CONTAMINANT FLOW IN GROUNDWATER IN HAWKESBURY SANDSTONE – EXPERIENCE FROM MAJOR BASEMENT EXCAVATIONS

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ABSTRACT

The geology and hydrogeology of the Hawkesbury Sandstone is well documented in relation to the construction of deep excavations and water resources. Less well known is the impact of structure/defects and bedding in relation to contaminant migration into excavations.

The Triassic Hawkesbury Sandstone is a quartz sandstone, cut by many igneous dykes and characterised by dominant NNE and ESE trending fault/joint zones. The sandstone can be divided into sheet, massive and mudstone facies (Hebert, 1983). In vertical section, the sheet (or cross bedded) and massive facies make up 95% of the formation (Pells, 1998). Tammetta and Hewitt (2004) indicate the hydraulic conductivity of the sandstone is related to defect characteristics, which is influenced by depth and in situ stress and ranges from a mean of 0.1 m/day near surface to 0.002 m/day at 50 m. Many studies also document the changes in vertical and horizontal permeability of the sandstone (AGL, 2013).

With urban renewal, many old industrial sites are being redeveloped for residential purposes. The developments are often multi-storey with multiple basement car parking levels. Investigations of groundwater contamination at these sites often requires installation of monitoring wells to below the basement depth to assess the potential risk to human health and the environment.

The migration of contaminants particularly hydrocarbon compounds can migrate into the defects in the unsaturated zone and may form light non aqueous phase liquids (LNAPLs such as petrol) in the fractures or dense non aqueous phase liquids (DNAPLs such as chlorinated solvents or coal tar) that sink below the water table.

Contamination assessments in Hawkesbury Sandstone should identify the various facies and target particular bedding planes and defects for groundwater sampling. Identifying the presence of major joint sets in vertical boreholes can be more problematic and may result in a poor understanding of the vertical migration. Often this can only be fully appreciated during excavation. In many areas, the water level measured, also represents a phreatic surface due to the location of the site within a catchment.

This paper provides examples showing how contaminant migration is driven by the vertical permeability in sub-vertical defects/joints and by the horizontal bedding planes between the various sedimentary facies in the sandstone.

1. BACKGROUND

Urban renew is transforming much of Sydney's landscape with the construction of many high rise residential properties. Small scale renewal is widespread in Sydney suburbs and is occurring on an individual lot basis particularly in the inner city suburbs and close to public transport hubs. In some areas, wholesale acquisition of commercial, industrial and isolated residential properties has allowed construction of multi-building developments such as at Erskineville, Leichhardt, Meadowbank and Mortlake. Many of the developments require excavation into the underlying sediments and bedrock to allow the construction of one to four basements. These basements often extend to the full area of the development requiring excavations from 3 to 12 m below ground level. This paper concentrates on excavations into Hawkesbury Sandstone.

Many of these commercial and industrial lots were former service stations, motor mechanics, dry cleaners, industrial/commercial units or estates, and small to large-sized industrial sites manufacturing paint, furniture, heavy engineering and clothes. Contamination assessment, remediation and/or management has become an integral part of the planning, approvals, and construction of these developments and is driven by widespread legislation such as the NSW Contaminated Land Management Act (1997) (CLMA, 1997) and the Environmental Planning and Assessment Act (1997) (EPAA, 1997).

The management of any contaminated site may include the following stages:

- Preliminary or desktop assessment (also called Phase 1 assessments, this may or may not include preliminary sampling)
- Detailed site investigation (Phase 2 assessments)
- Remediation Action Plan (RAP)
- Remediation Implementation, validation and site monitoring

Contamination management occurs throughout the development process and may include the:

