Hydraulic gradients modulate non-Fickian transport in heterogeneous porous media

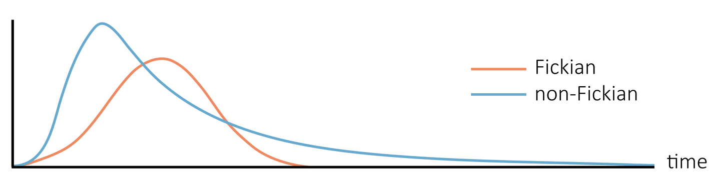
H21L-1912
AGU Fall Meeting 2019
San Francisco, CA

Rich Pauloo[1]* | Graham Fogg[1] | Zhilin Guo[2] | Christopher Henri[1]
[1] Univeristy of California, Davis | [2] South University of Science and Technology of China | * corresponding author

1. ABSTRACT

CORE QUESTION

> How does varying hydraulic gradient direction affect anomalous transport and applicability of the advection dispersion equation (ADE)?



Fluid flow and contaminant transport in heterogeneous porous media is critical in many applications from sustainable groundwater quality management [1] to radioactive waste disposal [2] and water filtration [3]. Accurate contaminant transport modeling is challenged by anomalous (non-Fickian) transport, characterized by early breakthrough, long tailing, non-Gaussian or multipeaked plume shapes, and non-linear scaling of the mean square displacement [4].

In regional alluvial aquifers, it is unknown how emerging nonpoint source contamination (e.g., salts and nitrates) will interact with aquifer heterogeneity and shifting hydraulic gradients. Pumping and recharge for irrigation significantly shift the magnitude and direction of regional hydraulic gradients but how variations in the hydraulic gradients, particularly direction, impact non-Fickian transport remains, to our knowledge, unexplored. We investigate the influence of hydraulic gradients on non-Fickian transport with a simple concept, the vertical to horizontal gradient ratio (VHGR):

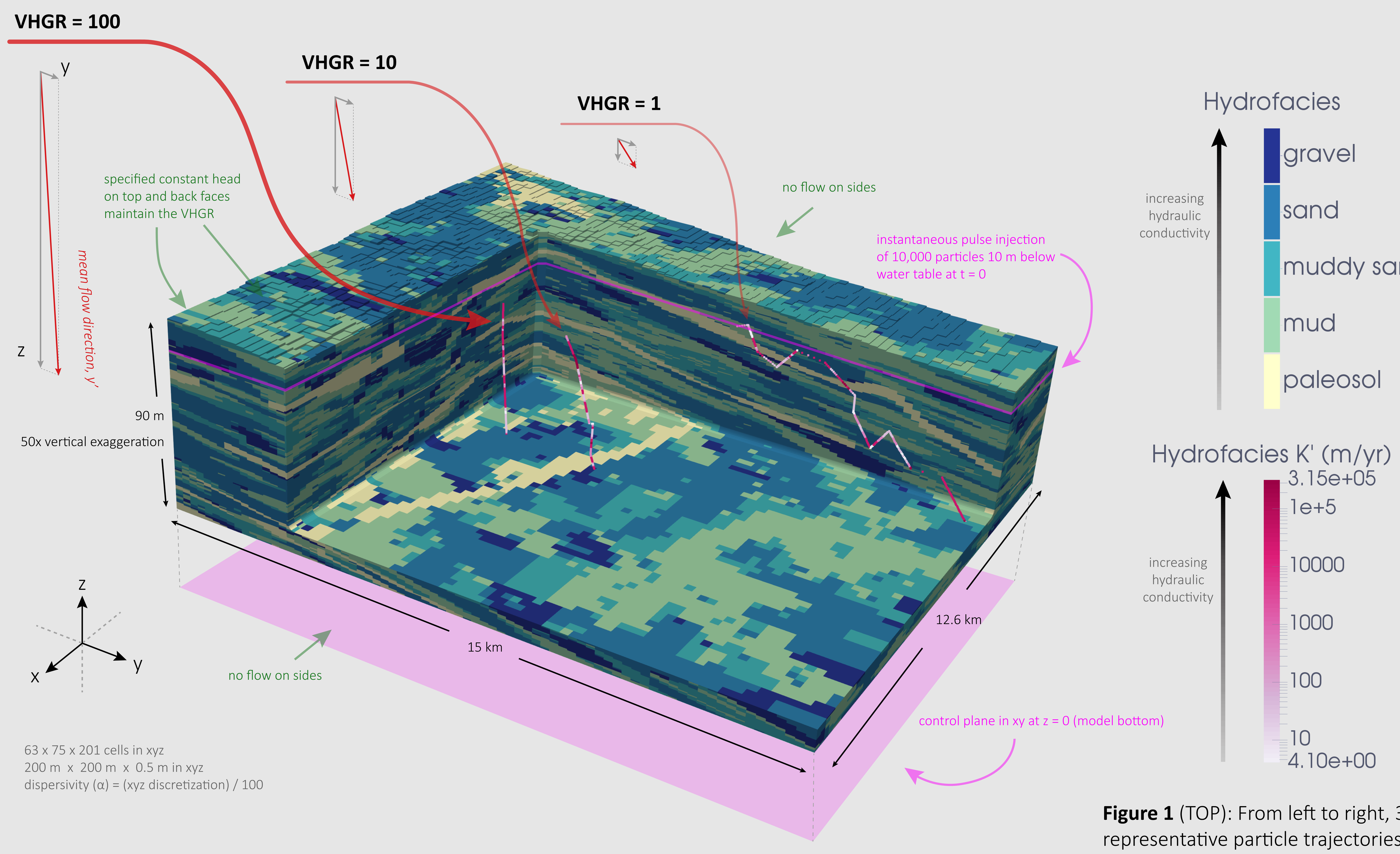
$$\text{VHGR} = \frac{\partial h/\partial z}{\partial h/\partial y}$$

