ENERGETIC MATERIALS CONTAMINATED SITE CHARACTERISATION AT THE FORMER EXPLOSIVES FACTORY MARIBYRNONG (EFM), VICTORIA, AUSTRALIA.

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ABSTRACT

Energetic materials contamination was investigated at the former Explosives Factory Maribyrnong, Victoria Australia. Spectrophotometric / HPLC analysis was utilized to delineate a five tonne crystalline 2,4,6-Trinitrotoluene (TNT) source in a former process waste lagoon that was found to be supplying contaminant leachate to the surficial clay aquitard with a maximum recorded concentration of 7.0 ppm TNT. Groundwater within underlying aquifers was found to be uncontaminated due to upward hydraulic gradients resulting in slow plume development and propagation. The simulated TNT plume in the clay acquitard using ATRANS20 software is localised within a few metres of the source. At steady state, though leaching rate calculations suggest that without mitigation or other changes to the system, persistence of the source would be approximately 2000 years. Remediation strategies may involve removal of the source zone and infilling with an impermeable capping to impede leaching while facilitation ongoing natural attenuation by anaerobic degradation.

RÉSUMÉ

Une évaluation de la contamination par des matériaux énergétiques a été faite à l'ancienne usine d'explosifs Maribyrnong, Victoria, Australie. Une zone source contenant 5 tonnes de 2,4,6-Trinitrotoluène (TNT) a été délimitée au fond d'une ancienne lagune recevant l'effluent liquide du procédé de fabrication. Celle-ci a laissé s'infiltrer dans l'aquitard sous-jacent d'argile des contaminants dissous dont la concentration maximale en TNT peut atteindre 7.0 ppm. L'eau souterraine dans les aquifères sous-jacents n'est pas contaminée puisqu'un gradient hydraulique ascendant existe. Selon les simulations avec ATRANS20, le panache de TNT dissous s'étend à quelques mètres de la source. Un bilan de l'infiltration d'eau en régime permanent suggère que sans mitigation ni autres changements au système, la source persisterait environ 2000 ans. Les stratégies de mitigation pourraient impliquer l'excavation de la zone source suivi d'un remblayage avec un matériau imperméable afin d'empêcher l'infiltration d'eau tout en facilitant l'atténuation naturelle des contaminants par biodégradation anaérobique.

1. INTRODUCTION

With a worldwide trend of ongoing demilitarisation and an increasing transparency of military/government bodies concerning environmental issues, it has become apparent that many military sites are contaminated by energetic materials. In the U.S. alone, 11000 sites are listed as being contaminated by nitroaromatic compounds (Hains et al. 2001). An increased awareness of the problem has triggered a subsequent increase in multidisciplinary research into understanding the behaviour of nitroaromatic compounds in the environment, with military facilities increasingly being targeted for assessment and remediation. The former Explosives Factory at Maribyrnong (EFM) is one such facility. With redevelopment for residential and recreational land use pending, assessment and understanding of the distribution, fate and transport of TNT and other energetics contaminants in soil and groundwater at the site is an essential precursor to the design and implementation of effective remediation strategies.

The current state of knowledge concerning the nature and extent of residual contamination at energetic materials contaminated sites is inadequate to ensure management of these facilities as sustainable resources. The potential for environmental impacts, including contamination of drinking water supplies, mandates that R&D be invested to understand and characterize potential contamination. The current study was integrated with an ongoing overall contaminant assessment of EFM conducted by private environmental consultants. In this context, groundwater, surface and subsurface soils were studied at specific target areas within the bounds of the site.

1.1 Objectives

Objectives of the study included;

Apply the Key Technical Area (KTA-4-28) protocol under the umbrella of the international collaboration panel of the TTCP (The Technical Cooperation Program) at an energetic materials contaminated site.

Characterise the hydrogeological setting at EFM with a view to assessing possible migration pathways for energetics contaminants towards likely/sensitive receptors.

Delineate the spatial extent of energetics contamination at the study areas via assessment of type, relative abundance, concentration and distribution of energetics contaminants in groundwater, surface and subsurface soils.

Develop a contaminant transport model using laboratory determined natural attenuation process rates, established literature constants, and field recorded hydrogeological characteristics/contaminant data to assist in predicting explosives migration.