- Planning and approval stage where the potential for contamination needs to be identified to highlight the need for preventative or corrective environmental works. This may include desktop and intrusive investigation studies to identify potential contaminated sources, the type and extent of and contamination and the potential environmental and human health risks. Council and/or regulators may also require the development and approval of the RAP for the soil, rock and groundwater to enable the site to be remediated. This may also require review by an independent NSW Environment Protection Authority (EPA) accredited site auditor and/or notification under the Duty to Report Contamination under the CLMA, 1997;
- Excavation/Construction stage where any remediation is undertaken including the assessment of any excavated materials for recycling or reuse (such as excavated natural materials (ENM) or virgin excavated natural materials (VENM). During this stage any remediation must be validated in accordance with the RAP to allow a site auditor to prepare a site audit statement (SAS) and site audit report (SAR) indicating that the site is suitable for the intended use and that the site works comply with NSW EPA guidelines and the development conditions of consent, and;
- Post construction stages where residual contamination remains and must be managed by a site specific environmental management plan (for example impacted groundwater in bedrock fractures presents a potential vapour intrusion risk). Longer term monitoring may also be required if residual groundwater contamination remains or the site is regulated under the CLMA, 1997.

This paper outlines examples of contaminant migration in Hawkesbury Sandstone to enable practitioners (developers, consultants and site auditors) to appreciate issues related to contaminant flow particularly in relation to excavations for basement car parking and other services. The aim of the contamination assessment is to ensure that the site is characterised to enough details so that remediation of contamination is maximised during the excavation works and that the sandstone is segregated, classified and recycled/disposed of in accordance with appropriate guidelines and that human and environmental health is protected.

2. HAWKESBURY SANDSTONE

Excavations into the Middle Triassic Hawkesbury Sandstone clearly identify the three sedimentary facies or depositional units outlined in (Herbert & Helby, 1980). These facies include:

a) Massive sandstone facies,
b) Sheet sandstone facies, and
c) Mudstone facies.

The massive facies comprise sandstone which is typically homogeneous in grainsize and is either uniformly massive or displays poor to well-developed undulose laminations. The lower bedding planes are commonly concave erosional surfaces with shale breccia frequently occurring in the erosional troughs. The sandstones are generally lighter in colour, have slightly finer grains and tend to weather more recessively than the sheet facies. The massive facies usually passes conformably into the sheet facies.

The sheet facies sandstones consist of sets of cross bedded strata which are bounded by planar horizontal surfaces or bedding planes. The cross bedding sets vary in thickness from a few centimetres to more than 6 metres.

The mudstone fades are generally less than 12 metres thick and typically range from 0.3 — 3 metres. They have limited lateral extent and can also be described as a shale lenses. The shale lenses comprise grey mudstone, which is often slightly carbonaceous and include fine sandstone laminations. Many of the various facies also have fining upward sequences which results in either finer sandstone or thin siltstone layers forming at the top of the sedimentary unit. These finer sandstone or siltstone layers can have a significant impact of groundwater and contaminant migrations as outlined in Section 6.

There is considerable lateral and vertical variation of facies within the Hawkesbury Sandstone making it difficult to correlate the three facies over long distances but they can usually be correlated in most basement excavations (See Figure 1).

Figure 1 Various sedimentary facies exposed over nearly 100 m at Mortlake, NSW.

3. STRUCTURAL GEOLOGY

Various fractures or defects (joints, bedding planes, crush and shear zone and faults) in the sandstone all impact the various weathering process, the topography and groundwater and contaminant migrations. Often the first expression of these defects is identified in geotechnical or environmental investigations which require coring of the sandstone for foundation, support, excavatability, groundwater and contamination assessments. A database of some 70 boreholes (De Castro et al, 2009) in Hawkesbury Sandstone identified that:

- Sub-horizontal defects comprised 68% of the total defects with sub-vertical defects comprising 32%;
- The number of sub-horizontal defects decreased with depth, and
- The aperture size varied from 0.3 mm to 500 mm for sub-horizontal defects and 0.3 mm to 100 mm for sub-vertical defects but generally they were 0.5 mm or small.

