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Journal of Hydrology 313 (2005) 158–165

Journal of Hydrology

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Two-phase flow of water and air during aerated subsurface drip irrigation

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Received 28 October 2004; revised 28 October 2004; accepted 17 February 2005

Abstract

Here, we investigate the two-phase flow problem as in aerated subsurface irrigation. We extend McWhorter's one-dimensional equation for the concurrent flow of air and water (CEFAW) to three dimensions, and present explicit solutions subject to linear functions for the two-phase unsaturated hydraulic conductivity, diffusivity and fractional flow function. We present both steady- and unsteady-state solutions to the CEFAW corresponding to two types of constant continuous sources (a line source and a point source), which are relevant to aerated subsurface irrigation using emitters. The two-dimensional solution appears as the modified Bessel function of the second kind of order zero while the three-dimensional one as a complex exponential function. Graphic illustrations of the mathematical solutions indicate asymmetrical distributions of water content around the supply source due to gravity at the steady state established at large time, which differ in patterns and magnitudes for the two types of supply sources.

Keywords: Two-phase flow; Airflow; Water flow; Subsurface irrigation; Mathematical models

1. Introduction

In this paper, we investigate aerated subsurface irrigation, i.e. the concurrent flow of water and air. We nominally name this method 'oxygation' as compared to 'fertigation' or 'chemigation' when fertilizers are added to the irrigation water supply. Oxygation is a typical two-phase flow problem.

Irrigation is an age-old practice and has been continuously refined to meet different requirements. While beneficial to plants, irrigation, when performed improperly, may have unwanted side effects on the environment such as irrigation-induced salinity in soils, groundwater and surface water bodies. In addition to those side effects, water applied during irrigation may not necessarily assist plants to function properly and achieve increased yield as expected.

During an irrigation event, with whatever delivery technique, the purging of the air in the soil by the infiltrating front of water will create a verifiable level of anaerobic condition in the irrigated zones (Sojka, 1992; Drew and Stolzy, 1996; Arteca, 1997; Rawler et al., 2002; Blokhina et al., 2003). Consequently, by reducing oxygen concentration in the soil as it is

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doi:10.1016/j.jhydrol.2005.02.025

irrigated, root metabolism is reduced in the zones where the irrigation waterfront arrives. As a consequence, this type of irrigation plays a passive role not only as the water supplier, but also constraining the functioning of crops and microbial communities. The intended benefits of irrigation, therefore, can be undermined by the imposed oxygen deficit in the soil through the creation of an unfavourable anaerobic condition. Even though this anaerobic condition is temporary, plant and microbial metabolism may be constrained. Such a decline in metabolism due to oxygen deficit is possibly responsible for an inefficient uptake of water during irrigation, resulting in added drainage and water loses through other routes such as evaporation. There is a large body of published work on the experimental evidence of the decline in metabolism due to a lack of oxygen which relates to the effect of permanent anaerobic (flooding) conditions on soil microbiology and root functions (Veen, 1988). However, little work exists on the effects of temporary flooding experienced during irrigation.

While the reported studies on irrigation in the literature so far fail to offer an option for substantial reduction in water use while maintaining crop production, in a recent report on glasshouse and field experiments, Bhattarai et al. (2004) confirmed that dramatic increases in crop yields, water use efficiency and salinity tolerance can be achieved with the use of oxygenated subsurface drip irrigation water, especially for crops grown on heavy clay soils. The research by Bhattarai et al. (2004) showed that for soybean, oxygation increased water use efficiency (WUE) by 54 and 70%, respectively, for hydrogen peroxide application and air injection using a venturi valve, and pod yield by 82 and 96%, respectively, for the two treatments. Likewise, for crops grown across a range of saline soil conditions, aeration using the venturi principle resulted in yields superior to those of the non-aerated controls (Pendergast and Midmore, unpublished, 2003). Benefits of aeration using the venturi principle in California (Goorahoo et al., 2002), or using hydrogen peroxide in Germany (Heuberger et al., 2001) on crop growth are also reported.

Aeration of subsurface drip irrigation water, using appropriate techniques such as the venturi principle, hydrogen peroxide, or even a twin vortex system, could be potentially the most significant recent approach to economise on large-scale water usage and minimise drainage in irrigated agriculture.

Oxygation is a two-phase flow problem. The classic issue of two-phase flow is an important topic in other fields such as chemical and petroleum engineering. In hydrology and soil physics, the issue of two-phase flow was raised by Green and Ampt (1911), and then after pursued only by a few researchers (Powers, 1934; Baver, 1937; Lewis and Powers, 1939; Elrick, 1961). But the effect of airflow on water movement in irrigated and non-irrigated soils has been largely neglected in subsequent studies over the past six decades. The revigoration following six decades of neglect of the quantitative studies of water movement and associated soil air effects was mainly due to Morel-Seytoux and his co-workers. The representative work include Brustkern and Morel-Seytoux (1970), McWhorter (1971), Morel-Seytoux (1973, 1983), Vachaud et al. (1973, 1974), Parlange and Hill (1979), Parlange et al. (1982), Sander and Parlange (1984), Sander et al. (1984, 1988a,b,c), and Philip and van Duijn (1999). Those studies were either theoretical or undertaken in the laboratory. While using the Burgers equation and high resolution recorded data using time domain reflectometry (TDR) to investigate flow patterns in a field soil, Su et al. (2004, p. 5) found that the effect of airflow on soil water movement in the topsoil is obvious due to large air-filled porosity. All these studies, however, were limited to the analysis of soil water movement as affected by air in non-irrigated soils, without considering important issues such as water saturation and air purge, anaerobiosis and subsequent gradual recovery of natural soil water–air relationships under irrigation conditions, and, surprisingly, the presence of plants.

The aim of this paper is to gain further understanding of the phenomenon of oxygation at the hydrological and soil physical levels by the quantitative analysis of concurrent air and water flow during subsurface drip irrigation.

2. Mathematical formulation

The equation governing the one-dimensional flow of water affected by airflow is given by McWhorter (1971, p. 53, Eq. (44). Sander et al. (1988c) rewrote