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Reactive transport in the complex heterogeneous alluvial aquifer of Fortymile Wash, Nevada

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HIGHLIGHTS

- Hierarchical facies-based model for Alluvium of Fortymile Wash is used.
- Lagrangian-model is developed to analyze reactive-solute dispersion.
- Effects of each heterogeneity scale is investigated.

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ABSTRACT

Yucca Mountain, Nevada, had been extensively investigated as a potential deep geologic repository for storing high-level nuclear wastes. Previous field investigations of stratified alluvial aquifer downstream of the site revealed that there is a hierarchy of sedimentary facies types. There is a corresponding log conductivity and reactive surface area subpopulations within each facies at each scale of sedimentary architecture. Here we use a Lagrangian-based transport model in order to analyze radionuclide dispersion in the saturated alluvium of Fortymile Wash, Nevada. First, we validate the Lagrangian model using high-resolution flow and reactive transport simulations. Then, we used the validated model to investigate how each scale of sedimentary architecture may affect long-term radionuclide transport at Yucca Mountain. Results show that the reactive solute dispersion developed by the Lagrangian model matches the ensemble average of numerical simulations well. The link between the alluvium spatial variability and reactive solute dispersion at different spatiotemporal scales is demonstrated using the Lagrangian model. The longitudinal dispersivity of the reactive plume can be on the order of hundreds to thousands of meters, and it may not reach its asymptotic value even after 10,000 years of travel time and 2–3 km of travel distance.

1. Introduction

Yucca Mountain, Nevada, had been extensively studied as a potential geologic repository for permanent disposal of high-level nuclear wastes. A critical performance requirement for such a nuclear waste repository is it must include both natural and engineered barriers. Although the saturated zone below Yucca Mountain constitutes a potential pathway for radionuclides to reach the accessible environment, the porous media in the saturated zone is also expected to act as a natural barrier to radionuclide transport (see Bodvarsson et al., 1999; Bandurraga and Bodvarsson, 1999; Arnold et al., 2003; Eddebbarh et al., 2003; McKenna et al., 2003). In particular, the alluvial aquifer of Fortymile Wash (FW), located just upstream of the 18 km compliance boundary, is conceptualized as the most significant component of the saturated zone natural barrier mechanism because of the slower groundwater flow velocity (compared to that of the upstream volcanic tuff aquifers) and higher sorption capacity associated with the saturated alluvium (Sun and Bertetti, 2007; Sun et al., 2008).

At Yucca Mountain, groundwater is conceptualized as flowing in a generally southerly direction from recharge areas at higher elevations north and northwest of Yucca Mountain and coalescing

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in the FW alluvial aquifer (see Fig. 1). Retardation of radionuclides in the saturated alluvium of FW had been identified as a process that is important in isolating high-level nuclear wastes (Bechtel SAIC Company, LLC, 2004). Therefore, evaluation of the capability of the saturated alluvial aquifer in controlling radionuclide transport was an essential part of the repository performance assessment.

U.S. Department of Energy (DOE) developed site-scale flow and transport models for the saturated zone covering an area of about 1350 km^2 with several kilometers in the vertical direction (Bechtel SAIC Company, LLC, 2004; Farrell et al., 2005). A typical numerical grid block in the DOE site-scale model spans hundreds of meters horizontally and tens of meters vertically. The FW alluvial aquifer unit is represented as a homogeneous zone with constant physical and chemical properties that were obtained through model calibration or expert elicitation (Bechtel SAIC Company, LLC, 2004). However, field studies conducted in the FW revealed significant spatial variability in facies distributions (Facies are three-dimensional (3D) bodies of sediments, whose differentiation provides a useful conceptual framework to characterize heterogeneity in attributes of interest (e.g., hydraulic conductivity, K); see Soltanian and Ritzi, 2014). For example, during an outcrop study, Ressler (2001) observed that alluvial hydrofacies with distinctively different properties exist at smaller scales than the numerical grid block scale. In fact, alluvial aquifers in general exhibit heterogeneities over a hierarchy of scales as a result of complex depositional and diagenetic processes (Bridge, 2003; Soltanian and Ritzi, 2014). A facies type defined at one scale consists of assemblages of different facies types at a smaller scale. And this continues across any number of hierarchical levels.