2.1 BEDDING

The regional dip of the Hawkesbury Sandstone is approximately 2 - 5 degrees to the southwest. Cross bedding generally dips at between 10 and 30 degrees toward the northeast (Herbert, 1980). The bedding between the various facies can either be planar as described above or form erosional surfaces and troughs and can be clearly seen in Figures 1 to 4. The bedding planes whether planar, erosional or troughs have a significant impact on groundwater and contaminant migration and aid with the overall weathering of the sandstone. Following rain, seepage from the sandstone bedding planes can be clearly seen in major road cuts such as those between Berowra and Ourimbah on the M1 motorway.

2.2 JOINTING

Widely spaced joint sets are common within the Hawkesbury Sandstone with spacing between major parallel joints ranging from 0.3 to 10 metres (Herbert, 1980). The dip of the joints is generally vertical to sub-vertical but some joints dipping at 30 to 45 degrees may also been encountered. The joint surfaces are generally rough and open in the upper weathering zones and coated with iron oxides. Even at depth in fresh rock the joints may be slightly open and may have coatings of pyrite, carbonate or quartz. High angle defects and joints in sandstone are frequently open to depths of 30 m and where jointing effects are more pronounced (e.g. in crush or shear zones or near dykes), the potential for water movement is considerably increased. (Chestnut in Herbert 1983, Dale et al, 1997).

Two dominant joint directions have been identified, oriented at 005 — 035 degrees (true) and 090 — 125 degrees. The latter coincides with the dominant igneous dyke directions (Herbert, 1980 & Dale et al, 1997). In addition to the dominant direction, joint swarms are noted in the NNE – SSW direction by many commentators and documented in Och et al 2012. Joint swarms have been observed by the author at approximately 300 m spacing in the inner city similar to those identified in Figure 2. The joints in the swarms tend to be relatively continuous across the sedimentary facies but may also be offset with both types visible in Figure 2.

Elsewhere, joints often terminate on a bedding plane visible in Figures 3, 4 and 8.

2.3 FAULTS & DYKES

Small scale fault and shear zones are often encountered in various excavation but are rarely detected or considered during contamination investigations.

As indicated above many igneous dykes closely follow the direction of the primary joint sets and can extend over many kilometres. Several dykes have been encountered in many excavations in the Sydney region (Dale et al, 1997) and can have a significant impact on migration pathways.

Figure 2: Sub-vertical continous and discontinuous joints within the Hawkesbury Sandstone in the Fort Street cut near the Habour Bridge.

Figure 3: Sub-vertical joint and primary migration pathway Ballast Point, Birchgrove, NSW.

