concentrations of CHCs in extracted groundwater have decreased by an order of magnitude (see Section 5.3.3).
- Effective hydraulic containment has been achieved at the BIP, PCA and SCA containment lines (JBS, 2012). This has resulted in ‘cut-off’ of plumes at the lines.
- All plume footprints have decreased in size over time, and maximum concentrations in all areas of the plumes have decreased. The extent of CHCs in the aquifer, particularly the extent of high concentration CHCs in plume cores (e.g. >100 mg/L EDC in the C1 Plume or >10 mg/L in Southern Plumes), has decreased although diffuse zones of lower CHC concentrations remain.
- Concentrations decreased faster in the shallower aquifer layers and are persisting longer in the deeper aquifer.
- Average concentrations of principal CHCs have decreased by up to an order of magnitude (with the exception of areas at depth near sources), with interpolated average plume concentrations over time presented by Geosyntec (2016) (see Diagram 5-17 for example). (Note that the apparent increase in interpolated average plume concentration from 2013 to 2015 is related to the deep aquifer (‘Layer 4’) and is considered likely to be largely a function of interpolation and monitoring locations).
- CHC concentrations have decreased significantly and are typically not present in the shallow aquifer outside of the Central and Southern plume cores. This may be related to:
  - Attenuation mechanisms (e.g. sorption, degradation).
  - Maintenance of downward vertical hydraulic gradients due to groundwater extraction in the deep aquifer, and maintenance of a ‘clean water’ lens at the water table.
  - An artefact of sampling (e.g. historical elevated CHCs at BP41 may have been related to deeper CHCs due to upward hydraulic gradients and interconnectivity at the bore).
- There is increased intermingling between plumes as groundwater flow regimes have changed.
- At Southlands, the Southern Plumes have shifted to the west as relatively clean water is drawn in through the plume margins by the PCA and plumes are drawn to the west by extraction bores.
- Concentrations are variable in areas of flat hydraulic gradients (e.g. between the PCA and Botany Road) due to increased mixing through the aquifer due to vertical hydraulic gradients induced by groundwater extraction, limited contaminant migration and degradation/transformation mechanisms within the aquifer.
- Continuing slow migration of the core of the C1 plume is observed south of Botany Road. Slow migration of the N1/N2 plume ‘front’ (EDC <10 mg/L) to the west near Botany Road has continued.

![Diagram 5-17: Interpolated Average EDC Concentration (Geosyntec, 2016)](image-url)
Further discussion is provided below of changes in aqueous phase CHC mass (Section 5.3.4), plume volume (Section 5.3.3), mass removal via the GTP containment system (Section 5.3.3) and bulk plume attenuation rates (Section 5.6.5).

5.2.5 Other Compounds

Other potential contaminants have been reported in groundwater within the model area. In most cases, they have not been fully characterised as they represent a small risk compared to that from the CHCs, are relatively immobile (e.g. HCE, HCBD), and/or they are captured by the GTP containment system. Key documents presenting relevant information (most often sundry to the primary focus of the assessments on CHCs) include Stage 2 reports, baseline GTP sampling (see Appendix D), unpublished data to assist in GTP system design (with average concentrations presented by URS (2004i)), an assessment of soil and groundwater in the eastern portion of BIP (upgradient of Central and Northern Source Areas) (Golder, 2011d), and as part of Southlands redevelopment (AECOM, 2015).

Those key contaminants that have the potential to influence the behaviour of CHCs, or interpretations, include:

- **Ammonia** is generally present at concentrations from <1.0 to 5 mg/L, with discrete zones exceeding 10 mg/L, along the majority of the northwest boundary of BIP. The downgradient extent of the ammonia plume is not known. These ammonia plumes are intercepted by the BIP containment line and treated at the GTP. Potential sources of ammonia include the former Ammonia/Urea Plants and SWSOOS. A portion of ammonia has degraded to nitrate.

- **Petroleum hydrocarbons**, including benzene, toluene, ethyl benzene and xylenes (BTEX) have been detected in the northern and western portions of BIP at the ALA site, surrounding the CPWE (see Section 2.5.3), within the Qenos Plant area (URS, 2004h, 2005c, 2007c) and at Southlands (AECOM, 2015). Concentrations of BTEX compounds are particularly elevated (in the range of 10-100 mg/L) in groundwater in the area extending from the northern boundary of BIP near the Olefines II Plant, to the southwestern boundary of BIP at the Pyrolysis Gas Tank. There are numerous off-BIP sources of petroleum hydrocarbons, including former Ampol and BP depots located immediately to the north of BIP, former Mobil depot, Qenos Nant Street storages and the fuel pipelines on Southlands. Low concentrations of benzene (<1 mg/L) are also associated with the Central Source Area.

- **Carbon disulphide** (the raw material for the production of CTC in the original CTC Plant and a raw material for production of rubber chemicals) has historically been distributed throughout the shallow and deep groundwater ranging from <0.1 mg/L to 75 mg/L (though is currently generally less than 1 mg/L), with the highest concentrations occurring in a zone extending from BIP through Block 1 Southlands to Springvale Drain. Quarterly monitoring under GCP/GTP programs (Appendix D) reported carbon disulphide concentration data.

- There is an extensive area of elevated fluid electrical conductivities (EC) (of the order of 50 mS/cm) and chloride (up to 19,600 mg/L) in groundwater under the FCAP and an associated plume (EC of the order of 10 mS/cm and chloride generally exceeding 1,500 mg/L) extending southwest in the deeper aquifer (Layers 2 and 3) towards Southlands and McPherson Street. See Section 2.5.2 for references of key information.

- There are localised areas of acidic (pH <2) and alkaline (pH >10) groundwater underlying the FCAP. See Section 2.5.2 for references of key information.

5.2.6 Uncertainties

There are several potential uncertainties in the representativeness of reported CHC concentration data which may have influenced apparent modelling or interpolation outcomes, and may have contributed to apparent changes since 2005 (rather than due to plume-scale solute transport mechanisms). These are hypothesised to be related to:

- Change in vertical hydraulic gradients caused by GTP system operation resulting in downward flow from the shallow aquifer (model Layer 1) in some areas of the plumes and increased formation of a freshwater layer at the water table due to infiltration and increased discharge from drains. Under this scenario, a groundwater sample collected from just below the water table will more likely result in a lower CHC concentration than one lower in the shallow aquifer.
• The change in vertical hydraulic gradients since commencement of GTP operation (e.g. upward to downward in some areas) may have induced changes in groundwater flow in the annulus of bundled piezometers or monitoring wells not adequately sealed. This would result in an apparent decrease in CHC concentrations due to vertical mixing in the bore annulus rather than from horizontal plume migration. An example of this has been previously reported for BP41 (URS, 2009a).

There are several potential uncertainties in the representativeness of reported concentration data which may account for some of the differences between model predictions/interpolations and observations (e.g. GTP abstraction data), including:

• Positive bias due to regulatory/risk based focus of monitoring programs (i.e. sampling programs target areas or depths of highest contamination, and these are then used as model target concentrations). Inferred dissolved CHC distributions (e.g. Golder, 2015) are based on the maximum dissolved concentration reported at any depth at each location and are inherently conservative.

• Influence of the sampling or monitoring method. For example, bundled piezometer ports typically target discrete high concentration zones, whereas monitoring wells are considered to be more representative of flux-averaged conditions over the screened interval (typically 3 m). For example, EDC concentrations at WG233D were approximately one OoM lower than at the adjacent piezometer BP52 (30 m port). The greater reliance on piezometers in earlier phases of the GCP monitoring program may have influenced overall plume interpretation. This is consistent with the concept that migration of high-concentration CHCs occur within discrete zones of the aquifer, with samples from screened wells considered more representative of flux-averaged concentration.

• Position of the sample port depth or screen interval in relation to the plume migration zone or layer.

• Modelling efforts (Laase, 2007, 2014; Geosyntec, 2016) have slightly different definitions of layers and do not take into account historical interpretations.

• Interpolation methods have a significant influence on CHC distributions, average plume concentrations and mass.

• Interpolations by Geosyntec (2016) considered GCP/GTP monitoring program wells but did not appear to consider GTP containment line data or the quality of data.

5.3 AQUEOUS PHASE PROCESSES

5.3.1 Advective/Dispersive Migration

The fate and transport of dissolved phase compounds in groundwater is governed by the following processes:

• **Advection** – the groundwater velocity and flow direction represent the principal mechanisms for the transport of dissolved phase chemicals in the aquifer.

• **Dispersion** – a process which results from groundwater travelling at different velocities through the pores in the aquifer material, the varying length of the flow paths on a microscopic and macroscopic scale, and varying hydraulic conductivities on a microscopic and macroscopic scale. This results in the lateral and vertical spreading of the chemicals beyond what would be predicted by the average pore velocity.

• **Diffusion** – occurs on a micro scale whereby molecules move in the direction of concentration gradients, i.e. contaminants will diffuse from areas of high concentrations to areas of lower concentration. Diffusion within sands will be insignificant compared to advective transport, but matrix diffusion is likely to be significant within low-permeability layers (Section 5.5).

• **Degradation** (transformation) – processes which remove the chemical from the groundwater system through abiotic and/or biotic processes which cause the compound to form new secondary products.

• **Sorption** (or partitioning between dissolved and adsorbed phases) – Section 5.5.

