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Evaluation of multiple tracer methods to estimate low groundwater flow velocities

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ABSTRACT

Four different tracer methods were used to estimate groundwater flow velocity at a multiple-well site in the saturated alluvium south of Yucca Mountain, Nevada: (1) two single-well tracer tests with different rest or "shut-in" periods, (2) a cross-hole tracer test with an extended flow interruption, (3) a comparison of two tracer decay curves in an injection borehole with and without pumping of a downgradient well, and (4) a natural-gradient tracer test. Such tracer methods are potentially very useful for estimating groundwater velocities when hydraulic gradients are flat (and hence uncertain) and also when water level and hydraulic conductivity data are sparse, both of which were the case at this test location. The purpose of the study was to evaluate the first three methods for their ability to provide reasonable estimates of relatively low groundwater flow velocities in such low-hydraulic-gradient environments. The natural-gradient method is generally considered to be the most robust and direct method, so it was used to provide a "ground truth" velocity estimate. However, this method usually requires several wells, so it is often not practical in systems with large depths to groundwater and correspondingly high well installation costs. The fact that a successful natural gradient test was conducted at the test location offered a unique opportunity to compare the flow velocity estimates obtained by the more easily deployed and lower risk methods with the ground-truth natural-gradient method. The groundwater flow velocity estimates from the four methods agreed very well with each other, suggesting that the first three methods all provided reasonably good estimates of groundwater flow velocity at the site. The advantages and disadvantages of the different methods, as well as some of the uncertainties associated with them are discussed.

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1. Introduction

Estimates of risks associated with groundwater contamination are typically very sensitive to groundwater flow velocity estimates at the site of interest. As an example, saturated zone model sensitivity studies conducted in support of the license application for the proposed high-level nuclear waste repository at Yucca Mountain, Nevada indicated that the most important parameter affecting predicted radionuclide concentrations and doses at the compliance boundary was the saturated zone flow velocity (SNL, 2005; Arnold et al., 2008). The saturated alluvium south of Yucca Mountain represented the final barrier to radionuclide migration from the proposed repository to the accessible environment (defined by a regulatory compliance boundary approximately 18 km from Yucca Mountain). Consequently, the flow and transport properties of this alluvium were the subject of much scientific investigation, and considerable effort was put into obtaining estimates of the ambient flow velocity in the alluvium. Estimates based on hydraulic gradients from water level measurements and hydraulic conductivities from aquifer pump tests were considered quite uncertain because of the shallowness of the horizontal gradient, a strong vertical gradient (making water levels a strong function of screen depth), and sparseness of wells in the alluvium. Thus, there was an incentive to obtain groundwater flow velocity estimates using methods other than the conventional approach of multiplying hydraulic conductivity and gradient.

In 2004 and 2005, two single-well injection-withdrawal tracer tests and two cross-hole forced-gradient tracer tests were conducted in the saturated alluvium at Nye County Early Warning Drilling Program Site 22 (NC-EWDP Site 22). The results and interpretations of these tests were previously reported by Reimus et al. (2006), with details of the method used to estimate flow velocity from the single-well tests described in Reimus et al. (2003a). However, these authors did not discuss the planned flow interruption during one of the cross-hole tests or the ambient flow velocity estimates that could be obtained from analyzing the tracer responses to this flow interruption. From August 2006 to

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October 2008, a natural gradient tracer test was conducted at Site 22. The results and interpretations of this test have not previously been reported other than in Yucca Mountain Project reports that have had limited distribution.

NC-EWDP Site 22 is located about 14 km south of Yucca Mountain with one large-diameter (6.75″) well that can be pumped at a relatively high rate (22S) and three 2-inch piezometers (22PA, 22PB, and 22PC) that can be used as observation wells in hydraulic testing or injection wells in cross-hole tracer testing. The site location and layout are shown in Fig. 1. The site is situated along a projected flow pathway from the proposed repository, so it is a good location for assessing flow and transport in the saturated alluvium. A summary of the well completions and site geology is provided in Fig. 2. All of the tracer tests discussed in this paper were conducted in the second screened interval from the top of the wells, which was more transmissive than the uppermost interval and thus considered to be the more likely radionuclide transport pathway and also the pathway that would result in the most rapid (pessimistic) travel times. Note that the local horizontal hydraulic gradient at the site was indeterminate because the water levels in the different wells of Fig. 1 were essentially indistinguishable in screened intervals completed at the same depth.

