Seasonal soil water repellency and evaporation in a Mediterranean climate

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This thesis is presented for the degree of Doctor of Philosophy of The University of Western Australia
School of Civil, Environmental and Mining Engineering, School of Computer Science and Software Engineering
Environmental Engineering and Computer Science
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A soil which is water repellent is able to resist penetration by moisture, even when initially dry, due to the coating of soil particles by hydrophobic substances of primarily organic origin. In the field, soil water repellency usually varies in an annual cycle, reaching a maximum intensity in summer and gradually breaking down through winter as preferential flow pathways form and spread. Although soil water repellence is known to be common in Mediterranean climates such as that of south west Western Australia, little is known about the seasonal development of wetting patterns in these soils, or their significance for the surrounding ecosystem. To examine seasonal trends in this environment, soil moisture was monitored using an array of 20 moisture sensors at a water repellent bushland site over a 4-year period. Seasonal trends were analysed using the Effective Cross-Section (ECS) metric which quantifies stages of water repellent breakdown in terms of uniformity of flow. Seasonal trends in this data were remarkably strong, demonstrating good correlation with antecedent rainfall. However, results also demonstrated significant inter-annual variation, with seasons preceded by unusually wet summers experiencing substantially more rapid breakdown of water repellence through winter. By truncating the period in which strong water repellency would usually re-establish, summer rain appeared to affect wetting pattern development over the following winter.

Sensor data highlighted the significance of vertical distributions of water repellence, which peaked in the organic-matter-rich A horizon near the shallower sensor depth (5 cm), gradually transitioning to wettable beneath at 15-30 cm. Flow pathways reaching progressively less water repellent zones were able to spread such that average moisture increased with depth, allowing moisture to drain from narrow pathways above.

As infiltration is trapped beneath a primarily dry surface layer, it has been suggested that soil water repellency may serve a key ecological role by reducing evaporative loss. To further investigate impacts on evaporation, flow pathway development and net evaporation rates were recorded in a series of laboratory soil tanks, which were placed outside during daylight hours to expose them to ambient rainfall and evaporation. Significant reductions in net evaporation were observed in tanks containing both uniform and layered water...
repellent soil. However, the most consistent reductions were produced by tanks containing distributions of water repellency similar to that recorded on site. Results suggested overall that water repellence was likely most effective at conserving moisture received during isolated summer rain events, when water repellence and moisture stress were at their annual peaks, but also that some degree of benefit likely persisted long into the winter breakdown season.

To better understand these patterns, a new metric (the Mean Modified Response or MMR) was developed to quantify site behaviour relative to the predictions of a one-dimensional hydrological model (Hydrus1D) calibrated to represent the same soil in a perfectly wettable state. Seasonal trends revealed by this new metric were overall comparable to those revealed by the existing ECS metric at the shallower sensor depth, however, the MMR was found to be substantially more useful in identifying trends in data from the deeper, wettable soil region, and in analysing how responses varied between the two layers. Infiltration patterns were 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. It is concluded that breakdown processes appear to be more complex than previously assumed, and the ability of water repellent surface layers to protect moisture from evaporative loss likely varies considerably in years of differing rainfall regime.
# TABLE OF CONTENTS

1. Introduction .......................................................................................................................... 1
   1.1. Objectives ....................................................................................................................... 3

2. Literature Review .................................................................................................................. 5
   2.1. Introduction ..................................................................................................................... 5
   2.2. Characterising water repellent effects ............................................................................ 9
   2.3. Breakdown and re-establishment of water repellency .................................................... 15
   2.4. Seasonal variation of water repellency ......................................................................... 20
   2.5. Hydrological modelling in water repellent soils ............................................................ 24
   2.6. Effects on soil evaporation .......................................................................................... 29
   2.7. Water repellency in Australia ....................................................................................... 36
   2.8. Summary and conclusions ........................................................................................... 41

3. Seasonal and interannual variability of the effective flow cross-sectional area in a water repellent soil ......................................................................................................................... 45
   3.1. Introduction ..................................................................................................................... 45
   3.2. Materials and Methods ................................................................................................. 48
      3.2.1. Site and soils ............................................................................................................. 48
      3.2.2. Site Rainfall ............................................................................................................. 49
      3.2.3. Site Water Repellency ........................................................................................... 49
      3.2.4. Sensor installation .................................................................................................. 50
      3.2.5. Effective Cross-Section Calculations .................................................................... 50
   3.3. Results and Discussion .................................................................................................. 53
      3.3.1. Rainfall ................................................................................................................... 53
      3.3.2. Site Water Repellency .......................................................................................... 53
      3.3.3. Soil Moisture ......................................................................................................... 55
3.3.4. Effective Cross-Section........................................................................................................57
3.3.5. Interannual variability........................................................................................................61
3.3.6. Impacts of summer rainfall ..............................................................................................64
3.3.7. Summary ..........................................................................................................................66

3.4. Conclusions .........................................................................................................................67

4. The effect of water repellent soil surface layers on preferential flow and bare soil evaporation.................................................................................................................................69

4.1. Introduction ..........................................................................................................................70
4.2. Materials and Methods ........................................................................................................72
  4.2.1. Soil Collection ..................................................................................................................72
  4.2.2. Experimental Design .......................................................................................................74
  4.2.3. Layered Soil Tanks .........................................................................................................75

4.3. Results ..................................................................................................................................77
  4.3.1. Infiltration into wettable soils .........................................................................................77
  4.3.2. Infiltration into uniform water repellent soil .................................................................78
  4.3.3. Infiltration into variably water repellent soil .................................................................79
  4.3.4. Evaporation from Uniform Soil Tanks ..........................................................................81
  4.3.5. Evaporation from Layered Soil Tanks .........................................................................83

4.4. Discussion ............................................................................................................................85
  4.4.1. Infiltration patterns ........................................................................................................85
  4.4.2. Relevance to Seasonal Field Conditions ......................................................................87

4.5. Conclusions .........................................................................................................................88

5. Seasonal variation of subsurface flow pathway spread under a water repellent surface layer ...........................................................................................................................................91

5.1. Introduction ..........................................................................................................................92
In early 2010, a set of 20 combined soil moisture and temperature probes were installed in the Underwood Avenue bushland, an area of native bushland reserve in Shenton Park, Perth, owned by the University of Western Australia. The installation of these devices was part of a joint project between the (then) School of Environmental Systems Engineering (since merged into the School of Civil, Environmental and Mining Engineering) and the Wireless Sensor Networks Group at the Computer Science and Software Engineering department. Sensors and logging hardware were developed and supplied by Professor Christof Hübner of the Institute for Industrial Data Processing and Communication at the University of Applied Sciences Mannheim.

The objectives of the project were to investigate wetting patterns in the near-surface region of the Shenton Park soil, which was known to be strongly water repellent. As moisture patterns in similar soils are known to be dominated by ‘fingering’ or preferential flow, producing great variation in moisture contents over short horizontal distances, sensors were installed in a densely-spaced array at intervals of 10-15 cm. Sensors were limited to only two depths, 5 and 15 cm, to maximise horizontal coverage. A rain gauge and an additional logger, produced by Decagon Devices, were added to the site in early 2010. These devices continued logging soil moisture, temperature and rainfall from early 2010 to late 2013. As water repellent characteristics have been observed to evolve in regular seasonal patterns at similar sites in other parts of the world, the resulting dataset would allow the investigation of both seasonal and interannual patterns of variation. The installation was finally destroyed by bushfire in early 2014, after nearly 4 years of largely continuous data recording.

At the outset of the measurement period, it was expected that variability in sensor readings would be primarily horizontal, with vertically aligned sensor pairs reporting similar data due to the presence of vertical flow fingers. However, from the earliest field tests, it became apparent that most sensors installed at the 15-cm depth were reporting consistently greater responses to wetting than those at 5 cm. A review of the literature showed that similar phenomena had been noted at other sites where water repellence was limited to a shallow surface layer, allowing flow pathways to spread in wettable soil at depth. The investigation
of the development and significance of wetting patterns of this type formed much of the inspiration for the remainder of this thesis.

In early 2011, an additional sensor installation was established a few hundred metres south of the original site, consisting of 16 moisture probes at 3 depths, at 5, 15 and 30 cm. These devices tested a new logger architecture which stored no local data, but was able to provide continuous wireless data which was uploaded to university servers. This second installation ceased functioning in early 2012, and the resulting data is not discussed in the remainder of the thesis, which relies instead on data from multiple years of records produced by the primary installation. Data from this second site did, however, demonstrate the rapid transport of moisture to depth following even shallow rain events, due to the occurrence of preferential flow, and that changes in wetting characteristics varied relatively little between the depths of 15 and 30 cm, relative to the more significant differences between 15 cm and the strongly water repellent soil at 5 cm.

In completing this thesis, I am indebted to the assistance of Professor Christof Hübner and his students from Mannheim, whose equipment proved capable of surviving almost everything short of explosive combustion. I am also greatly indebted to the advice and assistance of both my supervisors, Professor Rachel Cardell-Oliver of the CSSE, and especially Professor Keith Smettem of the SCEME for all their support throughout this project.

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1. Introduction

Dry soil particles ordinarily have a strong affinity for water and will readily absorb moisture introduced by rainfall or irrigation. However, a variety of hydrophobic substances, primarily plant-based in origin, are capable of coating soil particles and rendering them water repellent, and thus resistant to moisture entry. Though water repellence was once considered a rare and exceptional phenomenon, limited in occurrence to only a few extreme environments, over the past several decades, soils capable of becoming at least transiently water repellent have been discovered on every inhabited continent, across a wide variety of climates, soil types and ecosystems (Dekker et al., 2005). Some researchers have gone so far as to suggest that some degree of water repellence should be considered more the norm than the exception (Doerr and Ritsema, 2005; Wallis and Horne, 1992).

Water repellence is widespread across the soils of south-west Western Australia, under both native vegetation and cultivated regions, and in many locations across Australia’s eastern states. Though this phenomenon is by no means unique to Australia, a combination of factors, including our climate, the availability of coarse-textured soils, and the ubiquity of Eucalypts and other wax-cuticle generating vegetation, all contribute to the susceptibility of soils across the continent.

Soils affected by water repellency resist the entry of moisture, increasing runoff generation over short to moderate distances and limiting infiltration to narrow pathways, while intervening areas remain dry. The resulting wetting patterns are ill-suited to the needs of high intensity agriculture, and the task of modelling moisture movement in affected soils is greatly complicated as many standard simplifying assumptions are rendered inapplicable. Soil water repellency may, nonetheless, provide some significant benefits to vegetation by favouring deep drainage and conserving moisture against evaporative loss, especially in native ecosystems and arid environments.

Wetting patterns in water repellent soils will often recur at the same locations over successive wetting events, but are also known to gradually spread or retreat in response to ambient weather in extended seasonal cycles. As such, a full description of the effect of
water repellency requires repeated measurements in order to reflect how characteristics evolve throughout the year. Water repellency may be enhanced by periods of hot, dry weather, but typically decreases in intensity in the late wet season after many months of regular rain.

Over the last two decades, considerable progress has been made in the study of moisture distributions in water repellent soils using installed arrays of moisture sensors attached to automatic logging devices. Although automated sensors capable of directly measuring degrees of water repellence have yet to be developed, existing sensor technology is capable of producing high-frequency moisture, temperature or tensiometer data with great potential to inform future modelling efforts, to guide management practices and to better our understanding of the role of soil water repellency on native ecosystems.

Past sensor studies of annual or inter-annual moisture variation at water repellent sites have been undertaken primarily in temperate oceanic climates in locations such as Germany, the Netherlands or Japan. To the best of the author's knowledge, only one such study has been undertaken on an Australian soil, that of Hardie et al. (2013). They used a single vertical column of sensors to measure variation in moisture at a Tasmanian site, which was similarly characterized by a temperate oceanic climate. As rainfall is well-distributed throughout the year in oceanic climates, such locations lack highly distinct wet and dry seasons, and experience only moderate maximum summer temperatures.

Much less is known about the evolution of wetting patterns and preferential flow characteristics in water repellent soils in Mediterranean climates like that of south-west Western Australia. Although water repellence is known to be common in Mediterranean climates and countries such as Spain and Portugal, few previous studies have explicitly measured the effects on seasonal soil moisture variation. Given the hot, dry summer which characterises Mediterranean climates, and which is ideal for the development of strong water repellency, we may expect even stronger seasonal variation in wetting characteristics than those reported in oceanic regions, which have been better studied. Soil water repellence may also provide a more significant ecosystem service in conserving moisture
during summer and periods of drought. The investigation of these and related questions has been the subject of the thesis to follow.

1.1. Objectives

Work done on this project may be divided into two main categories, that of analysis of field data, and supplementary laboratory work.

Analysis of field data

- To examine both annual and interannual variability in wetting patterns in a West Australian native bushland site with a Mediterranean climate and a strongly water repellent surface layer. This was achieved using an installed array of moisture sensors.

- To quantify observed wetting patterns using the established metric of the Effective Cross Section, which was developed and used to quantify patterns at a comparable site elsewhere in the world.

- The development of a series of one-dimensional hydrological simulations, using calibrated soil parameters representing the field soil in a wettable or near-wettable state, with each simulation representing a singular rain event recorded in the field.

- To compare wetting patterns observed in the field to modelled predictions using a novel metric developed for this purpose. It was expected that this comparison would provide new insight into seasonal breakdown trends, and to what degree or under what conditions one-dimensional modelling may be appropriate at water repellent sites.
• To identify the impact of specific weather conditions on flow pathway formation and development.

• To investigate the specific significance of water repellence in an Australian environment.

**Laboratory work**

• To examine the effect of water repellence on preferential flow pathway formation and bare soil evaporation under ambient weather conditions. This work was performed in a series of transparent laboratory tanks, packed with either uniform soil of varying water repellence, or with water repellent surface layers of varying thickness. Tanks were placed outside during daylight hours to expose them to ambient rainfall and evaporative conditions, and weighed and photographed regularly to record flow pathway development and evaporation.
2. Literature Review

2.1. Introduction

That a dry soil should readily absorb moisture is an intuitive assumption implicit in most standard theories of soil infiltration and moisture movement. However, many soils are capable of becoming 'hydrophobic' or 'water repellent', and thus able to resist the entry of moisture, even when initially dry. By convention, a soil is held to be at least borderline water repellent if droplets placed on the soil surface generate initial contact angles of greater than 90° and take more than a few seconds to disappear (DeBano, 1981; Letey, 1969; Wallis and Horne, 1992), though in extreme cases affected soil may be capable of resisting penetration by water for periods of hours or even days (Doerr and Ritsema, 2005; Doerr and Thomas, 2000; McKissock et al., 1998; Regalado and Ritter, 2008). A soil with a contact angle less than 90° but greater than 0° (the value assumed for perfectly wettable soils) may furthermore be classed as subcritically water repellent, producing impeded infiltration rates despite apparently spontaneous wetting on contact with moisture (Lamparter et al., 2006; Tillman et al., 1989; Wallis and Horne, 1992).

Soils become water repellent due to the coating of soil particles by hydrophobic compounds of primarily organic origin. While water repellency may be induced under laboratory conditions (eg. Bachmann et al., 2001; Roberts and Carbon, 1972; Urbanek and Shakesby, 2009) and may be generated or enhanced by wastewater irrigation (Täumer et al., 2006; Wallach et al., 2005), fire (DeBano, 2000a; Doerr et al., 2009; Letey, 2001) or other agricultural practices (Roper et al., 2013), water repellency is best understood as a predominantly natural phenomenon (Doerr et al., 2005; Mainwaring et al., 2013; Mao et al., 2015; McGhie and Posner, 1981; Roberts and Carbon, 1972). Hydrophobic compounds capable of rendering a soil water repellent are produced in many native ecosystems as a by-product of decaying leaf matter, or by fungal and microbial activity, particularly in the organic-rich near-surface regions (Doerr et al., 2005, 2000; Franco et al., 2000; Roberts and Carbon, 1972).
Recognition of the widespread prevalence and significance of water repellency has grown considerably in recent decades (DeBano, 2000b; Dekker et al., 2005; Doerr et al., 2007), and affected soils have now been identified across a range of ecosystems, climates and soil types, and on all continents excluding Antarctica (Doerr and Ritsema, 2005; Jordán et al., 2013). Some authors have gone so far to suggest that some degree of water repellency, including subcritical repellency, should be regarded as more the norm than the exception (Doerr and Ritsema, 2005; Lamparter et al., 2006; Ritsema et al., 1998a; Wallis and Horne, 1992). As standard infiltration models have traditionally depended upon the assumption that soil is hydrophilic (Bachmann et al., 2003; Hallett, 2008; Tillman et al., 1989), a failure to account for water repellent effects may account for many historical difficulties in accurately predicting subsurface movements of fluid and solutes (Ritsema et al., 1998a; Tillman et al., 1989).

Detrimental effects on agriculture have long been a particular driver of research interest, with water repellency linked to reduced efficiency of agricultural irrigation (Blackwell, 2000, Yang et al., 1996, Thwaites et al., 2006), reduced germination rates for new plants (Moore and Blackwell, 2001, Osborn et al., 1967, Robinson et al., 2010), increased runoff and erosion (Doerr et al., 2003; Imeson et al., 1992; Leighton-Boyce et al., 2007; McGhie, 1980a; Nyman et al., 2011), and acceleration of pesticide and nutrient transport to groundwater (Blackwell, 2000, Nyugen et al., 1999, Nyman et al., 2010). The cost of water repellency to agriculture has also been a driver behind the need to develop representative hydrological modelling applications (Ritsema et al., 2005; Yang et al., 1996), and remediation possibilities including the use of surfactants, clay and other options (Hall et al., 2010; Moore and Blackwell, 2001; Roper et al., 2013; Thwaites et al., 2006).

