Journal of Contaminant Hydrology 203 (2017) 38–50

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

# Doublet tracer tests to determine the contaminant flushing properties of a municipal solid waste landfill

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ARTICLE INFO

*Keywords:*
Doublet
Tracer
Municipal solid waste
Flushing
Dual-porosity

ABSTRACT

This paper describes a programme of research investigating horizontal fluid flow and solute transport through saturated municipal solid waste (MSW) landfill. The purpose is to inform engineering strategies for future contaminant flushing. Solute transport between injection/abstraction well pairs (doublets) is investigated using three tracers over five separate tests at well separations between 5 m and 20 m. Two inorganic tracers (lithium and bromide) were used, plus the fluorescent dye tracer, rhodamine-WT. There was no evidence for persistent preferential horizons or pathways at the inter-well scale. The time for tracer movement to the abstraction wells varied with well spacing as predicted for a homogeneous isotropic continuum. The time for tracer movement to remote observation wells was also as expected. Mobile porosity was estimated as ~0.02 (~4% of total porosity). Good fits to the tracer breakthrough data were achieved using a dual-porosity model, with immobile regions characterised by block diffusion timescales in the range of about one to ten years. This implies that diffusional exchanges are likely to be very significant for engineering of whole-site contaminant flushing and possibly rate-limiting.

## 1. Introduction

Landfilling remains the main disposal method for municipal solid waste (MSW) globally. Of the estimated 1.3 billion t of MSW produced in 2012, the majority ended up in landfills or open dumps (Bhada-Tata and Hoornweg, 2012). Even where landfilled volumes are reducing (such as within the EU) it is very likely that there will be a continued need to dispose of 'residuals'.

The leachate generated by landfills represents a potential pollution risk to groundwater and surface water bodies (e.g. Christensen et al., 2011; Turner et al., 2017). This liability will often last for many centuries after a site has closed (Hall et al., 2004) and requires ongoing active aftercare to manage the risk. This potential burden to future generations contradicts one of the core principles of sustainable development, i.e. that the problems of today should not be passed on to future generations (United Nations, 1987). Since it is broadly recognised that landfill engineering systems will deteriorate in the long term (Drury et al., 2003; Rowe, 2005) there is a case for engineering in situ clean-up of existing sites to reduce the legacy handed to future generations (e.g. Scharff et al., 2011; Beaven et al., 2014; Kattenberg et al., 2013).

Concern over the potential for contaminant leakage from landfills has resulted in leachate heads often being kept at a low level within the waste and thus the majority of the waste in managed landfills is

*Abbreviations:* $b$, Thickness of saturated zone [mg/L]; $b_b$, Half-width of an immobile block [m]; B, Block Geometry Function (Barker, 1985) [−]; $c_X$, Background-corrected concentration at location $X$ (e.g. $X = M$ for monitoring point) [mg/L]; $C_A$, Concentration in abstraction well [mg/L]; $C_b$, Background concentration [mg/L]; $C_I$, Concentration in injection well [mg/L]; $C_M$, Concentration at the monitoring point [mg/L]; $C_P$, Concentration at any point within the waste (e.g. at an observation well) [mg/L]; $C_R$, Concentration returned to the injection well [mg/L]; $C_T$, Tracer input concentration [mg/L]; $D$, Spacing between injection and pumping well [m]; $D_a$, Apparent diffusion coefficient [m$^2$/d]; M, Transfer function for transport through return pipework to monitoring point [−]; $P$, Point in the waste (defined by horizontal coordinates x, y); $q$, Darcy velocity [m/d]; $Q$, Pumping (and injection) flow rate [m$^3$/d]; $r_w$, Well radius [mm]; R($s$), Transfer function for transport through return pipework to injection well [−]; $s$, Laplace variable [d$^{-1}$]; $s_d$, Slope of ln(concentration) against time in a dilution test [log(mg/L)/d]; $t$, Time [d]; $t_a(\psi)$, Advection time for a streamtube [d]; $t_A$, Time constant of abstraction well [d]; $t_b$, Time for fastest advection of tracer from injection to abstraction well [d]; $t_{cb}$, Characteristic diffusion time to/from immobile zone [d]; $t_{cf}$, Characteristic diffusion time to/from mobile zone [d]; $t_{fd}$, Time of first detection of tracer [d]; $t_I$, Time constant of injection well [d]; $t_M$, Advection time from abstraction well to monitoring point [d]; $t_P$, Advection time from injection well to point P in waste [d]; $t_R$, Return time from abstraction well to injection well [d]; $t_T$, Duration of tracer input for a top-hat input [d]; T($s$), Transfer function for transport from tracer injection point to injection well [−]; W(s), Transfer function for transport through waste; $z$, Distance along a streamtube [m]; $\alpha$, Dispersivity [m]; $\alpha_L$, Dispersivity per unit distance of travel, $\alpha/z$ [−]; $\gamma$, Specific weight [N/m$^3$]; $\theta$, Total volumetric water content (porosity) [−]; $\theta_{im}$, Immobile volumetric water content (porosity) [−]; $\theta_m$, Mobile volumetric water content (porosity) [−]; $\psi$, Angle from line joining doublet wells to streamline entering abstraction well [radians]