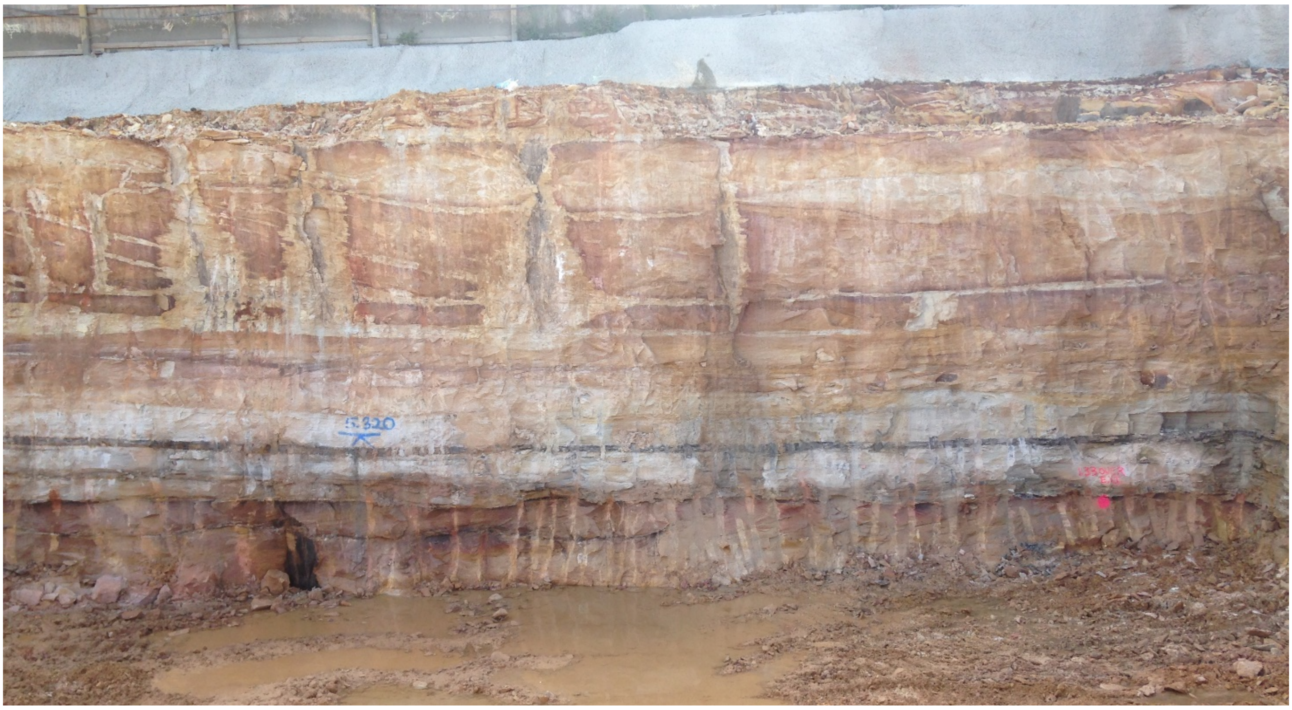

Figure 4. Discontinuous joints in Hawkesbury Sandstone at Mortlake. The joints clearly show the increased weathering around the fracture and iron staining on the lower joint resulting from probably contaminant migration.

4. WEATHERING, POROSITY & PERMEABILITY

Weathering within the Hawkesbury Sandstone closely follows the bedding planes (both the sub-horizontal and cross beds) and the various joints and other fractures. Groundwater flow is variable throughout the sandstone, and is generally dominated by secondary porosity and fracture flow. A good example of the weathering along these discontinuities are shown in Figure 5 and the associated nearby core in Figure 6. This type of weathering has geotechnical as well as environmental considerations when investigating a site to be excavated for a basement.

Figure 5: Weathering along cross bedding planes, and subvertical joints at Meadowbank

Figure 6: Borehole close to excavation in Figure 8 showing weathering in NMLC core

The weathering along the primary joint sets and bedding also determines the regional topography of the area with the sandstone forming benches, which step down from plateau or ridge crest areas, and detached blocks (formed by fractures along the bedding planes and joints allowing the block to rest on the underlying strata). While the joints are not mapped or logged during the initial phases of many subsurface contamination investigations, the use of the regional joint directions or strike from nearby outcrops can be useful in determining the approximate direction of vertical groundwater and contaminant flow.

Porosity of the Hawkesbury Sandstone depends on the cementation of the sandstone (and weathering at the other end of the depositional/weathering cycle) and ranges from 5 – 20% (Liu et al, 1996) with mean and median results for all 1228 cores at 14.8% and 15% respectively. Pells (2004) documents a mean porosity of 16% in the sandstone with the massive “yellow block” sandstone used on many Sydney buildings having a porosity of 8 – 11%.

Studies of the 1228 sandstone cores taken from an excavation in Sydney by Liu et al (1996), also found that the permeability of the Hawkesbury Sandstone did not show any obvious relationship to the porosity but was more closely related to the type of sedimentary facies. As a corollary, they also found that the subdivision of the sandstone into the relative facies types significantly improved the prediction of the permeability distribution.

Permeability information on the Hawkesbury Sandstone has been collected from major road Is available in the immediate area, however, a summary of permeability testing carried out for the urban road and rail tunnels such as the Eastern Distributor and Epping to Chatswood Rail Link and from individual groundwater resources, geotechnical and research studies. The available permeabilities are summarised in Table 1.