CHC advection within sands is considered the dominant transport mechanism within the model area. The observed plumes are generally narrow, with steep concentration gradients, and reflect the width of the DNAPL source zone. This indicates there is a low degree of dispersion (and diffusion) in sands. Advection within sands is at least several OoM greater than that within low-permeability layers (peat / clays / organic-rich sediments). This is reflected in the nature of the migration of the front of the plumes via distinct zones
rather than through the aquifer as a whole (e.g. initial migration of C1 plume core near Botany Road at distinct zones – 8-12 mBGL and below 20 mBGL) (distribution through the aquifer depth profile then occurs via dispersive and diffusive mechanisms).

Historical groundwater flow direction, velocity and flux have largely controlled the CHC distribution. This is also reflected in the significant distribution changes that have occurred since 2005, and CHC mass removed via the GTP containment system. The characteristics (rate and direction) of groundwater flow were discussed in Section 3.5 and CHC distributions and changes described in Section 5.2.

Since 2005 the most significant mechanism for removal of CHCs from the aquifer is considered to be via extraction and treatment at the GTP. This is supported by temporal CHC concentrations in the plume and extracted groundwater, volumes of extracted water, plume volumes, pore flushing and CHC mass balances.

5.3.2 Degradation

Degradation or transformation of dissolved phase organic chemicals can occur through a complex set of abiotic and/or biotic processes and has been the focus of significant research (e.g. Pankow and Cherry, 1996). Degradation pathways are presented in Appendix B. The primary transformation processes for chlorinated hydrocarbons include:

- **Hydrolysis (abiotic)** – the reaction of the relevant compound with hydroxyl radicals associated with water. Hydrolysis of EDC to VC (and aqueous HCl), favouring formation of VC and HCl increasingly as pH increases to alkaline conditions has been observed in the Central Plume and results in a lowering of pH and increased electrical conductivity.
- **Dehydrohalogenation (abiotic)** – an elimination reaction involving the removal of a halogen (chlorine ion) with concomitant removal of a hydrogen ion.
- **Hydrogenolysis (biotic)** – a form of reductive dechlorination in which replacement of a halogen substituent on an organic compound by a hydrogen atom. Reductive dechlorination transformations (either biologically-mediated or abiotic) are recognized as the most significant biotransformation process in the subsurface (Pankow and Cherry, 1996). Examples within the model area include CTC degradation to CFM, and PCE and TCE degradation (to \textit{cis}-1,2-DCE and VC).

Pankow and Cherry (1996) noted that most chemical reactions occurring in groundwater are likely to be slow compared to transformations mediated by microorganisms. However, the rate of degradation varies significantly in published literature, and reflects the variation in degradation that would be expected based on the site conditions. Ranges of degradation half-lives from various published literature have been reviewed as part of modelling (e.g. Laase 2010b, 2014). Geosyntec (2016) calculated bulk attenuation rates (Section 5.6.5), though there are insufficient data to calculate biodegradation rates. Geosyntec (2006b) suggested that, based on results of the pilot trial of bioremediation of EDC at Southlands in 2004, back-diffusion / desorption mechanisms were significant relative to degradation.

Qualitative evidence for biological or abiotic decay activity can be seen from geochemical trends, CHC and degradation by-products (e.g., dissolved hydrocarbon gases, chloride) temporal behaviour, and molecular analysis of dechlorinating bacteria. Quantitation of degradation rates typically requires completion of treatability studies (usually lab-based) or compound-specific isotope analysis.

Degradation rates may vary laterally and vertically on a macro- and micro-scale, though this has not been assessed and there are no clear geochemical or hydrogeological mechanisms to cause this on a macro scale. For example, migration of the Northern Plumes continues to occur even though EDC concentrations are inferred to be relatively low (\textit{circa} 10 mg/L west of the PCA). If degradation of EDC within the Central Plumes is significant, the mechanism for apparent limited attenuation of the Northern Plumes is uncertain (assuming sorption terms are similar). On a micro-scale there may conceptually be differences in degradation due to, for example, the possible increased presence of organic carbon, nutrients and sulfide minerals within seams of organic-rich sediments that may cause conditions more conducive to abiotic or biotic degradation/transformation reactions than within adjacent sands.

Degradation has not been quantified at the site, although ‘best fits’ and reviews of literature have been conducted as part of solute transport modelling, and specific microbial assessments have been conducted. Degradation at the site has been assessed by:

- **Stage 2 C6 Report** (Woodward-Clyde, 1996f) presented a discussion of biotic degradation processes, microcosm experiments (attached as Appendix B of the Stage 2 C6 report) and degradation rates.
• Bioremediation trials conducted on Southlands (Geosyntec, 2006b).
• Reviews by Laase (2014), Golder (2014b), JBS&G (2015b) and Geosyntec (2016).
• Various microbiology assessments and bioaugmentation trials (discussed below).

A balance of electron acceptors and electron donors, and/or parent and degradation end-products, is difficult within the model area due to:

• Complex source history - temporally changing DNAPL source characteristics, spatial uncertainties.
• Presence of most degradation/daughter products in sources.
• Anthropogenic sources of carbon are present (e.g. volatile fatty acids associated with paper waste products at Southlands, potentially the SWSOOS, and BTEX/TPH at BIP, Nant Street and Mobil Depot) and are spatially variable within the plumes.
• Data of non-CHC electron acceptors/donors (e.g. iron, ammonia, nitrate, sulphate) are temporally and spatially variable (due to natural and anthropogenic sources), and are relatively sparse on a site-wide scale.
• It is also noted that monitoring migration of plume fronts at sentinel wells has not been possible as CHCs associated with source areas had reached their current areal extent prior to intensive investigation and extensive monitoring programs were implemented (i.e. CHC compounds at distance form source areas were generally present prior to extensive site investigations).

Lines of evidence for degradation include:

• Geochemical conditions favouring the biologically-mediated transformation of CHCs in many areas include:
  o Anaerobic groundwater.
  o Mildly acidic to neutral pH (most subsurface bacteria prefer a pH in the range of 6.5 to 8). pH levels are lower than optimal (typically 4.5 to 6); however, prior work (Geosyntec, 2006b) has indicated that biological attenuation can occur at these low pH levels, albeit at slower rates.
  o Presence of ferrous iron and reduced manganese (electron donors) in groundwater.
  o Presence of relatively high concentrations of readily oxidisable organic carbon.
• The presence of primary CHC daughter products in plumes. Although some of these compounds are present within DNAPL sources (e.g. VC, CFM), elevated concentrations of intermediate degradation products of cis-1,2-DCE (from degradation of PCE/TCE), VC (from cis-1,2-DCE or EDC) and CFM (from CTC) are, or have historically been, present within plumes at concentrations higher than within sources.
• The sequential staging of consecutive peaks of PCE followed by TCE then cis-1,2-DCE is consistent with trends often observed during reductive dechlorination of PCE, and may suggest biodegradation of the chlorinated ethenes.
• There are limited data for degradation end-products. Concentrations of dissolved hydrocarbon gases were analysed for selected groundwater samples (URS, 2005a), and showed elevated concentrations (between 1.0 and 30 mg/L) of ethene, methane and (to a lesser extent) ethane.
• Some evidence of chloride enrichment at specific locations with elevated CHC concentrations (e.g. BP91) (Golder, 2014b), though there are no clear correlations on a plume scale. Comparison of chloride concentrations at BIP (approximately 100 mg/L) and upgradient of source areas (<50 mg/L) suggests chloride enrichment from degradation of CHCs may be occurring. This was quantified as part of estimating source flux (Section 4.4.7), but is considered of low reliability.
• Bioremediation trials suggested significant natural attenuation of EDC was observed in the shallower aquifer with half-lives on the order of 1-2 years and slower rates deeper where EDC concentrations were elevated (Geosyntec, 2006b), though this decrease with depth did not appear to be necessarily related to inhibitory EDC concentrations.
• The microbial community has adapted to exploit the CHC (and other) contaminants for growth, with changes in assemblages along plume flow paths shown to be correlated to the presence of CHCs (e.g. Stephenson et al., 2013).
• CFM- and EDC-degrading bacteria (specifically Dehalobacter, known for EDC degradation) are present in the PSRIB and aquifer. Isolated strains have been shown to be tolerant of CFM concentrations
observed at the site, but are inhibited by the presence of an unidentified inhibitory substance present in the groundwater preventing *Dehalobacter* species from degrading CFM.

- *Dehalococcoides* species known for their ability to degrade chlorinated ethenes are present in the aquifer at Southlands (Koenig et al., 2012).
- Ongoing modelling has found that a significant ‘sink’ term (modelled as a non-reversible biodegradation/sequestration sink term) was required to fit observed plumes (Laase, 2014), and that this decreased with depth. The mechanism for this is uncertain and is currently being assessed. This outcome may be partially attributed to other factors (e.g. interpolation of initial conditions, see Section 5.2.6).
- Conditions inhibitory to biotic degradation are likely present in some areas, e.g. in zones of very high CHC concentrations, acidic conditions (e.g. pH below 5), where there are competing microbiological species, zones limited in available organic carbon (e.g. possibly in some areas of BIP) or with excessive competing electron acceptors like nitrate, iron or sulfate.

