Nonpoint Source Pollutant Transfer across Deep Vadose Zones – A Multiscale Investigation to Inform Regulatory Monitoring, Assessment, and Decision Making

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Objectives and Previous Work

The overall objective of this project is to provide a rigorously upscaled modeling tool for basin-scale assessment of nonpoint source (NPS) pollutant transport in the heterogeneous, alluvial, and often deep vadose zones of California agricultural landscapes. Our principal research hypothesis is that flow and transport in these unsaturated sediment systems is subject to highly non-uniform, localized preferential flow and transport patterns that lead to accelerated solute transfer across the vadose zone with potentially limited attenuation not captured by current deterministic or stochastic vadose zone models. To test our hypothesis, we link core scale vadose zone information from two extensive deep vadose zone drilling projects (one completed, one ongoing) to the effective vadose zone transport of NPS pollutants at the field scale (orchard, field, corral, land application unit) and at the farm scale (farm, dairy) by using geostatistical analysis and by applying a high-resolution vadose zone flow and a transport model.

An extensive characterization and geostatistical analysis of the geology, hydraulic properties, and nitrogen distribution in a 16-m deep vadose zone across a nectarine orchard in Fresno County has been the starting point for this project. Significant variability of hydraulic properties was found between and within the different lithofacies that make up the vadose zone. Most importantly, we found that the total amount of nitrogen mass contained within the deep vadose zone was significantly (4x) smaller than would be expected, based on a nitrogen mass balance analysis (NMBA). Based on isotopic field evidence and a survey of literature data, large-scale denitrification and volatilization could not account for this discrepancy. Preferential flow was hypothesized to be the main reason for the lack of nitrogen stored in the vadose zone. Onsoy (2005) completed modeling of heterogeneous, transient flow and transport model of the entire 16-m deep vadose zone. In that work, heterogeneity of the flow parameters was implemented using a scaling factor approach (SFA) in which a single parameter describes the heterogeneity of the unsaturated flow parameters. However, Oliveira et al. (2006) demonstrated in principle that the SFA may lead to significant underestimation of unsaturated flow and transport variability.

Current Work

The previous modeling efforts were reviewed. Minor errors in the geostatistical analysis and in the flow and transport model implementation were fixed. To overcome the potential shortcomings of the SFA, we developed a fully non-linear, multi-parameter heterogeneity representation (MPHR). Unsaturated flow and transport simulations for both types of heterogeneity representations of the vadose zone were implemented with HYDRUS (Simunek et

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The flow velocity distribution in the MPHR-based simulations is indeed significantly more variable than in the SFA-based simulations (fig. 1a, b). Yet, after seven years of nitrogen management, which is simulated using the actual, transient weather, irrigation, and fertilization history of this site during 1990 – 1996, the concentration distribution for both simulation types did not show a significant difference (fig. 1c, d). Neither approach explained the low N storage in the deep vadose zone observed in the field.

We then hypothesized that we overestimated dispersion, which would counterbalance the strong heterogeneity in the advective transport of nitrate, effectively preventing preferential transport to be simulated accurately. We tested this hypothesis by implementing a transport model with negligible dispersion. HYDRUS does not offer such a transport code, hence a particle-tracking technique was developed that we could couple with HYDRUS. To simplify the coupling, a steady-state (constant) infiltration flux of 0.2-cm/day (the average flux during seven-year record) was assumed and the corresponding steady-state flow field was computed with HYDRUS prior to the transport simulation. Transient, advection-only transport was simulated for seven years, during which 40,000 particles were applied to the top of the domain each day. Figure 2 shows that many of the particles cluster along narrow strips of the domain which supports our preferential flow hypothesis. Moreover, these narrow strips are associated with the highest water flux, hence, most of the mass moves along relatively narrow pathways. Mass flux along preferential flow paths exceeds that in the remainder of the domain typically by a factor 2 – 5. Advection-only based results showed a notable decrease in the amount of nitrogen stored in the vadose zone but still show far higher vadose zone storage than was observed in our field measurements.

Discussion

We are finding that significant preferential flow occurs in the unsaturated zone due to its heterogeneous lithofacies composition. Yet, our initial hypothesis that a full accounting of heterogeneity in the simulation of flow based on Richards’ equation would explain the low nitrogen mass stored in the vadose zone, has been disproven. This is consistent with De Rooij (2000), Simunek et al. (2003), and Gardenas et al. (2006) who showed that Richards’ equation may be an inadequate model as it generally led to relatively uniform flow and transport. Other expressions or assumptions, such as dual porosity or mobile-immobile domains, need to be included in the model to yield results that account for strong non-equilibrium preferential flow and transport. There was initially not enough evidence in our field measurements that supports using these type of models, but we are reconsidering such a conceptual approach. Other conceptual elements to test include denitrification that impacts more stagnant zones of water flow, but not as much denitrification in preferential flow paths, nitrogen losses due to volatilization at the land surface, and a re-examination of the orchard nitrogen budget, particularly the N cycling through the leaf mass.

Future work

In the next phase, we continue our modeling efforts with a focus on testing alternative conceptual approaches, three-dimensional simulation, and high-resolution analysis. We also are beginning to analyze core samples that were obtained from 17 sites in Tulare and Kings counties, which will be used to further define nitrate distribution in deep vadose zones at actual field sites.
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References


Figure 1. Simulation results after four years for velocity in cm/day using A) scaling factors, B) full heterogeneity and log10 concentrations in mg/l for C) scaling factors, and D) full heterogeneity.
Figure 2. Number of particles after seven years of continuous fertilizer application using A), scaling factors, B) full heterogeneous case. Mass flux using C), scaling factors, D) full heterogeneous case.
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