Water repellency is itself a highly moisture-dependent property, and will ordinarily break down after some period of contact with water, allowing moisture to enter the soil matrix (Doerr and Ritsema, 2005). The mechanisms behind this delay are not well understood, but are believed to represent time required for slightly soluble hydrophobic molecules to realign in the presence of a polar fluid (Doerr et al., 2000; Hallett, 2008; Ma’shum and Farmer, 1985). Once wetted in this manner, soil at that location will typically produce less resistance
to later wettings. Consequently, although infiltration into wettable soils ordinarily displays an inverse relationship with time, decreasing as the infiltrated volume increases, infiltration into water repellent soils has frequently been observed to increase over the duration of a wetting event (Arbel et al., 2005; Bond, 1964; Burch et al., 1989; Clothier et al., 2000; Imeson et al., 1992; Letey et al., 1962a), inverting the normally observed behaviour.

Water repellent soils are sometimes discussed in terms of a 'critical soil water content' or transition zone above which the soil becomes wettable (Doerr and Thomas, 2000; Hardie et al., 2011; Kobayashi and Shimizu, 2007; Thwaites et al., 2006; Wessolek et al., 2008). Similarly, in measuring water repellency, some authors have distinguished between a soil sample's 'potential water repellency', which represents the repellency of that sample when dry, from its 'actual repellency', which may vary with moisture content (Dekker and Ritsema, 1994; Hardie et al., 2012; Jaramillo et al., 2000; Täumer et al., 2005; Wang et al., 2000).

Although water repellency increases a soil's resistance to infiltration, the net effect on larger temporal or spatial scales will rarely be to retard infiltration uniformly across a site. Wetting fronts generated under water repellent conditions tend to be unstable, leading to preferential or 'fingered' flow, where infiltration is limited to narrow pathways (Bauters et al., 1998; Hardie et al., 2011; Hendrickx et al., 1993; Ritsema et al., 1998a; Ritsema and Dekker, 1996a; Urbanek and Shakesby, 2009). Unstable wetting front theory discussed by Hendrickx et al. (1993) describes how localised perturbations in an unstable wetting front will tend to propagate downwards instead of spreading laterally to form an even front, leaving regions between pathways primarily dry. Preferential pathways may form in this manner even in relatively uniform hydrophobic soil, however, water repellency is rarely uniform over larger spatial areas in the field (Cammeraat and Imeson, 1999; Keizer et al., 2008; Lozano et al., 2013; Urbanek et al., 2015; Walsh et al., 2014), where textural irregularities such as cracks, macropores, localised depressions, and regions of less hydrophobic soil may also be significant in initiating preferential flow (Burch et al., 1989; Hardie et al., 2011; Lichner et al., 2013; Petter Nyman et al., 2010; Urbanek et al., 2015; Yang et al., 1996).
As wetted soil offers lessened resistance to later wettings, pathways once formed will often persist and reoccur at the same locations during subsequent wetting events while intervening regions remain strongly repellent, serving to channel moisture to points where prior infiltration has reduced soil resistance (Bond, 1964; Liu et al., 1994; Ritsema et al., 1998a). Even if soil is able to dry completely, pre-established pathways may continue to offer lowered resistance to later wettings because hydrophobic soil coatings have been leached by water flow (Arye et al., 2007; Hardie, 2011; Hardie et al., 2012; Ritsema et al., 1998a), or have failed to realign to their initial arrangement (Doerr and Thomas, 2000). With repeated, regular wettings, pathways will tend to spread gradually to colonise successively larger regions of soil (de Rooij, 1996; Täumer et al., 2006; Wessolek et al., 2008), until most or all of an originally water repellent region has transitioned to functionally wetting behaviour. As such, water repellency in the field has been observed to vary by season, gradually breaking down through the wet season, and being re-established again in summer once the soil dries out (Burch et al., 1989; Crockford et al., 1991; Hardie et al., 2012; Keizer et al., 2008; Leighton-Boyce et al., 2005; Oostindie et al., 2011; Summers, 1987; Täumer et al., 2006). In some cases, flow pathway locations have even been observed to occur at the same location in multiple years (Bond, 1964; Hagedorn and Bundt, 2002; Wessolek et al., 2009), though pathways may also form in new locations after a period of summer drying concludes (Wessolek et al., 2009).

Although preferential flow may occur in purely hydrophilic soils in various circumstances, it remains a characteristic feature of water repellent soils, and has provided a substantial driver for research into the phenomenon of water repellency (Dekker et al., 2005; Doerr et al., 2000). In a soil volume dominated by preferential flow, soil hydraulic parameters derived from averaged moisture contents over some representative volume will differ from that of the same soil in a wettable state (Hardie, 2011), and cannot be assumed to be necessarily representative of the same soil at different states of breakdown (Hardie, 2011; Wessolek et al., 2008). As moisture content in a water repellent soil may be highly bimodal across any horizontal section, it cannot be modelled effectively using simple one-dimensional or piston-flow assumptions (Ritsema and Dekker, 2000; Šimůnek et al., 2003; Wessolek et al., 2008), and although a variety of approaches have been proposed to model preferential flow, no
clear consensus has yet been reached, and no user-friendly solution is presently available (Ritsema et al., 2005; Šimůnek et al., 2003).

Furthermore, preferential flow cannot be sufficiently accounted for over longer timescales by assuming the active fraction of the soil profile remains static, as pathways will evolve with time, both on the timescale of a single rain event and on a seasonal or annual basis (Täumer et al., 2006; van Dam et al., 1996; Wessolek et al., 2009). Data establishing seasonal trends at various water repellent sites remain largely descriptive, having depended on a variety of measurement techniques which may not be directly inter-comparable, with few studies yet covering multiple years of variability. Prediction of the degree of water repellent breakdown or relative cross-sectional wetted pathway area eventuating from a particular series of wetting and drying events is not possible under the current state of knowledge.

The role that water repellency plays in the natural environments which produce it also remains poorly understood. While it has been suggested that water repellency represents a means by which plants are able to harvest and channel moisture deep into the soil profile, protecting it from evaporative loss (Imeson et al., 1992; Robinson et al., 2010; Verboom and Pate, 2006), the magnitude and significance of such effects has rarely been examined under field conditions. These and related topics will be elaborated upon further in the successive sections of this literature review.

2.2. Characterising water repellent effects

Past studies have employed a wide variety of tests and techniques to quantify the strength of water repellency, as well as its impact on soil moisture partitioning, such as the production of preferential flow. The following discussion provides a brief summary of the principles and relative advantages and disadvantages of those measures of most interest to later sections of this literature review. A detailed list of a greater variety of methods used to quantify water repellency is provided in Wallis and Horne (1992).
Direct tests for the presence or strength of water repellency may be broadly separated into those which measure the *severity* of water repellence, in terms of effects on contact angles or surface tension, and tests which measure the *persistence* of water repellence, in terms of time taken for water repellence to break down in the presence of moisture (Dekker and Ritsema, 1994; Doerr et al., 2000; Leelamanie et al., 2008). Measures of the severity of water repellency include direct measurements of contact angles under a microscope or by photography (Bachmann et al., 2000), or indirect measurement via rates of capillary rise (Emerson and Bond, 1963; Letey et al., 1962b).

The simplest test in this class is the Molarity of an Ethanol Drop test (MED) or Critical Surface Tension (CST) test (Roy and McGill, 2002; Watson and Letey, 1970), which relies on the fact that surface tension decreases with increasing aqueous ethanol concentration, allowing droplets to be more easily absorbed into water repellent soil. Higher concentrations of ethanol will be required to allow a droplet to enter a soil which is more strongly water repellent, thus water repellence may be quantified by identifying the minimum concentration of ethanol that will allow droplets to be absorbed into the soil within a short 5-10 second timescale, typically from a set of pre-prepared solutions. Comparisons of MED test results and direct measures of contact angle have generally found good correlation (King, 1981; Leelamanie et al., 2008), supporting the utility of the MED test as a representative measure of severity.

The most widely used test for the persistence of water repellency is the Water Drop Penetration Test (Doerr et al., 2004a; Letey, 1969). The WDPT test records the time taken for a droplet of moisture placed on the soil surface to be absorbed into the soil, which may vary from seconds to periods in excess of an hour (Doerr et al., 2004a; Wallis and Horne, 1992). Due to their relative simplicity and ease of use in the field, the WDPT and MED tests have been preferred by most researchers over other methods, which require laboratory analysis and produce greater disturbance of the soil (Doerr et al., 2004a; Hallett, 2008; Roy and McGill, 2002). Where studies have compared results of both tests on the same soils, MED and WDPT results have often been found to show some degree of correlation, though with best fits produced by regression of MED against log transformed WDPT times (Dekker
and Ritsema, 1994; Douglas et al., 2007; Hardie et al., 2012; Harper and Gilkes, 1994; King, 1981). As such, the WDPT may be better able to distinguish between soils at very high levels of water repellency than the MED test (King, 1981), though its practicality may be hampered by prohibitively long observation times as repellency levels rise, particularly under field conditions (Doerr et al., 2004a; Regalado and Ritter, 2008; Wallis and Horne, 1992).

An additional limitation of drop tests such as the MED and WDPT is that they are not readily able to distinguish soil that is subcritically water repellent from wettable soil. Methods suitable for measuring subcritical contact angles include the capillary rise test (Shokri et al., 2009) the sessile drop method (Bachmann et al., 2000; Wijewardana et al., 2016) or the Wilhelmy plate method (Bachmann et al., 2003; Lamparter et al., 2006). Some researchers have also quantified subcritical water repellency by comparing infiltration rates of water to that of ethanol or some other wetting agent (Lamparter et al., 2006; Madsen et al., 2011; Orfánus et al., 2014; Tillman et al., 1989), similar to the Repellency Index concept introduced by Tillman et al. (1989).

Although direct tests such as those described above are useful for identifying the presence and distribution of water repellency, they cannot be automated and are frequently destructive in nature, and are thus limited in their ability to quantify temporal variation. As water repellency is rarely contiguous over larger areas (Cammeraat and Imeson, 1999; Ritsema and Dekker, 1996b; Urbanek et al., 2015), direct tests may also struggle to characterise microscale variations in water repellency or the impact of structural features such as macropores, which may play a critical role in facilitating infiltration and reducing runoff generation over larger plot scales (Doerr et al., 2003; Ferreira et al., 2000; Gomi et al., 2008; Miyata et al., 2007). As such, tests which characterise water repellency directly are typically of little use in predicting soil response to wetting events such as rainfall or irrigation, and features such as runoff ratios and infiltration rates must be measured directly at water repellent sites to produce meaningful results. Measurements of runoff ratios or catchment outflow can, in turn, provide useful information about the relative states of apparent water repellent breakdown, either over the duration of a wetting event (Burch et
A considerable body of research has been dedicated specifically to describing the three-dimensional patterns of moisture which develop in water repellent soil, which in turn influence the availability of moisture for plant growth, potential for accelerated transport to deeper soil layers, and other issues of management concern. The incremental spread of flow pathways may additionally provide an important indicator of the progress of seasonal breakdown (Täumer et al., 2006; Wessolek et al., 2009). High resolution data is usually necessary to quantify these patterns in detail as, in water repellent soil, significant variations in moisture are often observed on the scale of decimetres or less (Ritsema and Dekker, 1996b; Wessolek et al., 2008). Flow pathways responsible for much or all net infiltration in water repellent soils may be narrow, representing only a few percent of soil cross-sectional area (Cammeraat and Imeson, 1999; Hardie, 2011; Petter Nyman et al., 2010; Wang et al., 1998), and may variously persist (Bond, 1964; Liu et al., 1994; Ritsema et al., 1998a), expand (de Rooij, 1996; Täumer et al., 2006; Wessolek et al., 2008) or relocate (de Rooij, 1996; Wessolek et al., 2009), depending largely on the frequency of rain events and other factors.

Data representing three-dimensional moisture variation at a high spatial resolution generally requires destructive methods, such as soil block sampling and the use of chemical tracers. Soil block sampling involves the excavation of a large volume of soil, usually of the order of one cubic metre in size, which is divided into discrete samples in a regular grid (Ritsema et al., 1997; Ritsema and Dekker, 1996a; Täumer et al., 2005). Each sample is then analysed for moisture content and water repellent properties, and the resulting data compiled to identify flow pathways (Ritsema and Dekker, 1996a; Täumer et al., 2005).

A related family of techniques involve treating the soil with chemical tracers before excavation. Tracers found in the literature include both substances which will stain the soil inside active flow regions such as iodine (I⁻) or commercial dyes (Hardie et al., 2011; Hendrickx et al., 1993; Kobayashi and Shimizu, 2007; Lichner et al., 2013, 2011; Roper et al., 2013; Wessolek et al., 2008), and chemical markers which may be readily identified in soil
samples, such as bromide (Br\textsuperscript{−}), chloride (Cl\textsuperscript{−}) (Hendrickx et al., 1993; Ritsema and Dekker, 1995; Wessolek et al., 2009) or radioactive isotopes (Lichner et al., 2013). Tracers are typically applied to the soil surface prior to rainfall or irrigation events, after which the treated region is excavated either in horizontal or vertical layers and photographed to record pathway locations, or broken into samples for laboratory analysis. Tracer concentration by depth may also be determined without destruction of the soil profile by taking only limited samples at depths of interest and measuring tracer content (Hendrickx et al., 1993; Lichner et al., 2013); however, only approximate pathway area shares are produced by this method.

These high-resolution sampling methods are necessarily destructive, and thus capable of capturing moisture distributions at only one point in time. In order to capture dynamic soil moisture data, Ritsema and Dekker (1996b) used an installation of Time Domain Reflectometry (TDR) probes in a 195 cm by 70 cm deep transect. Sensor data recorded by this installation was used to demonstrate the recurrence of flow pathways over three successive rain events occurring from December 1994 to January 1995. Sensor installations of this type must be closely spaced to effectively capture the scale of variation, and Ritsema and Dekker (1996a) recommended sensor spacings of not more than 22 cm. As the individual sampling volume of any sensor may intersect both wet and dry regions, moisture contents will reflect only an average value over that region, and variation occurring between moisture sensors may be invisible to researchers. Nonetheless, installed sensors with automatic loggers present the considerable advantage of being able to produce long term, dynamic information on soil moisture, requiring only minimal regular maintenance for recording to continue. This technique has the particular advantage of capturing soil water flow behaviour during and immediately following rain events, which are the periods of greatest significance (Leighton-Boyce et al., 2005; Ritsema et al., 1997) and which have been identified as essential to accurately describing the mechanisms of seasonal change (Keizer et al., 2008; Leighton-Boyce et al., 2005). For these reasons, similar installations have been used in a number of studies into long term variations in preferential flow (See section 2.3 for a summary of related studies).
One novel method of quantifying water repellent effects from sensor results was proposed by Täumer et al. (2006), who examined seasonal trends in water repellency using a two-dimensional array of 64 probes at a grassland site north of Berlin from April 2002 to April 2004. To describe changes in pathway share indicated by sensor data, Täumer introduced the concept of the Effective Cross Section (ECS), representing the percentage of total soil surface area responsible for 90% of cumulative change in moisture. This metric may be easily visualised as a representation of preferential flow pathway size, and may potentially serve as a hydrological modelling input reflecting active fraction of the soil cross-sectional area. By calculating ECS at various points through the study duration, the relative strength of water repellent effects was tracked through the cycle of breakdown and reestablishment (Täumer et al., 2006; Wessolek et al., 2009).

The ECS has been used in at least two unrelated studies since the original publication. Lichner et al. (2011) used the ECS to quantify differences in flow heterogeneity in adjacent plots of wettable sand (ECS between 0.839-0.882) and grass-covered water repellent sand (ECS between 0.694-0.858) based on a slightly modified method adapted for use with photographic data from a tracer experiment. Lichner et al. (2013) further adapted the ECS into a method described as the Degree of Preferential Flow (DPF) to examine the significance of macropore flow in a non-water repellent black clay loam, but reported both versions of the metric to be useful.

The concept of the Effective Cross-Section requires multiple moisture readings from the same soil layer, relying on horizontal variation to provide evidence of preferential flow. An alternative metric, capable of inferring preferential flow from high-frequency data from a vertical sensor installation, using only a single sensor at each depth, was proposed by Lin & Zhou (2008). Their approach, dubbed a ‘non-sequential depth response’ by Hardie et al. (2013) was to look specifically for cases in which a moisture sensor installed at depth recorded an earlier increase in moisture following rain than did sensors located closer to the surface, indicating moisture has bypassed the shallower region by preferential flow, or spread in deeper soil by subsurface lateral flow. Using this metric, authors were able to link
preferential flow to dry antecedent conditions, which is typical of water repellent sites (Lin & Zhou, 2008).

The concept of non-sequential depth response was further developed by Hardie et al. (2013), and expanded to include indications of high wetting front velocity of the order of 10 times greater than estimated saturated hydraulic conductivity for that soil, suggesting that channelling and ponding factors accelerated moisture movement. Hardie et al. (2013) additionally introduced the metric of rainfall effectiveness, defined as the ratio of total increase in soil moisture to total rainfall depth, normally close to 1.0 for a uniformly wetted soil. A rainfall effectiveness value greater than 1.0 suggests a region inside a flow pathway, while a value less than 1.0 suggests an inactive region of the soil. Both metrics were shown to be useful in describing moisture data recorded from sensors, and in assessing the relevance of particular patterns as indicators of preferential flow (Hardie et al., 2013).

