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Seasonal variation of subsurface flow pathway spread under a water repellent surface layer

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ABSTRACT

In water repellent soils, infiltration following dry periods will typically be limited to narrow pathways which enlarge gradually through winter to produce seasonal patterns of progressive water repellent breakdown. Simple, one-dimensional hydrological models, which assume moisture is horizontally uniform, will not produce representative results in soils where preferential flow dominates, but may produce good representations of moisture dynamics at late stages of the wet season, where declining water repellency has allowed pathways to spread to their maximum extent, producing flow which is close to homogeneous in nature. We propose a new metric, the Mean Modified Response or MMR, to quantify intermediate stages of seasonal water repellent breakdown in terms of the discrepancy between field data and a calibrated one-dimensional model representing the same soil in a hydrophilic state. The utility of this metric is demonstrated using four years of soil moisture sensor data collected at a woodland site in Perth, Australia with a highly water repellent A-horizon. Individual rain events were simulated using data from an on-site rain gauge.

MMR results show strong seasonal trends in all years of study, comparable to those revealed by an older metric, the Effective Cross Section, which provides a measure of flow heterogeneity. However, the new MMR metric is particularly useful for identifying variations in soil moisture responses by depth. We show that the highly water repellent surface layer diverts moisture preferentially to deeper layers to produce increasing moisture responses at depth, in patterns which sharply contrast with model predictions. This effect is shown to decrease through winter as surface repellency breaks down, but may be highly significant in conserving moisture against evaporative loss during dry periods. Results of the MMR analysis suggest that soil was most successful in diverting flow to deeper layers in periods where significant rain events were separated by dry periods of at least a week, but less successful where rain events were either highly isolated or closely spaced. We conclude that comparison to the 1D model presents a useful tool in demonstrating how patterns of infiltration are altered under water repellent conditions.

1. Introduction

Soils with the capacity to become at least transiently water repellent are now known to occur on all inhabited continents and across a variety of climates and soil textures. Soils become water repellent due to the coating of soil particles with hydrophobic molecules of organic origin, however, these compounds are typically slightly soluble, and will eventually detach after sufficient contact with moisture, allowing moisture to enter the soil (Doerr et al., 2000; Hallett, 2008; Ma'shum and Farmer, 1985). Consequently, wetting patterns at affected sites may be complex and vary continuously through the year, with water repellency reaching maximum effect in dry soil during summer, and gradually breaking down in winter as rainfall becomes more frequent (Crockford et al., 1991; Leighton-Boyce et al., 2005; Täumer et al., 2006; Wessolek et al., 2009). Though broad trends of this nature are now well-established, the manner in which wetting patterns evolve in response to varying weather regimes is not yet sufficiently understood to provide predictive power, or to fully analyse feedback effects on the surrounding ecosystem and source vegetation (Doerr et al., 2007; Müller and Deurer, 2011).

Infiltration into initially dry water repellent soils typically takes place via narrow preferential flow pathways, often originating from small textural irregularities such as cracks, macropores or depressions in the soil surface (Burch et al., 1989; Hardie et al., 2011; Lichner et al., 2013; Nyman et al., 2010; Urbanek et al., 2015; Yang et al., 1996). Once a pathway has formed, soil at that location will tend to exhibit reduced non-wetting behaviour on subsequent wettings, allowing pathways to recur at the same locations while intervening regions

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remain dry (Doerr et al., 2000; Ritsema and Dekker, 1995). However, as rain events continue, pathways will often spread to colonise successively greater fractions of the soil cross-sectional area, leading to a progressive breakdown of water repellency as soil transitions to a primarily or fully wettable state (Crockford et al., 1991; Leighton-Boyce et al., 2005; Täumer et al., 2006; Wessolek et al., 2009).

If soil is allowed to dry completely between wettings, it may regain its original water repellence (Dekker and Ritsema, 1994; Hardie et al., 2012; Täumer et al., 2005), or may exhibit reduced water repellence (Crockford et al., 1991; Doerr and Thomas, 2000; Ma'shum and Farmer, 1985). Factors influencing hydrophobicity after drying may include degree and duration of saturation (Doerr and Thomas, 2000; Urbanek et al., 2015), opportunities for leaching of hydrophobic substances (Arye et al., 2007; Hardie et al., 2012; Ritsema et al., 1998), and drying temperature (Dekker and Ritsema, 1996; Hardie et al., 2012; Ma'shum and Farmer, 1985), with higher temperatures believed to play a role rearranging and redistributing hydrophobic substances (Doerr and Thomas, 2000). The reestablishment of strong water repellency may require both heat and new input of hydrophobic material from the surrounding environment, thus ideal conditions are provided by spells of hot summer weather (Burch et al., 1989; Crockford et al., 1991; Doerr and Thomas, 2000; Leighton-Boyce et al., 2005; Wessolek et al., 2009). In combination, these factors may produce substantial variations in water repellence in response to seasonal weather and soil wetting history, whether over brief periods of the order of a week or less (Crockford et al., 1991; Keizer et al., 2008), or on the seasonal timescales which have been reported for many water repellent sites (e.g. Hardie et al., 2012; Leighton-Boyce et al., 2005; Summers, 1987; Täumer et al., 2006; Wessolek et al., 2008).