### Microbial Remediation-Related Research

Numerous studies have been conducted to understand the potential of the microorganisms indigenous to the Botany Sands Aquifer in the vicinity of the Botany Industrial Park to degrade the contaminant mass present. Most of this research has focused on bacteria referred to collectively as organochlorine respiring bacteria (ORB). Some of the key recent studies include:

- The presence of CFM- and EDC-degrading bacteria (specifically *Dehalobacter*) in groundwater (Geosyntec, 2016), and the PSRIB (Stening et al., 2010; UNSW, 2008) in response to the impact of the granular iron on the pH of the groundwater and the evolution of hydrogen during iron corrosion (Zemb et al., 2010).
- Characterisation of a *Dehalobacter* culture isolated from Southlands (Lee et al., 2012; Deshpande et al., 2013; Wong et al., 2016; Judger et al, 2016) and use in bioaugmentation trials (to degrade CFM and DCM) located adjacent to Penrhyn Estuary. Whilst it has been demonstrated that organo-halide respiring bacteria (ORB) that can also ferment complex organic substrates are present and active at the field site, these trials to date have proven unsuccessful owing to the presence of an unidentified inhibitory substance present in the groundwater that prevent the *Dehalobacter* species from degrading CFM. Laboratory and field data support the contention that the inhibitory substance is produced by sulphate reducing bacteria that compete with ORB for hydrogen in the subsurface aquifer environment. Research seeking to identify the inhibitory substance is ongoing.
- Isolation of a *Dehalococcoides* species known for their ability to degrade chlorinated ethenes from the Botany Aquifer at Southlands (Koenig et al., 2012). The *Dehalococcoides* species isolated has been shown to degrade all chlorinated ethenes, including vinyl chloride. The *Dehalococcoides* species has also been shown to work effectively in combination with biogeochemical processes such as sulfide production by sulphate reducing bacteria to degrade mixtures of CTC and PCE (Koenig et al., 2012).
- An EDC-respiring *Desulfotobacterium* species has also been isolated and subject to a bioaugmentation trial. In this study it was demonstrated that elevating the cell concentration of *Desulfotobacterium* in the aquifer accelerated EDC degradation above increased degradation rates obtained through addition of nutrients (biostimulation) or with pH adjustments alone or in combination.
- The effects of PCE, CTC, CFM and EDC on the growth of eight anaerobic bacteria (four fermentative and four respiring species), including two species cultured from the Botany Aquifer, have been evaluated (Koenig et al., 2014).
- Other studies have assessed the interaction between zero valent iron and *Dehalobacter* strains in the transformation of halogenated methanes (Lee et al., 2015) and ORB for the transformation of chlorinated ethenes (Koenig et al., 2016).

### 5.3.3 Plume Volume

The plume volume (as measured by EDC >1 mg/L) has been variously estimated to have an OoM of 10,000 ML (circa 8,000 ML by JBS&G, 2015b; 12,600 ML by Geosyntec, 2016). Laase (2014) interpolated a larger volume. On the basis that the cumulative GTP abstraction volume is 19,000 ML to September 2016, this implies approximately 1.5–2.0 plume pore volumes have been extracted and treated by the GTP.
Laase (2014) also looked at the spatial distribution of pore flushing, with higher flushing in certain areas. The assessment suggested that a significant portion of the aquifer upgradient of the PCA initially containing high EDC concentrations has been flushed with at least one pore volume of groundwater since 2005. This is consistent with the decrease in EDC concentrations in abstracted groundwater from the PCA (which have decreased to an apparent asymptote of approximately 45 mg/L), and is consistent with the hypothesis of increasing importance of desorption/matrix diffusion mechanisms.

### 5.3.4 Plume Mass

Aqueous phase mass estimates (URS, 2007f) were interpolated based on interpreted dissolved phase distributions. The mass estimates were for the plume as a whole, and did not separately consider sand and low-permeability layers. The estimated aqueous phase CHC mass was 1,500 tonnes (range of 1,023 – 2,033 tonnes) in 2005. Some CHCs that may be significant (e.g. cis-1,2-DCE) were not considered.

Laase (2014) interpolated EDC and CTC plumes:

- CTC plume masses - 38 tonnes (2005) and 3.4 tonnes (2013).

### 5.3.5 GTP Abstraction

The approximate total volume of groundwater treated since pump and treat activities commenced in 2005 to September 2015 is 19,010 ML, with typical rates of 6 ML/day. Flow proportions are typically 50% from BIP, 25% from the SCA and 25% from the PCA, though relative rates at PCA have decreased since 2012 due to cessation of extraction from plume centreline wells. Laase (2007, 2014) and Golder (2014b) have reviewed and presented historical GTP flow rates (and concentrations).

The estimated total mass of chlorinated hydrocarbons destroyed at the GTP is 1,360 tonnes (by early 2017), which is similar to the initial plume mass (1,500 tonnes).
Diagram 5-18 (above) presents total CHC concentrations in the extracted groundwater feed to the GTP. Concentrations in GTP feed were initially highest, primarily due to extraction from the core of the C1 plume at PCA, with a steady decrease since mid-2007 following an approximate first-order decay rate, though there is some evidence of non-first order behaviour since 2015 with GTP feed concentrations remaining steady in the order of 40 mg/L.

Overall, concentrations of CHCs in extracted groundwater from BIP and the PCA have decreased by 80-90% (i.e. approaching an OoM) and appear to have approached apparent asymptotes of approximately 35 and 50 mg/L, respectively. Concentrations of CHCs in extracted groundwater from the SCA have remained reasonably steady (approximately 40 mg/L), reflecting different effects of intermingling of plumes and migration of the C1 Plume core in the deep aquifer.

The rate of CHC mass removal has changed over time (Diagram 5-19), with the highest rate of mass removal for EDC observed in 2006 when the full GTP became operational (180 tonnes/year), reducing to less than 50 tonnes/year in 2015. The change in rate of mass removal over time is not just dependent on overall plume behaviour, but reflects operational conditions (i.e. changes in flow rates; which individual wells and containment lines were operating; improved consistency of GTP operation with time), initial pumping from the C1 plume core at PCA, different effects of intermingling of plumes, and (more recently) intersection of the C1 Plume core in the deep aquifer at SCA.

CHC concentrations at individual extraction wells have been periodically sampled as part of the GTP monitoring program (see Appendix D), and show similar trends.

Diagram 5-19: GTP Feed EDC Concentrations

The relative CHC load from each containment line has changed over the period 2005 to 2013 (Golder, 2014b) (with limited change over the period to September 2015):

- CHC mass discharge to the SCA was calculated to have remained relatively stable despite significant increases in CHC concentrations in the deep aquifer associated with the migration of the Central Plume towards the SCA. There is minimal mass discharge within the shallow aquifer.
• CHC mass discharge to the BIP and PCA has decreased in the order of 80-90% (due to a corresponding decrease in CHC concentrations and shrinking of the plume area). The calculated CHC load at PCA during the late-2013 to 2015 period was influenced by relatively lower flow rates at this time.

5.3.6 Modelling
A summary of numerical flow and solute transport modelling is presented in Appendix E. Solute transport modelling by Laase (2007, 2010b, 2014) simulated EDC and CTC migration, and future plume clean-up times under current (GTP containment system) and various remediation scenarios.

Recalibration of the 2007 model by Laase (2014) was completed using observed transient flow and plume behaviour between 2005 and 2013, and it was determined that the original contaminant fate and transport behaviour assumptions (including sorption and biological attenuation rate parameters) were too conservative. To calibrate the model a non-reversible biodegradation/sequestration ‘sink’ term (essentially modelled as biodegradation) needed to be modified to match actual plume behaviour. Refinement of the model, and the understanding of this term, is ongoing.

Best-fit attenuation rates by Geosyntec (2016) suggest that biological attenuation is a significant attenuation mechanism.

5.3.7 Interactions with Surface Water Receptors
As discussed in Section 3.5.7, interaction between groundwater and surface water bodies will occur. This includes discharge to Botany Bay at Penrhyn Estuary and discharge to or recharge from Springvale Drain and Floodvale Drain.

Drains
Prior to the early-2000s, shallow groundwater was intercepted by Springvale Drain, with the main area of discharge at the northern portion of Southlands. Total volatile CHC concentrations from shallow groundwater seepages into Springvale Drain have been of the order of 14 to 189 mg/L on the eastern bank of the drain and 0.9 to 12 mg/L on the western bank. Total semi-volatile CHC concentrations in seepages ranged up to 0.2 mg/L. Stage 2 works showed that the CHC concentrations in seepages were less than those in groundwater adjacent to the seepage point.

Based on the range of historical discharge rates (in the range of 40 to 210 m³/day, Section 3.5.7.1) and CHC concentrations, historical CHC mass discharges were in the order of 0.5 to 40 kg/day prior to early-2000s.

Since 2006/2007, operation of the GTP system has resulted in lowering of the water table, thereby decreasing discharge to the drain. The main point of discharge during GTP operation and dry weather is now inferred to be downstream (south) of Southlands; however, the changing pattern and composition of surface water suggests the greatest mass discharge of CHCs (other than EDC) is still at the north of Southlands. Current discharge of CHCs in shallow groundwater to Springvale Drain is considered minimal, though may increase for short periods during extended GTP shutdowns and/or significant rainfall events. Current mass CHC discharges are expected to be very low (orders of magnitude lower than early-2000s).

Groundwater previously entered stormwater lines running from BIP to Springvale Drain and may have been a historical source of CHC contamination in surface waters. The stormwater lines were repaired in 1999/2000, and it is unlikely that shallow groundwater currently impacts stormwater in the lines.

