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Procedia Earth and Planetary Science 7 (2013) 40 – 43

Procedia
Earth and Planetary Science

Water Rock Interaction [WRI 14]

Reactive transfer of pollutants through the unsaturated soil zone during an artificial aquifer recharge process

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Abstract

Artificial groundwater recharge of aquifers by percolating water through the unsaturated zone (UZ) is a technique to enhance the water quality for drinking, irrigation, and industrial water supplies. The performance of the UZ to purify the infiltrated water is based on both the chemical and hydrodynamic properties of the porous medium. The chemical and microbially-mediated redox-reactions involving the degradation of organic substances are the key phenomena controlling the efficiency of such a process, and allow developing filtrating and reactive zones beneath an artificial recharge system.

For several decades, the BRGM has been developing research and industrial projects to support the development of this technology and its implementation in various climates, soils, industrial contexts, and specific water uses. A part of the obtained results highlighting several physicochemical phenomena potentially favorable for the creation of pollutant-filtrating reactive redox zones will be presented. This study confirms the interest of the unsaturated zone for water purification processes.

Selection and/or peer-review under responsibility of the Organizing and Scientific Committee of WRI 14 – 2013

Keywords: artificial recharge of aquifers, kinetics, thermodynamic, reactive transport modeling, unsaturated zone.

1. Introduction

Artificial recharge of aquifers is achieved by infiltrating surface water through soil that moves downward to the aquifers. This technique is increasingly important to establish a relevant exploitation plan of the underground waters, to reduce seawater intrusion or land subsidence, to improve the water quality through soil aquifer treatment and to, in fine, sustain the growing needs of drinking water ([1], [2]

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1878-5220
Selection and/or peer-review under responsibility of the Organizing and Scientific Committee of WRI 14 – 2013
doi:10.1016/j.proeps.2013.03.169

and reference therein). The most commonly used technique includes aquifer storage and recovery, infiltration ponds, riverbank infiltration, placing wells in vadose zone or direct injection into aquifers. These common recharge techniques are used to either purify partially treated wastewater or to enhance the quality of surface water for both irrigation purposes and the augmentation of drinking water supplies [1]. When the purpose of recharging is improving water quality to sustain the needs of drinking water or use it for irrigation it is necessary to carry out a detailed diagnosis including petrophysics and mineralogy of the porous and conductive soil and the aquifer material [3]. As water to be injected has generally physicochemical properties quite different from those of the residual water, mixing effects and water - rock interactions can have a beneficial effect such as the degradation of organic matter and fixing (adsorption, co-precipitation or precipitation of minerals), leading to an improvement of water quality. The redox processes are crucial in the reactivity of soil, and the availability of oxygen in the unsaturated zone water amplifies these reactions and provides a strong potential for water purification. The performance of the UZ to purify the infiltrated water is based on geochemical reactivity, microbial activity and physical/petrophysical properties. Indeed, hydraulic process during recharge leads to oxygen deeply penetrating within UZ [4]. It is important to understand the development and the extension of the successive redox zones in the artificial recharge systems. The biodegradation of organic matter is coupled to the reduction of the terminal electron receptors such as O_2, NO_3, Mn(IV), Fe(III) and SO_4.

The purpose of this study is to develop a general methodology integrating the relative weight of different mechanisms easily adaptable to different geological, hydrogeological and climate contexts. This analysis should allow the identification of key phenomena including physical, physico-chemical and thermo-kinetics of mineral reactions integrating microbiological contribution in order to highlight the performance of the unsaturated zone in the purification of treated infiltrating wastewater.

2. The continuum Unsaturated – Saturated Zone concept

Figure 1 shows the overall dynamic of the continuum UZ – SZ through the soil toward the deep aquifers [5]. This is a comparison between a natural system of developed and mature soil, which provides the natural recharge of the aquifer and the severely disrupted soil by intense agricultural activity introducing new inputs, especially chemicals and solid particles or artificial recharge practices. Agricultural practices introduce fertilizers and pesticides, herbicides, etc. Similarly, the artificial recharge introduces reactive chemicals (organic and inorganic) leading to thermodynamic disequilibria in the vadose zone and the underground aquifer. In the latter case, there is a strong disturbance producing gas exchange with the surrounding atmosphere and allowing the leaching or the fixation of pollutants. These new inputs can be nutrients for the soil microorganisms that contribute heavily to the kinetics of redox reactions and impact the physical chemistry of unsaturated porous media (water and gas phases), produced chemicals (CO_2, N_2, NH_4, etc.) and pH.

Indeed, these microorganisms can have a fundamental role in the degradation of organic pollutants and the catalysis of a complex network of redox reactions that may be beneficial for the fixation of metal pollutants or in contrast inducing a negative effect in mobilizing these pollutants. Generally, these microorganisms are concentrated in the capillary fringe by turning it into a true reactive barrier and an effective stabilized filter zone for pollutants. The extent of the capillary fringe depends on petrophysical properties of the soil and the relative humidity of the surrounding atmosphere or local climatic conditions. Finally, the contact of the artificial recharge water with and aquifer original water, having contrasted physicochemical properties, generates water mixtures that can interact and generate “mixing reactive zone”.