Evaluate the fate and transport of TNT at the study areas, and hence develop a conceptual model describing contaminant persistence, mobility and the potential for natural attenuation as a remedial option.

1.2 Site Description

The EFM site is located approximately 12 kms north west of central Melbourne, Australia. The 77.6 ha site is bounded to the north, east and west by the Maribyrnong River. Surrounding land use is predominantly recreational/residential, hence the intended re-zoning of the site to residential land use. Production occurred between 1910 and 1991, with re-development targeted for completion by 2005.

The TNT production area and associated waste lagoons located on the northern floodplain on the inside bend of the Maribyrnong River were targeted as the main study area of expected residual energetic material contamination. TNT was manufactured at EFM from 1928 to 1944 with hot, acidified effluent wastes (HNO_3 and H_2SO_4) drained overland into nearby lagoons for settling and photodegradation. The adjacent Burning Areas, used for open burn disposal of munitions and chemicals was also identified as a region of interest (Figure 1).

Topographically, the main features include the northern floodplain, a hill to the southeast which rises to about +34m AHD (Australian Height Datum) and an elevated terrace between the western flank of the hill and the Maribyrnong River which rises +11m to +15m AHD (Figure 2). The geological sequence at EFM is deeply incised by the Maribyrnong River. Elevated areas of the site have outcropping Newer Volcanics basalt and Brighton Group sediments, while the lower areas are dominated by Pliocene to Recent age sand, silt and gravel deposits including Recent terrace alluvium (Maribyrnong Terraces) and Coode Island Silt (Bell et al. 1967). On the lower floodplain areas, alluvial deposits are underlain by the Older Volcanics basalt.

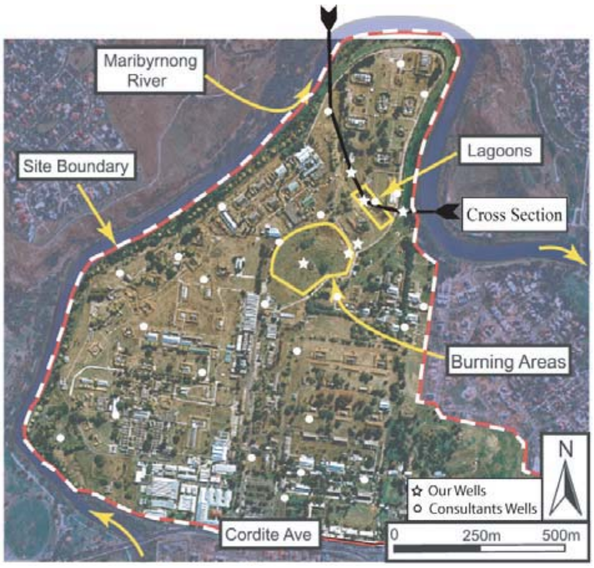

Figure 1. EFM Site layout showing the Lagoons study areas, geological cross section location and groundwater well locations.

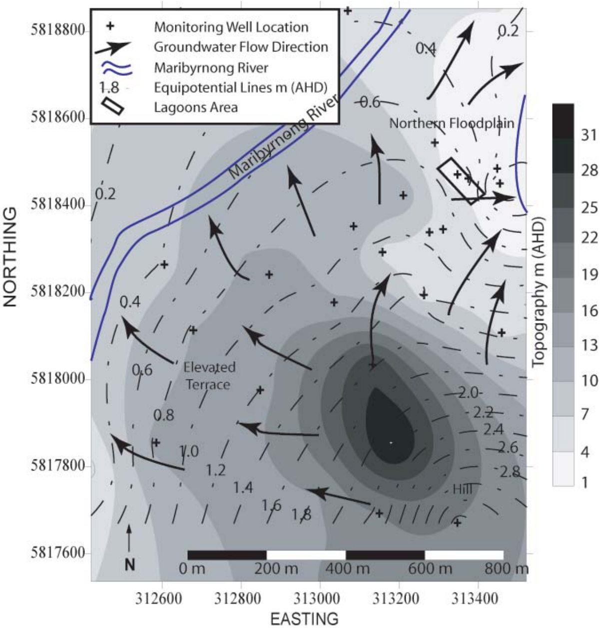

Figure 2. Topographical and Piezometric representation of EFM site showing the Lagoons area and groundwater flow direction.