Water repellent effects have also occasionally also been identified or quantified by comparison to modelled representations of soil response to wetting using assumptions of one-dimensional or uniform flow. This is discussed in more detail in section 2.5.

2.3. Breakdown and re-establishment of water repellency

Past studies which have attempted to quantify change in infiltration behaviour in response to short-term variations in weather have often emphasised the persistence of water repellency, requiring a prolonged period of heavy rain for breakdown, sometimes contrasted with a rapid return of water repellency after a comparatively short period of drying. Crockford et al. (1991) measured in-situ water repellency over a four year period in a Eucalypt forest east of Canberra, reporting that while some weeks of wet weather were required for breakdown, repellency could be re-established in only one week of hot, dry weather. Ritsema and Dekker (1996a) reported that moisture did not begin to penetrate a water repellent dune sand subsoil until moisture content in the wettable layer above had reached 20-25%. Leighton-Boyce et al. (2005) measured in-situ repellency under 4 Eucalypt plantations in Portugal over 16 months, finding that soil transitioned from repellent to
wetting between August and February, returning to entirely repellent over a 22 day period from May-June 2001. Keizer et al. (2008) examined in-situ repellency in two adjacent Eucalypt plantations in north-central Portugal over a 10-month period, finding that significant changes – both increases and decreases – could occur in as little as 6-7 days. The persistence of water repellency even after significant rainfall or irrigation has also been reported at other sites with comparable vegetation (Burch et al., 1989; Ferreira et al., 2000). However, such studies have relied primarily on drop tests performed on soil samples taken at intervals of a week or more, over periods totalling less than two years, and have thus had a limited ability to examine changes occurring at intervals of less than one week or over inter-annual periods.

Persistent breakdown of water repellence may require the removal of hydrophobic substances from soil interstitial spaces, such as when leached from the soil by infiltrating water. Ritsema and Dekker (1996a) reported that hydrophobic organic substances were absent from the near-surface regions of flow pathways identified within a soil block, but were present at the bottom of the pathway, suggesting that these compounds had been leached by the infiltrating water. It was proposed that leaching likely contributed to the recurrence of pathways at the same location, which occurred even where soil was able to dry between wetting events. Measurable impacts of leaching were also examined by Hardie et al. (2012), using a free-draining laboratory experiment with a highly water repellent soil sample of 1200 cm³. They reported that WDPT times reduced by 95% after 1L of water had passed through the soil, though multiple similar leaching events were required for comparable reduction in MED results. In a similar experiment, Arye et al. (2007) found increasing reductions in water repellence with increasing leaching fraction, and also that water repellence could be conferred on an initially wettable soil by wetting with a solution containing dissolved hydrophobic compounds. A variety of work by other authors has similarly reported that water repellence may be induced in a wettable soil by treatment with extracts from water repellent plant litter (Franco et al., 2000, 1995; McGhie and Posner, 1981; Roberts and Carbon, 1972).
According to this leaching model of breakdown, soil water repellence is a function of both hydrophobic compounds and moisture content (Dekker and Ritsema, 1994; Täumer et al., 2005). Though soil may become wettable after contact with moisture, its 'potential' water repellence will be restored on drying, provided that sufficient hydrophobic material remains after wetting (Dekker and Ritsema, 1994). Additional support for this theory can also be found in a variety of studies showing that high carbon contents (indicating presence of organic compounds) were moderate-to-good predictors of water repellence of different soil samples taken from the same site (Hardie et al., 2012; Harper and Gilkes, 1994; McGhie, 1980b; McKissock et al., 1998; Ritsema et al., 1997; Summers, 1987; Täumer et al., 2005; Wijewardana et al., 2016; Zhao et al., 2007).

The necessity of leaching in order to prevent soils from regaining their water repellence on drying was, however, challenged by Doerr and Thomas (2000), who demonstrated that small 10 g samples of highly water repellent soil, saturated under ponded conditions in the laboratory over a 30 day period without drainage or removal of moisture, did not regain their water repellence when air-dried. These results call into question the potential/actual water repellency distinction, demonstrating that drying alone may be insufficient to reproduce initial water repellence. Doerr and Thomas (2000) proposed instead that some input of heat may be required to provide the necessary energy to re-arrange or re-distribute hydrophobic substances, and that solar heating of soil during summer may provide this in the field. Additionally, it was speculated that some fresh input of hydrophobic substances or certain microbial or fungal activity may be required to re-establish strong water repellency after soil has been saturated.

Similarly, Crockford et al. (1991) found that water repellence was destroyed when 4 g samples were mixed with enough moisture to thoroughly saturate soil, then left wetted overnight. Furthermore, water repellency did not return to those samples even after 24 hours of drying at 43°C, which was estimated as the highest temperature that soil would ordinarily experience in the field. It should be noted both the work of Crockford et al. (1991) and Doerr and Thomas (2000) involved saturating soil to a degree and duration that would be highly unusual under field conditions, and some recovery of water repellence on soil
drying appears to be normal for lesser degrees of saturation (Doerr and Thomas, 2000). However, Roper (2005) also reported a steady decrease in water repellence, equivalent to over 1 M change in MED over six months, when soil was wetted to a constant 12% moisture by weight, though subsamples were dried at 105°C before final repellency measurements were made. Substantially greater and more rapid reductions were reported if lime was added to stimulate the growth of wax-degrading bacteria (Roper, 2005). That prolonged wetting alone may reduce or destroy water repellence is thus repeatedly supported by the literature.

The suggestion that heating may be an important factor in the establishment or reestablishment of water repellence is not new. Bushfire in particular has been widely attributed as a cause of water repellency at locations including Australia (Doerr et al., 2004b; McGhie and Posner, 1981; P Nyman et al., 2010; Prosser and Williams, 1998; Sheridan et al., 2007), Spain (Cammeraat and Imeson, 1999; Imeson et al., 1992), Portugal (Doerr and Thomas, 2000; Keizer et al., 2008) and the USA (DeBano, 2000a, 1981; Doerr et al., 2009). It should be recognised, however, that fire is not a prerequisite for strong water repellency, and that fires of particular severity may actually reduce or destroy water repellence in surface soil while increasing water repellence of deeper layers (Doerr et al., 2004b). While the precise mechanisms by which heat enhances water repellency remain to be clarified, researchers have speculated that it may provide the energy needed to reorient hydrophobic molecules and bind them to soil particles, whether that heat be provided by fire (DeBano, 2000a; Savage et al., 1972) or solar heating (Doerr and Thomas, 2000).

Oven drying has also been found to produce higher water repellency than air drying (Doerr et al., 2004a; Ma’shum and Farmer, 1985). Water repellence may also increase with oven drying temperature, though sensitivity may vary by site, as Hardie et al. (2012) found WDPT times increased by a factor of 6 if a texture-contrast Tasmanian soil was dried at 60°C rather than 40°C, whereas Roper (2005) found only modest increases in MED, of at most 0.6 M over an increase in drying temperatures from 43°C to 105°C, for a soil from south Western Australia, and Franco et al. (1995) similarly reported only small increases in water repellence associated with increase of oven-drying temperature for soil samples from south-east South
Australia. Dekker et al. (1998) found that increasing the drying temperature from 25° to 65°C produced greater water repellency in samples taken from 4 of 7 sites in the Netherlands, but reduced the water repellency of two others, and had no effect on the remainder, while Rodríguez-Alleres et al. (2007) also reported that increasing drying temperature made no difference. Ma’shum and Farmer (1985) additionally reported that, although freeze-drying could render a soil sample readily wettable, water repellence could be subsequently returned by wetting and oven-drying that sample.

Taking all the above factors into consideration, we may understand the strength of water repellence in the field as a product of an extended wetting and drying history at that particular soil location, as well as opportunities for the leaching or reintroduction of hydrophobic substances, also influenced by variations in soil temperature. The establishment of strong water repellency during summer may require both the drying and heating of the soil, while breakdown may depend on frequencies and intensities of rainfall during winter, as well as other factors influencing flow pathway formation, such as soil texture and topography. Analyses of this nature, however, remain substantially qualitative rather than quantitative, and results are rarely transferrable between different sites. Though soil water repellency is widely recognised to respond to environmental conditions, it is not yet possible to predict the response to any real degree of accuracy based on environmental data alone (Doerr et al., 2007).

Features evident on a larger scale, such as rainfall partitioning between infiltration and runoff and subsequent moisture availability for plant growth, will, of course, be affected by the fractional soil surface area in water repellent or wettable states, which may vary both seasonally and over the scale of a single rain event. Before the full effect of water repellence on such features may fully assessed, the variation in water repellence which may be expected based on seasonal or recent weather patterns must be understood (Täumer et al., 2006).
2.4. Seasonal variation of water repellency

Any detailed assessment of the long-term impacts of water repellence on moisture dynamics at any given site will require some understanding of how water repellence either persists or breaks down in response to seasonal climactic factors. Distinct seasonal variations in soil water repellency, reaching a maximum in the dry season and breaking down during the wet, have been reported in numerous countries including Australia (Burch et al., 1989; Crockford et al., 1991; Hardie et al., 2012; Oades, 1992; Sheridan et al., 2007; Summers, 1987), Portugal (Doerr and Thomas, 2000; Ferreira et al., 2000; Keizer et al., 2008; Leighton-Boyce et al., 2005), Germany (Täumer et al., 2006; Wessolek et al., 2008), Denmark (Wahl, 2008) the Netherlands (Oostindie et al., 2011), Iran (Mirbabaei et al., 2013) and the southern USA (DeBano, 1981; Hubbert and Oriol, 2005). Strong seasonal trends have frequently been described in climates of Mediterranean character (eg. Summers, 1987; Doerr and Thomas, 2000; Ferreira et al., 2000; Hubbert and Oriol, 2005; Leighton-Boyce et al., 2005; Keizer et al., 2008; Gabarrón-Galeote et al., 2013), characterised by a hot, dry summer, with the majority of rainfall received during the winter season. Distinct seasonality has also been described for a number of temperate maritime climates, which see rainfall more evenly distributed through the year (eg. Burch et al., 1989; Crockford et al., 1991; Benito et al., 2003; Täumer et al., 2006; Sheridan et al., 2007; Wessolek et al., 2008; Oostindie et al., 2011; Hardie et al., 2012), though seasonal variation in water repellency may be less pronounced in those locations.

Although water repellency has been identified in a number of humid climates (eg. Jaramillo et al., 2000; Kobayashi and Shimizu, 2007; Kettridge et al., 2014), less information is available on seasonal variation in these climes, and similar patterns may not apply. For example, in humid subtropical regions of Japan, where the majority of rainfall is received during summer, there appears to be little evidence of clear seasonal trends (Kobayashi and Shimizu, 2007; Miyata et al., 2007; Wijewardana et al., 2016). Stronger water repellency was nonetheless regularly associated with periods of low antecedent rainfall and reduced soil moisture (Kobayashi and Shimizu, 2007; Miyata et al., 2007) and runoff ratios were found to increase through the early summer season in a year where rainfall in that period was
unseasonably light (Gomi et al., 2008). As such, we may expect localised variations in
weather to be capable of producing some degree of short-term variation in water
repellency, either in the presence or absence or broader seasonal trends.

Results of such diverse studies as those available in the literature may not be directly
comparable, however, as different methods have been used as indicators of water
repellence in different work. Techniques used to demonstrate seasonal patterns include
direct tests such as the Water Drop Penetration Test (WDPT) (eg. Ferreira et al., 2000;
Hardie et al., 2012) or Molarity of an Ethanol Drop test (MED) (eg. Summers, 1987; Burch et
al., 1989; Crockford et al., 1991; Leighton-Boyce et al., 2005; Sheridan et al., 2007; Keizer et
al., 2008), as well as infiltration tests (eg. Burch et al., 1989; Ferreira et al., 2000; Nyman et
al., 2010a). Researchers have also examined seasonal patterns in terms of runoff ratios
(Burch et al., 1989; Ferreira et al., 2000; Gomi et al., 2008; Miyata et al., 2007; Sheridan et
al., 2007), which may reflect very different patterns over the duration of a rain event
depending on the initial water repellent breakdown state at that time of year.

As the process of breakdown in the field is perhaps best understood as the gradual spread
of pathways over multiple wetting events, annual variability at affected sites has also been
studied by recording wet and dry fractions in the subsurface during different seasons. Soil
block sampling or tracer studies can generate detailed pictures of flow pathway geometry,
and have occasionally been used to examine seasonal variation. In particular, Ritsema et al.
(1997) excavated soil blocks of area 120 cm by 60 cm by 52 cm deep on 10 dates over a
period of a year, analysing each block as 1400 samples to map flow pathway area. Wessolek
et al. (2009) was able to compare flow paths at two different points in the season by using
two different tracers (Br\textsuperscript{−} and Cl\textsuperscript{−}) applied at different dates, before finally excavating the
profile region so soil could be analysed for both tracers. However, a limitation of intense
sampling methods is that these require significant disturbance of the soil profile, and are
thus only able to characterise flow pathway shares on specific sampling dates.

In examining long term variability in flow patterns, soil moisture sensors with automatic
loggers offer the significant advantage of being able to produce theoretically unlimited
readings from the same section of the soil profile, without further disturbance after
installation. The technique of monitoring soil moisture using a densely spaced two-dimensional array of moisture sensors to track flow pathway recurrence was first demonstrated by Ritsema and Dekker (1996b), and has since been reused in several subsequent studies. As previously noted (Section 2.2), in developing the ECS metric, Täumer et al. (2006) measured soil moisture in a transect of 1.3 m by 60 cm deep at a grassland site north of Berlin at hourly intervals between April 2002 and April 2004, reporting recurrence of flow paths between subsequent events, though also gradual movement of flow paths over the longer term. Additionally, Wessolek et al. (2008) tracked soil moisture variation from November 2000 to October 2001 in a 2.1 m transect in a water repellent pine stand to examine seasonal changes in flow characteristics. Oostindie et al. (2011) measured moisture in a 4.5 m transect on a water repellent golf green from 2003 to 2006, with probes installed at 4 depths, using the resulting data to compare seasonal wetting characteristics in the first year of study to those of subsequent years, which followed the application of a surfactant to ameliorate water repellent effects.

Other researchers have occasionally examined seasonal changes using only a single column of sensors, with one sensor installed at each depth. This functionally one-dimensional arrangement is well-suited to wettable soils where flow is primarily one-dimensional in character, but less well-suited where infiltration is dominated by preferential flow, as it provides no means to evaluate lateral variation in soil moisture. Indications of preferential flow patterns may, however, be inferred by analysis of the resulting data. For example, Blume et al. (2009) measured soil moisture at 6 depths and 3 locations in a water repellent catchment in Chile, from March 2003 to May 2006. Although water repellent breakdown was not a primary focus of that work, sensors located near the surface reported substantially less response to rain events in summer when soil was hydrophobic than was evident during winter, which was taken as evidence of seasonal variation. A vertical array was also used by Kobayashi and Shimizu (2007) to record soil moisture at hourly intervals in a Japanese cypress forest. They quantified variations in water repellent effects by comparison to the results of a calibrated one-dimensional Hydrus simulation of each wetting event. Agreement between observed and modelled predictions reportedly
improved when soil was initially damp prior to the rain event (Kobayashi and Shimizu, 2007).

Lin and Zhou (2008) analysed high-frequency sensor readings from a dozen vertical sensor arrays installed at distributed locations in the shale hills of Pennsylvania from September 2006 to January 2007. Evidence of preferential flow was derived from the 'non-sequential depth response' phenomenon, whereby bypass flow manifested as incidents where infiltration reached sensors at depth before or in the absence of any increase in moisture in near-surface regions (see section 2.2 for more detail). Using this method, Lin and Zhou (2008) were able to associate the occurrence of preferential flow with the primarily dry antecedent conditions which characterised the first half of the analysis period. These methods were expanded by Hardie et al. (2013), who also introduced the metric of rainfall effectiveness to examine moisture contents with a vertical sensor array at 8 depths in a Tasmanian texture contrast soil between September 2007 and October 2009, at intervals varying from 1 minute to 1 hour. Using these metrics, antecedent moisture content and seasonal rainfall history was again reported as a useful predictor of the probability that preferential flow occurred (Hardie et al., 2013).

The work of Täumer et al. (2006) remains one of the more detailed examinations of long-term variation in flow pathway share on a water repellent soil available in the literature, noting both seasonal and interannual variation in its two years of study, from 2002-2003. Not only did that work introduce the metric of the effective cross-section (ECS, see section 2.2) as a means of quantifying flow pathway share based on the readings of a soil moisture sensor array, but also analysed the dependence of ECS values on initial water content and various climatic parameters. Best fit was achieved by regression against four variables, representing initial moisture content, rain event intensity, rain event depth, and antecedent 24 day potential evaporation, with initial moisture content having the greatest influence. Preferential flow was more likely to be triggered by high intensity events, whereas rainfall of lower intensity produced more gradual, uniform wetting of the soil. In particular, the results of Täumer et al. (2006) reiterate the progressive nature of water repellent breakdown, dependent both on ongoing rainfall and retained moisture status following previous events.
2.5. Hydrological modelling in water repellent soils

The standard model for moisture movement under unsaturated conditions is based on Richards’ equation (Equation 2.1).

\[ \frac{\partial \theta}{\partial t} = \nabla \cdot [K(\psi) \nabla (\psi + z)] \]  

(2.1)

Where \( \theta \) = soil moisture content (m\(^3\)/m\(^3\)), \( z \) = vertical depth (m), \( \psi \) = soil pressure head (m), \( K(\psi) \) = hydraulic conductivity at soil pressure \( \psi \) (m/s).

