



Influence of spatial and temporal variability of subsurface soil moisture and temperature on vapour intrusion



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HIGHLIGHTS

- Vapour intrusion is a major exposure pathway for volatile hydrocarbons.
- Certainty in transport processes enhances vapour intrusion model precision.
- Detailed understanding of vadose zone vapour transport processes save resources.
- Variation of subsurface environment equitably affects vapour intrusion processes.

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ABSTRACT

A comprehensive field study was conducted at a site contaminated with chlorinated solvents, mainly trichloroethylene (TCE), to investigate the influence of subsurface soil moisture and temperature on vapour intrusion (VI) into built structures. Existing approaches to predict the risk of VI intrusion into buildings assume homogeneous or discrete layers in the vadose zone through which TCE migrates from an underlying source zone. In reality, the subsurface of the majority of contaminated sites will be subject to significant variations in moisture and temperature. Detailed site-specific data were measured contemporaneously to evaluate the impact of spatial and temporal variability of subsurface soil properties on VI exposure assessment. The results revealed that indoor air vapour concentrations would be affected by spatial and temporal variability of subsurface soil moisture and temperature. The monthly monitoring of soil-gas concentrations over a period of one year at a depth of 3 m across the study site demonstrated significant variation in TCE vapour concentrations, which ranged from 480 to 629,308 $\mu\text{g}/\text{m}^3$. Soil-gas wells at 1 m depth exhibited high seasonal variability in TCE vapour concentrations with a coefficient of variation 1.02 in comparison with values of 0.88 and 0.74 in 2 m and 3 m wells, respectively. Contour plots of the soil-gas TCE plume during wet and dry seasons showed that the plume moved across the site, hence locations of soil-gas monitoring wells for human risk assessment is a site specific decision. Subsurface soil-gas vapour plume characterisation at the study site demonstrates that assessment for VI is greatly influenced by subsurface soil properties such as temperature and moisture that fluctuate with the seasons of the year.

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1. Introduction

Groundwater and soil contamination from volatile organic compounds (VOCs) such as chlorinated solvents (CHC) and petroleum hydrocarbon compounds (PHC) is a frequently encountered environmental issue (Barbee, 1994; Grandel and Dahmke, 2004).

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The large-scale production and use of chlorinated solvents such as trichloroethylene (TCE) in manufacturing industries has resulted in numerous documented cases of soil and groundwater contamination (Barbee, 1994; Schaumburg, 1990). Trichloroethylene is one of the most frequently detected organic environmental contaminants and is a carcinogen that persists, and is mobile, in both the vadose zone and groundwater, or as part of the non-aqueous phase liquid (NAPL) (Little et al., 1988).

Volatile organic compounds in contaminated soil or groundwater have been investigated under a variety of climatic conditions

and geological settings to describe the impact, transport mechanisms and the potential for vapour intrusion (VI) into buildings (API, 2005; ITRC, 2006; U.S. EPA, 2002a; Wong and Agar, 2009). The key to assessing VI pathways from underground sources to the interior of buildings is to investigate the fate and transport of vapours in the unsaturated subsurface soil and building properties. In practical situations however, determining the fate and transport of vapours in the subsurface is a challenging task, due to the heterogeneity of the subsurface soil in terms of geophysical and biochemical properties. The heterogeneity of soil resulting from temporal variability of moisture and temperature, and spatial variability of physiochemical properties, may affect risk assessments (Bekele et al., 2013). Reducing uncertainty in the prediction of human health risks from vapour inhalation requires a method that enables quantification of each of the transport processes in sufficient detail for a defensible assessment of potential inhalation exposure. Soil-gas vapour sampling is a reliable method that should also address sources of variability and thus minimise uncertainty in the prediction of risks when applying mathematical models.

As yet there are no guidelines or recommendations on the quantity of data needed to address sources of field variability for soil-gas or groundwater measurements for use in VI risk assessments. The approaches adopted by individual investigators vary widely. As a result, disagreements may arise between parties involved at a site regarding the adequacy of a field investigation (McHugh, 2008). This is further exacerbated by the lack of detailed information on the fate and dynamics of VOCs in the vadose zone. Presently in Australia there is no field investigation strategy in place by the Australian National Environmental Protection Measures or en-Health for VI field assessment. Australia also lacks guidelines on the field assessment of VOC-contaminated sites in terms of VI exposure pathways from subsurface groundwater and soil (Davis et al., 2009; NEPC, 2008).