Table 1: Published permeability data in Hawkesbury Sandstone (various authors)

Hawkesbury Sandstone	*Horizontal Permeability (m/day)*	*Vertical Permeability (m/day)*	*Range (m/day)*	*Mean (m/day)*	*Source*
Unconfined / semi- confined aquifer	0.1	0.05 – 6 x 10^{-4}			McKibben & Smith, 2000 & SCA, 2005
Sydney Road Tunnels[1]				3.5 x 10^{-2}	Burgess et al 1987
Top 20 m				0.1	Tammetta & Hewitt, 2004
Below 50 m				2 x 10^{-3}	Tammetta & Hewitt, 2004
Sandstone I I II[2]			1 x 10^{-4} - 2 x 10^{-2}	2 x 10^{-3}	Pells, 2004
Sandstone III[2]			1 x 10^{-3} – 0.5	1 x 10^{-2}	Pells, 2004
Sandstone IV I V[2]			1 x 10^{-2} -1.0	5 x 10^{-2}	Pells, 2004
Shale I I II[2]			1 x 10^{-4} – 0.25	2 x 10^{-3}	Pells, 2004
Shale III[2]			1 x 10^{-3} – 0.5	1 x 10^{-2}	Pells, 2004
Shale IV I V[2]			1 x 10^{-2} – 0.25	1 x 10^{-2}	Pells, 2004
Six Cores				1.9 x 10^{-3}	Tammetta & Hewitt, 2004
Poorly to Low angled X bedded[3]			9.6 x 10^{-2} - 1.1	4.5 x 10^{-1}	Liu et al, 1996
Large Scale X bedded to Massive[3]			3.4 x 10^{-4} - 6.9 x 10^{-1}	1.9 x 10^{-1}	Liu et al, 1996
Small Scale planar or trough X bedded[3]			8.6 x 10^{-5} - 7.5 x 10^{-2}	1.5 x 10^{-2}	Liu et al, 1996
Leichhardt to 8mBGL[4]			6 x 10^{-3} - 2	4.7 x 10^{-1}	EI, 2015
OVERALL RANGE			8.6 x 10^{-5} - 2		

1 – 50% probability not to exceed 4 x 10^{-7} m/s

2 - Measured in Lugeons = approx. 0.01 m/day, Log mean results

3 – 1228 core permeability measure with an air permeameter, md = 8.61 x 10^{-4} m/day
4 - Unpublished

5. HYDROGEOLOGY

Sydney's sandstone has been known as a groundwater resource from the time of settlement. The construction of Sydney's second water supply taking water from the Botany Sands in Centennial Park also found considerable seepage into the tunnel from fractures in the sandstone (Dale & Burgess, 1988). The Hawkesbury Sandstone is considered to be a layered aquifer system, with groundwater occurring in vertically discrete horizons that do not migrate downwards unless they are connected by flow along secondary sub-vertical fracture joints/fault zones or weathered zones. Groundwater movement is controlled by elevation of the potentiometric surface, which is a general expression of the topography and primary joint sets, and generally flows towards the direction of nearest drainage lines and creeks (AGL, 2013)

At most sites, the groundwater is present in the surficial fill and residual soil layers and in the underlying sandstone bedrock fractures. The amount of water will be dependent on the general surface water recharge and prevailing weather conditions of the local area. Sites near the top of a ridge crest area, may have limited catchment areas which is often restricted by paved surfaces, building footprints and the various street/stormwater drainage systems. The infiltration will migrate across the bedrock surface and into any weathered bedrock or bedrock joints and bedding planes. Vertical migration is controlled by the vertical or sub-vertical joint sets (and any faults or dykes) and the rock matrix permeability and the horizontal migration is controlled by the bedding planes and any structural unloading cracks, Migration pathways are often seen on selected bedding plane fractures and are visible in many of the core photographs provided in the various geotechnical and environmental reports (see Figure 7).

Figure 7 Migration pathway for chlorinated solvents along major bedding plane, Leichhardt

The overall permeability of the Hawkesbury Sandstone is related to defect characteristics, which in turn are heavily influenced by depth and in situ stress conditions. The hydraulic conductivity decreases with depth, due mainly to decreasing sub-horizontal defect aperture (from overburden pressure) with increasing depth. (Tammetta & Hewitt, 2005).