2. METHODS

2.1 Hydrogeological Characterization

2.1.1 Groundwater Monitoring System

Ongoing site characterisation of EFM by private consultants has led to the emplacement of 42 monitoring wells. Of these, 11 wells were specifically installed within the context of our own study to target three pertinent hydrostratigraphic units beneath the northern floodplain; the surficial clay/silt aquitard, the upper confined sand/gravel aquifer, and the lower confined sand/gravel aquifer. The clays were drilled with solid flight augers and installed with single casings, the upper sands drilled with hollow flight augers and installed with single casings, while the lower sand and gravels were drilled using mud rotary and were installed with double casings to minimise vertical cross contamination.

2.1.2 Tide Corrections

Given the close proximity of the EFM site to the tidally influenced Maribyrnong River, the effect of tidal variation upon groundwater levels was studied to investigate the connectivity of the aquifers with the Maribyrnong river, and to facilitate a hydraulic head correction enabling construction of accurate piezometric head maps. Level logger data was collected from our 11 groundwater wells, and concurrently from two in-river locations at the upstream and downstream extremities of the site. Five of the 11 wells subsequently required tidal correction using the collected data. The clay aquitard and lower sand/gravel aquifer were found to be unaffected by tides, while the upper aquifer wells were affected at a distance of up to 130 m from the river, thus indicating a degree of connectivity between this formation and the river.

2.1.3 Hydraulic Tests

Hydraulic conductivity was estimated via slug testing in 23 wells with data interpreted using the Dagan (1978) and Hvorslev (1951) methods. Hydraulic conductivity was also estimated using different empirical formulas (Vukovic and Soro, 1992) on 8 grain size curves obtained from soil samples collected from the screened interval of installed wells. Additoinally, hydraulic conductivity was estimated in one well based on tidal fluctuation according to two methods (Milham and Howes, 1995., Carr and Van der Kamp, 1969).

2.2 Contaminant Investigation

2.2.1 Laboratory Techniques

TNT concentration was delineated in collected soil samples via acetone extraction and quantification using EnSys® test kits (US EPA SW 846 Method 8515) and a HACH DR/2010 spectrophotometer. Absorbance change in the extract after addition of indicator and organic interference correction (subtract 2 x background) was quantifiable at 254 nm (Jenkins et al. 1997). High Performance Liquid Chromatography (HPLC) was utilized (US EPA Method 8330) to verify spectrophotometry accuracy (R2 between spectrophotometry and HPLC across 136 soil samples was 0.80) and provide concentrations for a suite of energetic materials in selected soils and groundwaters. Analysis was conducted on an Agilent 1100 HPLC, using normal phase separation on a reverse phase zorbax C18 column with a diode array detector.

2.2.2 Surface Soil Sampling

Collecting representative soil samples from an explosives contaminated site is the most difficult stage of delineating contamination, and as such has a major influence on the accuracy of site characterization (Jenkins et al. 1997). A multi-faceted sampling regime was developed as part of the KTA protocol, utilising various sampling techniques to promote representative sampling and hence combat the extreme spatial heterogeneity often observed in contaminant distribution at explosives sites, with the aim of focusing upon surface crystalline contaminant reservoirs for further characterization by depth sampling.

2.2.3 Depth Soil Sampling

Surface contaminant sources (hotspots) were subsequently depth profiled by excavation of test pits to 3.0 m depth via backhoe. Samples were collected from pit walls or the excavator bucket (> 1.0m) for each 0.5m interval enabling an assessment of near surface stratigraphy beneath the hotspot, and the extent of explosives contaminant propagation throughout the profile.

2.2.4 Groundwater Sampling

Groundwater samples were collected via Waterra pump equipped with a foot valve with physiochemical parameters (pH, Redox potential, dissolved oxygen, temperature, conductivity) measured on site during collection.

2.3 Model Development

A simplified mathematical model and its analytical solution were applied to simulate 3-D transport of a single chemical constituent in groundwater from a “patch” source in unidirectional flow field (Figure 3). Assuming 1st order decay, linear sorption and that the x-axis is aligned with the unidirectional flow velocity vector (v) the governing transport equation is;

$$R\frac{\partial C}{\partial t} = D_x\frac{\partial^2 C}{\partial x^2} + D_y\frac{\partial^2 C}{\partial y^2} + D_z\frac{\partial^2 C}{\partial z^2} - \nu\frac{\partial C}{\partial x} - \lambda RC$$

where C is the dissolved concentration of the substance, [ML-3]; ν - the seepage velocity, [LT-1], R - the retardation coefficient, [dimensionless]; Dl - the component of the dispersion coefficients along the i – dimension; λ - the degradation rate constant, [T-1].