Wetting patterns may also vary due to vertical distributions of water repellency through the soil profile. Strong water repellence is often limited to a shallow surface layer, which contains the highest concentration of organic matter (Cammeraat and Imeson, 1999; Crockford et al., 1991; Jaramillo et al., 2000; Keizer et al., 2008; McGhie and Posner, 1981; Moore and Blackwell, 2001; Wahl, 2008). Narrow flow pathways through this layer will often spread laterally upon reaching wet or less water repellent soil at depth (Ritsema et al., 1998), producing a redistribution zone in the wettable sublayer in which pathways expand and merge, allowing moisture to drain from near-surface regions (Ritsema et al., 2005, 1993). The result is to trap moisture beneath a predominantly dry surface layer, which may present a significant barrier to evaporation, conserving moisture which will later be available for plant growth. As such, it has been widely theorised that water repellent surface layers present an adaptive advantage to deep-rooted plants responsible for generating the same hydrophobic substances responsible for rendering soils water repellent (Doerr and Ritsema, 2005; Imeson et al., 1992; Moore and Blackwell, 2001; Robinson et al., 2010; Verboom and Pate, 2006). Examining how moisture distributions vary by depth in a water repellent soil, and how depth variations evolve over a seasonal timescale, is of obvious interest from the perspective of clarifying the ecological significance of the phenomenon.

The task of capturing these moisture distributions is, however, complicated in strongly water repellent soil layers as flow pathways may represent only a small percentage of soil cross-sectional area. Soil moisture sensors are able to report only an averaged moisture content over their sensitive volume, which may intersect both wet and dry regions, or miss narrow flow pathways altogether. Nonetheless, in combination with automatic loggers, installed sensors can gather long term, high frequency soil moisture data in a non-destructive manner, and will enable the capture of soil moisture data during and immediately after rain events, which are the periods of greatest significance (Leighton-Boyce et al., 2005, Ritsema et al., 1998). As such, sensor arrays have proven highly valuable in determining flow patterns in water repellent soils and their recurrence across multiple events (Wessolek et al., 2008, Ritsema et al., 1998).

To interpret seasonal trends from an array of soil moisture sensors installed at different points in the same water repellent soil layer, Täumer et al. (2006) introduced the concept of the Effective Cross Section (ECS). The ECS specifically serves as an index of flow heterogeneity, representing a percentage of total soil surface area responsible for 90% of total flow (Täumer et al., 2006). This allows temporal variation (Rye and Smettem, 2015; Täumer et al., 2006; Wessolek et al., 2009) or variation among surface treatments (Lichner et al., 2011) to be quantified and compared.

An alternate method of identifying preferential flow, using sensors installed in a single, vertical column, was described by Lin and Zhou (2008). Although a vertical array provides no information on horizontal variation, preferential flow effects were inferred where a sensor installed deeper in the soil profile showed a clear response to a rain event earlier than the sensors above, due to bypass or sub-surface lateral flow. Hardie et al. (2013) further developed this concept, referring to it as a 'non-sequential depth response', as well as introducing the metric of 'rainfall effectiveness', defined as the maximum change in soil moisture recorded after a rainfall event, divided by the depth of precipitation in millimetres. In locations where pathways bypassed or only partially intersected moisture sensors, rainfall effectiveness may be close to zero, whereas rainfall effectiveness may be > 1 inside pathways due to funnelling effects (Hardie et al., 2013).

Common to all these metrics is that evidence of preferential flow is conceptually derived by comparison to the expected behaviour in a wholly wettable soil, in which moisture is able to spread to form an even, horizontal wetting front. Under such conditions, the ECS would show 90% of soil surface area to be responsible for 90% of flow, non-sequential depth responses should not occur, and rainfall effectiveness should be close to 1.0.

In this paper, we investigate whether a more representative metric, termed the Modified Response (MR), can be obtained by comparing local or depth-averaged soil moisture data to a one-dimensional hydrological model of infiltration, drainage and evaporation behaviour. By calibrating the model to match water retention characteristics recorded at a late stage of seasonal breakdown, we produce a representative simulation of the same soil in a wettable state. The strength of water repellent effects in modifying soil moisture response to rainfall is quantified by calculating the difference between modelled and recorded behaviour to produce the MR metric. We examine soil moisture data collected from a sensor network installed at a water repellent field site over a four-year period, and demonstrate the use of this new metric to highlight seasonal trends and interannual variation. Corresponding values of the ECS metric calculated for the same sensor data, previously published in Rye and Smettem (2015), are reproduced for comparison, and in order to demonstrate the differing flow features highlighted by both methods.

2. Materials and methods

2.1. Site description

Experimental data was collected at a native bushland reserve on the Spearwood dune system in Perth, Western Australia (−31.950396, 115.796294). Water repellency was measured using the Molarity of an Ethanol Drop (MED) test, which quantifies repellency by determining the minimum concentration of ethanol solution that will allow droplets to be readily absorbed into the soil (wettable soil produces an MED of 0 M, whereas extremely water repellent soil may be above 4.0 M). Soil at the field site is classified as yellow-phase Karrakatta sand (Salama et al., 2001) or as Dystric Xeropsamments (Soil Survey Staff, 2014), consisting of highly water repellent dark brown topsoil (MED test 2.5–4 M) transitioning to a non-repellent (0 M) yellow sand B-horizon at a typical depth of 10–25 cm (Fig. 1). Climate is classified as Mediterranean, characterised by hot, dry summers and cool, wet winters. Annual average rainfall is 729.5 mm, of which 80% is received during