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http://dx.doi.org/10.1016/j.jconhyd.2017.05.008
Received 8 October 2016; Received in revised form 8 May 2017; Accepted 30 May 2017
Available online 07 June 2017
0169-7722/ 

unsaturated. Nonetheless, where the landfill basal drainage system is non-existent or malfunctioning (for example, clogged), vertical wells are frequently used for leachate extraction in landfills to reduce water levels and control hydraulic heads. In many older landfills in the UK, significant depths of saturated waste exist (and are permitted) in sites benefiting from natural containment created by surrounding geology with low permeability. Although there are presently regulatory barriers to raised leachate tables, increasing water levels would potentially encourage greater microbial activity and allow a higher flushing efficiency (Beaven et al., 2004). In such cases vertical wells could be used to provide an accelerated flushing of the waste. This could be achieved by inducing flow within the landfill between vertical wells. Clean water would be injected into one or more wells and leachate pumped out from others. Such systems are used for contaminant clean up in soils (e.g. Lee et al., 2014).

The basic concept is to accelerate the chemical and biological stabilisation of the landfilled waste to a point of "completion" where fluxes of contaminants released from the solid waste can be attenuated by the surrounding receiving environments. This has the result of shortening landfill aftercare management periods. Long term environmental risks are also reduced as there is less reliance on the long term functioning of engineering barriers and environmental control systems (e.g. Turner et al., 2017). One of the main methods to accelerate landfill completion is enhanced flushing of fluids through the site to encourage both degradation and the removal of soluble contaminants from the waste (e.g. Wang et al., 2012; Beaven et al., 2014). A 10-year accelerated flushing field trial is about to commence in the Netherlands to investigate the extent to which the above approach is viable (Kattenberg et al., 2013).

The basic hydraulic unit for the flow system produced from such systems is a well-pair doublet, whereby fluid is injected at one well and abstracted at a second one at the same rate. Proper understanding of a flow and solute movement in a doublet unit can potentially be applied to the design of a system of multiple-wells for flushing the site at full-scale.

Given previous difficulties interpreting pumping tests in waste (Burrows et al., 1997; Burrows, 1998; Cossu et al., 1997; Rees-White, 2007; Giardi, 1997) it is conceivable that the complexities of an actively degrading waste body may make pumping between wells difficult to characterise. Furthermore, it is possible that heterogeneity causes a highly non-uniform flow which results in a less effective sweep of the waste mass than would have occurred in a uniform flow regime. Heterogeneities within the waste may concentrate flow within discrete horizons, isolating the remaining saturated thickness from the flow of clean water. Reductions in hydraulic conductivity with depth due to increasing overburden may cause systematic reductions in flow rates with depth (Powrie and Beaven, 1999), reducing the flow and therefore clean-up rate for the deeper layers. For wells too close together, fast pathways could potentially be created between wells causing short-circuiting. For more widely spaced well-pairs, larger-scale heterogeneities and even the boundaries of the landfill cell may affect the flow. Consequently, there is a need for the quantification of how uniformly between-well flow passes through saturated waste both in vertical and lateral extent.