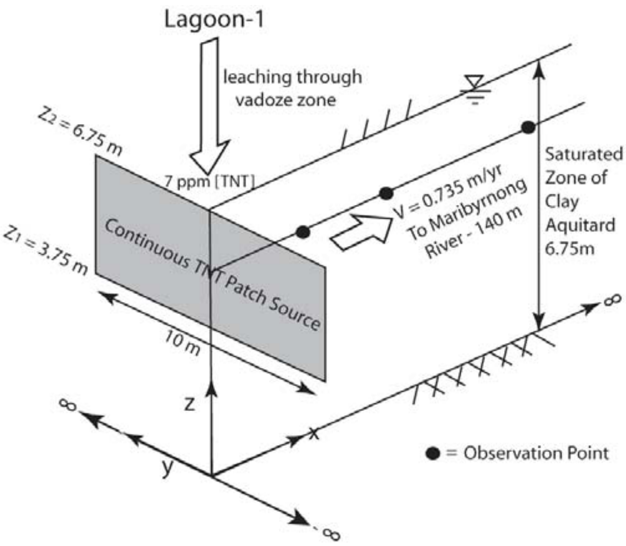

Figure 3. Contaminant transport schematic for the shallow clay aquitard.

3. RESULTS

3.1 Hydrogeology

Interpretation of bore logs obtained during well installation enabled the construction of an north east – south west trending cross section, summarising the stratigraphy of the northern floodplain beneath the Lagoons study area (Figure 4).

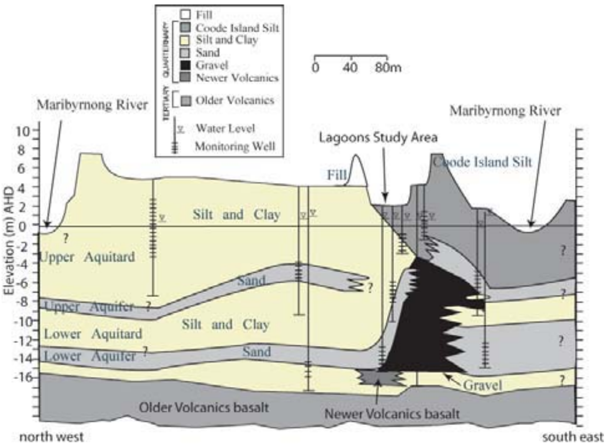

Figure 4. North West – South East hydrostratigraphic cross section through Lagoon-1 (location on Fig. 1).

Stratigraphy on the northern floodplain consists of a complex sequence of inter-layered alluvium, with fractured silty clays grading into sands and gravels with depth. The sequence beneath the lagoons is as follows; Upper Silts and Clays (Upper Aquitard), Upper Sands and Gravels (Upper Aquifer), Lower Silts and Clays (Lower Aquitard), Lower Sands and Gravels (Lower Aquifer), and Older Volcanics basalt at depth.

3.1.1 Definition of the hydrostratigraphic units

Saturated hydraulic conductivity and specific storage are displayed in (Table 1) for the Upper Aquitard, Upper Aquifer, and Lower Aquifer unit. The value of hydraulic conductivity for each hydrostratigraphic unit is a logarithmic mean of values derived from slug test and grain size estimates.

Table 1. Hydrostratigraphic unit characteristics

Unit name	Lithology	No. Slug Tests	No. Grain Size Estimates	Saturated hydraulic conductivity (K_{sat}) (ms^{-1})		Thickness (m)	Specific storage (S_s) (m^{-1})
				Range	Mean		
Upper Aquitard	Silts and Clays	9	0	7.37×10^{-7} - 1.72×10^{-5}	2.47×10^{-6}	0.2 to 5	5×10^{-3}
Upper Aquifer	Upper Sands and Gravels	12	6	3.69×10^{-7} - 1.71×10^{-2}	1.38×10^{-4}	3 to 8	5×10^{-4}
Lower Aquifer	Lower Sands and Gravels	4	2	5.05×10^{-6} - 5.96×10^{-4}	6.22×10^{-5}	2 to 5	1×10^{-3}

3.1.2 Piezometry

A piezometric map of the Upper Aquifer was created based upon tide corrected groundwater levels measured on 2nd August 2002 (Figure 2). Horizontal groundwater velocities from the Lagoons study area eastwards towards the Maribyrnong river were estimated at 0.7 m/yr for the Upper Aquitard, and 78 m/yr for the Upper Aquifer.