Penrhyn Estuary
Discharge to Penrhyn Estuary is largely related to CHCs that had migrated past Foreshore Road prior to commencement of hydraulic containment in late 2004. JBS (2012) assessed effective containment, including quantification of minor mass of CHCs that may migrate south of the SCA.

Historical discharge has not been assessed. Although discharge rates were simulated in flow modelling (Laase, 2005), there is significant attenuation of CHCs within the intertidal discharge zone (Section 6.3.1) prior to discharge to Penrhyn Estuary.
5.4 VAPOUR PHASE INTERACTIONS

Vapour phase CHCs overlying plumes occur from volatilisation of CHCs in the aqueous phase. Plume properties, water content and matrix properties will affect volatilisation. Air emissions from the ground surface and vapour transport within the vadose zone will occur, with the key mechanisms of vapour fate and transport described in Section 4.6.

Assessment of ambient air, soil vapour and surface flux emissions overlying plumes off BIP and Southlands was conducted in the mid-1990s and is currently routinely conducted to facilitate risk quantification (e.g. AECOM, 2016). The CHHRA (EnRiskS, 2010) consolidated available soil vapour, air emission and ambient air CHC data at that time.

Discussion of air quality associated with Springvale Drain is discussed in Section 6.2.

5.4.1 Soil Vapour

Volatile CHCs at the water table will volatilise into soil gas. Soil gas assessments have been targeted to specific areas on the basis of elevated volatile CHCs in shallow groundwater (typically VC) and proximity to receptors. These have included at Excel Street (BP41, south of Southlands) in 2006 and Botany Golf Course (near BP77, WG154S) (URS, 2006d, 2007d and see Appendix D). Soil gas assessments have found the following:

- Despite elevated concentrations of VC in shallow groundwater at BP41, BP77 and WG154S, VC is not detected in overlying soil gas (and not in surface air emissions). A soil gas assessment at the golf course overlying shallow groundwater containing VC with an OoM of 10 mg/L indicated the following:
  - Due to operation of the GTP lowering the water table, groundwater could not be sampled from the top of the water table. Hence, the presence of a clean water lens, or presence of vinyl chloride at the top of the water table could not be confirmed.
  - VC was not detected in soil gas at any depth sampled (up to 2 mBGL). This is consistent with surface flux emissions sampling conducted at the same location, where no VC has been detected and results of vapour migration modelling predicting concentrations less than the method limit of reporting at the surface.

- VC degrades readily in the presence of oxygen, and elevated levels of oxygen have been reported throughout the soil profile during soil gas assessments overlying the plumes (consistent with the porous nature of the Botany sands). Hence, any VC vapours are expected to degrade rapidly.

- Concentrations of the principal volatile CHCs in groundwater have been reported in soil gas (see EnRiskS, 2010; AECOM, 2016), with concentrations of PCE and TCE historically the highest.

5.4.2 Surface Flux

Diffusion and some degradation (depending on the CHC) of soil vapour at the water table surface will occur. This means that surface emissions will be lower than soil vapour concentrations. Historically, the principal CHCs in groundwater (EDC, PCE, TCE, CTC, CFM) have been reported in air emission samples, with the exception of VC which is typically not detected. However, since 2007 CHCs are typically not detected, with the exception of low concentrations of PCE and TCE at some locations (consistent with soil gas sampling results), and DCM. DCM has been previously found to be related to sampling and analytical background concentrations.

Average surface air emission fluxes of CHCs at sampling locations during the period 1995-2006 (OoM of 1 µg/min/m²), which did not represent an unacceptable risk (EnRiskS, 2010), may have represented a small but significant mass transfer component. For example, if the average surface flux (1 µg/min/m²) was representative of the plume area in 2005 (assumed to be 100 hectares), then the mass transfer from surface emissions would be of an OoM of 1 kg per day. Recent data (AECOM, 2016; GSI, 2016) would suggest total surface emissions of CHCs are at least an OoM lower. Extrapolation of relatively few data points at low concentrations over a large surface area means there is significant uncertainty in these indicative estimates.

Conceptually, this shows that although CHC concentrations in air emissions are low, due to the historically large surface area of the plumes, volatilisation to the vadose zone may have formerly been a small but significant mass transfer component.
5.4.3 Temporal Changes

Soil gas and surface emission will change over the short-term (e.g. due to changes in pressure, moisture, water table and temperature) and longer-term due to plume changes. Over longer periods, fluxes of volatilisation of CHCs from plumes have likely changed proportional to CHC concentrations at the water table and relative composition, with mass transfer also related to the areal extent of plumes. This suggests there would have been higher volatilisation and surface air emissions during periods of maximum plume development and higher concentrations in the upper aquifer, most likely prior to the 2000s, with significant decreases since, in particular, post-2007. Formation of higher volatility CHCs from degradation processes (e.g. DCM, CFM and VC) may also have influenced changes in vapour emissions.

This is supported by elevated CHC data in soil gas reported during the Stage 1 works (AGEE, 1990), and higher average surface air emission fluxes of CHCs during the period 1995-2006 (OoM of 1 µg/min/m²) compared to post-2007 (OoM of 0.1 µg/min/m²)²¹ overlying plume cores. CHCs were not detected in surface emissions in 2015 (AECOM, 2016).

The apparent decrease in CHC surface air emissions since 2007 is inferred to be mostly related to decreasing CHC concentrations in the upper aquifer and increased propensity for formation of a clean water lens at the water table from infiltration due to maintenance of downward vertical hydraulic gradients caused by the GTP system.

5.5 SOLID PHASE INTERACTIONS

As discussed in Section 4.2.4, there is a lower level of understanding of solid-phase characteristics and interactions within plumes relative to those in the aqueous phase, reflecting the focus and practicalities of historical investigations and relatively few reliable solid-phase data. The majority of solid-phase CHC data targeted source areas, with relatively few data available within plumes – these were discussed in Section 4.5.2 and Section 4.5.4.

5.5.1 Mechanisms

Within plumes, partitioning between aqueous-phase CHCs and soils, and diffusion of aqueous-phase CHCs into low-permeability layers, will occur. These processes represent a reversible sink of CHCs termed ‘sorption capacity’ and ‘matrix storage’, respectively. While matrix diffusion is technically a mechanism of the aqueous phase, it is strongly related to low-permeability layers and sorption and is discussed in this section.

Sorption/desorption and diffusion/back-diffusion process occur concurrently, with the term differential sorption/matrix diffusion describing the net difference. Desorption and back diffusion is slower than the sorption and initial inward diffusion process, meaning that it can sustain plumes for extended periods even after all DNAPL is depleted (Sale and Newell, 2011) (see Diagram 5-20).

Diagram 5-20: Diffusive mechanisms leading to plume attenuation and plume persistence (after AFCEE, 2007)

Sorption (or partitioning between dissolved and sorbed phases) occurs whereby compounds adhere to aquifer materials including soils, sands and secondary minerals. The process is reversible, although there may be hysteresis, with sorption/desorption processes varying spatially and temporally. Although there are

²¹ Based on surface emission data for all sampled locations presented by AECOM (2016)
relatively few data for the site, the fine-grained low-permeability zones (peats, organic-rich sediments) have higher sorption capacities due to their inferred greater organic carbon contents and higher surface area per unit volume than adjoining transmissive sand zones.

A partitioning coefficient ($K_d$) is often used to represent the sorption process, which for sorption of CHCs to organic carbon in the aquifer can be estimated by literature values of the octanol-carbon partitioning coefficient ($K_{OC}$) and measured values of the fraction of organic carbon ($f_{OC}$) in the aquifer. A relationship between the mass sorbed and the concentration of the chemical in solution can be derived experimentally and is termed the adsorption isotherm (fixed temperature).

There are few $f_{OC}$ data available, and there is considerable uncertainty, for sands and low-permeability layers within the model area, with available data from Stage 2 works summarised in Diagram 5-22 (below) showing significant variability. In general, there is low $f_{OC}$ in sands (>0.04%) and high $f_{OC}$ in organic-rich sediments/peats (<14%). The conceptual relationship between $f_{OC}$ and partitioning between aqueous and solid phase is presented in Diagram 5-21, suggesting that in sands only 20% of CHC mass may be stored in the sorbed phase, while within organic silt/peat layers up to 80% may be sorbed.

**Diffusion** of aqueous phase CHCs into low-permeability units (e.g. layers of peat, organic-rich fine sediments, clays) will occur, driven by concentration gradients. The process is reversible with diffusion into and out of these low-permeability units varying spatially and temporally as these concentration gradients change. Matrix diffusion is interrelated with sorption processes as higher organic carbon content increases the contaminant storage capacity of low-permeability layers and accelerates the diffusion of chlorinated solvents into the low-permeability materials (Sale and Newell, 2011).
5.5.2 Sorption / Matrix Diffusion

Laboratory sorption/desorption experiments and field-scale (forced gradient) desorption experiments (McLaughlan, 1995; McLaughlan et al, 1995 – included in the Stage 2 C6 report) evaluated the sorption/desorption of selected CHCs onto/from aquifer material in the model area finding that the use of literature values and measured organic carbon content may not accurately predict the actual sorption onto relatively clean aquifer material collected from the site.

