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A high-resolution non-invasive approach to determine transport of oxygen across the capillary fringe

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Mass transfer of volatile compounds between the vadose and the saturated zones is an important mechanism for a variety of natural subsurface processes and engineered applications including groundwater contamination, natural attenuation, waste management and in situ remediation. In this study a detailed investigation was carried out with the aim of improving the understanding of oxygen transport across the capillary fringe. Oxygen was chosen as the compound of interest as it plays an important role for microbial processes in groundwater – either by influencing the redox conditions present in the aquifer or by replenishing electron acceptors needed for microbial growth and respiration.

Earlier works showed that transverse vertical dispersion is essential for mass transfer of volatile compounds across the capillary fringe. Therefore the objective of this work was to determine transverse vertical dispersion coefficients in this transition zone under stationary conditions by measuring oxygen gradients across the saturated/unsaturated interface at grain scale resolution. For this purpose a high-resolution non-invasive method was developed.

Bench-scale two-dimensional flow-through experiments have been conducted under different experimental conditions to investigate the influence of different porous media (i.e. grain size) and horizontal flow velocities. Transverse dispersion coefficients across the capillary fringe were determined for steady-state flow conditions. These Dt-values were directly compared with the transverse dispersion coefficients obtained from tracer tests in the fully water-saturated zone performed in the same experimental setup, under identical hydraulic conditions.

In order to study also transient processes, various water table fluctuation amplitudes and frequencies have been applied. Vertical oxygen concentration profiles across the capillary fringe were measured over time at distinct positions along the main flow direction and evaluated with regard to oxygen mass fluxes measured at the outlet ports. Under dynamic conditions, i.e. having changed the position of the water table, the measured concentration profiles are different with regard to the process of imbibition and drainage. The outcomes show that drainage does not produce a significant change in concentration profiles compared to the steady-state case. On the contrary, rising water tables (i.e. imbibition) lead to the entrapment of air bubbles, resulting in a smaller gradient of oxygen concentrations. The gradual dissolution of entrapped oxygen into the bypassing oxygen-depleted water could be observed as well over time.

The proposed method demonstrated that the measured transverse vertical dispersion coefficients across the capillary fringe are very similar to those determined in the underlying fully water-saturated zone. It could also be observed that the dynamics of water table fluctuations affects the oxygen distribution in the capillary fringe. Additionally, this method can be extended to reactive processes involving oxygen as a reactant (i.e. redox reactions).