3.1.3 Aquifer Recharge

Incident recharge was estimated for the EFM site via a simplified water balance from meteorological data. Climatological data for the site spanning from 1915 – 1991 indicates an average annual precipitation of 553 mm while, evapotranspiration was estimated by the Thornwaite method (1948). Recharge to the aquifer system was found to occur between May and October, with peak recharge in August (12.2 mm) and annual recharge to the aquifer system estimated at 48.9 mm/yr across the catchment.

The Lagoons area is the lowest point for a steep sided local catchment, where clayey soils and low vegetative cover dictate that most runoff will be retained and consequently undergo evapotranspiration and infiltration at the lagoon base. Mapping software was used to define the catchment area (5096 m^2) providing runoff to Lagoon-1 (807 m^2) (Figure 5). The ratio of lagoon area : catchment was hence 1 : 6.3. Assuming 100% runoff from the catchment contributes to the lagoon, we can calculate total infiltration/recharge at the lagoon base as 309 mm/yr (48.94 mm/yr x 6.3) or a total of 249 kL/year for the entire lagoon base.

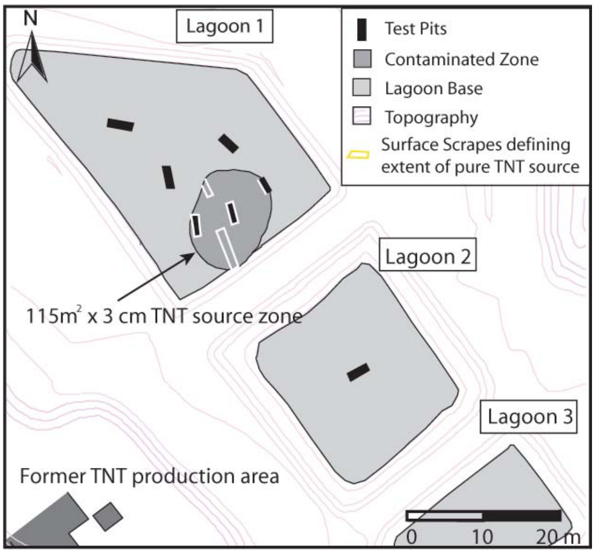

Figure 5. Lagoons study area showing location of a TNT layer within Lagoon-1 defined during depth sampling.

Hydrogeochemistry

Variation in groundwater geochemical parameters within the alluvial aquifer system was investigated across a W-E transect through Lagoon-1 (Figure 6). High dissolved oxygen and positive redox potential within the fractured clay aquitard beneath Lagoon-1 (distance = 141 m) indicate that the lagoon acts as a preferential recharge point, and that aerobic conditions prevail in the fractured clay aquitard. Analytical results indicated that groundwater samples collected at EFM were generally saline Na^+, K^+, Cl^- SO_4^{2-} type, with TDS up to 9690 mg/L.

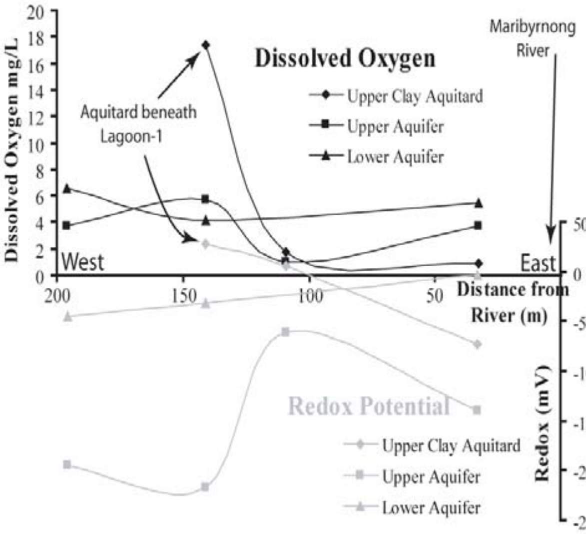

Figure 6. Dissolved oxygen content and Redox potential in groundwater wells of the northern floodplain aquifer system. Distance shown is along a west-east transect relative to the Maribyrnong River (i.e. River to the east = 0).

