Journal of Hydrology 514 (2014) 233–248

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Infiltration of water and ethanol solutions in water repellent post wildfire soils

Sarah M. Beatty, James E. Smith *

McMaster University, School of Geography and Earth Sciences, Canada

ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form 9 April 2014
Accepted 11 April 2014
Available online 21 April 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of J. Simunek, Associate Editor

Keywords:
Tension disk infiltrometer
Wildfire
Contact angle
Soil water repellency
MED
Sorptivity

SUMMARY

Dynamic soil water repellency is a pending challenge in water repellency research. The dynamic change or temporal dependence of repellency is commonly expressed as the persistence of repellency. Persistence, or dynamic changes in contact angle, are however, difficult to directly measure and incorporate into mechanistic conceptual and numerical models. To provide insight into the mechanistic nature of infiltration in variably repellent porous media over larger spatial and temporal scales than afforded by commonly applied characterization approaches (i.e. drop tests), this study reports upon observations made during *in situ* 3D tension infiltration experiments conducted at a post-wildfire site. Tension infiltration tests have proven to be uniquely sensitive to changes in repellency over time. Tension infiltration experiments using mini-disk infiltrometers were conducted. Drop tests provided initial measures of repellency. Tension infiltration experiments were used to generate insights on longer term infiltration behaviours using water, ethanol, and aqueous-ethanol solutions. Molarity of Ethanol Drop (MED) – derived aqueous ethanol solutions (of 5%, 25% and 50% ethanol concentration) were used as intermediate infiltration fluids to generate greater insight into the transitional behaviours between repellent and apparently wettable infiltration. Early time infiltration rates are not reliable indicators of longer term infiltration rates. However, relating the two measures was informative in characterising repellency across materials and at different sites, while preserving temporal differences in fluid behaviours. Comparison of the late-time infiltration rates of aqueous solutions of varying ethanol concentrations proved a useful indicator of repellency and fractional wettability effects.

1. Introduction

Dynamic soil water repellency is a pending challenge in water repellency research. The dynamic change or temporal dependence of repellency is commonly expressed as the persistence of repellency. Persistence, or dynamic changes in contact angle, are however, difficult to directly measure and incorporate into conceptual and numerical models. Natural and anthropogenically altered soils exhibit variability in the severity and persistence of water repellency.

Fractional wettability is a term commonly used in the multiphase flow and contaminant literature that describes bulk media in which some portion are water-wettable (with contact angles less than 90°) and some portion of the surfaces are water-repellent (with contact angles greater than 90°) (Al-Futaisi and Patzek, 2004; O'Carroll et al., 2005). In natural media, fractional wettability speaks directly to the 'severity of repellency' and heterogeneity of observed contact angles, implicitly describing a theoretical continuum over which a given porous media can exist ranging from wholly water wettable to wholly water repellent. While contact angles at the extremes (of 0° and 180°) are theoretical in nature, e.g. there is always some attraction between a liquid and solid (Doerr et al., 2000), 0° is used by convention to facilitate calculations of pore radius and/or for scaling purposes. It is questionable whether these extreme contact angles (particularly with respect to the use of 0°) generate meaningful results in hydrologic models. Additionally, in natural media, where non-zero contact angles are common, contact angle dynamics generate time dependent changes in relative proportions of wettable and non-wettable fractions (Beatty and Smith, 2013). Contact angle dynamics speak directly to the 'persistence of repellency', and indicate a physical mechanism. Quantitatively speaking, mechanistic challenges are presented when trying to reliably simplify fractionally wettable systems, non-uniqueness being the most significant culprit. This has made these systems difficult to track, quantify, and model accurately using traditional approaches. Not surprisingly,

* Corresponding author. Address: McMaster University, 1280 Main St. W, Hamilton, ON L8S 4K1, Canada. Tel.: +1 905 525 9140x24534.
E-mail address: smithja@mcmaster.ca (J.E. Smith).

http://dx.doi.org/10.1016/j.jhydrol.2014.04.024
0022-1694/

mechanistically oriented studies investigating fractional wettability and contact angle dynamics in natural materials are uncommon.

In spite of oft-cited limitations, Water Drop Penetration Time (WDPT) and Molarity of Ethanol Drop (MED) tests capture fundamental information about fractionally wettable and dynamically changing materials through simple and reliable methodologies (Dekker et al., 2009; Letey et al., 2000). As two of the most frequently applied methods in water repellency research, WDPT measures the dynamic change of repellency or persistence of water repellency when exposed to water and MED (or Critical Surface Tension, Alcohol Percentage) tests approximate the surface tension required to initiate infiltration instantly (Letey et al., 2000). While more sophisticated measures of repellency are available, no particular approach has found such widespread utility and acceptance as these.

While informative at the small scale and in a variety of testing environments, the prevalent use and reporting of drop tests has emphasised the measure, analysis and reporting of rapidly measured small spatial scale/small volume data in water repellency investigations. This is particularly the case for field investigations where longer term or larger scale testing is functionally difficult (Logsdon, 1997). Infiltration investigations in water repellent media do employ larger volumes and sample larger areas (e.g. Beatty and Smith, 2013; Clothier et al., 2000; Doerr and Thomas, 2000; Ganz et al., 2013; Pierson et al., 2008; Woods and Balfour, 2010). Systematic evaluations, however, tend to occur more often in the laboratory and remain subject to shorter duration testing experimental bias. Clothier et al. (2000) drew attention to this during an infiltration investigation in naturally repellent loams, noting the expression of wettable-like infiltration behaviour at early time with subsequent repellent behaviour being expressed at much later time, beyond time frames which would normally be observed by an operator. Beatty and Smith (2013) observed a possible transition between primarily hydrophobic and primarily wettable states occurring at later time during laboratory infiltration tests on 'undisturbed' post-wildfire soil materials.