Large VHGR is predominately vertical flow and flow is increasingly horizontal as VHGR decreases toward 1.

In horizontally stratified clastic sedimentary deposits, horizontal K' is commonly 100 to 10,000 times greater than vertical K'. In these systems, groundwater pumping at depth and irrigation recharge from above create very large VHGR (e.g., 100). When pumping and/or recharge is decreased, VHGR values typical of pre-development conditions (e.g., 1 to 10) can prevail. This works shows that the significance of non-Fickian transport processes depends greatly on these differing hydraulic gradient forcings.

We test three hypothetical VHGR scenarios representing intensive to reduced pumping (VHGR = 100, 10, 1) in a highly stratified heterogeneous alluvial aquifer [5]. We find that lower VHGR in our study site results in increased non-Fickian behavior, illustrated by increased spreading in longitudinal and transverse directions, and increased mass holdback and tailing. Thus, regional-scale nonpoint source contaminant management under reduced pumping and recharge may need to account for increased non-Fickian transport (i.e., longer contaminant residence and greater spatial spreading) than previously considered. Conversely, under conditions of strong vertical gradients that drive mass more or less straight through confining beds rather than allowing mass to find preferential flowpaths around them, the ADE may be a very good approximation of the transport physics.

2. FLOW & TRANSPORT IN A HETEROGENEOUS ALLUVIAL AQUIFER UNDER VARYING VHGR



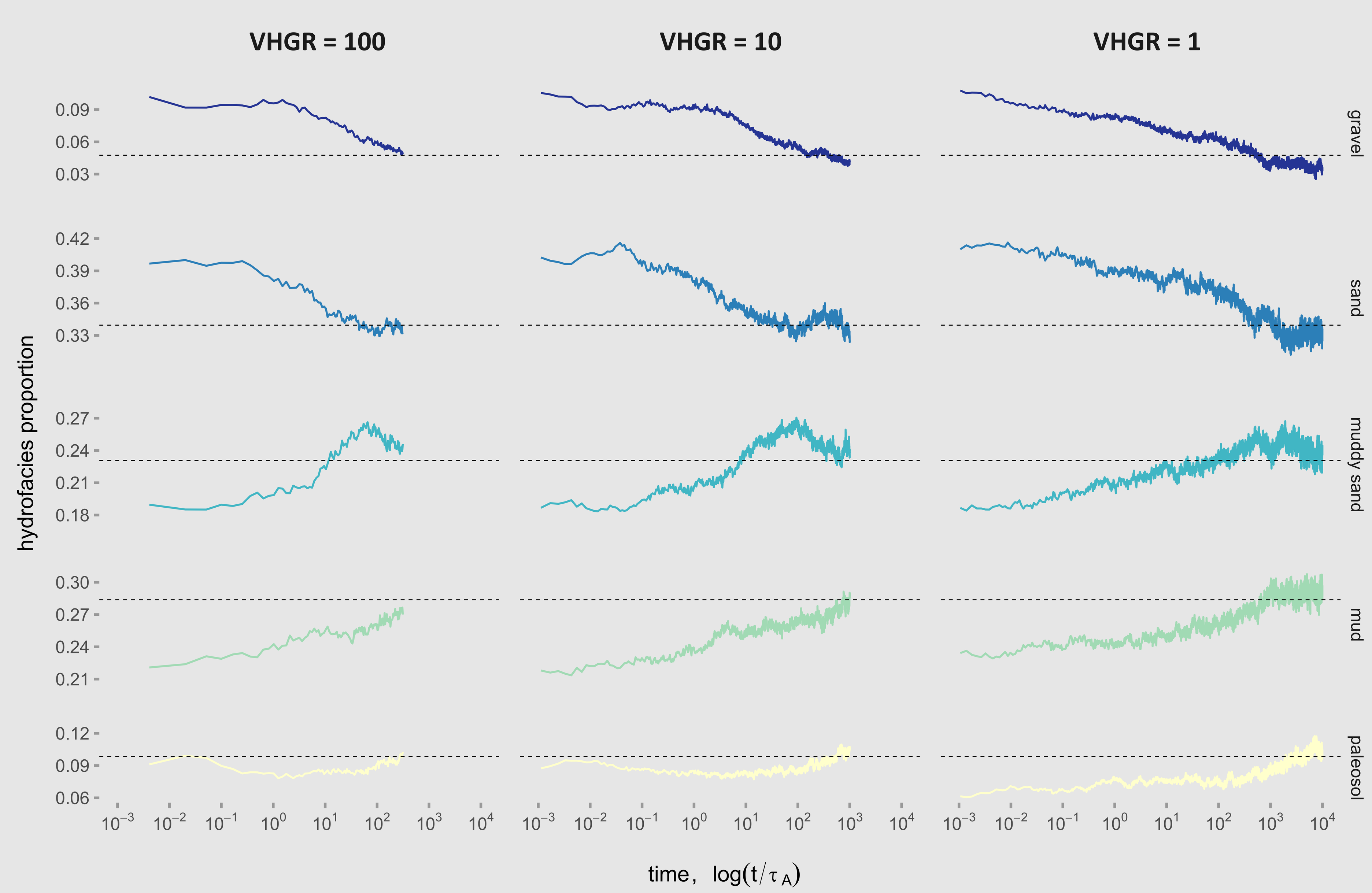
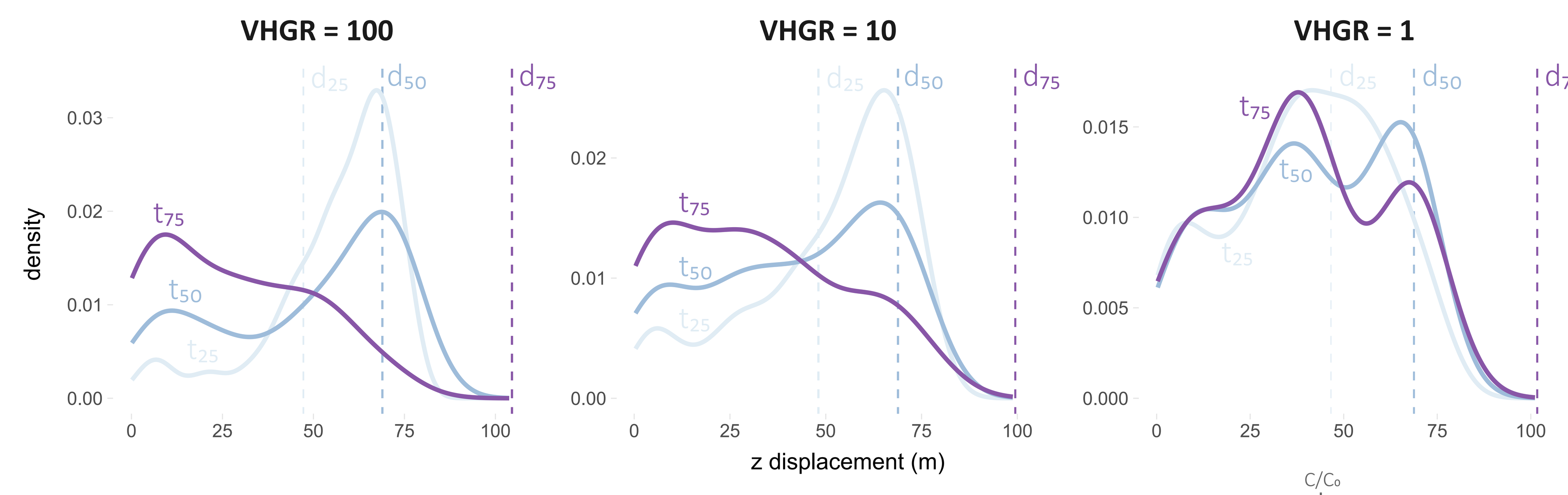


