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Influence of vertical flows in wells on groundwater sampling

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ABSTRACT

Pumped groundwater sampling evaluations often assume that horizontal head gradients predominate and the sample comprises an average of water quality variation over the well screen interval weighted towards contributing zones of higher hydraulic conductivity (a permeability-weighted sample). However, the pumping rate used during sampling may not always be sufficient to overcome vertical flows in wells driven by ambient vertical head gradients. Such flows are reported in wells with screens between 3 and 10 m in length where lower pumping rates are more likely to be used during sampling. Here, numerical flow and particle transport modeling is used to provide insight into the origin of samples under ambient vertical head gradients and under a range of pumping rates. When vertical gradients are present, sample provenance is sensitive to pump intake position, pumping rate and pumping duration. The sample may not be drawn from the whole screen interval even with extended pumping times. Sample bias is present even when the ambient vertical flow in the wellbore is less than the pumping rate. Knowledge of the maximum ambient vertical flow in the well does, however, allow estimation of the pumping rate that will yield a permeability-weighted sample. This rate may be much greater than that recommended for low-flow sampling. In practice at monitored sites, the sampling bias introduced by ambient vertical flows in wells may often be unrecognized or underestimated when drawing conclusions from sampling results. It follows that care should be taken in the interpretation of sampling data if supporting flow investigations have not been undertaken.

1. Introduction

Groundwater quality observed from the sampling of monitoring wells (or boreholes) is fundamentally controlled by the origin of the groundwater extracted. Sample provenance may depend upon a complex interplay of the scale (e.g. screen length) of the monitoring well, the sampling method and protocol employed and the prevailing local hydrogeological conditions. The latter's influence may prove to be significant between wells even where similar sampling protocols are adopted that are designed to promote consistency in approaches. Variation in the local permeability field (and hence natural groundwater flow regime) may cause traditional well purging approaches advocating removal of three to five or more well volumes (ASTM International, 2013) to exhibit contrasting interactions with the various (hydro)geological units present. Likewise, increasingly adopted, passive zero-purge or low-flow (0.1–0.5 l/min) sampling methods (Puls and Barcelona, 1996), may extract samples significantly influenced by the natural groundwater flow regime that is sensitive to local hydrogeological scenario (and the well's potential perturbation of that regime). Zero purge or low-flow sampling might not always be recommended (US EPA, 2010), but are nevertheless often attractive

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compared to onerous well purging due to their potential benefits of reducing purge volume, minimizing in-well disturbance, reducing mixing with casing water, and shortened sampling times (Barcelona et al., 1994, 2005; Puls and Barcelona, 1996; Stone, 1997). It is hence important that potential influences of the local hydrogeological flow regime upon groundwater samples withdrawn by both modern and established sampling protocols are rigorously assessed to allow more appropriate sampling of wells and interpretation of the groundwater quality data arising.

While the influence of the local permeability field on sample origin is widely recognized through the concept that pumped samples are permeability weighted (i.e., higher permeability layers contribute a greater proportion to the sample obtained (Church and Granato, 1996; Hutchins and Acree, 2000; Puls and Barcelona, 1996)), consideration of local hydraulic, particularly vertical gradients, is often neglected. Critically, the monitoring well may serve as an artificial conduit allowing vertical flows between otherwise unconnected geological units. This can result in unforeseen sample origins that may remain unrecognized in the absence of supporting flow or gradient data. Our primary interest herein is to evaluate the influence of vertical flows in wells on the provenance of the pumped sample and groundwater quality determined.

Our research adds to that undertaken on the provenance of pumped samples from wells. At long time, pump intake position may not be important and the sample origin is directly related to the permeability distribution over the well screen interval (Varljen et al., 2006). However, it may take a significant time, often longer than the typical sampling time, before this permeability-weighted sample concentration is attained due to the later arrival of groundwater entering the distant ends of the screen farthest from the pump intake (Martin-Hayden, 2000a,b; Martin-Hayden et al., 2014; Reilly and Gibs, 1993). Well casing storage (Barber and Davis, 1987), well screen and sand pack design (Kozuskanich et al., 2012), the partial mixing of inflowing water with water within the well screen during pumping (Martin-Hayden and Wolfe, 2000) and even the purging method (Robbins and Martin-Hayden, 1991) may additionally affect the stabilization time. With increasing screen length in particular, chemical stability may take a very long time to occur, even if pumping rates are increased (Mayo, 2010; Rivett et al., 1990).