The objective of this paper is to provide the reader with some perspective on the advantages and disadvantages of each of the three tracer-based methods for estimating natural flow velocities, with the natural gradient test result serving as a "ground truth". While natural gradient tests certainly provide the best possible information, they can be expensive and risky in deep systems that require costly well installations. They typically require many wells to ensure success because slight deviations in true flow direction from anticipated flow direction or inadvertent installation of wells into low permeability subdomains can result in tracers completely missing downgradient wells. In this regard, it was considered quite fortuitous that a successful natural-gradient test was conducted for this study with only a single downgradient well. This fortunate result provided the opportunity to evaluate the ability

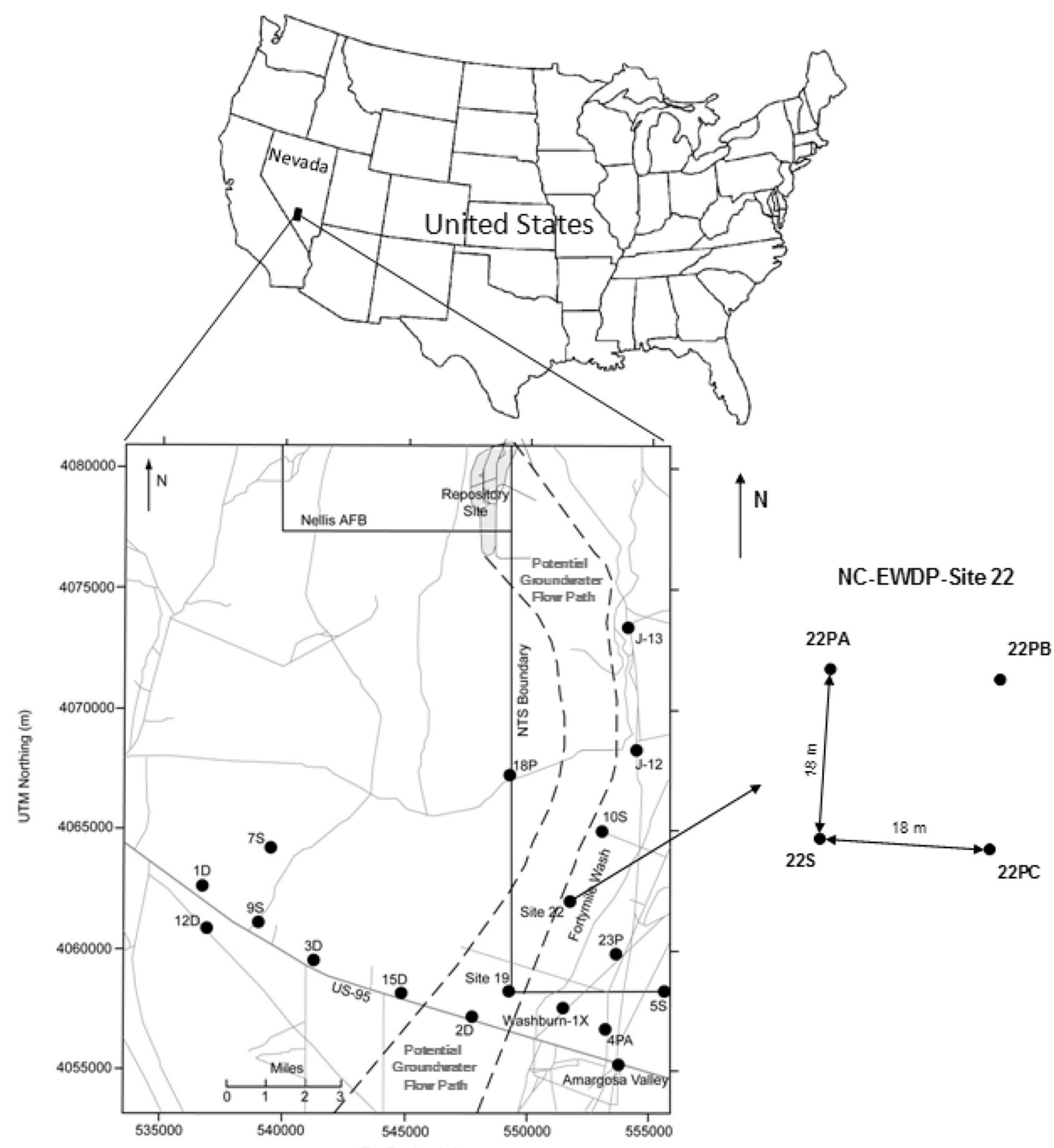

Fig. 1. Location and layout of Nye County Early Warning drilling program Site 22 relative to Yucca Mountain repository site and projected groundwater flow path from Yucca Mountain (approximately bounded by the dashed lines). Note that the distances between wells are at the surface. The distance between 22PA and 22S in the tracer test interval is 16.7 m because of deviations of the borehole from vertical and the orientation at depth is almost due north-south.