Mass transport parameters (e.g., retardation and dispersion) are known to be scale-dependent (Dai et al., 2004, 2009; Deng et al., 2010, 2013; Soltanian et al., 2015a,b, 2017). This scale dependency and the related problem of incorporating the effects of missing scales is a grand challenge in stochastic hydrogeology. This problem has stimulated tremendous interests in developing multi-scale flow and transport models in the last two decades (e.g., Rubin, 1995, 2003; Scheibe and Yabusaki, 1998; Lu and Zhang, 2002; Dai et al., 2004; Proce et al., 2004; Ritzi and Soltanian, 2015; Soltanian et al., 2015a, b, c).

Sun et al. (2008) used many types and sources of data (e.g., outcrop exposure, cutting logs) to parsimoniously characterize the hierarchical sedimentary architecture of the FW alluvial aquifer. The heterogeneity model captures all aspects of sedimentary architecture relevant to mass transport processes. The goal of the present study is to use this parsimonious, quantitative, 3D conceptual heterogeneity model in a multi-scale Lagrangian-based reactive transport model by Soltanian et al. (2015). The Lagrangian model was developed to compute reactive solute dispersion undergoing equilibrium sorption in 3D anisotropic heterogeneous porous media with hierarchical organization of reactive minerals. The spatial correlation structure of K and sorption distribution coefficient, K_d, and their cross-correlation is considered in the model. The model follows upscaling approach using stochastic averaging (e.g., Gelhar and Axness, 1983; Dagan, 1984, 1989; Dentz et al., 2011, 2017). Other examples of upscaling methods include volume averaging (e.g., Whitaker, 1999), homogenization (e.g., Lunati et al., 2002), and renormalization (e.g., Zhang, 1998). Importantly, one of the reason to utilize upscaling methods is to avoid extensive computational burden involve in numerical

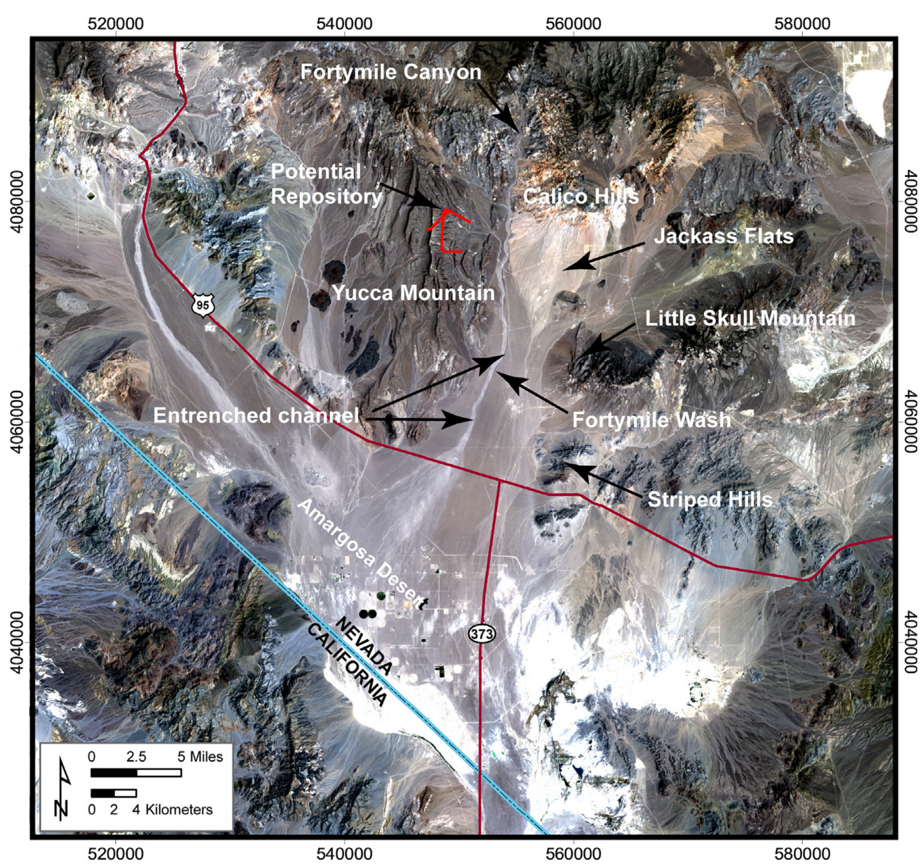

Fig. 1. Satellite image of Yucca Mountain and its vicinity. Fortymile Wash and its entrenched channel are labeled on the picture. Map coordinates are in Universal Transverse Mercator, Zone 11, North American Datum of 1983, meters.