Figure 1 (TOP): From left to right, 3 representative particle trajectories for VHGR = 100, 10, and 1. Particle trajectories are colored by the hydraulic conductivity of the hydrofacies they reside in at the time of the snapshot. The alluvial aquifer T-PROGS domain [5] connects in 3D via sand and gravel lenses. Characteristic length scales in xy are 2-3 orders of magnitude greater than those in z. Flow and transport are solved with MODFLOW [6] and the random walk code RW3D [7].

Figure 2 (LEFT): Mean Lagrangian hydrofacies proportions converge on the actual proportions (black dashed line) over increasing time scales as VHGR decreases. Relatively higher muddy sand and paleosol proportions for VHGR = 100 and 10 suggest advection-dominated transport. As VHGR decreases, late time oscillations in hydrofacies proportion--caused by diffusion-dominated trajectories that exchange mass between facies--are increasingly common. Time is rescaled by $\tau_A = \lambda_c/\bar{v}$ where λ_c and $\bar{v}$ are the characteristic length and mean velocity along mean flow direction y'.

3. TRANSPORT IS INCREASINGLY NON-FICKIAN AS VHGR DECREASES



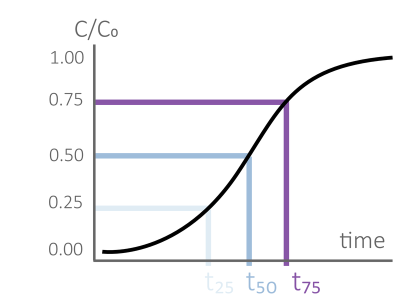


Figure 3 (TOP): Mass displacement along the z direction at t_{25}, t_{50} and t_{75} of the cumulative breakthrough curve (right). Vertical dashed lines are mean mass locations d_n at time n predicted by the mean vertical velocity $\bar{v}$ via Darcy's law: $d_n = \bar{v}t_n$. Mass is increasingly held back with decreasing VHGR, resulting in greater spreading along the longitudinal and transverse directions (Figure 4), and increased tailing measured at a control plane at bottom of the model (Figure 1).