3.2 Contaminant Investigation

3.2.1 Energetics in Soil

Surface sampling revealed that the region of highest TNT contamination onsite was within Lagoon-1 soils. Subsequent depth sampling uncovered a near pure contaminant layer 10-15cm below surface level, with an average thickness of 3cm, and an inferred lateral extent of $115m^2$ (defined by conducting shallow surface scrapes with the backhoe – Figure 5). Sharply decreasing TNT concentrations were observed with distance from the source both laterally and with depth, although concentrations still exceeded residential preliminary remediation goals (>16 mg/kg) at 3.0m at the centre of the hotspot (Figure 7).

Mass balance estimates were developed using the volume (3.47 m3) of the near pure TNT layer (estimated at 70% pure) (Elovitz and Weber, 1999) to estimate mass (TNT density = 1.654 g/cm3), combined with interpolated results of Lagoon-1 test pit soil sampling [TNT] in soil – Figure 7 to define a 5 tonne source with ~80% of contaminant mass within the top 25 cm of the profile. Recharge estimates (309 mm/yr-1 = 35.7 kL/yr flowing through the $115m^2$ source zone) used in conjunction with an estimate of TNT solubility (½ aqueous solubility = ~65 mg/L) (Comfort et al. 1995) to approximate dissolution rates from the near surface contaminant source revealed that without mitigation, a dissolved TNT flux of 2.32 kg/yr resulted in a total leaching time of ~2000 years (propagated uncertainty +/- 55%).

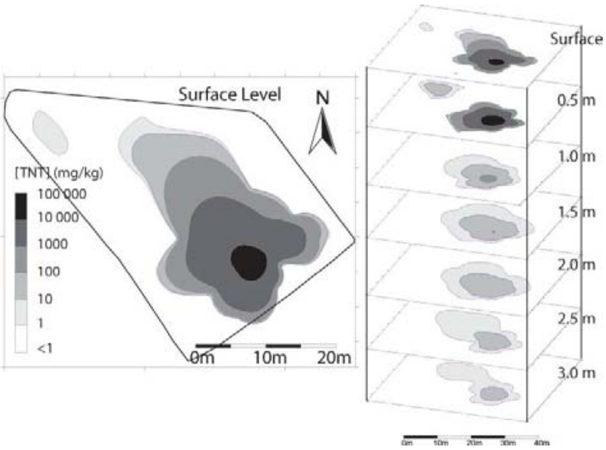

Figure 7. TNT concentration in soil with depth in lagoon-1. Constructed with SURFER-3D v.8.0 using kriging interpolation of TNT concentration at 0.5 m depth intervals as obtained from test pit results.

3.2.2 Energetics in Groundwater

Six of the 49 collected groundwater samples displayed traces of energetic materials and their degradation products, with three hits in the Upper Aquitard, and three in the Upper Aquifer. Most hits were for isomeric mixtures of 2,4 and 2,6-DNT (dinitrotoluene) at localities beneath or adjacent to the Burning Areas. RDX (hexahydro-1,2,5-trinitro-1,3,5-triazine), TNT and its metabolites were only detected in one well, directly beneath Lagoon-1 at 2.0m depth into the clay aquitard. Maximum energetics concentrations were recorded for this location as follows; 7 ppm of TNT, 2.2 ppm 2ADNT (2-amino-4,6-dinitrotoluene), 1.4 ppm 4ADNT (4-amino-2,6-dinitrotoluene), 0.38 ppm 2,4-DNT, 0.35 ppm 2,6-DNT and 0.25 ppm of RDX.

3.3 Transport Model

ATRANS20 software (Neville, 2002) was used to simulate the development of a TNT plume in groundwater in the Upper Aquitard beneath Lagoon-1. Calculated values of hydraulic conductivity (hence seepage velocity) were integrated with established literature constants to model fluid behaviour. The model considers that a TNT plume will evolve in the saturated clay aquitard after leaching through the vadoze zone from the previously defined near surface crystalline TNT layer. The maximum recorded TNT concentration of 7 ppm was used as the input concentration for the model, while the patch source size (10m x 3m) was defined based upon the dimensions of the observed pure product contaminant zone within Lagoon-1 (Figure 5).

