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The uncertainty of mass discharge measurements using pumping methods under simplified conditions

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ABSTRACT

Mass discharge measurements at contaminated sites have been used to assist with site management decisions, and can be divided into two broad categories: point-scale measurement techniques and pumping methods. Pumping methods can be sub-divided based on the pumping procedures used into sequential, concurrent, and tandem circulating well categories. Recent work has investigated the uncertainty of point measurement methods, and to a lesser extent, pumping methods. However, the focus of this study was a direct comparison of uncertainty between the various pumping method approaches that have been used, as well as a comparison of uncertainty between pumping and point measurement methods. Mass discharge measurement error was investigated using a Monte Carlo modeling analysis as a function of the contaminant plume position and width, and as a function of the pumping conditions used in the different pumping tests. Results indicated that for the conditions investigated, uncertainty in mass discharge estimates based on pumping methods was 1.3 to 16 times less than point measurement method uncertainty, and that a sequential pumping approach resulted in 5 to 12 times less uncertainty than the concurrent pumping or tandem circulating well approaches. Uncertainty was also investigated as a function of the plume width relative to well spacing. For a given well spacing, uncertainty decreased for all methods as the plume width increased, and comparable levels of uncertainty between point measurement and pumping methods were obtained when three wells were distributed across the plume. A hybrid pumping technique in which alternate wells were pumped concurrently in two separate campaigns yielded similar uncertainty to the sequential pumping approach. This suggests that the hybrid approach can be used to capitalize on the advantages of sequential pumping yet minimize the overall test duration.

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1. Introduction

Flux is a fundamental concept used to describe the transport of mass, momentum, or energy per unit area and time in fluid mechanics. It is a key concept in all groundwater flow and mass transport equations used in groundwater hydrology. Examples include the volumetric flux or Darcy flux q [LT^{-1}] described by Darcy's Law, and the advective mass flux J [$ML^{-2}T^{-1}$], equal to the product of q and concentration C [ML^{-3}]. A related fundamental measure is mass discharge $\dot{m}$ [MT^{-1}], defined as

$$\dot{m} = \int J dA, \tag{1}$$

where A is the area [L^2] over which J is distributed. Direct measurement and use of J or $\dot{m}$ for field-scale site characterization activities, however, are a relatively new focus that has developed over the last approximately fifteen years. Field-scale measurements of J or $\dot{m}$ have been used to assess degradation rates (Borden et al., 1997; Kao and Prosser, 2001; Kao and Wang, 2000, 2001; King et al., 1999; Semprini et al.,

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1995; Suarez and Rifai, 2002), characterize source zones and associated plumes (Basu et al., 2006, 2009; Einarson and Mackay, 2001; Fraser et al., 2008; Guilbeault et al., 2005; King et al., 1999; Newell et al., 2011), characterize back diffusion from aquitards (Chapman and Parker, 2005), and assess benefits of partial mass removal from DNAPL source zones (Brooks et al., 2008; DiFilippo and Brusseau, 2008). Measurements of J or $\dot{m}$ provide a useful metric upon which to base site management decisions because they combine two important features of contaminant risk: concentration and mobility (Suthersan et al., 2010).

Methods to measure $\dot{m}$ can be divided into two broad categories: point-measurement (PM) and pumping-based methods. Both methods most often use one or more control planes, which consist of multiple wells aligned perpendicular to the average groundwater flow direction. PM methods are based on well sampling techniques with relatively small sampling volumes, and most often consist of applications based on multi-level samplers (Freitas et al., 2011; Guilbeault et al., 2005; Kao and Wang, 2001) or passive flux meters (Annable et al., 2005; Hatfield et al., 2004). In contrast, pumping methods integrate information over a much larger sampling volume, and thereby reduce the uncertainty due to un-sampled regions between point-measurement locations. Pumping methods can be broadly classified into two groups: steady-state and transient methods. Steady-state methods (Bayer-Raich et al., 2004; Einarson and Mackay, 2001; Holder et al., 1998) provide reliable estimates of $\dot{m}$ captured by the pumping well(s), but require long-term data, such as those associated with pump-and-treat systems (Brusseau et al., 2007).