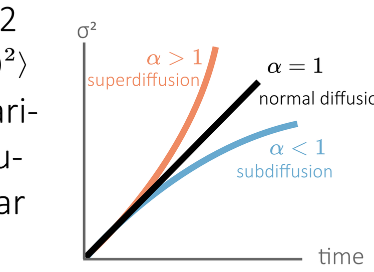
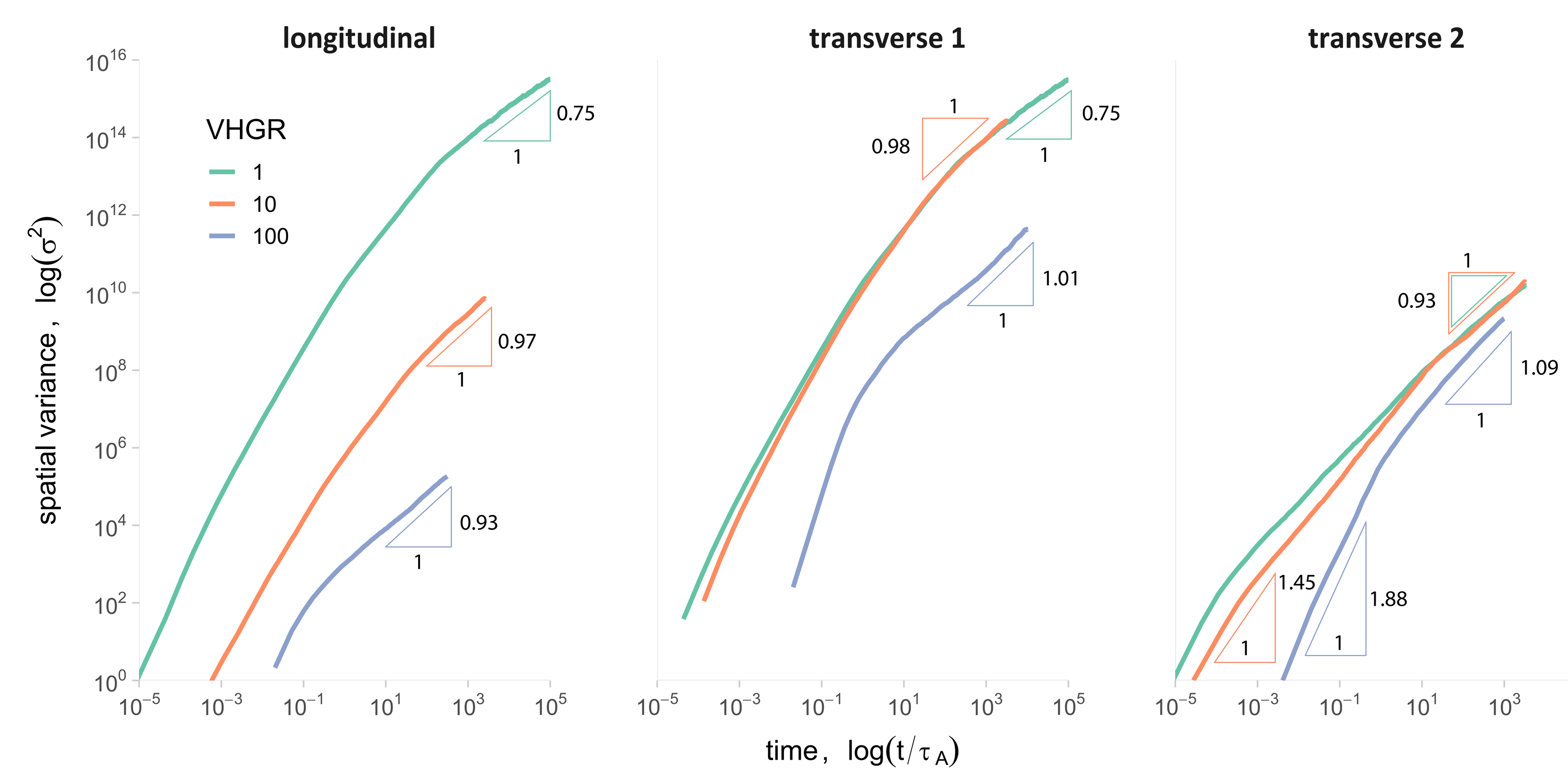