It is common to capture short duration (early time) data sets in wettable media, however, non-wettable media express a wider range of behaviours and non-uniqueness over the course of infiltration (Imeson et al., 1992) which may or may not be systematically indicated by early-time infiltration behaviour. Questions still remain around time and spatial scales appropriate for capturing characteristic and meaningful responses of fluid behaviours in hydrologic systems expressing dynamic hydraulic properties (Moody et al., 2013; O'Carroll et al., 2010). With this in mind, understanding infiltration behaviours during critical transitions and across a range of time scales is important to accurately quantify, model, and make predictions about infiltration responses and infiltration-related processes in water repellent media. In the presence of techniques capable of greater spatial and temporal sensitivity to repellency, there is an opportunity to utilize existing sophisticated methods developed for infiltration into wettable media, while incorporating repellency-oriented analytical approaches that generate greater mechanistic insights for non-wettable systems.

Through an *in situ* systematic field investigation in post-wildfire materials that (1) links existing and often-used methodological approaches, and (2) develops mechanistic insight into the nature of fractional wettability and contact angle dynamics in naturally occurring water repellent soils, we sought to answer the following questions. First, can early and late time tension infiltration rate data be directly related to enhance understanding of fractional wettability and contact angle dynamics? And second, can infiltration experiments using different aqueous ethanol solutions (between 0% and 100% ethanol concentration) provide additional insight into the nature of contact angle dynamics and fractional wettability in dynamically wettable materials during longer term testing?

2. Theory

Differences between simple wettable porous media, upon which many of our conceptual and theoretical models are built, and fractionally wettable and dynamically changing media are well expressed during infiltration. One of the most obvious differences between water wettable and water repellent infiltrations are the shapes of infiltration rate and cumulative infiltration plots (Clothier et al., 2000; DeBano, 1981; Pierson et al., 2008; Wallach and Graber, 2007). With or without the application of positive pressures at the surface, in layered systems, infiltration rates in wettable soils will decrease over time (Feng et al., 2001; Hillel, 1982). This can be related to the sorption of water into wholly or partially wettable materials (DeBano, 1981; Beatty and Smith, 2013). This early time behaviour is for the most part well defined, being driven primarily by capillarity, water capacity, and a steep hydraulic gradient associated with the wetting front (Hillel, 1982). In contrast, non-wettable materials can exhibit increases in infiltration rate during a single tests (Beatty and Smith, 2013; Clothier et al., 2000; DeBano, 1981; Fischer et al., 2013; Wallach and Graber, 2007) and/or over the course of successive infiltrations (Leighton-Boyce et al., 2007; Quyum et al., 2002). In more complex layered systems, particularly in the field, early time infiltration rates, which may exhibit either wetting or non-wetting behaviours, can be followed by longer term highly nonlinear behaviours that include both increasing and decreasing rates (Beatty and Smith, 2013; Clothier et al., 2000; DeBano, 1981; Imeson et al., 1992; Pierson et al., 2008). In dynamically water repellent materials hydraulic gradients are initially substantially diminished, capillarity impedes water flow (Feng et al., 2001; Wang et al., 2000) and repellent fractions of the porous media are unable to participate until later time (Beatty and Smith, 2013). Consequently, it is less clear which mechanisms are acting primarily, when they are acting, in what magnitudes, and for how long. This helps to explain why sorptivity is a concept with limited meaning in water repellent media.

Tension infiltrometers have proven to be uniquely sensitive to spatial differences (Lewis et al., 2006; Hallett et al., 2004) and temporal changes (Beatty and Smith, 2013; Clothier et al., 2000) in repellency. During longer term testing, laboratory work using tension infiltrometers has shown that two distinct mechanisms can contribute to observed later time increases in infiltration rates: (1) the dynamic change of contact angles in bulk media (Beatty and Smith, 2013) and/or (2) the build-up of local pressures in the presence of internal ponding (Clothier et al., 2000; Feng et al., 2001). When observed in cumulative infiltration vs. time or square root of time plots, this behaviour manifests as a convex (Wallach and Graber, 2007) or a "hockey-stick-like" (Lichner et al., 2013) curve and is unique to that typical of wettable soils, showing concave infiltration behaviour.

One way to investigate soil water repellency is to use an infiltrating fluid other than water. Ethanol and aqueous solutions of ethanol are assumed to perfectly wet hydrophobic media and have been used as test fluids in drop penetration tests (Letey et al., 2000) and tension infiltration experiments (Hallett et al., 2004; Hardie et al., 2012; Hartmann et al., 2010; Lamparter et al., 2010; Nyman et al., 2010; Tillman et al., 1989). Repellency Index expresses a ratio of the sorptivities of ethanol to water, taking into account the difference in mobility of ethanol relative to water through a multiplier (of 1.95) (Wallis and Horne, 1992). This measure places emphasis on the acquisition and analysis of early time data.