Human health risk assessment for a VI exposure pathway involves a complex set of data objectives, including when samples should be taken and where and how much sampling is adequate to address the spatial and temporal variability of soil-gas samples (ITRC, 2006; Tillman and Weaver, 2007). A recent field study conducted by Folkes et al. (2009) demonstrated that indoor air and sub-slab concentrations of VOCs show considerable temporal variation and that vapour concentrations at soil-gas sampling locations do not correlate very well with those of the next location.

A significant number of VI case studies have been reported in U.S. EPA databases based on subsurface sources and measured indoor air vapour concentrations. In addition, an excellent review published recently Rivett et al. (2011), reported values mainly of paired groundwater or soil sources along with indoor air vapour concentration measurements. Reviewing and comparing these studies is helpful for obtaining a general understanding of the fate and transport of VOCs. However, a major limitation of the existing case study sites is that they reported only source and indoor air concentrations without considering the fate and dynamics of VOCs in the subsurface environment. In the absence of such data, it is difficult to ascertain the potential attenuation of volatiles as the vapour migrates upwards from the source zone. Furthermore, Folkes et al. (2009) and McHugh et al. (2007) demonstrated the effects of seasonal variations of spatial and temporal relationships between source concentrations in contaminated groundwater and indoor air concentrations. However, these researchers did not monitor variations in moisture and temperature, both of which are likely to govern vapour transport processes.

Given the limitations of previous studies, we conducted a detailed investigation of the effect of soil moisture and soil temperature on the transport of vapour in the vadose zone soil profiles. Field investigations were conducted to develop an improved

understanding of the impact of spatial and temporal variability of physical properties on vapour transport and intrusion into dwellings. The field investigations focussed on determining the effects of variations of physical properties in the vadose zones on vapour transport, and its implications to potential health risks emanating from VI interpreted using the vapour intrusion models.

2. Experimental work

2.1. Site background and hydrogeology

The case study site is near residential property located adjacent to an automobile-assembling plant dating back to the early 1950s in a suburb of Adelaide (Evans et al., 2010). As part of routine environmental assessments associated with the decommissioning of the vehicle manufacturing plant, it was noted that there were onsite groundwater TCE concentrations of >5 mg/L and soil-gas TCE concentrations of >60 mg/m³ in an area adjacent to a number of residential properties (Evans et al., 2010). Observations made during site characterisation suggested that contamination stretched horizontally to nearby residential blocks and a detailed site assessment was conducted to address the potential for VI into these dwellings (South Australia EPA, 2009). The potential sources of contamination in the area so far have not been identified. However, a detailed review of historical site reports and discussions with local authorities South Australia EPA (2009) helped identification of several potential sources of contamination. Although TCE was expected to be the major contaminant in groundwater, its degradation by-products were also included as target analytes: cis-dichloroethylene (cis-DCE), trans-dichloroethylene (trans-DCE) and chloroform (CFM).

The general site stratigraphy consists of fill material up to a depth of 30 cm associated with construction and gardening near the building being investigated. The site has a sequence of natural soils characterised by the presence of the Pooraka Formation, which has variable calcium carbonate content, immediately overlying silty or sandy clay of the Hindmarsh Clay Formation (South Australian Dept of Mines and Energy, 1989), characterised by high plasticity. Soil profiles generally showed considerable variability in their properties (such as fine to coarse granular material content and plasticity), which is apparent both laterally (between well locations) and vertically (with depth at each well location).

Hydrogeological investigations confirmed the presence of a shallow aquifer with water levels approximately between 10.5 m and 14.9 m below ground surface level (bgs). Its general flow is in a north-westerly direction. The locations of previously installed groundwater sampling wells are illustrated in Fig. 1. Earlier field investigations showed a horizontal groundwater seepage velocity of up to 20 m/year for the deeper aquifer. Groundwater had been sampled from monitoring wells in the immediate vicinity of investigated buildings to confirm the extent of the contamination plume and concentrations of the contaminant of concern (TCE). Monitoring data from these wells suggested that TCE contamination extended beyond the former industrial compound. Given the duration and magnitude of on-site contamination it was postulated that substantial lateral infiltration in subsurface layers had occurred and TCE was no longer confined within the boundary of the industrial site.

2.2. Field investigation design

2.2.1. Soil and groundwater

Soil samples were collected using a hollow auger drill up to 3 m deep bgs and samples were preserved for laboratory analysis of soil chemical properties and soil type classifications as suggested by

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