A parallel study was undertaken on soils collected from the site to estimate natural attenuation process rates for use as input data in the model (Robertson, 2002). Microbial and abiotic transformation of TNT was investigated in clays collected from the Lagoons area under various environmetal conditions (anaerobic, aerobic, photolysis). Hydrogeochemistry analysis revealed aerobic conditions due to Lagoon-1 acting as a recharge point for a steep sided local catchment, hence the aerobic-biotic degradation rate (0.882 yr-1) was selected as the input degradation rate for the model.

Partitioning of TNT onto clay material from the Lagoons area was investigated by adsorption tests, resulting in the observation of Freundlich described adsorptive partitioning. The Freundlich isotherm for the Lagoons clay (S = KF CbF = 28.9 C 0.833) was used to approximate retardation at 7 ppm according to;

Model output data (Table 2) demonstrated that plume migration is extremely localized close to the source zone. Base case analysis indicates that at only 1m from the source along the flow path, aqueous concentrations were always sub-ppb level, while at 0.5 m from the source a steady state concentration of 22 ppb was established after 9 years. Plume migration vertically (downwards – z axis) or laterally (y axis)(Figure 3.) away from the source was even less pronounced. Sensitivity analysis indicated that variation of hydraulic conductivity, partition co-efficient and transformation rate had similar effects upon the lateral extent of plume development; however variance of transformation rate by 10^{-1} had the effect of increasing the time required for the plume to reach steady state. In all cases variation of these parameters by +/- an order of magnitude resulted in only a few meters of extension of the contaminant plume before concentrations were sub-ppb, reaffirming that the plume is localised to the vadose zone and clay aquitard. Sensitivity analysis was undertaken by variation of hydraulic conductivity/seepage velocity (K), partition co-efficient/retardation (K_F) and aerobic transformation (μ) by +/- 1 order of magnitude.

Hence an input retardation value of 70.8 was determined to approximate linear adsorption. This value is conservative given that contaminants exhibiting Freundlich described partitioning where bF < 1.0 are increasingly retarded at lower concentrations, as would be expected as the plume migrates further from the 7 ppm patch source.

While the aforementioned parameters have a similar relative effect on plume extension, hydraulic conductivity is the parameter most sensitive to change. If the plume was to migrate through the clay Upper Aquitard into the sands and gravels of the Upper Aquifer, hydraulic conductivity and hence seepage velocities would be 100 times greater while retardation would be concurrently

Table 2. Sensitivity analysis for the transport model at four observation points, demonstrating time for steady state concentration to be reached, and the value of concentration at that time.

	Distance from patch source (m)							
Paramateter	0.5		1		2		5	
	Time (yrs)	Conc (ppb)	Time (yrs)	Conc (ppb)	Time (yrs)	Conc (ppb)	Time (yrs)	Conc (ppb)
Base Case	9	22.06	17	0.07	25	7.0×10^{-7}	-	-
K x 10	5	1428	8	292.6	12	12.25	22	9.0×10^{-4}
λ x 0.1	43	1465	94	310.5	107	13.75	183	1.2×10^{-3}
Kd x 0.1	5	1470	10	310.5	11	13.75	19	1.2×10^{-3}
K x 0.1	19	9.1×10^{-4}	30	1.2×10^{-10}	-	-	-	-
λ x 10	3	3.4×10^{-5}	4	1.7×10^{-13}	-	-	-	-
Kd x 10	21	3.4×10^{-5}	34	1.7×10^{-13}	-	-	-	-

Where; K = hydraulic conductivity, λ = biodegradation rate, Kd = partitioning.

diminished due to a lessened sorptive capacity of the sandy quartz matrix to TNT. This could potentially lead to rapid propagation of the plume toward the Maribyrnong River. When running the model to consider 2 orders of magnitude increase in seepage velocity (K x 100) coupled with an order of magnitude decrease in retardation (KF x 0.1), the plume extended to ~140 m before reaching steady state sub-ppb concentrations after 18 years, thus indicating the potential for contamination of the Maribyrnong River 140 m to the east of Lagoon-1.