The standing water level in the monitoring wells may also reflect the screened interval and the location of the well in the catchment. Monitoring wells constructed on the side slopes or foot slopes of the catchment may exhibit pressure differential resulting in the standing water level being measured as a phreatic or potentiometric surface reflecting the pressure gradient rather than the actual water level (and amount) within the sandstone formation. It is also important to consider the layered geometry of the sandstone with groundwater movement along separate bedding planes, which may result in different water quality at different depths (e.g. more oxygenated water from surface infiltration or more contaminated water from lighter or denser chemical compounds.

Sandstone groundwater is commonly acidic with pH often recorded below pH 5. In association with the low pH, dissolved oxygen levels are low and elevated iron is present in the ferrous state (Fe^{2+}). On exposure to air in basement excavations the iron oxides to the ferric state (Fe^{3+}).

6. CONTAMINANT MIGRATION

Understanding the mechanisms governing groundwater migration through fractured rock is essential for design and implementation of site assessment, site characterisation and any subsequent remediation or management of the contaminated groundwater. In most bedrock, groundwater flow systems (both groundwater and contaminant migration) is primarily through perched flow over the top of the bedrock, through interconnected fracture and bedding planes systems, or some minor flow through the rock matrix. The amount of flow through the Hawkesbury Sandstone matrix depends primarily on the degree of cementation (silica) and weathering. Contaminant migration into and out of the rock matrix is dependent on the contaminant type but is typically diffusion-controlled, and the weathered rock matrix may act as a long term, low concentration residual or secondary source after contaminant sources (such as underground tanks or other infrastructure) are removed.

Fracture/bedding patterns can be identified and developed into a conceptual site model (CSM) from regional data (as indicated above); but, details regarding specific fracture/joint orientation, bedding plane locations, depths, and interconnections (continuous or discontinuous) on a local site scale is much more uncertain without detailed investigation. Water transmitting characteristics of individual fractures are related to aperture size, openness, and interconnections with other fractures or bedding planes. Fractures in the Hawkesbury Sandstone within the top 20 m, generally tend to be more open and transmissive than those in fresher sandstone at depth (Tammetta & Hewitt, 2005). For example, a permeability of 2 m/d was measured near the bedding plane in Figure 7 at 5.7 m below the surface.

Groundwater flow through discrete, planar bedding planes with a higher degree of variability in permeability can result in a wide range of velocities within a given rock mass. The more open, permeable fracture/bedding plane networks serve as primary conduits for large scale groundwater and contaminant migration. Due to fracture control over groundwater flow directions, anisotropic behaviour of groundwater flow (from continuous or discontinuous defects) is predominant on a local scale; but as the scale increases, overall flow patterns should become more predictable (but not always). The sloping planar surfaces of fractures and bedding planes (regional dip or erosional troughs) provide conduits for hydraulic head or gravity driven migration of contaminants (particularly DNAPL).

The impact of open discontinuous fractures can be seen in the Hawkesbury Sandstone at Ballast Point (Figure 8) which was a former oil and grease terminal and now developed into a harbour side park. Residual hydrocarbon contamination which is present in the open joints and the rock matrix is seeping out of the sandstone on the planar and cross bedded bedding planes (above layer S1). The contamination is degrading within the fractures and rock mass resulting in the development of a low oxygen environment causing the iron to convert to the ferrous state (Fe^{2+}). On exposure to air the iron converts to ferric iron (Fe^{3+}), often with a bacterial slime as depicted in Figure 8. The joint terminates on the S1 layer with seepage and build-up of saturated rock on the planar surface. The resultant saturation has also allowed seepage from the cross bedding planes sloping downwards from the main joint. On some days the hydrocarbon odour is still present but was previously assessed as very low risk to human health and the environment.

Figure 8 Hydrocarbon impacted seepage visible on bedding planes at Ballast Point, Birchgrove.