Results of GIR commissioning trials suggested there was limited sorption/desorption of CHCs in Layer 2 sands at BIP following injection of groundwater extracted from the SCA (Golder, 2011c).

Sorption is likely to have played a major role in early time mass disappearance and plume migration. On the basis that the plumes are mature and decreasing in extent and concentration, there is inferred to currently be limited net increase in sorption. Key exceptions include near migrating fronts of the Northern Plumes and the Central Plume core in the vicinity of Botany Road where increased sorption of CHCs may be occurring. Sorption has been built into solute transport models; however, increased certainty in the understanding of the mass sorbed and fraction organic carbon is required.

5.5.3 Desorption / Back-Diffusion

Concentrations within significant portions of the plume are considered to be controlled, or increasingly dominated, by desorption and back-diffusion, with the exception of:

- Between the PCA and SCA where migration of the C1 Plume core ‘slug’ continues slowly and ongoing sorption is inferred to occur.
- Downgradient of the Central Source Area towards the BIP containment line and S1/S2/S3 Source Areas in the deep aquifer (due to ongoing input from DNAPL dissolution).
- Possibly west of the PCA where the zone of elevated EDC concentrations (<10 mg/L) of the Northern Plumes continues to migrate towards the SCA.

This is supported by:

- Decreasing mass fluxes and concentrations, with recent tailing, in groundwater extracted from the GTP containment system (especially at the BIP and PCA containment lines).
- Similar patterns of tailing in CHC concentrations observed at many monitoring locations within the plumes.
- Low level but persistent CHC concentrations in areas outside plume cores and source areas.
- Approximately 1.5 to 2.0 plume pore volumes and a CHC mass approximately equivalent to the initial estimated plume mass have been extracted and treated by the GTP. While there is ongoing input from DNAPL source areas (Section 4.4.7), a significant portion of this is captured at the BIP containment line, the low but persistent CHC concentrations and plume mass must be partially due to desorption/back-diffusion.

McLaughlan et al (1995) found rapid rates of desorption for the two compounds tested (PCE and 1,1,2,2-TeCA) from sands. Field-scale desorption experiments conducted at Southlands involving flushing reasonably uniform sand with tap water and measurement of downgradient groundwater quality revealed:

- Flushing of the aquifer pore contents (300 mg/L total CHCs) in the test zone was achieved with between 2 and 4 pore volumes of pore water.
- Considerably more pore volumes (18 to 45 pore volumes) were required to flush the sorbed CHCs (to less than 0.1 mg/L).

Geosyntec (2006b) suggested that, based on results of the pilot trial of bioremediation of EDC at Southlands in 2004, back-diffusion / desorption mechanisms were significant relative to degradation.

Desorption and back-diffusion mechanisms may be kinetically limited, as indicated by anecdotal reports of ‘higher’ CHC (and other compounds like volatile fatty acids) concentrations in extracted groundwater immediately following extended (weeks) GTP shutdowns.
5.5.4 Sorbed Mass

Sorbed phase mass estimates (URS, 2007f) were calculated (rather than based on field or laboratory measurements) based on interpreted dissolved phase distributions, literature partitioning coefficients, relatively few measurements of organic carbon content and assumed physical characteristics (bulk density and thickness of sand and peat/silt layers). The mass estimates were for the plume as a whole, and separately considered sand and organic-rich low-permeability layers. Estimated CHC masses were 79 – 224 tonnes (sand) and 1241 – 4604 tonnes (organic-rich low-permeability layers) in 2005. Some CHCs that may be significant (e.g. 1,1,2-TCA, cis-1,2-DCE, heavy ends) were not considered.

5.6 BULK PLUME BEHAVIOUR

5.6.1 Phase Partitioning

Phase partitioning within plumes (see Diagram 4-14 in Section 4.2.3) suggests 30% of the overall CHC plume mass was in the aqueous phase in 2005 (URS, 2007f). This is inconsistent of what may be expected from a system dominated by sands of low sorption capacity (see Diagram 5-21 in Section 5.5.1), suggesting the importance of sorption within organic-rich layers.

Consideration of the estimated sorbed CHC mass in sand only (79 – 224 tonnes) and aqueous phase CHC mass range (1,023 – 2,033 tonnes) suggests 90% of the overall CHC plume mass was in the aqueous phase in 2005. While there is considerable uncertainty in these estimates, this is considered consistent with sands of low sorption capacity, and is consistent with the hypothesis that there is significant storage of CHCs within organic-rich low-permeability layers.

JBS&G (2015b) suggested that a simple pore flushing model as developed by Newell et. al. (1994) suggests that if there has been an overall 80% reduction in EDC plume mass (and concentration on the basis that overall plume volume is largely unchanged) (as indicated by Laase (2014) and Geosyntec (2016)) (i.e. C/C₀ = 0.2) then in the order of 1.4 pore volumes of flushing would be required if retardation and degradation are excluded. With consideration of retardation (22) (but excluding degradation), in the order of 1.5 pore volumes of flushing would be required. This supports that, while degradation may be significant, the most significant portion of the decrease in CHC mass (and concentrations) since 2005 is most likely related to flushing of the aquifer with capture and removal via the GTP system.

5.6.2 Mass Balance

As discussed above, a phase mass balance (URS, 2007f) and cumulative mass balances over the period 2005-2013 have been simulated for EDC and CTC (Laase, 2007, 2010b, 2014). Geosyntec (2016) also reviewed interpolated EDC and CTC masses in the aqueous phase and compared these to masses removed and treated via GTP extraction over the period 2005-2015 to infer likely relative sorption/desorption and degradation mass transfer rates.

The following are noted:

- Bulk attenuation rates (Section 5.6.5) show significant plume decay, but this is inclusive of all fate and transport mechanisms.
- Approximately 1.5 – 2.0 plume pore volumes, and a CHC mass approximately equivalent to the initial estimated plume mass in 2005, are likely to have been extracted and treated by the GTP. This suggests advection and extraction via the GTP system are the dominant transport mechanisms.
- There is ongoing input from DNAPL source areas (Section 4.4.7) but a significant portion of this is captured at the BIP containment line.
- Input from desorption / back-diffusion has likely contributed to current plume mass.
- In recent times (post circa 2011) the rate of change of the interpolated dissolved phase EDC and CTC mass continues to be less than the amount of mass being extracted. This suggests that the input of

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22 Bulk density of 1.86 kg/L, porosity of 0.35, foc = 0.1%, Koc = 14 L/kg
mass into the plume from DNAPL dissolution and desorption/back-diffusion is still occurring at a rate greater than the various attenuation mechanisms (i.e. sorption, degradation) in many areas.

- Lines of evidence suggest degradation is occurring, though the rate has not been quantified. The rate of degradation is likely similar to the rate of desorption/back-diffusion in many areas.

- The uncertainties in many of the mass estimates are significant relative to the differences in mass transfer between phases.

### 5.6.3 Mass Flux Estimates

Mass fluxes/discharges have generally been estimated only at the BIP, SCA and PCA containment lines. On the basis that hydraulic containment has been achieved, this is considered to reasonably represent the CHC flux/discharge within the plumes. However, it is important to note that operation of the GTP system is variable and the capture zone changes (more often exceeding the extent of plumes).

### 5.6.4 Plume Migration Rates

Comparison of historical distributions of CHCs (e.g. see Stage 2 C6 report, GCP/GTP quarterly reports and Appendix C) illustrate migration of the plumes towards Botany Bay in the deep aquifer. EDC has migrated the furthest, followed by TCE, PCE and CTC. CFM and VC migration are difficult to ascertain due to their rapid degradation (relative to other CHCs) in the subsurface and formation from parent compounds. This order of mobility in the model area aquifer approximately correlates to physicochemical properties (Appendix B) of the compounds and aquifer properties, and estimations of retardation summarised in Table 5-13 below. The historical migration of the front of the C1 Plume core to BP59 (north of Botany Road) approximately correlates to the retardation factor presented in Table 5-13.

#### Table 5-13: Estimated CHC Retardation via Sorption

<table>
<thead>
<tr>
<th>Compound</th>
<th>EDC</th>
<th>TCE</th>
<th>PCE</th>
<th>CTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log ( K_{OC} )</td>
<td>1.15</td>
<td>1.81</td>
<td>2.42</td>
<td>2.62</td>
</tr>
<tr>
<td>( K_d )</td>
<td>0.06</td>
<td>0.26</td>
<td>1.05</td>
<td>1.67</td>
</tr>
<tr>
<td>( R_c )</td>
<td>1.29</td>
<td>2.33</td>
<td>6.41</td>
<td>9.58</td>
</tr>
<tr>
<td>Approximate plume velocity (m/year)</td>
<td>93</td>
<td>52</td>
<td>19</td>
<td>13</td>
</tr>
</tbody>
</table>

*a see Appendix B

*assumes average \( f_{OC} \) (0.4 %) – typical \( f_{OC} \) for sand is lower; typical \( f_{OC} \) for organic silts / peats is higher.

*assumes bulk density (1,800 kg/m³) and porosity (0.35)

*assumes a linear groundwater velocity of 120 m/year and ignores other attenuation mechanisms.

However, Golder (2014b) reviewed migration of plumes:

- The C1 plume core front took approximately five years to migrate 120 m from BP59 to Botany Road. A conservative solute would have been expected to have migrated of the order of 180 m in this time period (lower seepage velocities are apparent due to low hydraulic gradients in this area). This suggests retardation of EDC occurred (retardation coefficient of 1.5), though it is difficult to discern between physical (dispersion/diffusion), sorption and degradation attenuation mechanisms. Geosyntec (2016) hypothesised that significant mass loss from the plume occurred via sorption in this area.