4. CONCEPTUAL MODEL

The source zone within Lagoon-1 presents a significantly large (~5 tonnes) and extremely persistent (~2000 years) crystalline TNT reservoir, supplying ongoing contaminant flux directly to the soil profile and the fractured clay aquitard via leaching. A 10 cm layer of sediment shields this reservoir from exposure to sunlight, thus extending persistence by limiting photodegradation, while biotic transformation has been limited close to the source by the high toxicity of pure TNT to soil microbes (Chapelle, 1992). Slow leaching rates due to TNT's sluggish dissolution kinetics and limited aqueous solubility have rendered the total contaminant mass within the source zone relatively unchanged since TNT production ceased in 1944. Energetic materials contamination at the Lagoons area appears to be localised to the vadose zone and fractured clay aquitard, due to a combination of natural attenuation processes and hydrogeological constraints. The contaminant profile and associated degradation signature observed within the vadose zone is a product of; extended leaching, recrystallization of energetics lower in the profile, sorptive partitioning, transformation reactions, precipitation of TNT at the water table interface and aqueous transport processes (advection, dispersion, diffusion) (Figure 8).

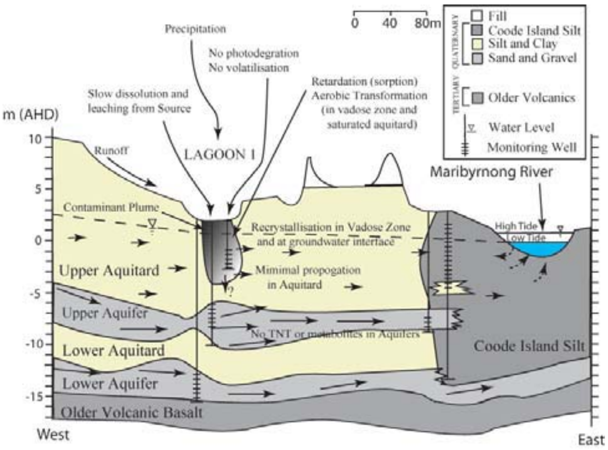

Figure 8. Conceptual model of TNT behavior beneath the Lagoons area at EFM.

The Lagoons area acts as a drainage point for a steep sided local catchment, with preferential infiltration occurring through its denuded base – hence the highly aerobic conditions, and water balance calculations for the catchment estimating an annual recharge through the lagoon base (807 m^2) of 249 kL. Low hydraulic conductivity and gradient within the clay aquitard result in slow lateral migration of water (0.7 m/yr east) and contaminants toward the river, resulting in long contaminant residence time within the clays. Increased residency equates to greater interaction with the highly sorptive soil matrix and elements responsible for transformation, thus serves to enhance natural attenuation in a positive feedback loop further retarding plume migration. Regionally, recharge through elevated regions of the site in the south results in an upward component to hydraulic gradient in the Upper and Lower confined aquifers beneath the Lagoons area. As such, infiltrating water at the Lagoons area is limited to the fractured clay aquitard, thus hindering the downward propagation of explosives to lower aquifers. Interconnectivity between the clay and underlying aquifers was defined for the winter only, using a limited number of wells. Therefore, it is unknown if upward hydraulic gradients are maintained throughout the year, or if climatological influence on recharge alters interconnectivity. If vertical migration was to occur, sand and gravel layers would act as a preferential pathway for flow, with effective velocities 100 times greater (78 m/yr east) than the clay aquitard, thus swiftly transporting energetics towards the river. Given the slow aqueous transport in the clays, defining interconnectivty to lower aquifers is of primary concern in predicting fate.

5. REMEDIATION STRATEGIES

Possible contaminant receptors include: underlying sand and gravel aquifers, the Maribyrnong River, and future land-users through dermal contact, inhalation or ingestion of contaminated soil or groundwater. In view of poor water quality and limited usage of regional aquifers, it is considered that remedial efforts not be channelled into decontamination of the already heavily contaminated aquifer system, but aim to render the near surface soil environment safe for redevelopment. Given that the bulk of contamination is within the top 25 cm of the profile, a likely scenario for lagoon-1 would involve excavation and removal of the top 2.0 m of contaminated soil for off-site treatment or disposal, then re-filling the lagoon with an impermeable capping. This would isolate the relatively low residual explosives concentrations at depth, limit infiltration thus reducing leaching rates and hindering plume development while also promoting the development of anaerobic conditions to enhance biodegradation rates.

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