Several zones of groundwater were encountered in the Hawkesbury Sandstone at Mortlake (Figures 1, 4 & 9). The perched zone identified localised seepage water present at the fill / sandstone interface, and was influenced by fresh surface infiltration. The upper groundwater zone was present within a water bearing zone highly weathered, iron stained sandstone present beneath the site (depicted in Figure 4), at an approximate depth of 6 – 8m below the surface. Below this cross bedded and laminated (with siltstone) sandstone, massive fresher sandstone was encountered which was saturated (the lower groundwater zone) and continually seeped into the excavation. The base of upper groundwater zone overlying the fresher massive rock an erosional surface characterised by a siltstone breccia.

Standing water levels were found to be significantly higher than water bearing zones observed during drilling. The groundwater levels were also fairly consistent between the wells even though the wells were screened different intervals suggesting that the water levels were indicative of a semi-confined aquifer affected by relatively uniform potentiometric pressure. The groundwater contours developed closely follow the topography which in turn closely reflected the predominant regional joint pattern which had formed a typical stepped surface profile.

During excavation a number of dominant sub-vertical ENE – SSW joints were identified which intersected the sandstone strata. Four major joints were identified and may represent a joint swarm (see Figure 9). While discontinuous joints were also detected (Figure 4), they appeared to be largely in the top 5 m of the sandstone profile. The location of one of the primary joints was considered to be the primary migration pathway for organic contamination from the tank storage. The organic contamination was detected in the most downgradient wells but was not detected in the shallower or offset monitoring wells. This reinforces the need to consider the Hawkesbury Sandstone as a layered aquifer system where the layers may be fed by different infiltration water.

While the majority of the monitoring wells were impacted with heavy metals copper, nickel, mercury and zinc, there was no significant variation detected within the different groundwater zones and the metals were detected on the upgradient site boundary. The metals were therefore considered to represent regional heavy metal concentrations in groundwater, and were not considered to represent a risk to environmental human health.

As the primary sub-vertical and sub-horizontal migration pathways were excavated as part of the development (see excavation extent on Figure 9), the potential for residual groundwater contamination or LNAPL within the fractured sandstone strata was removed and validated with extensive groundwater monitoring and vapour assessment.