As Richards’ equation is strongly non-linear, analytical or quasi-analytical solutions are only possible under a very limited range of conditions, and modelling efforts have thus focused primarily on developing numerical solutions (Celia and Binning, 1992; Haverkamp et al., 1977). As soil infiltration is driven primarily by gravity and vertical gradients, processes can be represented to a reasonable degree of accuracy using models which use one-dimensional implementations of Richards' equation (Equation 2.2), allowing for variability only in the vertical direction (Romano et al., 1998).

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(\psi) \left( \frac{\partial \psi}{\partial z} + 1 \right) \right] \]  

(2.2)

One-dimensional flow models have the significant advantage that they are relatively simple to implement and run as compared to multi-dimensional solutions, having lower computational requirements and requiring fewer inputs to define the soil profile (Van Dam et al., 2005). The availability of free or open-source 1D models such as Hydrus1D (Šimůnek et al., 2009, 2008) and SWAP (Kroes and Van Dam, 2003) has added to their popularity.

However, where infiltration is dominated by preferential flow, moisture distributions and flow rates may vary substantially in the horizontal plane, and thus cannot be simplistically averaged into one-dimensional processes. Better representations may be possible by modelling processes in two or more dimensions (for example see Robinson et al., 2010), and multi-dimensional implementations of Richards’ equation are now also widely available. However, regardless of the number of dimensions of the solution, processes involved in
generating preferential flow usually cannot be accurately represented using Richards’ equation alone (Beven and Germann, 2013; Nieber et al., 2003).

Preferential infiltration may additionally vary in character depending on its cause, which may involve unstable processes such as water repellency, or structural irregularities, such as macropores, cracks, and fractures. Although a variety of modelling solutions developed with reference to both of these broad categories of preferential flow can be found in the literature, it should be recognised that approaches suitable for one class of preferential flow may not be applicable to the other (Diamantopoulos and Durner, 2012). Consequently, although macropores and textural features may be significant in facilitating infiltration at some water repellent sites, the discussion below will focus upon models developed for horizontally uniform soils, where fingering is primarily instability-driven.

The simplest class of solutions for water repellent soil infiltration retain the basic one-dimensional framework but divide the soil volume into mobile and immobile fractions, which may vary in cross-sectional area share with depth. An early implementation of such a scheme, using a constant reduction factor F to reduce the active flow domain, is described by van Dam et al. (1990), who used this model to analyse water flow and solute transport in water repellent soil, using data from field experiments. A modified version of the same concept was incorporated into SWAP93 by van Dam et al. (1996), who tested the model with data from a 77 day sensor study. This implementation allowed for temporal variations in flow path area by implementing dynamic rather than static reduction factors, functioning on the assumption of a linear relationship between the reduction factor F and hydraulic head (van Dam et al., 1996).

Kramers et al. (2005) and Ritsema et al. (2005) presented another modified version of SWAP aimed at aiding agricultural management in water repellent conditions. A new fingered-flow module allowed flow to switch from uniform to preferential based on the critical water content. Flow area reductions were estimated based on the depth of the water repellent soil layer and inputs defining the maximum and minimum relative cross-sections for the fingers. The performance of this module was compared to the mobile/immobile concept introduced by van Dam et al. (1990), using data from a tracer experiment, as part of work
comparing various ameliorative strategies for water repellent conditions. The new module was found to be more successful than the mobile/immobile concept in accounting for resulting differences in production, though both provided improved results over the classic 1D flow alone (Kramers et al., 2005).

More precise simulations of preferential flow have been generated using modified two-dimensional models, which can produce explicit representations of variability in soil properties and moisture in the horizontal plane. In some cases, workers have produced useful modelling solutions by limiting the problem domain to cases where wetting patterns may be readily predicted. For example, Yang et al. (1996) developed a numerical model of combined heat and water movement for furrow-sown water repellent agricultural soil, which was used to optimise furrow design for optimal moisture harvesting and crop growth. Model operation depended on the fact that infiltration would occur consistently at the base of the furrows, where moisture was able to pond and infiltrate (Yang et al., 1996).

In most field conditions, however, flow pathway locations cannot be reliably predicted based on ground topography alone. One approach to the problem of modelling instability-based preferential flow, based upon the known dependence of flow pathways on soil wetting history, was to incorporate hysteretic effects. Specifically, Nieber (1996) developed a finite element model to implement Richards’ equation with parameter equations for capillary hysteresis to model the growth of gravity driven fingers in two dimensions. Ritsema et al. (1998) used this model to demonstrate how flow pathways in a water repellent soil can form and propagate from initially small instabilities in the wetting front, even in a texturally uniform soil medium. This concept was further developed by Ritsema and Dekker (2000), who used the model to demonstrate the effect of antecedent moisture conditions on preferential flow.

Although methods based on capillary hysteresis alone were able to account for the persistence of flow fingers (Nieber et al., 2003), this approach has been since deemed insufficient to adequately account for fingering based on flow instabilities, as such methods remain dependent on stable implementations of the Richard’s equation solver (Cueto-Felgueroso and Juanes, 2009; Nieber et al., 2003). Researchers have instead turned to non-
equilibrium methods, which allow for variation in the relationship between moisture content and hydraulic pressure, based on rate of flow (Diamantopoulos and Durner, 2012). One such effort was that conducted by Nieber et al. (2003), who used a non-equilibrium Richard’s equation model which added a method of relaxation in the relationship between moisture content and pressure. The resulting model was employed to demonstrate how instabilities can form under only slightly water repellent conditions. An alternate model using methods relating to the dynamic non-equilibrium approach was developed by Deurer and Bachmann (2007), who simulated preferential flow using a dynamic contact angle approach. The same study reported a good qualitative match to field data collected during a three week wetting and drying cycle at a water repellent forest site. Cueto-Felgueroso and Juanes (2009) were similarly critical of the potential for accurate modelling of flow fingers based on hysteresis alone, instead modelling gravity fingers using a model based on a modified Richards' equation incorporating a fourth-order derivative in space, reporting a good qualitative match to results from laboratory experiments.

The literature on the modelling of moisture movement in water repellent soil thus shows that a variety of approaches have been proposed, implemented, and often tested with encouraging results, but little clear consensus as to the best-practice approach, with most models lacking independent verification under varying conditions. Although some widely or commercially available hydrological models have already incorporated schemes to represent preferential flow due to structural irregularities such as cracks or macropores (eg. Šimůnek et al., 2009), comparable modules suitable for simulating instability-driven flow are not presently available.

Standard one-dimensional hydrological models have also occasionally been used as a comparison point in the study of water repellency, against which variations to 'normal' soil behaviour may be demonstrated and quantified. Kobayashi and Shimizu (2007) compared moisture sensor data from a Japanese cypress plantation to one-dimensional Hydrus simulations, calibrated using a thoroughly-wetted soil sample from the same location. By comparing field measurements to model results representing the same rain events, researchers attempted to identify the critical water content, beyond which field model
results and model results could be expected to come into alignment (Kobayashi and Shimizu, 2007). Wessolek et al. (2008) used a version of SWAP with reduction factors to represent the mobile/immobile concept, as developed by van Dam et al. (1996), to describe seasonal variation in TDR data recorded in a pine forest. Reduction factors were found to improve results during rewetting in autumn-winter, but simple one-dimensional modelling was better able to reproduce de-watering in spring, when water repellency was at a late stage of breakdown, and thus close to a fully wettable state (Wessolek et al., 2008). Similarly, Hardie (2011) found generally poor agreement between moisture contents recorded in a water repellent texture contrast soil and predictions from a Hydrus1D simulation, but noted that agreement improved in periods which followed some months of significant rainfall, during which water repellency decreased. Hardie (2011) also reported substantial differences in soil parameters, estimated from moisture data using an inverse fitting procedure, depending on whether a water repellent soil was initially wet or dry.

Results from a one-dimensional simulation model were also used to shed light on evaporative effects by Bachmann et al. (2001), who implemented a finite-difference model using the Philip and De Vries (1957) theory for thermal gradient effects on moisture movement to simulate simultaneous transport of heat, moisture and moisture vapour. The model was used in conjunction with a laboratory experiment examining the effects of water repellency on evaporation in both isothermal and non-isothermal conditions, and found to be able to predict evaporation rates from wettable soil to a reasonable degree of accuracy, but poorly able to represent evaporation from water-repellent soils. Model results were interpreted as suggestive that strong water repellency may influence thermal vapour diffusion, in addition to other known effects of water repellence on soil evaporation (see section 2.6 below) (Bachmann et al., 2001).

Although the development of a well-verified and practical simulation model of moisture movement under water repellent conditions remains an ongoing problem, such studies demonstrate that even relatively simple hydrological models have been used to provide valuable insight into water repellent phenomena, particularly in those cases where relative wettability varies on a seasonal or weather-dependent basis.
2.6. Effects on soil evaporation

Because it limits the spread and absorption of moisture in shallow soil, water repellency has traditionally been considered detrimental to plant growth. Under turf, pasture or crops, water repellency can generate dry patches where plants will not readily germinate, lowering productivity in agricultural regions (Bond, 1972; Moore and Blackwell, 2001; Müller and Deurer, 2011; Osborn et al., 1967; Roper et al., 2015) and damaging aesthetics on golf greens and lawns (DeBano, 1981; Oostindie et al., 2011). As water repellency can reduce grass coverage and enhance surface runoff, rates of soil erosion may similarly be enhanced (McGhie, 1980a; Nyman et al., 2011; Prosser and Williams, 1998; Sheridan et al., 2007). For these and related reasons, the development of management and amelioration techniques for water repellency in agricultural regions has long been a core driver for research into the phenomenon (e.g. Yang et al., 1996; Crabtree and Gilkes, 1999; Hall et al., 2010; Oostindie et al., 2011; Müller and Deurer, 2011; Roper et al., 2015). Some authors have also suggested water repellency may increase evaporative losses if moisture is trapped near the surface (DeBano, 1981; Hallett, 2008), and that it may enhance drought stress in affected regions (Goebel et al., 2011; Horwitz and Sommer, 2005; Orfánus et al., 2014).

Comparatively little work has examined the role of soil water repellency in native ecosystems (Müller and Deurer, 2011), or its feedback effects on vegetation responsible for producing the hydrophobic compounds which induce water repellency in the soil. However, the possibility that soil water repellency actually serves to conserve soil moisture against evaporative loss by several mechanisms, and thus provide beneficial effects to vegetation, has received some attention in the literature.

Perhaps the earliest recognition of this possibility was raised by Letey et al. (1962a), who recorded evaporation rates from a saturated sand which had been treated with hydrophobic extracts in a laboratory column, reporting that evaporation decreased by as much as a half when compared to a wettable control. Significantly, no discrepancy was found in evaporation rates for ethanol from the same soil samples, demonstrating that treated and untreated soil had retained comparable hydraulic characteristics (Letey et al.,
1962a). The discrepancy in rates of evaporation of water was attributed to the greater contact angle associated with the water repellent sample: as water is less attracted to hydrophobised soil particles, the maximum height of capillary rise in the soil matrix is reduced, and thus moisture lost to evaporation from upper soil regions will be less rapidly replenished from below (Bachmann et al., 2001; Birdi and Vu, 1993; Letey et al., 1962a). A related mechanism described in later work suggests that evaporation may also be reduced due to alterations to the liquid/gas interface in partially saturated water repellent soil regions: as moisture is discouraged from 'spreading out' as it would in contact with a wettable soil particle, the surface area of the liquid/gas interface is reduced, and less surface area is available from which evaporation can take place (Bachmann et al., 2001; Birdi and Vu, 1993).

More recent investigations into evaporation from evenly wetted soil have supported and expanded upon these results. In particular, Bachmann et al. (2001) measured evaporation rates in laboratory soil columns in both isothermal and non-isothermal conditions, the latter heated from the base of the column to produce a constant temperature gradient. Isothermal evaporation after 195 days was reported as 25% lower for water repellent soil than wettable soil, the difference magnified under non-isothermal conditions. The authors suggested that water repellent soils diffuse water vapour by a mechanism that differs from that for wettable soils, and that evaporation rates may be effectively controlled by moisture contents in a thin surface layer, < 1 cm thick (Bachmann et al., 2001).

Evaporation from hydrophobic soil which has been evenly wetted under laboratory conditions has been examined in a variety of other circumstances. Shahidzadeh-Bonn et al. (2007) found evaporation was reduced in subcritically hydrophobic soil relative to a wettable analogue, noting that the hydrophobic soil developed a sharp drying front which appeared to act as a strong barrier to further evaporation. Surprisingly, exposing wetted hydrophobic soil to greater airflow was found to produce slightly lower net evaporation over the longer term. Authors suggested that the increased airflow had resulted in the rapid drying of near-surface region to near-zero moisture status in early phases of evaporation,
which may have interrupted capillary pathways which would have otherwise supported sustained residual evaporation (Shahidzadeh-Bonn et al., 2007).

Shokri et al. (2008) measured evaporation from soils containing hydrophobic layers of variable depth, finding that evaporation decreased with the maximum depth of the hydrophobic layer. Evaporation was found to be comparably suppressed even where the hydrophobic layer was overlain by a region of hydrophilic soil, as even a thin hydrophobic region was able to act as a significant capillary barrier. Shokri et al. (2009) measured evaporation from soils containing mixtures of hydrophilic and subcritically hydrophobic particles, finding that the duration of first stage or 'constant rate' evaporation decreased with increasing hydrophobic fraction (notably, both Shahidzadeh-Bonn et al. (2007) and Shokri et al. (2008) also associated hydrophobicity with truncated first stage evaporation phases). A theoretical model for calculating the depth of the drying front at the end of first stage evaporation in partially wettable porous media was presented and tested in the same work (Shokri et al., 2009). Shokri and Or (2013) measured evaporation from soil containing horizontal variations in water repellency, in tanks divided into vertically uniform but connected domains of hydrophobic and hydrophilic soil. Although evaporation took place primarily through the hydrophilic soil surface, moisture was replenished by flow from the hydrophobic region, such that it was the hydrophobic region that dried more quickly (Shokri and Or, 2013). Evaporation from soil with water repellent surface layers was also examined by Ahn and Im (2010), who generated hydrophobic layers by burning water repellent leaf litter on the soil surface on laboratory soil columns. Soil was wetted from beneath and subsequent evaporation recorded, with results demonstrating rates of evaporative loss reduced as the width of the hydrophobic layer increased (Ahn and Im, 2010).

Common to the studies described above is the finding that evaporation was significantly reduced by evenly-wetted soils which were either uniformly or partially hydrophobic. However, in the field, water repellent soils will rarely wet uniformly, and there is compelling evidence that the patterns of irregular wetting which typify infiltration into water repellent soil may produce even greater impacts on evaporative loss. As only a limited fraction of the soil surface is active in absorbing moisture, the wetting front is able to bypass considerable
regions of the soil matrix, reaching deep into the profile long before sufficient rainfall has occurred to thoroughly wet upper soil regions (Ritsema and Dekker, 2000; Robinson et al., 2010; Stephens, 1994; Stoof et al., 2014) (Figure 2.1A, B). The result of such patterns is to sequester a significant fraction of moisture at depth, where better thermal insulation and increased path lengths to the surface will substantially improve barriers to evaporation (Figure 2.1D, E). Additionally, as strongly water repellent soil is frequently a near-surface feature in the field, wettable regions underlying a shallow water repellent region (Figure 2.1C) may form a 'redistribution zone' where flow pathways are able to spread, leading to rapid drainage from the channels above (Doerr et al., 2000; Ritsema et al., 1998b, 1993). This further depletes moisture in regions where it is most susceptible to evaporation (Figure 2.1F).

The potential for soil water repellency to provide significant benefits to vegetation by conserving moisture in this manner was first raised by Imeson et al. (1992), who examined runoff and infiltration after simulated rainfall experiments in a Catalonia forest, concluding that the hydrophobic surface layer acted to trap moisture in subsoil layers beneath, extending the path length to the surface and thus producing a significant barrier to evaporation. Although evaporation rates were not measured in that study and the impact of water repellent surface layers was determined primarily by inference, the concept that water repellency may act to conserve moisture has been widely cited (eg. Yang et al., 1996; Jaramillo et al., 2000; Moore and Blackwell, 2001; Doerr and Ritsema, 2005; Hallett, 2008; Lozano et al., 2013; Kettridge et al., 2014) and expanded upon in later work.

Several related mechanisms have been proposed by which patterns of infiltration produced by soil water repellency may provide specific benefits in making moisture available for plant growth. Studies from multiple locations have recorded infiltration patterns suggesting that vegetation-induced water repellency can serve to channel moisture directly to the base of the plant, where stemflow and root-induced preferential flow will aid in producing preferential infiltration (Blackwell, 1993; Cammeraat and Imeson, 1999; Imeson et al., 1992; Robinson et al., 2010; Verboom and Pate, 2006). If soil moisture is restricted to a limited pathway, it may additionally be available at higher hydraulic potential, facilitating uptake by
Figure 2.1. Illustrative wetting patterns and evaporation from wettable and water repellent soil. In wettable soil (A), water forms a shallow, even front, which rapidly dries (D). In water repellent soil (B), moisture forms flow fingers, which channel some moisture to depths where it is more effectively protected from evaporative loss (E). In shallow water repellent soil overlying a deeper wettable layer, flow fingers spread on reaching the wettable layer (C), leading to rapid drainage from the regions above, and sequestering greater fractions of infiltrating moisture at depth (F).

that plant (Robinson et al., 2010). By limiting moisture storage near the surface, water repellency may also represent a means by which deep-rooted plants suppress the germination of shallow-rooted competition (Blackwell, 1993; Osborn et al., 1967; Robinson et al., 2010). In other environments, where water repellency is associated with shallow-rooted pasture species, it may occur as a sublayer underlying a shallow wettable region, trapping moisture in the root zone where it will be available for growth (Ritsema and
Dekker, 1996a). Verboom and Pate (2006) go so far as to suggest that water repellency represents a form of bioengineering, by which specific plant species are able to modify their environment to their own advantage.