This paper uses artificial tracers to reveal the dynamics of fluid movement within doublets at different scales. This allows a number of questions to be addressed: How well does an idealised homogenous porous medium assumption predict water movement in a doublet within MSW? Can short-circuiting be observed between wells? What is a practical scale to flush landfills using wells?

The overarching aim of this paper is therefore to provide a quantification of the nature of flow and transport of leachate in a doublet well-pair at a range of scales in a (MSW) landfill site. Specifically we aim to test the hypothesis that a doublet in MSW can be reliably simulated using a continuum mass-transport model, sufficient to design effective flushing strategies.

## 2. Methodology

### 2.1. Field site and method

The tests were carried out at a 66 ha restored landfill located in an old clay quarry in Southern England which had been excavated to a depth of approximately 19 m below surrounding ground levels (at ~14 m above mean sea level, MSL). The earliest waste was deposited in the 1980s and landfilling continued until the site was completed in 1996, having accumulated ~20 M tonnes of predominantly MSW and commercial/ industrial wastes. Restoration took the form of a 1 m rolled-clay cap and protective soil layer with a minimum depth of 1.8 m. The final landform was a dome-shaped land-raise with a current maximum elevation of ~15 m above MSL and an average waste depth of ~27 m.

The contours of the base of the site are close to being horizontal and there is no basal liner or drainage system. Leachate extraction is in the order of 1500 $m^3$/year, collected from vertical wells installed with submersible pumps. The closest pumped well to the test wells is ~100 m away, from which up to 100 $m^3$ is extracted annually. The saturated thickness of the waste above the landfill base (which was at -14mAML) was 17.2 m on average during the three-year experimental period. Landfill gas is collected from vertical wells install in the unsaturated zone. The closest gas extraction well is approximately 50 m from the test wells. Current gas extraction from the entire landfill is between 800 and 1000 $m^3$/h.

The area used for the tracer tests reported herein surrounded an existing 180 mm ID leachate abstraction well ('AW'). Four new 150 mm ID wells (A to D) and two 58 mm ID observation wells (O1 and O2) were installed. Wells A to D were fully screened within the saturated zone whereas the observation wells were screened over a much narrower depth interval (O1 from − 11.1 to 10.1 m above MSL and O2–2.4 to − 1.4 m above MSL). Fig. 1 shows the relative positions of the wells and Table 1 details each well. The abstraction and injection wells A to C were close to fully penetrating the entire saturated thickness. All doublet tracer tests followed the same general method. Leachate was pumped from the abstraction Well (AW) at a constant flow rate and injected back into one of Wells A, B or C (D was not used) via 272 m of 40.8 mm internal diameter pipe which passed through a control room. The control room was located on the edge of the site approximately 130 m from the testing field. The flow rate in all tests was controlled to a constant 47.7 $m^3$/d (~2 $m^3$/h) using a PID controller that used the output from an electromagnetic flowmeter (Endress + Hauser, Promag 50) to operate an actuated valve (Samson V2001-3321-E3) in the flow line. The advection time in the pipe between wells was therefore relatively rapid (0.07 h). Prior to each individual tracer test there was a period of pumping to allow hydraulic equilibration and where background concentrations of the tracers were monitored in-line at the abstraction well and from point samples taken at observation wells. When hydraulic equilibrium had been reached, tracer(s) were injected into the recirculation pipework in the control room and pumped into the landfill at the relevant injection well. A summary of tests undertaken is provided in Table 2.

### 2.2. Selection of tracers

Tracer testing in landfills is challenging due to the high ('background') concentration of most elements within the leachate, the reactive nature of leachates and the multi-component nature of the waste medium (Blakey et al., 1998; Woodman, 2007). Given this heightened chance of reaction, there is an advantage in using multiple tracers in the investigation to provide a means to establish whether tracers are behaving conservatively, or otherwise.

Therefore, three different tracers were selected for injection into the doublet systems: Rhodamine WT (RWT), bromide, and lithium. The details of the tracers and the quantities injected are given in Table 3.