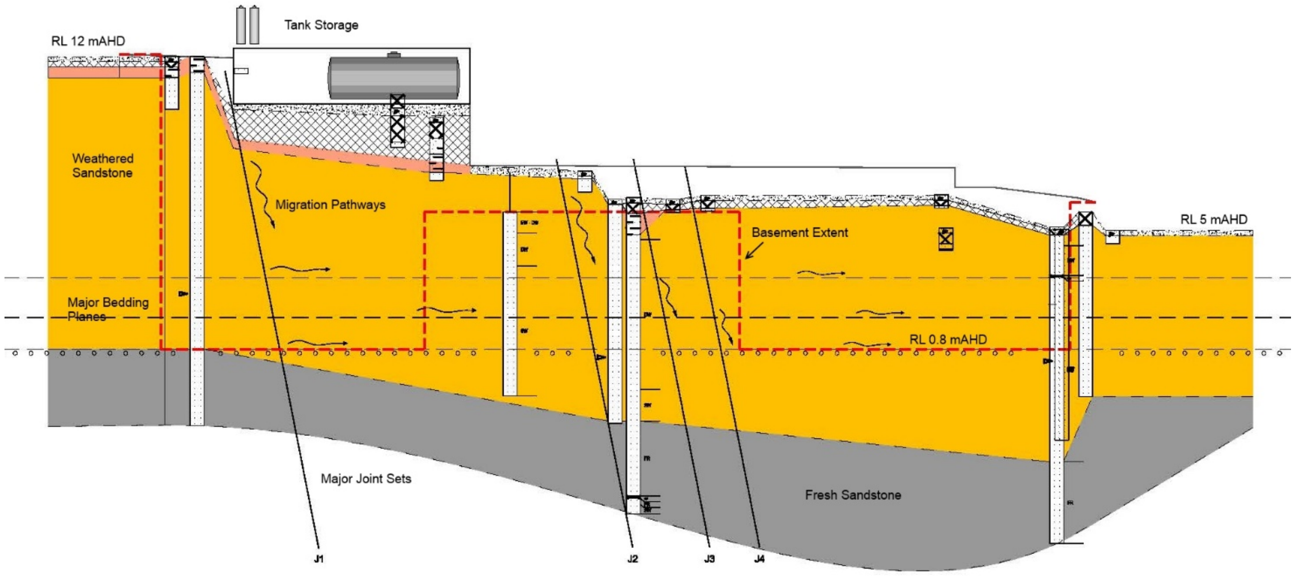

Figure 9 Cross section of major excavation at Mortlake showing migration pathways.

7. IMPACT TO EXCAVATIONS

The development of a site conceptual site model (CSM) allows the identification of contamination sources (and types), migration mechanisms and exposure pathways to any potential on-site and off-site receptors. Receptors can be considered to be the:

- Site workers during excavation and construction (inhalation, ingestion and dermal contact with contaminants);
- Future residents and occupiers of the development (these may be commercial or residential users);
- Surrounding residents and occupiers (particularly during excavation and construction);
- Underlying and off-site groundwater and groundwater from dewatering, and
- Environmental receptors like creeks, stormwater systems, wetland and the marine environment (particularly as many of the new development surround the foreshores of Sydney Harbour).

Increasingly problematic for development in Sydney is the potential for vapour intrusion of toxic chemicals from impacted soils, groundwater and any residual LNAP or DNAPL. Should contaminated groundwater (or sandstone) be present under basements or seeping into the basement the risks posed from vapour intrusion may remain. Should this be assessed as a potential risk expensive vapour mitigation measures may be required including passive or active ventilation systems, specially designed vapour barriers and/or groundwater pumping systems that require special licences to water disposal or on-going water treatment systems. If these are not identified early in the investigation process and addressed at part of the site excavation and site remediation they can result in considerable cost to the development.

Other impacts include but are not limited to:

- Whether the removal of concrete slabs would allow more infiltration of the contamination to the underlying bedrock or groundwater;
- The cost of specialist contaminant assessment (such as passive and active vapour sampling or multi-level well installation as outlined in Parker, 2007) and remediation technology (e.g. in situ chemical oxidation or vapour extraction or vapour membranes);

- Restrictions on use (recycling and reuse) of the excavated sandstone following the waste classification;
- The cost of removal of potentially contaminated seepage into the excavation and whether this may require treatment before disposal;
- Increased work health and safety requirements to protect site workers and the surrounding residents.

Off or on-site migration of contaminants are often identified during contamination assessments and may require regulation under CLMA, 1997, extensive vapour and groundwater monitoring and the development of a long term Environmental Management Plan to be managed by the site owners or body corporate.

8. CONCLUSIONS

The assessment of groundwater contamination in the Hawkesbury Sandstone requires the development of a detailed conceptual site model to fully understand the migration pathways of organic contaminants and implications to the design of an effective remedial system. This conceptual site model may only be fully developed after a number of investigation stages to understand the local geological and hydrogeological conditions of the sandstone. Further the full impact of the layered sandstone may only be seen with multilevel groundwater sampling points and time series contaminant data or sometimes not until the sandstone is excavated.

In conclusion, contamination of the Hawkesbury Sandstone and the associated groundwater is commonly found during urban renewal of former commercial and industrial sites. When assessing and remediating potential contaminants within the sandstone, it is important to consider that:

- the underlying Hawkesbury Sandstone is a layered aquifer system with layers that may be discontinuous over relatively short distances;
- the vertical and horizontal permeability within the sandstone may be different;
- contaminant flow may not follow the expected pathways particularly if the sub-vertical fractures are continuous or discontinuous over the different layers,
- the regional fracture/joint sets and the overall topography are a good indicator of the direction of potential contaminant movement (which may include off-site migration);
- the various sedimentary facies and the primary bedding planes should be identified, where possible, using coring and selective or multi-level sampling to fully understand the extent of any impacts; and
- the cost of remediation or management of any residual contamination may be high and require longer term solutions.

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