- The ‘front’ of elevated EDC concentrations of the Northern Plumes to the west of PCA has taken the order of seven years to migrate 220 m. A conservative solute would have been expected to have migrated of the order of 680 m in this time period. This suggests retardation of EDC occurred, though it is impossible to discern between physical (dispersion/diffusion), sorption and degradation attenuation mechanisms using available data.

### 5.6.5 Bulk Attenuation Rates

The bulk attenuation behaviour (defined by the bulk attenuation rate) represents the net contribution from various attenuation mechanisms, including GTP extraction, DNAPL dissolution, sorption/desorption, diffusion/back-diffusion, dispersion, volatilisation, and degradation. The individual contribution of each cannot be distinguished from solely assessing the bulk attenuation behaviour as a whole; however, some components (e.g. GTP extraction) are known.
Bulk attenuation rates for EDC were estimated by Geosyntec (2016) for all CHCs at each location with sufficient data and detections, based on temporal concentration trends and assuming first-order concentration decay behaviour. Average half-lives ranged from a low of 0.7 years (PCE and CTC) up to 1.2 years (EDC and VC), with DCM on average doubling (i.e., increasing by a factor of two) every 0.7 years. Maximum half-lives ranged up to an OoM, reflecting the significant uncertainty in these calculated rates.

Laase (2014) ‘best-fit’ half-lives for the ‘sink’ term (non-reversible sequestration and biodegradation term) for EDC ranged from 25 to 625 days for model Layers 1 to 4, respectively.

Plume ‘lifetimes’ (assuming ongoing GTP operation) have been estimated by Laase (2014) and Geosyntec (2016) for EDC, both predicting a range of lifetimes in the order of 15 years (i.e. 2030) depending on DNAPL source behaviour.

5.7 17C MODEL

The following provides an OoM semi-quantitative balance of CHC masses for each phase (where known), and key interactions between these phases within plumes.

CHC Phase Balance:

1. Vapour: CHC mass in soil gas overlying the plumes has not been quantified.

2. Aqueous: Aqueous CHC mass has been estimated in 2005 (1,500 tonnes), and interpolated for EDC (1,365 tonnes in 2005) and 233 tonnes in 2013) and CTC (38 tonnes in 2005 and 3.4 tonnes in 2013). Between 2005 and 2013, overall plume concentrations have decreased by 80-90% in most areas, and mass fluxes at BIP and PCA containment lines have decreased by 1 OoM. CHCs are typically not detected in the shallow aquifer outside the plume core. Plume concentrations have varied south of Southlands and the CHC mass flux increasing at SCA, due to ongoing migration of the C1 Plume core and Northern Plume front.

Degradation of CHCs in the plumes is occurring. However, the degradation rate has not been quantified. Bulk attenuation rates have been estimated, but these are not specific to the various attenuation mechanisms.

3. Sorbed: Estimated CHC masses were 79 – 224 tonnes (sand) and 1,241 – 4,604 tonnes (low-permeability layers) in 2005. Some CHCs that may be significant (e.g. 1,1,2-TCA, cis-1,2-DCE, heavy ends) were not considered. The sorbed mass has not been estimated for other times.

Phase Interactions:

1. CHC volatilisation flux from aqueous phases, and migration in the vadose zone, has not been quantified. Although CHC

2. Mass transfer from source areas in the aqueous phase was discussed in Section 4.4.7 and has been estimated to be in excess of the order of 500-600 kg/d in 2005 and has decreased to in excess of the order of 100-150 kg/d in 2013. Degradation and sorption/diffusion mechanisms mean actual flux from sources may be higher. The mass flux has likely varied over time (e.g. higher during the late 1990s and early 2000s).

3. Differential sorption and matrix diffusion fluxes are uncertain as they cannot be easily differentiated from degradation and advective migration (with extraction via the GTP system). Sorption is considered to have played a major role in early-time mass disappearance and retardation of plume migration. However, on the basis that the plumes are mature and decreasing in extent and concentration, there is inferred to currently be limited net increase in sorption. Exceptions include net sorption of the C1 Plume upgradient of the SCA.

Decreasing and ‘tailing’ of aqueous CHC concentrations (and fluxes) within the plumes and at BIP and PCA containment lines suggest desorption and back-diffusion are becoming increasingly significant in controlling plume behaviour (with the exception of upgradient of SCA within Northern and C1 plume cores).

4. The mass flux in groundwater transferring from the plumes is dominated by extraction and treatment via the GTP system. The estimated total mass of CHCs destroyed at the GTP is 1,360 tonnes (by early 2017). The rate of mass removal has changed over time, with the highest rate of mass removal for EDC observed in 2006 when the full GTP became operational (500 kg/d), reducing to 140 kg/d from 2015.

Other mass transfer components are currently minor. This include potential for a minor portion of mass flux at SCA that passes through the containment line, and discharge to Springvale Drain during high rainfall events and/or extended shutdown periods of the GTP.

Prior to late-2004, CHC in groundwater would have migrated past Foreshore Road towards Penryhn Estuary, although
concentrations in air emissions are low, due to the historically large surface area of the plumes, volatilisation may have formerly been a small but significant mass transfer component. Degradation of vapour-phase CHCs will occur. Significant attenuation occurred prior to discharge to surface waters. Prior to early 2000s, CHC mass discharge to Springvale Drain is estimated to have been in the order of 0.5 to 40 kg/day.

### FURTHER READING

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGEE (1990)</td>
<td>Key historical interpretations of CHC areal (and vertical) distributions in the aquifer prior to GTP system operation.</td>
</tr>
<tr>
<td>Woodward-Clyde (1996c/f)</td>
<td>In particular, September rounds have the most extensive monitoring, and GTP system sampling results.</td>
</tr>
<tr>
<td>URS (2004d)</td>
<td>Solute transport modelling of EDC and CTC. Included review of source history, literature fate and transport parameters.</td>
</tr>
<tr>
<td>Quarterly monitoring programs since late-2004 (see Appendix D)</td>
<td>Review of lines of evident for attenuation mechanisms – plume composition, chloride enrichment, plume migration/retardation, GTP extraction rates/mass removal, flux estimates.</td>
</tr>
<tr>
<td>Laase (2007, 2014)</td>
<td>Reviewed modelling by Laase (2014) and previous estimates of CHC discharge at GTP containment lines. Also provided an indicative estimate of source dissolution from Central and Northern Source Areas based on potential chloride enrichment calculations.</td>
</tr>
<tr>
<td>Golder (2014b)</td>
<td>Interpreted EDC distributions by model layer (Layer 1 to Layer 4) in 2005 and 2013 are included in Appendix C.</td>
</tr>
<tr>
<td>JBS&amp;G (2015b)</td>
<td>Consolidation of historical groundwater and GTP feed quality data. Interpolated EDC and CTC distributions, plume statistics, calculation of bulk attenuation rates.</td>
</tr>
<tr>
<td>Geosyntec (2016)</td>
<td>Estimate of CHC mass in DNAPL, solid and aqueous phases.</td>
</tr>
<tr>
<td>URS (2007f)</td>
<td>• GTP abstraction rates (for each containment line and combined feed).</td>
</tr>
<tr>
<td>Orica (unpublished data)</td>
<td>• GTP feed water quality (daily).</td>
</tr>
<tr>
<td></td>
<td>• GTP containment line water quality (monthly since November 2013).</td>
</tr>
</tbody>
</table>
6 RECEIVING ENvironments

6.1 GTP SYSTEM

The GTP is technically considered a receiving ‘environment’ but was considered in the plume discussions in Sections 5.3.5 and 5.6.

6.2 SPRINGVALE AND FLOODVALE DRAINS

6.2.1 Aqueous Phase

Aqueous phase CHCs within the drains are mostly related to discharge of shallow groundwater. The CHC concentration in surface water will be related to the relative rates of groundwater discharge and stream flow (i.e. mixing), volatilisation and partitioning to sediments. These processes vary along the drain flow path (e.g. the highest CHC concentrations at Springvale Drain have typically been observed at the downstream boundary of Southlands) and have changed significantly over time (both short and long time scales). The drains discharge to Penrhyn Estuary, and are considered the key historical contributor to CHCs within the estuary.

