Special Section: Dynamic Processes in Capillary Fringes

The guest editors introduce the seven contributions to the special issue on processes in capillary fringes, with a focus on the complex interaction of biological, chemical, and physical processes in this environemnt.

Dynamic Processes in Capillary Fringes

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Processes in capillary fringes (CFs) have a complex nature due to the interactions between the solid, liquid, and gaseous environments. Despite a considerable body of literature on CFs coming from different disciplines, the ongoing processes and their complex interactions are yet only partially understood.

Abbreviations: CF, capillary fringe.

Capillary fringes are highly dynamic and periodically changing zones at the interface between the water-saturated aquifer and the unsaturated zone. As a consequence, we observe steep gradients in terms of hydraulic state variables, biogeochemical conditions, and thus, biological activity (Berkowitz et al., 2004). With fluctuations of the groundwater table, this reactive zone moves dynamically along the vertical direction, further complicating our understanding of specific processes that occur in both space and time. This special compartment is not only an interesting and challenging subject of research, it is also highly relevant for mass fluxes with terrestrial systems (Silliman et al., 2002; Haberer et al., 2011) and especially the biodegradation of contaminants (Lahvis et al., 1999; Dobson et al., 2007).

To gain a comprehensive understanding of the mass transfer and transformation in the CF, the close interactions of physical, chemical, and biological processes call for an interdisciplinary approach. This was the motivation to establish the interdisciplinary research group DyCap, funded by the Deutsche Forschungsgemeinschaft for a period of 6 years. The aim was to explore the basic physical, (hydro-)geological, chemical, and microbiological processes in CFs and their interaction, while collaborating closely with an interdisciplinary team of researchers. This special issue contains some of the latest results of DyCap, together with other actual research related to the dynamics of capillary fringes.

The sequence of papers comprises physical, chemical, and microbiological processes within CFs and a modeling approach covering their interactions. Mohammadian et al. (2015) explored trapping of the gas phase as a consequence of a fluctuating water table, which is one of the important causes for local gradients within CFs. Their column experiments demonstrated that gas trapping mainly depends on capillary and buoyancy forces, with negligible effects of viscous forces. Trapping was found for various dynamics of the water table fluctuation, which all were relatively slow, as expected for natural systems. The morphology of trapped gas clusters was analyzed using X-ray microtomography. Mohammadian et al. (2015) showed that with increasing importance of capillary forces the trapping pattern changed from gas bubbles in single pores to larger gas clusters.

Persson et al. (2015) performed five sand tank experiments, in which they established a groundwater table in the lower part of the tank and horizontal groundwater flow across the tank, to study the transport of a solute percolating downward through the vadose zone. The temporal dynamics of the concentration distribution was studied with optical image analysis and ERT measurements, which both produced results in reasonable agreement. The tracer plume was transported horizontally at the interface between unsaturated zone and capillary fringe and did not reach the groundwater table before reaching the tank boundary. This was also confirmed by simulations with HYDRUS-2D. They concluded that sampling only the groundwater could underestimate contaminant transport rates.

The effect of abiotic Fe(II) oxidation on the (diffusive) propagation of oxygen through the capillary fringe into an anoxic groundwater was studied by Haberer et al. (2015). The

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concentration of oxygen in one-dimensional columns and two-dimensional flow-through experiments was measured with a noninvasive optode technique at high spatial and temporal resolution. The speed of propagation of oxygen into the anoxic solution was significantly reduced by the reaction. Furthermore, the chemistry of the anoxic solution and especially its pH buffering capacity were found to exert a decisive influence on the system behavior. While the kinetics of FE(II) oxidation was found to be relevant at all time scales in unbuffered systems, the reaction at large time scales could be described as an instantaneous process in pH-buffered systems. The authors showed that the system behavior could be predicted very well using independently measured transport and reaction parameters.

Jost et al. (2015b) developed a method to estimate the number of microbial cells of *E. coli* within pseudo two dimensional experiments in a Hele-Shaw cell. The method is based on autofluorescence and, after calibration, it allowed the number density of cells in situ to be quantified with a high spatial resolution of some millimeters. Using this experimental setup they demonstrated a clear dependence of biological growth and activity as a function of the distance to the groundwater table+. The authors explained the dependence by the local availability of oxygen and substrate. Moreover, the dynamics of biological activity in response to lateral water flow and water table fluctuations could be measured.

The method developed in the previous paper was used by Jost et al. (2015a) to investigate the interaction between oxygen transport on the growth of *E. coli* under different nutrient concentrations (eutrophic and oligotrophic) and flow conditions (with or without changes of the groundwater table height). Under eutrophic conditions, the highest bacterial concentrations were found higher up in the capillary fringe, producing a steep gradient in oxygen concentration. This effect was less pronounced but still distinguishable compared to an abiotic scenario under oligotrophic conditions. Both lowering and raising of the groundwater table height resulted in increased cell densities in the transition region between the unsaturated and the saturated zone.

In column experiments, Rühle et al. (2015) investigated transport parameters, geochemical gradients, and microbial colonization and community structure within CFs for situations with and without fluctuating water tables. Results indicated that neither the longitudinal dispersivity nor the column geochemistry was changed by water table fluctuations. Water content and flow velocities, however, seemed to vary with time and dimension of the fluctuation zone. The main difference between both column systems was a clearly different depth-resolved bacterial community composition, with additional populations detected especially in the fluctuation zone. However, the overall bacterial diversity in both columns remained similar. Spatial and temporal changes of the water content and thus availability of oxygen for respiration may have caused the differences in microbial diversity.

Hron et al. (2015) addressed the question: Is it possible to predict the growth of microorganisms based only on independent measurements without additional calibration? To this end, flow-through experiments with *E. coli* in a Hele-Shaw cell filled with quartz sand were simulated with a newly developed numerical code for reactive multiphase multicomponent flow, using hydraulic parameters determined by multistep outflow experiments and parameters for the microbial growth model obtained from batch experiments. Very good agreement was observed between predicted and measured cell concentrations, when the kinetics of the gas–water phase exchange in the unsaturated zone and of the attachment of cells to the solid phase were adequately described.

This special issue presents examples of complex processes within capillary fringes. The contributions demonstrate the intensive coupling of biological, chemical, and physical processes relevant for a profound understanding of mass fluxes and turnover within this hot spot at the surface of the groundwater table. We hope these papers and increased knowledge will inspire future research on dynamic capillary fringes.

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