As water repellence is at its strongest in periods of dry, hot weather, it may be of especial use to the plant in conserving moisture following isolated summer rain (Cammeraat and Imeson, 1999) and in improving drought resistance (Robinson et al., 2010), especially in arid or desert environments (Jaramillo et al., 2000; Lozano et al., 2013). At the same time, as water repellence has been observed to persist in some environments even after considerable wetting (Burch et al., 1989; Crockford et al., 1991; Ferreira et al., 2000; Leighton-Boyce et al., 2005; Ritsema and Dekker, 1996a), and to re-establish rapidly during brief periods of hot weather (Crockford et al., 1991; Keizer et al., 2005; Leighton-Boyce et al., 2005), some evaporative benefit may persist well into the wet season. The mulch-like effect generated by near-surface water repellent soil layers as they dry likely confers an additional barrier to evaporation (Ritsema and Dekker, 1996a; Yang et al., 1996).

It is widely recognised that, by promoting deep preferential flow pathways, soil water repellency may accelerate the transport of contaminants to the groundwater (eg. Hendrickx et al., 1993; Nguyen et al., 1999; Blackwell, 2000; Darnault et al., 2004; Ritsema et al., 2005; Hardie et al., 2013). Less often recognised is that these mechanisms may also serve a key role in facilitating groundwater recharge (Kramers et al., 2005; Scott and Lesch, 1997; Stephens, 1994). Preferential flow may be particularly significant in replenishing deep storage of moisture in arid or semi-arid regions where potential evaporation far exceeds annual precipitation (Jaramillo et al., 2000; Stephens, 1994), or during summer, when vadose regions are primarily dry (Blume et al., 2009). The combined effect is of obvious benefit in conserving and channelling moisture to the benefit of deep-rooted vegetation.

A complicating factor among the reasons why water repellence has been traditionally cited as detrimental to plant growth is the issue of enhanced runoff generation. High runoff ratios from water repellent hill slopes have been reported in a number of published studies (eg. Osborn et al., 1967; McGhie, 1980; Sheridan et al., 2007; Nyman et al., 2011), which should theoretically reduce the availability of moisture for infiltration. However, efforts to quantify
the effect over larger scales have typically reported that net contributions to streamflow at
catchment outlets may be comparatively modest (Burch et al., 1989; Cammeraat and
Imeson, 1999; Doerr et al., 2003; Imeson et al., 1992; Prosser and Williams, 1998) with the
majority of contributing runoff generated within only a few metres of the channel (Sheridan
et al., 2007). Such observations reflect the fact that although water repellency can be
effective in generating runoff over short distances, hydrophobic surface layers are rarely
contiguous over larger distances, with entry points for infiltration such as macropores or
wettable soil regions playing a key role in facilitating infiltration (Burch et al., 1989; Doerr et
al., 2003; Imeson et al., 1992; Leighton-Boyce et al., 2007; Petter Nyman et al., 2010).

Runoff over short to moderate distances may also play a role in funnelling and
concentrating moisture, and thereby increasing its maximum infiltration depth. For
example, Arbel et al. (2005) reported that a plantation of Tamarix aphylla in Israel, a deep-
rooted tree species with repellency-inducing litter, had greater survival rates when planted
near the peak of steep dunes, relative to plantations on shallow dunes, as the steeper
slopes favoured downhill flow and deep infiltration. Shallow infiltration on lower dunes, by
contrast, could be quickly lost to evaporation (Arbel et al., 2005).

In discussing the potential adaptive advantages of vegetation-induced water repellency, it
should be recognised that the production of plant waxes and other hydrophobic compounds
that cause water repellency in soil will usually also provide more direct benefits to their host
vegetation, such as minimising water loss from leaves and providing a self-cleaning
mechanism (Doerr et al., 2000; Neinhuis et al., 2001; Shepherd and Wynne Griffiths, 2006).
The effect of such compounds in inducing water repellency when leaf litter decays may be
better regarded as a by-product of their 'primary' function in many environments. Similarly,
although distributions of water repellency in the field appear well-engineered to conserve
moisture, that water repellency occurs primarily in shallow soil layers may be attributed to
the greater organic matter content of near-surface regions. Nevertheless, the possibility
that in at least some environments, soil water repellency may represent a distinct adaptive
benefit sufficient to provide source vegetation with a competitive advantage, is certainly
apparent from a review of the literature.
Despite this wide array of interest, the magnitude of long-term evaporative benefits provided by soil water repellency in the field has yet to be quantified by either experiment or calculation. While laboratory work cited above has provided considerable insight into the effects of water repellence on evaporation from evenly wetted soils at constant temperature, such studies neglect the impact of preferential flow effects and daily temperature regimes which will occur in the field. This gap in current knowledge has occasionally been cited as a matter of potential concern – for example, the application of wetting agents to improve production on water repellent soil may also enhance evaporation, and thus may have a detrimental effect on water budgets if misused (Hallett, 2008; Müller and Deurer, 2011). There may also be considerable scope for the development of engineering solutions which make use of water repellency for water harvesting purposes (Shokri et al., 2009, 2008; Yang et al., 1996). Further research remains necessary to clarify the effect of water repellence on soil evaporation and groundwater recharge in native ecosystems (Kettridge et al., 2014; Müller and Deurer, 2011; Stephens, 1994; Verboom and Pate, 2006), and its potential implications for a variety of management issues.

2.7. Water repellency in Australia

Soil water repellency is widespread across the Australian continent, and has been recorded in at least six states, including Western Australia (McGhie and Posner, 1980; Roberts and Carbon, 1972; Roper, 2005; Summers, 1987), South Australia (Franco et al., 2000; Ma’shum and Farmer, 1985; Oades, 1992), Victoria (Burch et al., 1989; Sheridan et al., 2007), New South Wales (Crockford et al., 1991; Prosser and Williams, 1998), Tasmania (Hardie et al., 2012) and Queensland (Bridge and Ross, 1983; Costantini et al., 1995; Loch, 2000). Although water repellency has occasionally been reported in soils with high clay content (McGhie and Posner, 1980), in Australia, it is primarily associated with coarse-textured soils, with soil texture having served as a main predictor of the potential for a particular soil to become water repellent in wide-scale surveys (Harper and Gilkes, 1994; McKissock et al., 1998; van Gool et al., 2008).
Especially affected are the southern states (Bond, 1969; Oades, 1992), which may represent the largest region of water repellency-affected agricultural soil in the world (Blackwell, 2000). In the south-west agricultural region alone, more than 10 Mha are estimated to be at least moderately susceptible to developing water repellence, with around 3.3 Mha (approximately 18% of the total region) in the high risk category (van Gool et al., 2008). In the late twentieth century, costs to agriculture of the south west region were estimated at $10-15 million per annum (Oades, 1992; Summers, 1987) with total costs across all agricultural areas perhaps as high as $45 million per annum (Robertson, 1987). More recent reviews of remediation options (Hall et al., 2010; Hardie et al., 2012; Roper et al., 2015) have continued to note the cost to Australian agriculture, putting costs for short-term remediation by ploughing or surfactant application at around $10-$50 per hectare, and longer term solutions such as clay entrainment at $300-$900 per hectare (Roper et al., 2015).

Recognition of the existence of water repellency in Australian soils dates back at least as far as 1930s, when Prescott and Piper (1932) identified water repellent characteristics in soils of South Australia, there associated particularly with xerophytic vegetation. Strong soil water repellency has particularly been associated with various Australian *Eucalyptus* species, both at sites within Australia (Burch et al., 1989; Crockford et al., 1991; Doerr et al., 2004b; Franco et al., 2000; McGhie, 1980b; Petter Nyman et al., 2010; Prosser and Williams, 1998; Sheridan et al., 2007), and where Eucalypts have been introduced as a plantation species in Portugal (Doerr and Thomas, 2000; Ferreira et al., 2000; Keizer et al., 2008; Leighton-Boyce et al., 2005), Spain (Rodríguez-Alleres et al., 2007) and South Africa (Scott, 2000).

Characteristic of species in the *Eucalyptus* genus is the production of aromatic oils and thick leaf cuticles of hydrophobic waxes, which reduce moisture loss and provide a self-cleaning mechanism, in addition to other benefits such as increasing leaf albedo, frost resistance, and discouraging insects and parasites (Edwards, 1982; Shepherd and Wynne Griffiths, 2006; Zobayed et al., 2001). These hydrophobic compounds appear to be readily transferred to soil when leaf litter decays, producing strong soil water repellency (Doerr et al., 2000; Martínez-Zavala and Jordán-López, 2009; Scott, 2000). Water repellency generated under Eucalypts has also frequently been described as more severe than that produced by other
vegetation, including pines (Bond and Harris, 1964; Doerr et al., 2006; Doerr and Thomas, 2000; Rodríguez-Alleres et al., 2007), Acacia (Scott, 2000) and pasture (Harper et al., 2000; McKissock et al., 1998).

Strong water repellency has also been associated with Banksia species of south Western Australia (Harper et al., 2000; McKissock et al., 1998; Moore and Blackwell, 2001; Roberts and Carbon, 1972; Verboom and Pate, 2006). The ubiquity of bushfire in the Australian landscape has also been widely cited as a factor contributing to water repellency (Doerr et al., 2004b; McGhie and Posner, 1981), particularly in association with concerns of runoff and debris flow following fire (Nyman et al., 2011; Prosser and Williams, 1998; Sheridan et al., 2007). Doerr and Thomas (2000) suggest that high diurnal surface soil temperatures recorded in parts of Australia, which may exceed 50°C, may also be an important contributing mechanism in the generation of water repellence and its rapid return after short-term wetting events. Soil temperatures of up to 70°C were reported by Franco et al. (1995), and shown to be effective in facilitating the induction of water repellency to soil particles from wax-containing interstitial matter. Clearing of native vegetation for agriculture may lead to some reduction in water repellency (Roper et al., 2015), however, pine plantations, agricultural crops and common pasture species have also been widely found to induce water repellency in Australian soils (Crabtree and Gilkes, 1999; McGhie and Posner, 1981; Roberts and Carbon, 1972; Roper et al., 2015).

Within Australia, research into repellency has included examinations of the origin of hydrophobic compounds (McGhie, 1980, Ma’shum and Farmer, 1985, Bond and Harris, 1964), relationships to soil organic carbon and clay contents (Harper et al., 2000, Harper and Gilkes, 1994, Summers, 1987) and relationships with bushfire (Sheridan et al., 2007, Doerr et al., 2006, Prosser and Williams, 1998, Nyman et al., 2010). Recurring themes of Australian research have also included runoff and erosion generated under water repellent conditions (Burch et al., 1989; Crockford et al., 1991; Nyman et al., 2011; Prosser and Williams, 1998; Sheridan et al., 2007), and particularly remediation possibilities for agriculture by means of use of surfactants, clay additions and other techniques (Crabtree and Gilkes, 1999; Hall et al., 2010; Moore and Blackwell, 2001; Roper et al., 2015, 2013; Yang et al., 1996).
Seasonal trends in soil water repellency have been reported in Australian environments in a few studies, primarily through either direct tests or as part of runoff measurement studies. Summers (1987) conducted an extensive study of spatial and temporal variation in water repellence in the south-west agricultural region of WA, quantified using the MED test. Significant correlation was reported between the water repellence of weekly soil samples and rainfall in the week before sampling, explaining 62% of variation (Summers, 1987). Burch et al. (1989) examined the persistence of water repellency in terms of MED results and impacts on runoff and infiltration at a forest catchment in Victoria, finding that runoff ratios following summer storms were higher than those produced following winter storms, and that infiltration rates were an order of magnitude higher during winter. Strong persistence of water repellence was also reported, with repeated wetting by artificial irrigation producing little reduction in water repellence over a 39 hour period (Burch et al., 1989).

Crockford et al. (1991) similarly examined runoff and MED results at a forest catchment in NSW. Water repellence was again noted to be highly persistent, with a period of some weeks of consistent rainfall required for appreciable breakdown to occur, with rapid return to a water repellent state after only 6-9 days of hot, dry weather. Salama et al., (2005) found deeper preferential flow in dry periods than those with wet antecedent conditions during tracer studies in the Spearwood and Bassendean sands of the Gnangara Mound in Western Australia. Sheridan et al. (2007) measured infiltration and runoff under simulated rainfall over 3 years after wildfire in a forest in north east Victoria, finding comparable patterns of seasonal oscillation in both burnt and unburnt sites. Nyman et al. (2010a) similarly examined water repellence, infiltration and runoff in a burnt forest in south-east Australia, reporting that water repellency distributions could be linked to seasonal factors of rainfall and temperature via a two-parameter function.

Hardie et al. (2012) examined seasonal changes in a texture-contrast soil at a Tasmanian agricultural site with native pasture vegetation, sampling soil at 9 dates over a 1 year period and quantifying water repellence using the WDPT and WEP tests. Strong seasonal variation was reported, with significant correlations with cumulative rainfall up to 90 days before
sampling. At the same site, Hardie et al., (2013) examined temporal variation in soil moisture over a 2 year period using an installed capacitance probe capable of measuring moisture at 7 depths. Although seasonal factors were not explicitly discussed, antecedent moisture content was reported as the best predictor of probe responses to rain, and a time series of rain events from June-July 2008 showed clear evidence of progressive water repellent breakdown as moisture increased (Hardie et al., 2013). This work appears to represent the only examination of moisture distributions in a water repellent soil using installed sensors conducted in Australia to this date.

Despite the ubiquity of water repellency in the Australian landscape, it appears to have been considered in relatively few hydrological modelling efforts. A review by Hardie (2011) identified only three papers which applied preferential flow models to Australian soils, none of which appear to have been specifically concerned with hydrophobic effects. Modelling by Hardie (2011) in the same publication demonstrated that conventional one-dimensional models such as Hydrus1D and MACRO were unable to reproduce observed wetting characteristics during periods of high water repellency. Data from Australian sites has at least once been used in testing models developed elsewhere, as Kramers et al. (2005) used field data from an Australian site to demonstrate the effectiveness of a module for preferential flow developed for the SWAP model developed in the Netherlands (Ritsema et al., 2005), but this appears to be the only example of this type.

A more significant modelling effort was that made by Yang et al. (1996), who used the fact that regular patterns of infiltration are generated in furrow-sown water repellent soil to develop a two-dimensional finite element model for heat and water movement. This model was used to optimise furrow design for improved crop production in the northern wheat belt region of Western Australia. A significant conclusion was that water repellence provided a real advantage, as water repellent ridges generated a water-harvesting effect, channelling moisture into the furrows and thereafter providing a dry mulch-like barrier to evaporation. Though Yang et al. (1996) were able to use this model to good practical effect, the method is not readily transferrable to a non-agricultural environment lacking artificially generated furrows of regular interval.
Though the potential for water repellence to minimise evaporation and thus conserve moisture for the use of deep-rooted plants has been recognised in a variety of Australian sources, including soil management guides which deal with the subject of water repellence (Blackwell, 1993; Moore and Blackwell, 2001; Müller and Deurer, 2011; Roper et al., 2015) and even some general soil textbooks (Young and Young, 2002), it has attracted little dedicated research. Where attention has been paid to the effects of water repellence on groundwater, concerns have focused on enhancement of runoff (Horwitz and Sommer, 2005) and the risk of groundwater contamination (Blackwell, 2000; Hardie et al., 2013; Kramers et al., 2005; Salama et al., 2005; Thwaites et al., 2006).

Similarly, though it has been noted that groundwater recharge rates are often higher under native vegetation than under pine plantations, this has been attributed primarily to pines using more water (Le Maitre et al., 1999; Salama et al., 2005; Scott and Lesch, 1997). Less often considered is the possibility that deeper drainage favoured by the especially strong water repellence under native Australian species may also contribute to increased recharge rates (Scott and Lesch, 1997). Given our arid environment and the wide association of water repellency with endemic deep-rooted species, soil water repellency may very well represent an adaptive method by which native vegetation has engineered its environment to conserve moisture during periods of high moisture stress (Lozano et al., 2013; Robinson et al., 2010; Verboom and Pate, 2006). Such possibilities highlight the need to better understand the role water repellence plays in the native Australian environment, and particularly its significance when managing water resources.

2.8. Summary and conclusions

There is a significant existing body of research into the seasonality and hydrological impacts of soil water repellency, but many studies remain largely descriptive, and may be highly location-specific in their findings. The questions of how water repellency develops under different vegetation and climates, how it evolves in response to weather and other environmental factors, or how it in turn impacts hydrological variables such as evaporation or groundwater recharge, have yet to be sufficiently resolved to allow experimental results
to be extrapolated to different circumstances. Impacts such as that on runoff generation appear to vary significantly by scale, as well as temporally and by location. Models capable of providing useful predictive power, comparable to those available for wettable soils, remain the subject of ongoing development, and the question of how water repellency may best be quantified in order to inform modelling efforts remains unclear. Promising developments are offered by various non-equilibrium modelling techniques, but development and validation of such models is ongoing.