Figure 4 (BOTTOM): Mean squared displacement, σ², in the longitudinal (along y'), transverse 1 and 2 (vertical and horizontal relative to y' respectively) directions. σ² in direction j is: $\sigma_j^2(t) = \langle (j(t) - \langle j(t) \rangle)^2 \rangle$ where $\langle \cdot \rangle$ is the average over all particles. As VHGR decreases: *(a)* increased spatial and temporal variance is observed in all directions, and *(b)* late time longitudinal and transverse 1 σ² are more subdiffusive and show pre-asymptotic behavior. Sub- and superdiffusion in direction j are defined as nonlinear scaling of σ² with respect to time, $\sigma_j^2 \sim D_j t^{\alpha}$ and indicate anomalous transport (left).



4. DISCUSSION

VHGR varies by orders of magnitude in heavily managed groundwater systems due to pumping and recharge. We show that decreasing VHGR in our study site increases non-Fickian transport, illustrated by increased--and non-Gaussian--mass holdback along the vertical direction (Figure 3), and increased spreading and preasymptotic behavior in the second spatial moments of the plume (Figure 4) along the mean flow direction.

At high VHGR (100 and 10), strong advection forces particle trajectories along nearly vertical paths (Figure 1) and straight through high and low-K zones, evidenced by higher early-time muddy sand and paleosol proportions (Figure 2).

Significant pumping for irrigation has depleted global groundwater reserves [8-9], and established strong vertical hydraulic gradients due to pumping at depth (i.e., high VHGR). Sustainable groundwater management regimes that reduce pumping and increase recharge will effectively decrease VHGR. Thus, regional-scale groundwater quality models will need to account for increased non-Fickian transport (i.e, longer contaminant residence and greater spatial spreading) under these conditions. Conversely, if vertical gradients are sufficiently strong, the ADE may be a very good approximation of physics because the mass may be driven more or less straight through the aquitards. When the vertical gradients are weaker, mass can flow around the aquitards, triggering both preferential flow through high-K pathways and transverse dispersion and diffusion into and out of the aquitards, augmenting early- and late-time tailing.

UC DAVIS
UNIVERSITY OF CALIFORNIA

rpauloo@ucdavis.edu
richpauloo.com
@RichPauloo

Acknowledgements

This work was supported by NSF DGE # 1069333, the Climate Change, Water, and Society IGERT, to UC Davis, and by the U.S./China Clean Energy Research Center for Water-Energy Technologies (CERC-WET).

References

[1] Weissmann, Gary S., et al. "Dispersion of groundwater age in an alluvial aquifer system." Water resources research 38.10 (2002): 16-1.
[2] Berkowitz, Brian, and Harvey Scher. "Theory of anomalous chemical transport in random fracture networks." Physical Review E 57.5 (1998): 5858.
[3] Elliott, M. A., et al. "Reductions of E. coli, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter." Water research 42.10-11 (2008): 2662-2670.
[4] Kang, Peter K., et al. "Pore-scale intermittent velocity structure underpinning anomalous transport through 3-D porous media." Geophysical Research Letters 41.17 (2014): 6184-6190.
[5] Weissmann, G.S., S.F. Carle, and G.E. Fogg. 1999. Three dimensional hydrofacies modeling based on soil surveys and transition probability geostatistics. Water Resources Research 35, no. 6: 1761–1770.
[6] Harbaugh, Arlen W., et al. "MODFLOW-2000, The U. S. Geological Survey Modular Ground-Water Model-User Guide to Modularization Concepts and the Ground-Water Flow Process." Open-file Report. U. S. Geological Survey 92 (2000): 134.
[7] Fernàndez-Garcia, Daniel, Tissa H. Illangasekare, and Harihar Rajaram. "Differences in the scale-dependence of dispersivity estimated from temporal and spatial moments in chemically and physically heterogeneous porous media." Advances in water resources 28.7 (2005): 745-759.
[8] Famiglietti, James S. "The global groundwater crisis." Nature Climate Change 4.11 (2014): 945.
[9] Gleeson, Tom, et al. "Water balance of global aquifers revealed by groundwater footprint." Nature 488.7410 (2012): 197.