Compared to steady-state pumping tests, transient pumping tests for $\dot{m}$ measurement have greater utility as a tool for site characterization and remedial performance assessment, because they can be conducted in a shorter amount of time and produce less waste. Integral Pumping Tests (IPTs) have been the most commonly used transient pumping method for contaminant flux measurement (Bayer-Raich et al., 2004, 2006; Bockelmann et al., 2001; Schwartz et al., 1998). As originally introduced, wells in the control plane are pumped sequentially and at a constant rate. An alternative to this sequential pumping, constant rate (SPCR) approach is to pump wells concurrently using either variable pumping rates (Brooks et al., 2008; Goltz et al., 2009) or constant pumping rates (Béland-Pelletier et al., 2011; Dietze and Dietrich, 2011; Kavanaugh et al., 2011; Leschik et al., 2009, 2011). Concurrent pumping variable rate will be referred to as CPVR and concurrent pumping constant rate as CPCR hereafter. In addition, another technique has been proposed based on a combination of injection and extraction wells (tandem circulating wells, or TCW) that eliminates the need for the disposal of extraction well effluent (Goltz et al., 2009).

The proper use of any measurement depends on an understanding of its error and uncertainty, and this is likewise the case for flux measurements. Approaches based on PMs provide a robust estimate of $\dot{m}$ only if the spacing of the sampling devices is appropriate for the scale of subsurface heterogeneity. Studies on PM uncertainty (Cai et al., 2011; Kübert and Finkel, 2006; Li and Abriola, 2009; Li et al., 2007; Mackay et al., 2012; Schwede and Cirpka, 2010; Troldborg et al., 2010) have investigated impacts resulting from the site conceptual model, geologic heterogeneity, source-zone NAPL distribution, distance from the source zone, sampling density, and the position of the sampling network relative to the contaminant distribution. Uncertainty in passive flux meter measurements was investigated by Klammer et al. (2012). Moreover, PMs used to estimate q can be subject to uncertainty due to the convergence or divergence of the flow field resulting from permeability contrasts between the natural formation and the installed monitoring device (Klammer et al., 2007).

Studies on pumping method uncertainty have for the most part focused on the IPT approach. Jarsjö et al. (2005) conducted an IPT sensitivity analysis for assumed groundwater recharge conditions and concentration distributions within pumping well capture zones at a heterogeneous study site. While the error in $\dot{m}$ based on their analysis was as large as an order-of-magnitude, it more typically ranged from 10% to 40%. Zeru and Schäfer (2005) and others (Bayer-Raich et al., 2007; Schäfer and Zeru, 2007) discussed errors introduced when concentration gradients exist parallel to the flow direction, in contrast to the underlying assumption used in the SPCR analytical solution (Bayer-Raich et al., 2004) that concentration gradients exist only in the dimension perpendicular to the flow direction. For the conditions investigated, Zeru and Schäfer (2005) found errors ranging from −10% to 80%. Error was also investigated by Jarsjö and Bayer-Raich (2008) considering changes in concentration due to degradation, and their results showed that no errors occur if concentration can be assumed to decay linearly in the flow direction, and that positive errors up to 17%, for the conditions investigated, may occur if concentration decays exponentially in the flow direction.

Dietze and Dietrich (2011) conducted a sensitivity analysis on a pumping test they completed, in which half the wells in a six-well control plane (the first, third, and fifth) was pumped in one campaign, followed by a five-day interval of no pumping, and then the remaining wells (second, fourth, and sixth) were pumped in a second campaign. A numerical inversion procedure that accounted for the complex flow field was used to estimate $\dot{m}$ from the concentration-time (CT) series. Results were found to be relatively insensitive to porosity η [−] and hydraulic conductivity K [LT^{-1}]: a 40% change in η produced an 11% change in $\dot{m}$, and a 150% change in K produced a 35% change in $\dot{m}$. Béland-Pelletier et al. (2011) reported a maximum IPT uncertainty of 28% in a field-based comparison of a pumping test to PMs, in which all wells were pumped simultaneously. Their analysis was based on an evaluation of both the propagation of uncertainty in fundamental measurements, and in an evaluation of uncertainty resulting from a failure to meet underlying test assumptions.

Studies on $\dot{m}$ errors in other pumping tests include Goltz et al. (2009) and Kavanaugh et al. (2011). Goltz et al. (2009) tested TCW and CPVR approaches in an artificial aquifer. Errors associated with the TCW approach ranged from 2% to 16%, while errors associated with the CPVR approach were as large as −70% for the conditions tested. Kavanaugh et al. (2011) reported results from a field study in which the injection of a bromide tracer served to create known $\dot{m}$ conditions, and three applications of a CPCR method resulted in errors ranging from −8% to 31%.

While $\dot{m}$ error and uncertainty have been the subject of various investigations, what has not been previously addressed is a comparison of uncertainty associated with the various