Geophysical Research Abstracts
Vol. 15, EGU2013-3343, 2013
EGU General Assembly 2013

Mass transfer processes across the Capillary Fringe: Quantification of gas-water interface and bubble mediated mass transfer

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The Capillary Fringe (CF) is a highly dynamic zone at the interface between the water-saturated aquifer and the vadose zone, where steep biogeochemical gradients and thus high bioactivities are expected. Mass transfer processes between the unsaturated zone and the atmosphere, like Greenhouse gas emissions and evaporation, are controlled by the highly temporal and spatial variable gas-water interface across the capillary fringe. Due to water table fluctuations, gas phase may be entrapped or released at/from the CF, which extremely affects the hydraulic properties of the porous medium as well as the mass transfer processes in the partially saturated zone. Most of these processes (gas entrapment and bubble mediated mass transfer (BMT)) are governed by the interactions between the interfaces of gas, water and soil phases. Quantification of these parameters requires a pore-scale approach, which can determine the phase volumes and interfaces with high accuracy. For the understanding and prediction of the involved processes, experiments and modeling at the pore scale are the necessary prerequisites for upscaled, effective modeling approaches.

To achieve this aim, we conducted a set of column experiments using X-Ray Computed Tomography (CT). Using this technique, we are able to quantitatively analyze the desired variables in 3D inside the actual bulk volume of the porous media. Water table (WT) elevation was raised at different velocities in the column filled with 1mm-glass beads. After each rise, the column was scanned with CT. We used an intelligent multi-phase segmentation method, considering grey value frequency and voxel neighboring, to separate gas, water, and solid phases in the CT images. The saturation of the gas phase, distribution of the trapped gas bubbles and clusters, and their size, shape, and area are quantified and analyzed at pore-scale. We developed a new segmentation algorithm to distinguish the gas/water interface from the gas/solid interface. Only the first plays the key role in BMT. Parallel to the CT-column experiments we measured in the same experimental setup (column, sediment, WT-rise velocity) the dissolution of trapped Oxygen gas bubbles using optode spots along the capillary fringe inside the column. For the first time we quantify BMT based on pore-scale process characteristics of gas phase distribution using two different models: (i) an effective 1D-diffusion model and (ii) a Multisphere diffusion model.