Significant monitoring of surface water has been undertaken since the 1990s in Stage 1 and Stage 2 investigations, as part of Stage 3 works, and throughout Stage 4 works as part of the GCP/GTP monitoring programs and specific monitoring programs for Springvale Drain and Penrhyn Estuary (see Appendix D). Monitoring of surface water has been focussed on CHC contaminants, with temporal EDC concentrations presented in Diagram 6-23 (below), with key observations including:

- Volatile CHCs have historically been present along the entire length of the drain from upstream of BIP to Penrhyn Estuary, with the concentrations of volatile CHCs typically highest at the downstream boundary of Southlands near McPherson Street (SW005 monitoring location) and in the re-alignment channel.
- High temporal variability in concentrations of volatile CHCs has been shown.
- Historical maximum CHC concentrations (up to 250 mg/L) occurred in 1999/2000 when stormwater pipe relining and drain sediment remedial works were being undertaken, and decreased to relatively stable concentrations of between 20 and 50 mg/L by the end of 2002.
- Since commencement of groundwater extraction from the BIP and PCA hydraulic containment systems (late-2006), CHC concentrations have decreased significantly to the order of less than 0.01 mg/L (a two to three OoM decrease for EDC and for total CHCs). This is inferred to be due to a combination of decreasing concentrations in shallow groundwater, decreased discharge to the drain from lowering of the water table and downward hydraulic gradients induced by pumping the deeper aquifer.
- The main point of discharge during GTP operation and dry weather is inferred to be downstream (south) of Southlands. However, more recently (e.g. 2015), the highest concentrations of CHCs associated with the Southern Plumes were observed at the northern end of Southlands suggesting the greatest mass discharge of CHCs (other than EDC) is still at the north of Southlands.
- Prior to 2006, the major component of the CHCs in surface water at McPherson Street (SW005) was EDC, with total CHC mass typically comprising of 80 to 90% EDC. However, the proportion of a number of other CHCs has increased since late-2006 (primarily due to the relatively more significant decrease in EDC compared to other CHCs), with the proportion of EDC now less than 20% of total CHC mass.
- There is a correlation between groundwater levels and contaminant concentrations in the surface water within the drain – i.e. periods of elevated CHCs in Springvale Drain generally coincide with periods of elevated shallow groundwater elevations.
- Historical CHC mass discharges from Springvale Drain to Penrhyn Estuary would have been less than in the order of 0.5 to 40 kg/day (on the assumption that attenuation of CHCs occurs from the point of groundwater discharge to the drain and the estuary). The current contribution would be several OoM lower.

Low concentrations (<1 mg/L) of volatile CHCs were historically present in Floodvale Drain at upstream and downstream locations on Southlands, suggesting that Floodvale Drain intercepted shallow groundwater in a manner similar to Springvale Drain. Since GTP operation commenced, CHC concentration have decreased and remain low.

6.2.2 Vapour Phase

Volatilisation of CHCs within surface waters in Springvale Drain have the potential to cause elevated concentrations in the ambient air adjacent to the drain. The rate of volatilisation will be largely related to aqueous phase CHC concentrations at the water surface, which in turn is related to shallow groundwater discharge.

Monitoring of ambient air adjacent to the drain at, and downstream of, Southlands has been undertaken with historical data considered by EnRiskS (2010) and EnRiskS (2013b). Ongoing monitoring is conducted (see Appendix D) and remediation at Southlands has addressed risks from potential CHC vapour inhalation (Section 2.5.4).
Previous assessments have found:

- Concentrations of EDC and VC were most elevated in areas immediately adjacent to Springvale Drain in Southlands. Significantly lower concentrations were measured at the northern end of Southlands and along Floodvale Drain. Air concentrations were lower in areas located further from the drain.

- Based on surface water sampling results, it was considered likely that the contamination detected in the ambient air monitoring on Southlands was probably more closely related to vapours emanating from the re-alignment channel than from the main channel of the drain.

- URS (2009b) determined that there was a relationship between shallow groundwater levels and air concentrations adjacent to Springvale Drain and that the potential for elevated inhalation exposures to occur as a result of the discharge of shallow groundwater into Springvale Drain can be effectively monitored on the basis of groundwater level data.

- Since 2007, the concentrations of CHCs in ambient air adjacent to the drain have been low with few detections of CHCs above the LOR. There have been instances of elevated CHCs in ambient air (e.g. May 2013) that are likely to be due to elevated groundwater resulting from rainfall events and potentially associated with the temporary shutdown of the GTP. Elevated concentrations do not appear to be long lasting and low ambient air concentrations are re-established shortly thereafter.

- The non-detects (i.e. below LOR) of CHCs in ambient air adjacent to the drain generally coincide with low concentrations in surface water.

- Elevated CHCs in ambient air adjacent to the drain generally coincide with periods of shallow groundwater elevations significantly above the drain invert (EnRiskS, 2012).

### 6.2.3 Solid Phase

Discharge of CHCs in shallow groundwater and subsequent partitioning to sediments, and possible erosion and entraining of contaminated soils adjacent to the drains, resulted in sediments containing CHCs in Springvale Drain.

Sediment samples were collected from various locations throughout Southlands (the ‘SRA’ drain and paper waste ponds), Springvale Drain and Penrhyn Estuary during Stage 1 (AGEE, 1990) and Stage 2 (Woodward-Clyde, 1996c) investigations. Further investigations of sediments in Penrhyn Estuary and Botany Bay were undertaken for the then Public Works Department in 1992, in the Stage 3 program (Woodward-Clyde, 1997a) and in 2003/2004 (URS, 2004g). A conceptual sediment transport model for Springvale Drain was developed during the Stage 3 program (Woodward-Clyde, 1997a).

Sediment samples from the SRA drain and ponds located on Block 1 Southlands had elevated concentrations of semi-volatile CHCs (HCBD up to 85 mg/kg), PCE (up to 480 mg/kg) and TCE (up to 360 mg/kg), with concentrations decreasing with depth.

The section of Springvale Drain which passes through Southlands has had the highest CHC concentrations in sediments (Woodward-Clyde, 1996a). The CHCs detected at the highest concentrations were PCE, TCE, CTC, VC and CFM and ranged up to 760 mg/kg. EDC were detected at low (<1 mg/kg) concentrations. A range of semi-volatile CHC compounds were detected, the most significant being HCB (up to 118 mg/kg mid-Southlands) and HCBD (up to 16 mg/kg). DNAPLs were not detected in any dye field tests of sediments and soils (Woodward-Clyde, 1996f).

The relatively high concentrations of CHCs and other contaminants in Springvale Drain sediments, and the inferred transport of these sediments into Penrhyn Estuary, prompted the remediation of sediments in the drain in 1999/2000. The realignment channel was constructed in order to divert surface water flow and thus enabled excavation of contaminated sediments in the main channel. The drain was also lined with a low-permeability geotextile and coarsely crushed rock. The realignment channel was closed off but not filled in after the remedial works and is not directly connected to Springvale Drain. Since these remedial actions were completed, sediment buildup in the drain has occurred, though the more recent investigation of Penrhyn Estuary sediments did not detect HCB in sediments at the Springvale Drain outlet (URS, 2004g).

Minimal sediment sampling of Floodvale Drain has been conducted, with low (<1 mg/kg) concentrations of CHCs detected.
6.3 PENRHYN ESTUARY

6.3.1 Aqueous Phase

Significant monitoring of surface water has been undertaken, including a baseline survey (URS, 2004a) prior to GTP commissioning, and the GCP/GTP monitoring programs and specific monitoring programs for Springvale Drain and Penrhyn Estuary (see Appendix D).

Diagram 6-24: EDC and PCE concentrations in groundwater discharge zone at Penrhyn Estuary (September 2006, high tide)
CHCs in groundwater and surface waters within Springvale Drain and Floodvale Drain have the potential to discharge to Penrhyn Estuary. However, surface water flow from Springvale Drain (and Floodvale Drain to a lesser extent) is inferred to be the key contributor to CHCs in surface water within Penrhyn Estuary. The majority of CHCs other than EDC within Penrhyn Estuary are derived from the Southern Plumes, with a significant portion likely to be from Springvale Drain. In many recent instances (since late-2006), concentrations of volatile CHCs in surface water within the estuary have exceeded those reported in the pore water at the groundwater discharge interface, suggesting that discharge from Springvale and Floodvale Drains may have a more direct influence on Penrhyn Estuary surface water quality than groundwater discharge through the intertidal zone.

6.3.1.1 Drain Discharge

EDC concentrations within surface water have historically been low (<0.01 mg/L), with other principal CHC concentrations close to or less than the limit of reporting (typically 0.001 mg/L).

CHC concentrations at the drain outlets are typically at least one order of magnitude greater than detected in the estuary (e.g. see EDC concentrations in Diagram 6-23 (above). The trend of decreasing surface water CHC concentrations in a seaward direction is due to bulk mixing with seawater within Penrhyn Estuary.

In general, high tide surface water concentrations have historically been approximately one order of magnitude lower than at low tide, and reflect the dilution of Springvale Drain waters by seawater on the rising tide and tidal pumping, though this pattern has become less prevalent as concentrations have decreased.

6.3.1.2 Groundwater Discharge

As described in Section 3.5.7.2, groundwater does not discharge directly to Penrhyn Estuary, but is mixed with saline water in a transition zone approximately 2 m below the intertidal ground surface (URS, 2007a) (see also Diagram 3-13). Attenuation of CHCs within this zone will occur, with processes similar to those described for groundwater in Section 5.3.1, prior to discharge into the water column. A trend of decreasing groundwater concentrations at all depths is evident in a seaward direction, and concentrations decrease by approximately one to two orders of magnitude towards the discharge interface (see examples for EDC and PCE under high tide conditions in September 2006 in Diagram 6-24). The presence of this transition zone between groundwater and seawater is clearly delineated by pH, electrical conductivity and CHC concentration data.