Options for the amelioration of water repellency, with the aim of increasing agricultural productivity and minimising irrigation costs, remain one of the better explored areas where scientists have been able to provide clear advice to farmers (eg. Yang et al., 1996; Müller and Deurer, 2011; Roper et al., 2015). As agriculture offers both a comparatively structured and controlled context for research (relative to natural environments) and clear incentive and funding for research, this is not surprising. Such efforts could, however, certainly benefit from fully-developed models characterising the functionality of water repellency. Further research may also help to resolve concerns that unintended or negative consequences may sometimes result from the removal of water repellency (Hallett, 2008; Müller and Deurer, 2011).

It has been widely suggested that some degree of soil water repellence, including subcritical repellence, may be more the norm than the exception (Doerr and Ritsema, 2005; Ritsema et al., 1998a; Wallis and Horne, 1992), and that failures to account for such effects may explain the failure of existing soil water transport models to reproduce observed behaviour in many environments (Bachmann et al., 2003; Ritsema et al., 1998a; Tillman et al., 1989). Nonetheless, even relatively simplistic models of water repellent effects on moisture dynamics have already been occasionally used to inform engineering solutions for water harvesting, soil moisture conservation, or prevention of groundwater contamination (eg. Yang et al., 1996; Kramers et al., 2005), and there may be considerable scope for similar applications which have not yet been explored (Shokri et al., 2009, 2008; Shokri and Or, 2013). Given the manner in which water repellence both responds to variations in weather, and alters the partitioning of moisture, there is real reason to expect it will play some role in
determining how climate change impacts many environments, with varying authors predicting a climate-based increase in water repellency will result in either negative (Goebel et al., 2011) or positive (Kettridge et al., 2014; Orfánus et al., 2014; Robinson et al., 2010) outcomes for subsequent moisture availability. In particularly, the potential significance of water repellency in moisture conservation remains poorly quantified, and has been oft-overlooked in many discussions of the subject.

A number key questions remain to be resolved regarding the functionality of soil water repellency in the field before it will be possible to answer broader questions about its significance in natural environments with any precision. The lack of data regarding the effect of water repellency on soil evaporation in the field remains one of the more obvious gaps in current knowledge. The scarcity of studies covering multiple years of seasonal variation in the field also limits our understanding of the scale of variability, and its sensitivity to varying ambient and seasonal weather conditions. The degree to which evaporative benefits persist as water repellency breaks down through the season is similarly uncertain.

Additionally, although a number of studies have now been published which examine seasonal variation by use of installed moisture sensor arrays, these have been conducted primarily in temperate or oceanic climes (see section 2.4 for a summary of this work). Studies of this type are immensely valuable in quantifying seasonal changes, as they can record both at high temporal resolution and over extended time periods. Little comparable work has been conducted at sites of Mediterranean climate, though water repellency is known to be common in these environments, and the strong seasonal contrasts characteristic of these climates make them excellent candidates for investigations of seasonal variation. As these climates also experience substantial precipitation deficits during the summer season, water budgets may be expected to substantially benefit from evaporative reductions produced by water repellent soil layers. The application of studies of this type to the south west Western Australian environment thus presents ample opportunities to advance the state of knowledge of the field.
3. Seasonal and interannual variability of the effective flow cross-sectional area in a water repellent soil

Abstract

By limiting infiltration and facilitating preferential flow, water repellency in surface soils produces wetting patterns which differ substantially from those in comparable wettable soils. Seasonal variation in water repellency usually follows a pattern of breakdown during periods of persistent rainfall and re-establishment over dry periods, complicating the prediction of moisture partitioning processes at affected sites. To examine the influence of annual water repellency variation on soil moisture, twenty SISOMOP moisture sensors were installed horizontally at depths of 5 and 15 cm at a highly water repellent Banksia woodland reserve in Western Australia, recording soil moisture contents over a 42 month period from 2010-2013. Stages of water repellent breakdown were quantified in terms of the Effective Cross-Section metric (ECS), which indicates the relative area share of flow pathways responsible for 90% of total flow across a horizontal plane at a specified depth. ECS data showed a steady spread of flow pathways throughout wet winter months of all years on record, consistent with a gradual breakdown of water repellency, and usually reaching a maximum state between July and September. The reestablishment of sufficient water repellency to recreate persistent flow paths of low ECS was found to require a prolonged period of some months of hot, dry weather. Summer rainfall was found to be a significant factor in determining the degree of reestablishment during the warmer months, with a year preceded by an unusually wet summer leading to more rapid breakdown of non-wetting behaviour over the following winter.

3.1. Introduction

Soil water repellency is now recognised to be a worldwide phenomenon that affects the partitioning and transport of soil moisture across a variety of soils and climates under both natural and agricultural vegetation (DeBano, 2000b; Doerr et al., 2007). Under water
repellent conditions, soils resist penetration by water after rainfall or irrigation, reducing both immediate infiltration rates and long term soil water availability in affected layers. Soils attain water repellency when particles become coated by hydrophobic substances derived primarily from decaying plant matter lying on or below the surface (Bond, 1964; Doerr et al., 2000; McGhie, 1980b; Roberts and Carbon, 1972) which may in some cases be exacerbated by fire (Cammeraat and Imeson, 1999; Prosser and Williams, 1998). Worldwide, water repellency has been reported to result in increased runoff and erosion (Leighton-Boyce et al., 2007; Prosser and Williams, 1998), acceleration of pesticide and nutrient transport to groundwater (Blackwell, 2000; Nguyen et al., 1999; Ritsema and Dekker, 2000), reduced efficiency of agricultural irrigation (Blackwell, 2000; Ritsema et al., 2005; Yang et al., 1996) and reduced germination rates for new plants (Osborn et al., 1967; Robinson et al., 2010). In natural terrestrial ecosystems, it has also been suggested that repellency may represent a way in which plants suppress competition and sequester moisture against evaporative loss (Cammeraat and Imeson, 1999; Imeson et al., 1992; Kobayashi and Shimizu, 2007; Robinson et al., 2010).

Under water repellent conditions, infiltration is not uniform but is limited to locations where textural irregularities allow water to pond or where repellency is less severe, resulting in fingered flow (Doerr et al., 2000; Ritsema and Dekker, 1996a). Affected soils typically exhibit maximum repellency and minimum infiltration when dry, with water repellency decreasing as moisture content increases up to a 'critical soil moisture content' at which the soil becomes wetting (Dekker and Ritsema, 1994; Imeson et al., 1992; Täumer et al., 2005). Ponded infiltration rates at water repellent sites are thus often seen to increase as moisture accumulates, rather than the reverse. Water falling on dry water repellent soil will tend to be preferentially routed to existing flow pathways formed during previous wettings, which remain relatively stable and spread only incrementally over subsequent events (Ritsema and Dekker, 1996a, 1995; Täumer et al., 2006). The spread of flow pathways over many rain events leads to a gradual breakdown in water repellency as successively greater areas transition to wetting behaviour. In this manner, many water repellent sites have been observed to exhibit strong seasonal trends, with repellency breaking down over winter, to
be re-established during summer when the soil dries out (Crockford et al., 1991; Doerr and Thomas, 2000; Keizer et al., 2008; Leighton-Boyce et al., 2005; Täumer et al., 2006).

As a consequence of these seasonal trends, flow dynamics at a water repellent site may vary continuously through the year. While there is now a wealth of research establishing seasonal trends, results may be highly climate and vegetation-specific, and interpretations may vary depending on measurement techniques employed. Past studies have primarily quantified seasonal changes either in terms of runoff ratios at plot or catchment scale (Burch et al., 1989; Ferreira et al., 2000; Sheridan et al., 2007), or by point sampling methods which measure water repellency using the Water Drop Penetration Test (WDPT) (Ferreira et al., 2000; Hardie et al., 2012) or Molarity of an Ethanol Drop test (MED) (Burch et al., 1989; Crockford et al., 1991; Keizer et al., 2008; Leighton-Boyce et al., 2005; Sheridan et al., 2007; Summers, 1987). While sampling methods are capable of generating fine-grained data on the distributions of both water repellency and soil moisture, these methods are necessarily labour intensive, and thus limited to either short term studies or infrequent sampling over longer periods. Water repellency classifications based on direct measurements such as the WDPT or MED may correlate poorly with other parameters such as infiltrative resistance under ponded conditions (Doerr and Thomas, 2000), and cannot provide direct insight into other key aspects of hydrological behaviour, such as flow path area or average moisture flux.

The study of moisture dynamics through the use of installed moisture sensors with automatic loggers presents the opportunity to generate long term, high-frequency soil moisture data in a non-destructive manner, requiring only minimal regular maintenance. This technique has the particular advantage of capturing soil water flow behaviour during and immediately following rain events, which are the periods of greatest significance (Leighton-Boyce et al., 2005; Ritsema et al., 1997) and which have been identified as essential to accurately describing the mechanisms of seasonal change (Keizer et al., 2008; Leighton-Boyce et al., 2005). Installed sensor arrays have previously been used in a few studies to establish flow patterns in water repellent soils and their recurrence across multiple events (Kobayashi and Shimizu, 2007; Oostindie et al., 2011; Ritsema et al., 1998a;
Wessolek et al., 2008). In particular, Täumer et al., (2006) examined seasonal trends in water repellency using 64 probes installed in a transect at a grassland site north of Berlin from April 2002 to April 2004. To describe seasonal variation in observed wetting patterns, Täumer et al., (2006) introduced the concept of Effective Cross Section (ECS) as the percentage of total soil surface area responsible for 90% of total flow, a metric easily understood as a representation of preferential flow pathway size. By calculating ECS at various points through the study duration, the relative strength of repellent effects was tracked through the cycle of breakdown and reestablishment.

In this paper, we use the ECS to quantify flow pathway sizes from in soil moisture data recorded by 20 moisture sensors installed at a water repellent native Banksia woodland site, over a three year period, on a per-rain event basis. The resulting data was examined for evidence of seasonal trends consistent with broad patterns of water repellent breakdown and reestablishment, as established elsewhere in the literature. Of particular interest was under what conditions (if any) soil behaviour would approach a perfectly wetting state (ECS=0.9), whether comparable trends would be reproduced in different calendar years, or to what degree differing rainfall regimes of different might contribute to varying rates of flow pathway development and spread. Where such trends did differ, we consider some possible mechanisms affecting the degree of water repellency reestablishment observed in different calendar years.

3.2. Materials and Methods

3.2.1. Site and soils

The experimental field site was located in a bushland reserve of approximately 32 hectares situated 2.5 km west from the Perth CBD, Western Australia (-31.950396, 115.796294). The reserve is located on the Spearwood dune system, comprising yellow phase Karrakatta sands (McArthur and Bettenay, 1960) classified as Dystric Xeropsamments under the U.S. system of soil taxonomy (Soil Survey Staff, 2014), with the soil characterised by a nutrient-poor yellowish sandy B horizon beginning at 15-20 cm depth under a dark brown sandy
topsoil. Karrakatta sands have low organic matter content, typically around 1% organic carbon in the surface layer, decreasing with depth as the soil transitions to the lighter coloured B horizon (McArthur et al., 1991; Salama et al., 2001). Soils in this class are coarse and poorly structured with typically low (<2%) clay content (Bolland, 2006; Moore and Blackwell, 2001; Salama et al., 2001), and thus non-swelling and poorly suited to macropore formation. Typical soil temperatures vary from a minimum of 5°C in winter to a maximum of around 50°C on some summer days (Foster, 2012). Vegetation is low woodland dominated by a mixture of small *Eucalyptus marginata* [Jarrah] and *E. gomphocephala* [Tuart] over *Banksia attenuata*, *B. menziesii* and *Allocasurina fraseriana* [Sheoak] (Wells et al., 1986).

3.2.2. Site Rainfall

Monthly and historical precipitation data was sourced from the Floreat Park Weather Station operated by the Australian Bureau of Meteorology 1962-1998 (Australian Bureau of Meteorology, 2012), and the Department of Agriculture and Food from 1999-present (Foster, 2012). The station is located approximately 500m west of the experimental site.

In analysing rainfall patterns for this location, we use ‘water years’, defined here as a twelve month period running from March to February. A water year thus starts at the beginning of autumn and ends in summer, inclusive of one complete cycle of wetting and drying.

3.2.3. Site Water Repellency

Water repellency at the field site was determined from 30 disturbed soil samples, taken in the late summer to autumn of 2011 between February and April before major winter rainfall began. Soil at this time had experienced some months of summer drying under conditions suitable for water repellent reestablishment, and was thus expected to represent the site at close to maximum water repellency. Samples were extracted using a ring corer of approximately 66 cm³ at depths from 0 to 40 cm below the surface in 5 cm increments. Repellency was determined under laboratory conditions using the MED (Molarity of an Ethanol Drop) test with pre-diluted ethanol concentrations of up to 5.2M (Osborn et al., 1967).
3.2.4. Sensor installation

Soil moisture and temperature were recorded using 20 SISMOP sensors (SImple SOil MOisture Probe), developed as a low-cost capacitance soil moisture sensor by Professor Christof Hübner of the Institute for Industrial Data Processing and Communication at the University of Applied Sciences Mannheim (Hübner et al., 2010). SISOMOP sensors use an architecture based on a ring oscillator, which indicates soil moisture changes by reporting the impulse delay experienced by an oscillating signal in a closed loop transmission line running along a narrow (0.2 cm width) 3 cm height by 10 cm length probe. As soil moisture surrounding the probe increases, the frequency of the ring oscillator experiences a corresponding decrease, allowing moisture content to be estimated.

Sensor calibration work was performed with soil samples from both the A and B horizons under laboratory conditions, using four SISOMOP sensors in cylinders of 9 cm diameter and 15-cm depth. Average moisture contents within the soil cylinders were determined by gravimetric methods during incremental wetting and evaporative drying phases.

Moisture data was recorded by five recording nodes, each providing connections for four SISOMOP sensors and comprised of a microcontroller board and sensor interface with a 1 GB SD card for data storage. Sensors were inserted horizontally into the wall of a 1.5 m long trench at depths of 5 and 15 cm and at horizontal intervals of 15-20 cm. The trench was backfilled after installation. Data was recorded on an interval of five minutes. Recorded data was retrieved manually on a weekly basis, with a recording interval of 5 minutes on all devices for the trial duration, except for some short periods of battery outage or other equipment faults.

3.2.5. Effective Cross-Section Calculations

In water repellent soils, moisture will typically enter the soil via preferential flow pathways of limited diameter, rather than as a uniform wetting front. The Effective Cross-Section index developed by Täumer et al. (2006) can be used to quantify the ‘degree’ of preferential flow apparent in a soil profile in terms of the area occupied by flow pathways passing...
through a layer of uniform depth. Specifically, the ECS is defined as the minimum fractional area responsible for 90% of the total flow. In an area experiencing perfectly uniform homogeneous flow the ECS will thus be equal to 90%. However, in an area where flow is limited to one or two preferential flow pathways with the remainder of the soil remaining dry, ECS may decline to 20% or less.

With data recorded by installed soil moisture sensors, the ECS may be calculated as follows. Total flow and flow share area are estimated by calculating the increase in soil moisture \(\theta\) occurring in response to a distinct rainfall event (i.e., preceded by a defined minimum dry period) between the beginning of the event \(t_0\) and the time of maximum water content across the profile \(t_{\text{max}}\). Provided sensors are spaced so as to represent equal area shares of the complete cross-sectional area, the fractional contribution \(f_{x,z}\) to total flow for each sensor \(x\) during rain event \(z\) may be calculated as given by Equation 3.1.

\[
f_{x,z} = \frac{\theta_{x,z}(t_{\text{max}}) - \theta_{x,z}(t_0)}{\sum_{x=1}^{n} \left[ \theta_{x,z}(t_{\text{max}}) - \theta_{x,z}(t_0) \right]} \quad \text{with} \quad \sum_{x=1}^{n} f_{x,z} = 1
\]

(3.1)

The resulting values \(f_{x,z}\) are sorted in descending order. For a soil layer fitted with \(n\) sensors, each sensor represents an area share of \(1/n\). Cumulative water content changes by fractional area can now be calculated as in Equation 3.2.

\[
C_m = \sum_{x=1}^{x=m} f_{x,z} \quad \text{with} \quad \sum_{x=1}^{n} f_{x,z} = 1
\]

(3.2)

where \(C_m\) is cumulative water content for each increment \(m\), where \(1 < m < n\).

The Effective Cross-Section is the point at which \(C_m = 0.9\). To determine this intersection, Täumer et al. (2006) fitted cumulative water content data to the beta function (Equation 3.3).

\[
p(x; \alpha, \beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}
\]

\[
(\alpha > 0, \beta > 0, 0 \leq x \leq 1)
\]

(3.3)
where $\Gamma$ is the Gamma function and $\alpha$ and $\beta$ are free parameters.

Figure 3.1 illustrates this process for an event recorded at the Perth site in May, 2010, showing both ranked $f_{x,z}$ values for each sensor, and cumulative water content by area share, as well as the fitted beta function. For comparison, cumulative water content for a perfectly uniform wetting front, having ECS=0.9, is also plotted in the red.

**Figure 3.1.** Ranked and cumulative water content changes by sensor for an event recorded 26-5-2010, having an ECS of 0.6. Cumulative water content changes for a perfectly wetting ECS=0.9 scenario are shown for comparison.