Implicit to many groundwater sampling evaluations is the (perhaps unrecognized) assumption that pumping overcomes any ambient vertical gradients and a permeability-weighted sample (also referred to as a flow-weighted average sample or a screen-weighted sample (Church and Granato, 1996; Hutchins and Acree, 2000; Martin-Hayden, 2000a)) is eventually obtained. However, rather than being the exception (Giddings, 1987), ambient vertical flows in wells are expected to be as ubiquitous as vertical flows in aquifers and will occur at least to some degree in all aquifers (Elci et al., 2001). Naturally occurring vertical hydraulic head gradients which may induce significant vertical flows in wells are widely reported in a variety of hydrogeological settings (Brassington, 1992; Church and Granato, 1996; Dumble et al., 2006; Furlong et al., 2011; Ma et al., 2011; Metcalf and Robbins, 2007; Streetly et al., 2002; Taylor et al., 2006). Ambient vertical flows in wells are likely to be greater where well screens are longer and geological layering promotes increased vertical head gradients. Use of shorter screens (low-flow sampling is typically recommended for well screens <3 m (e.g. US EPA, 2010)) may reduce ambient vertical flows, however, ambient vertical flows of 0.015–2.3 l/min have been reported in wells with screens between 3 m and 10 m in length (Elci et al., 2001). It is important to recognize the influence of vertical flows in wells as they may cause aquifer cross-contamination (Lacombe et al., 1995), passive sample concentration bias (Elci et al., 2001; Konikow and Hornberger, 2006), errors in hydraulic head and hydraulic conductivity estimation (Elci et al., 2003; Kaleris et al., 1995) and misinterpretation of tracer test results (Riley et al., 2011). The effect and sensitivities of ambient vertical flows on sampling provenance in pumped groundwater samples has not been systematically mapped out.

Our goal is hence to examine the phenomenon of ambient-flow biased samples and answer the question—can the literature-reported range of vertical flows in wells bias sampling results and lead to samples that are weighted by ambient head gradients in addition to other hydraulic influences? We present herein our numerical modeling study designed to address this question.

2. Materials and methods

2.1. Numerical modeling overview

Numerical flow modeling with particle tracking was used to investigate pumped sample provenance under ambient horizontal head gradients and for increasing vertical gradients for 14 different model scenarios with varying screen lengths, well diameters, pumping rates, aquifer depths, permeability distributions and boundary conditions (Table 1). For each scenario the relative influence of vertical head gradients was varied by varying the position of the monitoring well in the aquifer. Each vertical flow simulation was compared with a corresponding baseline case with the same scenario parameters but no ambient vertical head gradients.

We consider well screen lengths of 3–10 m and pumping rates that vary from those recommended for low-flow sampling through higher pumping rates perhaps adopted in purging. While the lower end of the above screen range is typically recommended for low-flow sampling (e.g. US EPA, 2010), some authors have suggested such sampling can be used with screen lengths >3 m (Barcelona et al., 2005; Metcalf and Robbins, 2007; Varljen et al., 2006). Indeed, low-flow or zero-purge sampling options are doubtless attractive in longer screen wells as the removal of fixed purge volumes becomes increasingly onerous. From a UK perspective, while well screens <3 m are advocated for monitoring wells (BS ISO, 2010), other guidance suggests that low-flow sampling is most applicable in wells with long screen lengths (BS ISO, 2009). It is recognized that well screen lengths <3 m are becoming more prevalent in contaminated site investigations and that a 10 m well screen may perhaps be perceived to be unreasonably long. However, the use of 10 m, or even longer, well screens still remains significant internationally. For example, within the UK context, they can be used in the monitoring of thick (>c. 100 m) aquifer resource units and low storage aquifers with high amplitude dynamic