Key CHC migration and attenuation processes in this transition zone include:

- Advective flow and mixing between groundwater and saline waters as described in Section 3.5.7.2. The degree of mixing will be influenced by groundwater flow, seawater salinity, wave action and tidal conditions.
- Dispersion and diffusion – diffusion processes within finer grained sediments in the transition zone may have a greater influence on CHC migration than in the broader sand aquifer.
- Degradation (transformation) processes have not been assessed at Penrhyn Estuary but will conceptually be more dynamic than in the broader aquifer due to the potential for different (and changing) redox conditions in groundwater and surface water, and biological activity near the discharge interface. Organic-rich bottom sediment and mud typically produce highly reducing conditions, which may be conducive to reductive dichlorination processes.
- Sorption (and desorption) of CHCs may be greater than within broader aquifer sands as estuarine sediments are typically organic rich and are more likely to have a higher sorption capacity.

6.3.2 Vapour Phase

Volatileisation of CHCs from surface water surface and exposed sediments is minimal at Penrhyn Estuary. Sampling of ambient air concentrations at Penrhyn Estuary was undertaken in 2005 and considered in the 2005 CHHRA (URS, 2005d). Since 2005 operation of the GTP has resulted in lower CHC concentrations in surface waters of Penrhyn Estuary (and Springvale Drain which flows into Penrhyn Estuary), and current air emissions are considered negligible.
6.3.3 Solid Phase

Sediments

A range of volatile and semi-volatile CHCs have been detected in sediments near the Drain outlets and within the inner Penrhyn Estuary in the Stage 1 and Stage 2 surveys. Penrhyn Estuary sediment samples collected during the Stage 2 investigations had few volatile CHCs. Semi-volatile compounds were more widely detected and HCB ranged from 0.004 mg/kg to 0.3 mg/kg (Woodward-Clyde, 1996f). Most of these samples were collected from the channel of Springvale Drain and Floodvale Drain.

The historically low concentrations of semi-volatile CHCs in groundwater in the vicinity of Foreshore Road, and elevated concentrations in Springvale Drain sediments, suggest that the presence of these compounds in Penrhyn Estuary sediments is largely due to sediment transport from Southlands via Springvale Drain, rather than groundwater discharge and subsequent sorption. This is supported by the distribution of HCB in Penrhyn Estuary sediments, which is consistent with the historical source of HCB contamination being Springvale Drain. However, samples collected from Springvale Drain did not contain detectable concentrations of HCB suggesting that the drain does not present an ongoing source of HCB to the estuary (URS, 2004g).

Sediment samples collected from background areas of Botany Bay reported concentrations of all of the target chemicals to be below the limit of reporting (URS, 2004g).

Biota

The ecological studies undertaken for the Port Botany EIS (Sydney Ports Corporation, 2003) indicated that Penrhyn Estuary was a functioning ecological unit with abundant and diverse benthos providing a foraging habitat for a variety of shorebird species. The foraging habitat has been identified as the prime ecological value of the estuary within the wider ecology of Botany Bay.

Biota, including fish, oysters, other fauna and flora, have been sampled in Penrhyn Estuary during various programs, with data summarised in the 2005 CHHRA (URS, 2005d) and 2010 CHHRA (EnRiskS, 2010). Site-related chemicals reported in biota were HCB, HCBD and mercury. HCB and HCBD were detected in numerous samples above expected background concentrations.

6.4 HUMAN HEALTH RISKS

Human Health Risk Assessments (HHRA) have been undertaken to assess human health risk issues in areas surrounding the BIP resulting from contamination associated with current and historical operations at BIP. The focus of the HHRAs has been risks to human health in areas located off BIP as risk issues on BIP are managed under Site Management Plans.

The prime document detailing the risks to human health is the 2010 Consolidated Human Health Risk Assessment (EnRiskS, 2010). The 2010 CHHRA updated and consolidated previous HHRAs, and is itself currently being updated to incorporate recent remediation projects (e.g. FCAP, CPWE) and Southlands remediation and development.

The prime focus on human health is a consequence of the mixed residential (including schools) and commercial land uses surrounding the BIP as well as recreational features such as the Botany Golf Course, parks and sports fields, as well as Penrhyn Estuary which was, at the time of writing the 2010 CHHRA, accessed by the general public for a range of recreational purposes.

The CHHRA (EnRiskS, 2010) concluded that:

- For realistic exposure scenarios, combined risks associated with emissions from all sources on the BIP, groundwater plumes and air emissions from the CPWE are below the adopted non-threshold target risk level of $1 \times 10^{-5}$ and below the threshold target level of 1.
- Potential risks to human health in areas off the BIP associated with all sources are considered low and acceptable.
• If activities associated with elevated individual risks (such as use of extracted groundwater, fishing in and access to Penrhyn Estuary) are included, then the total combined risk will be above the adopted target non-threshold risk level of $1 \times 10^{-5}$ and equal to the target threshold level of 1.

Risks associated with contamination at Southlands were assessed (EnRiskS, 2013b), with remediation/management measures to mitigate the risk implemented as part of the redevelopment (Section 2.5.4).

6.5 ECOLOGICAL RISKS

Environmental risks are considered to be associated with the potential for adverse effects on ecosystems or biota within ecosystems of Penrhyn Estuary. There are no ecosystems of concern within BIP or the immediate surrounding areas.

The environmental/ecological risks associated with the CHC and related contamination from BIP have not been assessed in an integrated manner, with assessments instead focussed on risks to human health. However, in relation to CHC contaminants the following points are of note:

• The estuary is considered to be a functioning ecosystem providing a valued wading bird habitat. This has developed under past conditions over a relatively short time frame (aerial photos from the early 1980s show the estuary to be barren sand dunes) and with contamination (from BIP and other sources within the stormwater catchment) likely to have been significantly worse than currently (post-GTP operation) observed.
• Appropriate ecological risk criteria include ANZECC (2000) guideline values.
• Contaminants that have the potential to bioaccumulate are related to historical stormwater discharges rather than groundwater.
• Irrespective of the current status as a functioning ecosystem, the groundwater remediation program has reduced groundwater flows to Springvale Drain and reductions in contaminant concentrations have occurred.

6.6 17C MODEL

The following provides an OoM semi-quantitative balance of CHC masses for each phase (where known), and key interactions between these phases within receiving environments.

<table>
<thead>
<tr>
<th>CHC Phase Balance:</th>
<th>Receiving Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vapour:</strong> CHC mass in ambient air overlying surface water is negligible.</td>
<td></td>
</tr>
<tr>
<td><strong>Aqueous:</strong> Aqueous CHC mass within the receiving environment has not been quantified and is in a high state of flux. Degradation of CHCs will occur, particularly in marine sediments of the intertidal zone of Penrhyn Estuary.</td>
<td></td>
</tr>
<tr>
<td><strong>Sorbed:</strong> Sorbed CHC mass to sediments has not been estimated.</td>
<td></td>
</tr>
</tbody>
</table>

1. CHC volatilisation flux from aqueous phases has not been quantified. Volatilisation from Springvale Drain may have been significant during periods of elevated CHCs in surface water (e.g. prior to early 2000s), but the mass transfer would have been small relative to that for plumes (on the basis of very small relative surface area). Volatilisation from Floodvale Drain and Penrhyn Estuary was/is considered negligible.

2. Mass transfer from shallow groundwater discharge to Springvale Drain (and subsequent discharge to Penrhyn Estuary) was discussed in Section 6.2 and has been estimated to have been in the order of 0.5 to 40 kg/day prior to early-2000s. Current mass transfer is expected to be orders of magnitude lower.

3. Differential sorption to sediments is uncertain. Given the highly dynamic environment and significant fluxes of stream flow in drains and tidal exchanges in the estuary, sorption/desorption is unlikely to represent a significant phase interaction relative to aqueous processes.

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23 Noting that groundwater extraction for non-industrial purposes is prohibited with the GEEA.
24 There has been a ban on fishing in Penrhyn Estuary since late 2004.
25 Since publication of the 2010 CHHRA public access restrictions have been imposed at Penrhyn Estuary as part of the Port Botany expansion.
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8 PRINCIPLES AND LIMITATIONS

Use of this document is subject to the limitations on the following page and the following principles intended to be referred to in resolving any ambiguity or exercising such discretion as is accorded the user of this document.

Elimination of Uncertainty
Some uncertainty is inherent in all conceptual models. Professional judgment and interpretation are inherent in the process, and even when exercised in accordance with objective scientific principles, uncertainty is inevitable. Additional assessment beyond that which was reasonably undertaken may reduce the uncertainty.

Limitations of Information
The conceptual model may be compromised by limitations, defects and uncertainties in the information used to develop the model.

Level of Assessment
The conceptual model herein should not be considered to be an exhaustive assessment of environmental conditions or contaminant behaviour at the site. There is a point at which the effort of information obtained and the time required to obtain it outweigh the benefit of the information gained and, in the context of private transactions and contractual responsibilities, may become a material detriment to the orderly conduct of business. The extent of further assessment is a function of the degree of confidence required and the degree of uncertainty acceptable in relation to the objectives of the assessment.

Comparison with Subsequent Inquiry
The justification and adequacy of the model findings in light of the findings of a subsequent inquiry should be evaluated based on the reasonableness of judgments made at the time and under the circumstances in which they were made.

Data Useability
The conceptual model is based on data presented by other parties that generally only represent the site conditions at the time and location the data were generated. Therefore, the usability of data collected as part of this model may have a finite lifetime depending on the application and use being made of the data. In all respects, a future reader of this report should evaluate whether previously generated data and opinions are appropriate for any subsequent use beyond the original purpose for which they were collected, or are otherwise subject to lifetime limits imposed by other laws, regulations or regulatory policies.