For our own data, $n=10$, and the beta function was fitted using a recursive method to reduce SSE to below a minimum threshold. A distinct rain event was defined as that preceded by a dry period of at least 12 hours, having at least 3 mm total rainfall. Events with
an average increase in moisture across all sensors of under 1% were also excluded. A total of 112 events meeting the selection criteria were identified during the four year period of data collection. In 5 of these events, the 1% margin was exceeded in only one of the two soil layers; where this occurred, ECS was calculated for only that layer, and the event was excluded from cross-correlation analysis. Due to occasional battery failures in one or more node, ECS values were calculated from less than 10 sensors on some dates. Events during which less than three nodes were working were excluded from ECS calculations.

3.3. Results and Discussion

3.3.1. Rainfall

Average rainfall data as recorded by the Floreat weather station since 1962 and data for each of the three years of the study are shown in Figure 3.2. Total rainfall for each year and percentile rank relative to all data available from the Floreat gauge is shown in Table 3.1. Average rainfall for the same period is 729.5 mm.

<table>
<thead>
<tr>
<th>Rainfall year</th>
<th>Annual rain (Floreat station)</th>
<th>Percentile (1962-present)</th>
<th>Water year</th>
<th>Water year percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2011</td>
<td>554.6</td>
<td>8.1%</td>
<td>572.6</td>
<td>12.5%</td>
</tr>
<tr>
<td>2011-2012</td>
<td>810.2</td>
<td>69.3%</td>
<td>819</td>
<td>75.0%</td>
</tr>
<tr>
<td>2012-2013</td>
<td>675.8</td>
<td>38.7%</td>
<td>656.6</td>
<td>29.1%</td>
</tr>
<tr>
<td>2013-2014</td>
<td>779.2</td>
<td>59.9%</td>
<td>771.4</td>
<td>61.4%</td>
</tr>
</tbody>
</table>

3.3.2. Site Water Repellency

Water repellency decreased with depth (Figure 3.3) at an average rate of around 0.1M/cm ($R^2=82.3\%$), corresponding to visible changes in soil colour associated with decreasing organic matter content. An average water repellency of 3.25M was recorded in the dark brown surface layer, with soil transitioning to completely wetting (MED equal to 0M) at a depth of about 20-25 cm, with no repellent samples retrieved from 30 cm or deeper.
Figure 3.2. Monthly rainfall at Floreat weather station 2010-2013, with mean historical rainfall for Floreat since 1962

Figure 3.3. Repellency decrease with depth, as measured by 30 disturbed samples taken from locations adjacent to the sensor installation site
3.3.3. Soil Moisture

Moisture sensors commenced recording on the 16th April 2010. From February to April that year there were two unseasonably large rainfall events with a combined total of 100 mm, resulting in moisture contents in the range of 2-12% VMC at the time recording commenced. Average moisture data per layer, with regions indicating the complete range from minimum to maximum moisture content recorded for that layer, are shown for each of the four trial years in Figure 3.4.

For all study years the data show a steady increase in average soil moisture content as the winter season (May –Sept) progresses. Variability in simultaneous moisture readings reported by different sensors was considerable, with results suggesting the majority of sensors likely intersected flow pathways over only some fraction of their sensitive length. The range and standard deviation in moisture contents by layer usually peaked after the first significant rains and generally decreased thereafter (Figure 3.4), consistent with a steady seasonal breakdown of preferential flow pathways established in the early season. Regular winter rainfall patterns had ceased by late September of all years, resulting in comparatively rapid periods of drainage and drying.

Although both instrumented soil layers showed generally similar trends, the lower 15-cm layer recorded slightly but consistently higher moisture during summer and early winter rainfall events, likely due to the lateral spread of flow pathways at the sensor length-scale in the less repellent soil found at depth. This observation would be consistent with the existence of a ‘redistribution zone’ existing in hydrophilic soil beneath the primary fingering zone (Deurer and Bachmann, 2007; Doerr et al., 2000). By late winter of all years, the difference in average moisture between the layers had disappeared (2010) or reversed (2011, 2012 and 2013) to produce consistently higher moisture in the upper soil layer.

Wetting patterns recorded over the last quarter of the year, comprising spring to early summer, demonstrated more significant interannual variability. Unusually high rainfall was experienced in 2011 in the October-December period, totalling 162 mm or 20% of the annual total, returning moisture contents to near winter maximum levels in October, and
Figure 3.4. Average moisture by layer for 2010-2013 monitoring period. Shaded regions indicate the full range of moisture contents recorded on that date, bounded by minimum and maximum moisture contents for that layer.
again in December. Regular rainfall events continued through spring of 2013, maintaining average moisture contents at winter levels until as late as November. By contrast, 2012 recorded only 99 mm or 15% of total rainfall through the final quarter, with average moisture never exceeding 10%, and 2010 recorded only 45 mm or 8% of total rainfall in the same period, with little soil response.

3.3.4. Effective Cross-Section

In our calculation of the Effective Cross-Section, we have modified the methodology of Täumer et al. (2006) slightly by broadening our definitions of a rain event, requiring only 12 hours between events rather than 36, and by calculating ECS for two soil layers at 5cm and 15cm. By limiting our consideration to rain events preceded by some hours or days of dry weather, we exclude from the data set events where initial conditions would represent a soil still undergoing significant drainage after prior rain. Reducing the minimum gap between events has the effect of increasing the total number of rain events which may be considered. Experimentation with different minimum gaps ranging from 5 to 36 hours with our own data showed that broad patterns in ECS data remain regardless of gap chosen. However, the scatter around the broader trends increases for gaps of 10 hours or less.

To analyse the effect of equipment failures whereby one or more nodes ceased recording, ECS data was recalculated with one or two nodes excluded. Results were found to be generally similar in overall trends, though some additional scatter was again introduced. A minimum of six working sensors was considered reasonable for ECS values to be included in the data set described below; periods with less than three working nodes have been excluded from consideration.

Over the full four year period, 112 distinct rain events were identified as meeting the criteria for ECS calculation. For each year, flow pathway share was thus able to be assessed on a minimum of 17 different dates, the majority of these falling within the autumn-winter period of water repellent breakdown. Five events produced responses sufficient for ECS calculation in only one layer, four of which occurred in 2012 (ECS calculable only at 5-cm depth) and one in early 2010 (ECS calculable only at 15-cm depth). Effective Cross-Section
values calculated during significant rainfall events are shown for each of the four years on record in Figure 3.5. Results for the two layers were generally similar and significantly correlated ($R^2=47.1\%$), though ECS values for the 15-cm layer in 2012 were consistently lower than the 5-cm layer through most of the year. In 2013, a greater frequency of recording failures began to occur, primarily due to the age of equipment, such that four or fewer nodes were functioning during the majority of events. Greater scatter was consequently evident in ECS values for 2013, with less consistent correlation between the 5- and 15-cm layers than was observed during 2010 or 2011, however, broad seasonal trends remained comparable with other years.

![Figure 3.5. ECS data for 5 cm and 15-cm depths plotted for the water years of 2010 (5A); 2011 (5B), 2012 (5C) and 2013 (5D). Grey regions indicate dates outside of the recording period.](image-url)

Strong seasonal trends are clearly evident in these results, with minimum ECS values typically seen in early autumn or during isolated spring/summer rain events, and maximum
ECS values occurring late in the winter season from late July to September. While regular autumn and winter rainfall occurred, primarily through the period from May to August, a steady increase in ECS data up to an annual maximum of around 0.8 is evident for all years. These results are consistent with a gradual though not unbounded spread of flow pathways in response to regular winter rain. Although rainfall continued after ECS values close to the 0.8 mark were first recorded in 2011, 2012 and 2013, ongoing rainfall appears to have had little ability to increase results much closer to the theoretical maximum of 0.9.

A single exception to the usual winter trend occurred in 2013, when ECS values decreased substantially over three successive events in late May before resuming the established increasing trend. This result can be traced to the four sensors located at the northern-most extent of the trench, which showed flow pathways established in early May actually retreated and subsequently disappeared over several smaller rainfall events, remaining so throughout June before being re-established by heavier rain on July 9th. No comparable incident was reported on any other node during the winter periods, though large gaps in rainfall of a week or more would occasionally be associated with some short term recovery (for example, as occurred between events on the 8/5 and 31/5/2012), the effect not ordinarily persisting over subsequent events. There is some evidence of limited periods of early reestablishment of water repellent effects associated with gaps in rainfall of a week or more in early spring; for example, two significant outliers representing ECS values 0.2 lower than surrounding events were calculated for the 1st of and 16th of September 2011 respectively following 7 and 12 days without rain. Heavier and more regular rain occurring from the 17th to the end of September returned ECS values to the seasonal maximum of 0.8. Note that gaps of similar length occurring in other years (for example, between 21/8 to 31/8/2010) were not necessarily associated with similar recovery.

Trends in ECS values calculated during isolated spring and summer events are less consistent, in part due to the sporadic nature of summer rainfall. While a general increasing trend may be apparent over subsequent events, flow pathway share during recovery appears to be highly unstable, and trends similar to winter breakdown patterns may emerge where successive events occur close together. The unseasonably high rainfall received in
October of 2011, for example, is associated with an increase in ECS values suggesting evidence of relatively rapid pathway spread, particularly over two very large events occurring between 24-27 October totalling 52 mm. Large ECS values were also associated with another two large rain events occurring later that summer, between 6-12 December, totalling 58 mm. Recovery trends differed also for 2013 due to an even more prolonged winter rainfall period. Whereas regular winter rainfall ceased during September of all other years, regular events continued through September and October of 2013. Consequently, ECS data shows no significant reduction in pathway share before November of 2013, and no evidence of significant water repellency reestablishment during this time.

Täumer et al. (2006) reported good correlation between ECS values from a two year study with a multivariate regression against four variables representing average initial moisture content across all sensors at a uniform depth, average event intensity (mm/h), rainfall amount (mm) and potential evaporation for a 24 day period. Data recorded at the Perth site was found to be strongly correlated (p<0.001) with initial moisture content, but only weakly correlated with total rainfall (p<0.1), and poorly correlated with average event intensity or 24 day evaporation (p>0.2). However, the fit was improved significantly by multivariate regression against potential evaporation history measured over longer periods up to 90 days, and also to antecedent rainfall over a 60-day history prior to the event (p<0.01 for all variables, $R^2=69.1\%$, see Equation 3.4), though both these variables were also highly correlated with the initial moisture variable.

$$ECS = 2.47 \cdot 10^{-4} E_{90} + 6.86 \cdot 10^{-4} C_{60} + 3.33 \theta_5 + 2.01 \cdot 10^{-3} R + 1.75 \cdot 10^{-1}$$  \hspace{1cm} (3.4)$$

where $E_{90}$ = potential evaporation over a 90 day period prior to event (mm), $C_{60}$ = 60 day antecedent rainfall (mm), $\theta_5$ = average initial moisture content at 5 cm, $R$ = rainfall amount.

Correlation with all variables was significantly reduced for ECS data recorded at 15-cm depth, but 15-cm ECS data remained strongly correlated with initial moisture at 15 cm (p<0.001, $R^2=46.7\%$) and ECS data at 5-cm depth (p<0.001, $R^2=47.1\%$), consistent with a gradual modification of rainfall input with depth through the soil profile.
3.3.5. *Interannual variability*

Notable in the annual ECS data plots is that ECS values increase in a relatively linear fashion for the majority of the autumn-winter period, during which period rainfall events suitable for ECS calculations were typically recorded at intervals of less than two weeks. Comparable linear trends are absent from spring and summer periods, likely due to the irregular and highly unpredictable rainfall patterns recorded during these months. As rainfall is considered the primary forcing factor in flow pathway spread and water repellent breakdown, the relationship between ECS data and increasing cumulative rainfall during the main period of breakdown is of interest. To examine whether the apparently linear trends evident in Figure 3.5 were consistent across differing rainfall years, independent of differences in annual rainfall regime, ECS data from the autumn-winter period was plotted against cumulative rainfall as measured from the start of that water year. Regression and correlation coefficients for cumulative rainfall for 5cm ECS data are shown in Table 3.2.

<table>
<thead>
<tr>
<th>Year</th>
<th>ECS</th>
<th>X</th>
<th>Slope</th>
<th>Constant</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>5 cm</td>
<td>Cumulative rainfall</td>
<td>7.16E-04</td>
<td>0.43</td>
<td>77.2%</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>90 day rainfall</td>
<td>1.34E-03</td>
<td>0.35</td>
<td>76.1%</td>
</tr>
<tr>
<td>2011</td>
<td>5 cm</td>
<td>Cumulative rainfall</td>
<td>1.22E-03</td>
<td>0.31</td>
<td>84.9%</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>90 day rainfall</td>
<td>1.32E-03</td>
<td>0.30</td>
<td>86.0%</td>
</tr>
<tr>
<td>2012</td>
<td>5 cm</td>
<td>Cumulative rainfall</td>
<td>5.45E-04</td>
<td>0.57</td>
<td>58.8%</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>90 day rainfall</td>
<td>9.40E-04</td>
<td>0.52</td>
<td>70.6%</td>
</tr>
<tr>
<td>2013</td>
<td>5 cm</td>
<td>Cumulative rainfall</td>
<td>6.70E-04</td>
<td>0.42</td>
<td>75.9%</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>90 day rainfall</td>
<td>1.12E-03</td>
<td>0.37</td>
<td>69.1%</td>
</tr>
</tbody>
</table>

The relationships between 5cm ECS and cumulative rainfall for all years of study are plotted in Figure 3.6A. For 2010 and 2013, the relationship between rainfall and increasing ECS is almost identical, although 2010 received less total rainfall and the plot is truncated at an earlier stage. By contrast, 2011 had a significantly steeper increase in ECS with increasing rainfall. This is likely related to the significantly greater winter rainfall received during that year compared to other years on record (Table 3.1), with average rainfall over the main
period of winter breakdown of 4.2 mm/day in 2011, as compared to 3.3 mm/day for 2013 and 2.9 mm/day for 2010 and 2012, and no significant breaks between rainfall events greater than 7 days during the winter period from June-August, as compared to gaps of 10 days or greater occurring for all other years. From this and evidence of moderate recovery over relatively brief gaps in rainfall of 10 days or more in early spring periods from August-September of 2010, 2011 and 2012, we conclude that the spacing of rain events retains some significance in the breakdown and recovery rates of water repellent properties, particularly when gaps occur in the warmer periods of autumn or early spring.

Past studies have also found relationships between indicators of water repellency and antecedent rainfall recorded over a prescribed number of days prior to the event (e.g. Summers, 1987; Doerr et al., 2003; Leighton-Boyce et al., 2005). An antecedent period of 90 days was found to produce best fit with autumn-winter ECS values (Figure 3.6B). Regression and correlation coefficients for ECS against both cumulative autumn-winter rainfall and 90 rainfall history are shown in Table 3.2. Antecedent rainfall figures typically approximate cumulative autumn-winter rainfall for the majority of the period, however, the 90 day margin allows some rainfall events received in summer to influence the fit for ECS values recorded early in autumn, while disregarding the effect of rainfall data recorded in autumn.

**Figure 3.6.** Breakdown phase (March-September) ECS at 5 cm versus cumulative rainfall from A: Start of water year and B: over 90 days prior to the rain event for which that ECS value was calculated.
or before in influencing late winter ECS values. Regression against 90-day antecedent rainfall was found to produce comparable correlation coefficients to those of cumulative rainfall (Table 3.2), with similar rates of increase found for 2010, 2011 and 2013, the sharper increase in ECS values seen when plotted against cumulative rainfall not evidenced by this method. By comparison, ECS values for 2012 remained a notable outlier with both cumulative and antecedent rainfall, which will be discussed below.

Data from the 15-cm layer for individual winter periods correlated less well with cumulative rainfall or 90-day antecedent rainfall totals (Table 3.3) than did ECS data for the upper layer. However, autumn-winter 15-cm ECS values continued to show consistent relation to 5-cm ECS values when data from individual years was considered separately (Figure 3.7, Table 3.3).

Regardless of the regression scheme employed, data for 2012 remained a significant outlier, with ECS values at 5 cm consistently higher than those recorded at an equivalent stage of cumulative rainfall from the other years (Figure 3.6A and B). Notably, while the best-fit relationship between 15-cm and 5-cm ECS data for 2012 appears similar to that of other years in Figure 3.7, the correlation coefficient was negligible and far weaker than those for other years (Table 3.3). The discrepancy between ECS values at 5 and 15 cm for 2012 was also associated with significantly higher absolute $f_{x,z}$ values across most locations in the 5-cm layer relative to the 15-cm layer for that year, including four events during which $f_{x,z}$ were too low at 15-cm depth for ECS values to be calculated. This would appear to suggest that larger pathways and greater moisture retention at 5-cm depth from early in the year may have prevented flow reaching the 15-cm depth after many small events in 2012, possibly limiting the development of preferential flow pathways at that depth. Assuming ECS to be a representative indicator of the relative strength of water repellency, this data suggests that soil was significantly less water repellent in early 2012 than for other years.
Figure 3.7. Breakdown phase (March-September) ECS at 15 cm versus ECS at 5 cm for all years

Table 3.3. Linear regression statistics for cumulative rainfall, 90 day antecedent rainfall and 5-cm ECS versus 15-cm ECS recorded during the breakdown phase (March-September) of all years of study

<table>
<thead>
<tr>
<th>Year</th>
<th>ECS</th>
<th>X</th>
<th>Slope</th>
<th>Constant</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>15cm</td>
<td>Cumulative rainfall</td>
<td>6.17E-04</td>
<td>0.48</td>
<td>48.7%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>90 day rainfall</td>
<td>1.23E-03</td>
<td>0.38</td>
<td>54.5%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>ECS 5 cm</td>
<td>8.44E-01</td>
<td>0.12</td>
<td>73.2%</td>
</tr>
<tr>
<td>2011</td>
<td>15cm</td>
<td>Cumulative rainfall</td>
<td>1.09E-03</td>
<td>0.31</td>
<td>80.2%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>90 day rainfall</td>
<td>1.24E-03</td>
<td>0.28</td>
<td>81.9%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>ECS 5 cm</td>
<td>8.78E-01</td>
<td>0.03</td>
<td>83.0%</td>
</tr>
<tr>
<td>2012</td>
<td>15cm</td>
<td>Cumulative rainfall</td>
<td>2.32E-04</td>
<td>0.58</td>
<td>9.8%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>90 day rainfall</td>
<td>4.07E-04</td>
<td>0.55</td>
<td>12.6%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>ECS 5 cm</td>
<td>6.47E-01</td>
<td>0.18</td>
<td>42.5%</td>
</tr>
<tr>
<td>2013</td>
<td>15cm</td>
<td>Cumulative rainfall</td>
<td>4.48E-04</td>
<td>0.52</td>
<td>41.3%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>90 day rainfall</td>
<td>6.88E-04</td>
<td>0.49</td>
<td>31.6%</td>
</tr>
<tr>
<td></td>
<td>15cm</td>
<td>ECS 5 cm</td>
<td>7.20E-01</td>
<td>0.20</td>
<td>63.0%</td>
</tr>
</tbody>
</table>

3.3.6. Impacts of summer rainfall

The discrepancy in rates of water repellency decline between 2012 and the remaining study years cannot be explained by differences in winter rainfall alone. We therefore examined the rainfall records in more detail to investigate if summer rainfall is a forcing factor.
Rainfall totals received during October-February for all years 2009-2013, corresponding to the main period of spring and summer drying, are presented in Table 3.4. In 2012, the wet season was preceded by an unusually wet summer, with a total of 161.6 mm of rain recorded between October and December, followed by an additional event of 26.6 mm in February. Placed in context with the full rainfall record from 1962 to the present, the 2012 Oct-Feb rainfall falls in the 95.8 percentile, representing double the average rainfall for this period. By contrast, summer rainfall preceding the winters of 2010 and 2011 placed only in the 4.1 and 22.9 percentiles respectively.

A result of the unusually wet summer of 2011-2012 was to significantly truncate the usual period of hot, dry weather suitable for the reestablishment of strong water repellency. Under such conditions, it is reasonable to assume that there was no opportunity for water repellency to re-establish to the same levels observed in 2011 and 2010, which may explain the unusually rapid breakdown of water repellent effects relative to the other years.

Above average, though not extreme, rainfall occurred during the same period before winter of 2013, placing in the 68.4 percentile. This may be related to moderately higher ECS values recorded early in that winter season relative to 2010 and 2011, though irregularities during May of that year obscure the effect on the overall trend. Summer rainfall for 2012-2013 remained only just over half that received in 2011-2012, the majority completed before January of 2013, leaving at least two months of relatively hot, dry weather for reestablishment of water repellency.

Table 3.4. October-February rainfall totals for 2009-2013, and percentile ranks relative to the complete 1962-2013 record

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-2010</td>
<td>13</td>
<td>24.8</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>38</td>
<td>4.1%</td>
</tr>
<tr>
<td>2010-2011</td>
<td>19.2</td>
<td>8.6</td>
<td>17.6</td>
<td>18.2</td>
<td>0</td>
<td>63.6</td>
<td>22.9%</td>
</tr>
<tr>
<td>2011-2012</td>
<td>65.2</td>
<td>30.2</td>
<td>66.2</td>
<td>0.4</td>
<td>26.6</td>
<td>188.6</td>
<td>95.8%</td>
</tr>
<tr>
<td>2012-2013</td>
<td>15.2</td>
<td>50.4</td>
<td>33.2</td>
<td>6</td>
<td>1.8</td>
<td>106.6</td>
<td>68.4%</td>
</tr>
<tr>
<td>Floreat avg.</td>
<td>32.0</td>
<td>23.2</td>
<td>13.6</td>
<td>17.7</td>
<td>9.0</td>
<td>95.5</td>
<td></td>
</tr>
</tbody>
</table>
3.3.7. Summary

In the course of this study, we have been relatively fortunate in capturing years which represent a wide range of rainfall regimes, both in total rainfall (ranging from the 8th to the 71st percentile, relative to the historical record) and summer rainfall (4th to the 95th percentile). Recorded soil moisture data thus reflects one year with well below average rainfall preceded by a very dry summer (2010), a year of above average rainfall preceded by an above average summer (2011), a year of slightly below average rainfall preceded by an exceptionally wet summer (2012), and a year of average though unusually prolonged rainfall preceded by an above average summer (2013). Contrast between the resulting data sets has allowed us to make some inferences about the forcing factors responsible for the observed trends in non-wetting behaviour.

The resulting data suggests that rates of water repellency breakdown and flow pathway spread follow a relatively regular annual pattern with a clear relationship to recent rainfall history, though some features may vary depending on the rainfall regime of a particular year. Maximum states of breakdown evident from pathway share may be reached either early or late in the season, depending on prevailing conditions; for example, ECS values had exceeded 0.75 in the 5-cm layer by early June in 2012 (after 190 mm cumulative rainfall) and by July in 2011 (342 mm), but not until August of 2010 (394 mm) and 2013 (430 mm). While the dependence of annual patterns on cumulative and seasonal total rainfall is obvious, data suggests that breakdown rates may also be influenced by the strength of water repellency re-established prior to the winter season, which may in turn be influenced by summer rainfall. Thus 2011, a wetter than average year preceded by a dry year and an unusually dry summer, had lower initial ECS after the first recorded autumn rains than did 2012 or 2013 (note that the first autumn rains of 2010 preceded the start of the study), but saw rapid spread of pathways through winter under regular, heavy rain. By contrast, 2012 was a below average rainfall year, preceded by an above average rainfall year and an extremely wet summer. Despite lower winter rainfall, pathway share throughout 2012 exceeded that for 2011 throughout the early autumn-winter season, both by date and cumulative rainfall. The possibility that ECS values, and thus active regions of soil cross
sectional area, may be predicted for a given site within a reasonable degree of accuracy based on knowledge of recent rainfall history is raised by the data presented.

3.4. Conclusions

In this paper, we present evidence of seasonal trends in water repellency-driven preferential flow pathways from a four-year study of a highly water repellent woodland site. Our results demonstrate the value of the Effective Cross Section or ECS (Täumer et al., 2006) as a useful metric in tracking seasonal trends in water repellency-related characteristics. ECS data shows a steady, gradual spread in pathway share throughout the main rainy season of autumn and winter, consistent with the gradual breakdown of water repellent characteristics over this period. This is followed by a more irregular decrease in pathway share over scattered events through summer, which otherwise provides the hot, dry weather associated with periods of water repellency reestablishment. Significant interannual variability was evident in annual patterns, largely attributed to variations in rainfall regime. In particular, our data highlight the potential for an unusually wet summer to significantly limit the degree of reestablishment of water repellency for that season, leading to unusually rapid breakdown during the following winter. ECS values calculated at the 5 and 15cm depths were found to be similar and well-correlated on most dates. However, ECS data calculated from probes installed at the 5-cm depth, representing the most highly water repellent soil, was found to be most well correlated to environmental forcing factors including cumulative and antecedent rainfall, and most useful in identifying overall trends in non-wetting behaviour.
4. The effect of water repellent soil surface layers on preferential flow and bare soil evaporation

Abstract

Wetting patterns produced by water repellent soils are able to preferentially channel moisture deep into the soil profile, minimising storage in surface layers where it is most susceptible to evaporative loss. Although this effect has been repeatedly described in the literature, the significance of such effects under field conditions remains unclear. In order to quantify the impact of water repellency, preferential flow and evaporation rates were monitored in a series of portable soil tanks packed with soil sourced from a water repellent field site. Tanks were placed outside to expose them to environmental forcing factors, and their weights after rainfall and subsequent periods of drying were recorded daily.

Increasing water repellency was associated with an increase in maximum pathway depths, and a decrease in cumulative evaporation rates, across the wettable, low and medium water repellency classes, though high repellency soil produced no additional improvement over medium repellency soil. Soils layered to generate decreasing water repellency over 10-30 cm depth in distributions similar to that seen in the field recorded evaporative losses 70-80% lower than that in wettable control soils over 4 days of drying in autumn. Shallower layers of 5-15 cm examined during winter had evaporation reduced by 40-80% over a 4 day period even in a period of much reduced potential evaporation. It is concluded that water repellent surface layers are able to effect significant reductions in net evaporative moisture loss, in patterns which may be particularly beneficial during periods of high moisture stress in summer or during low-rainfall years. Though water repellency substantially breaks down in the field during winter, our results suggest it may continue to aid moisture conservation well into the winter season.
4.1. Introduction

Soil water repellency occurs when soil particles become coated with hydrophobic chemicals produced by decaying leaf litter or fungal activity (Doerr et al., 2000; Franco et al., 2000; Roberts and Carbon, 1972). Thorough wetting of affected soils requires prolonged contact with moisture, and water repellent effects typically peak under dry summer conditions, gradually breaking down through the rainy season (Crockford et al., 1991; Doerr and Thomas, 2000; Keizer et al., 2008; Rye and Smettem, 2015; Täumer et al., 2006). The detrimental effects of water repellency are well documented in agricultural soils where partial wetting can lead to spatially variable crop growth and generally reduced yields overall (Burch et al., 1989; Ferreira et al., 2000; Leighton-Boyce et al., 2007; Prosser and Williams, 1998; Sheridan et al., 2007). However, the effects of water repellency in natural ecosystems are less well understood. It has been proposed that water repellent soil layers may allow deep-rooted plants to sequester moisture against evaporative loss (Goebel et al., 2011; Imeson et al., 1992; Lozano et al., 2013; Robinson et al., 2010; Verboom and Pate, 2006), but there is still relatively little published work which attempts to quantify this effect (Hallett, 2008; Kettridge et al., 2014; Stephens, 1994).

In water repellent soils infiltration is typically dominated by preferential flow, with active pathways representing only a small percentage of the soil cross-sectional area (Cammeraat and Imeson, 1999; Hardie et al., 2011; Petter Nyman et al., 2010; Wang et al., 1998). Intervening regions often remain dry, allowing infiltrating moisture to bypass large fractions of the soil volume. Strong water repellency is typically confined to shallow surface layers which contain the highest concentrations of organic matter, with repellency generally decreasing or disappearing with depth (Cammeraat and Imeson, 1999; Jaramillo et al., 2000; McGhie and Posner, 1981; Woche et al., 2005). The presence of hydrophilic soil at depth may serve as a ‘redistribution zone’ where flow pathways are able to spread laterally, drawing moisture rapidly down from domains above (Doerr et al., 2000; Ritsema et al., 1998b; Ritsema and Dekker, 1995). Although increased evaporation has occasionally been reported where water repellent layers served to trap moisture in thin, overlying layers of hydrophilic soil (DeBano, 1981), the highly heterogeneous nature of water repellent soils
means that most moisture will simply travel down slope until it encounters an infiltration site (Doerr et al., 2003; Sheridan et al., 2007). Net effects of water repellency are thus to channel moisture deep into the soil profile while minimising that stored in the uppermost soil layers that are most susceptible to loss during first stage evaporation.

Field studies have demonstrated that water repellency can also serve to channel and concentrate soil moisture around the base of plants in the field (Cammeraat and Imeson, 1999; Jaramillo et al., 2000; Robinson et al., 2010), with some authors inferring evaporative benefits from observed infiltration patterns (Imeson et al., 1992). It has also been suggested that water repellency and related preferential flow mechanisms facilitate groundwater recharge (Kramers et al., 2005; Scott and Lesch, 1997; Stephens, 1994) particularly in arid or semi-arid regions where potential evaporation far exceeds precipitation (Lozano et al., 2013; Stephens, 1994).

Non-wetting characteristics can also reduce evaporative loss both by altering the geometry of the liquid/gas interface in partially saturated regions (Bachmann et al., 2001; Birdi and Vu, 1993), and by reducing rates of replenishment to upper soil layers by capillary rise (Bachmann et al., 2001; DeBano, 1981; Letey et al., 1962a). Laboratory studies of evaporation rates from evenly wetted hydrophobic soils have thus reported consistently suppressed evaporative losses relative to both wettable soils (Bachmann et al., 2001; Letey et al., 1962a; Shahidzadeh-Bonn et al., 2007; Shokri et al., 2009) and modelled predictions of evaporation based on soil hydraulic properties alone (Bachmann et al., 2001). Similarly, evaporation may be reduced by even a shallow surface layer of water repellent material, with reductions increasing with the maximum depth of the hydrophobic layer (Ahn and Im, 2010; Shokri et al., 2008). There is some evidence to suggest that rates of vapour flow and diffusion may also be suppressed in very strongly water repellent soils (Bachmann et al., 2001; Davis et al., 2014).

Though effects on evaporation have been widely recognised in reviews of water repellency (eg, Doerr et al., 2000; Moore and Blackwell 2001; Young and Young, 2002; Goebel et al., 2011), studies into the phenomenon (eg, Cammeraat and Imeson, 1999; Imeson et al., 1992; Kettridge et al., 2014; Robinson et al., 2010; Verboom and Pate, 2006) have depended
largely on inference to support the conclusion that water repellent soil layers aid moisture conservation. Attempts to precisely quantify the magnitude of such effects remain confined to laboratory examination of evenly wetted soil samples (eg, Letey et al., 1962; Bachmann et al., 2001; Ahn and Im, 2010), which neglect the significant effects of preferential flow. In the field, the effect of a water repellent soil layer on evaporation will be further complicated by seasonal variation in both the weather and the water repellent soil layers themselves, which have been found to vary in strength in a regular annual cycle at many sites. Work remains to be done to clarify the impact on annual water budgets of water repellency in native ecosystems (Kettridge et al., 2014; Müller and Deurer, 2011), and to better quantify how activities which enhance or reduce water repellency may influence evaporation rates (Hallett, 2008; Müller and Deurer, 2011; Shokri et al., 2008).

In this study, we seek to quantify water repellent evaporative effects by examining flow pathway formation and subsequent relative evaporation rates in layered soil of various water repellencies, including wettable control soils. To generate data reflective of field conditions, soils have been sourced from a water repellent woodland site, and wetting and evaporation rates monitored under ambient weather conditions. Results provide insight into the magnitude of evaporative reduction produced by water repellent soil layers, and the degree to which this advantage is able to persist through the season.

### 4.2. Materials and Methods

#### 4.2.1. Soil Collection

Soils were obtained from a native bushland field site on the Spearwood dune system in Perth, Australia, approximately 2.5km west of the city centre. The soil is classified as yellow-phase Karrakatta sand (Salama et al., 2001), consisting of highly water repellent dark brown topsoil over a wettable yellow sandy B-horizon. Soils of the Spearwood system are characterised by coarse textures and low organic carbon content, with Karrakatta phases having silt and clay fractions comprising only 1-2% of the soil volume, and carbon contents less than 1.5% in the topsoil layers, falling to less than 0.5% in the B-horizon (Salama et al.,
Water repellency was quantified from samples using the Molarity of Ethanol Drop (MED) test (Osborn et al., 1967). Water repellency was found to decrease with depth (Figure 4.1), varying from an MED of around 4.0M at the surface, and transitioning to full wetting at depths between 20 to 30cm.

Soil was collected from the field site at a variety of depths during summer and sieved to remove leaf debris and particles larger than 2 mm. Soil was oven dried at 105°C, and allowed to cool. Well-mixed quantities of dried soil were tested for MED in 0.2 M increments and categorised into one of four water repellency classes. Oven drying was found to have little effect on MED values, excepting slight increases where soil was initially damp. Soil weights increased slightly when left to cool in the laboratory before being packed into soil tanks, suggesting that a small amount of moisture was absorbed from the air. Initial moisture contents after cooling varied somewhat between soil classes; average moisture contents by weight and water repellency class are provided in Table 4.1.

![Figure 4.1](image.png)

**Figure 4.1.** Soil repellency represented by MED plotted against depth, as measured using 30 disturbed samples.

Fine river sand sourced from the banks of the Swan River in Nedlands, Perth and thoroughly washed to remove any salt was also collected to provide a perfectly wettable reference material.
Table 4.1. Soil categories by water repellency and source, with estimates of initial moisture contents by weight after oven drying and cooling in laboratory conditions, prior to packing into soil tanks

<table>
<thead>
<tr>
<th>Class</th>
<th>Wettable (river sand)</th>
<th>Wettable (B-horizon)</th>
<th>LR (Low Repellency)</th>
<th>MR (Medium Repellency)</th>
<th>HR (High Repellency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MED (M)</td>
<td>0</td>
<td>0-0.4</td>
<td>0.4-1.2</td>
<td>1.2-2.8</td>
<td>2.8-4.0</td>
</tr>
<tr>
<td>Bulk density (g/cm$^3$)</td>
<td>1.54</td>
<td>1.42</td>
<td>1.40</td>
<td>1.31</td>
<td>1.01</td>
</tr>
<tr>
<td>Moist. by weight</td>
<td>0.19%</td>
<td>0.42%</td>
<td>0.48%</td>
<td>0.51%</td>
<td>1.67%</td>
</tr>
</tbody>
</table>

4.2.2. Experimental Design

Evaporation rates were measured in a set of ten portable clear perspex soil tanks of dimensions 0.40 m high, 0.40 m long and 50 mm in width, with walls 6 mm thick. Tank bases were impermeable, limiting moisture addition or loss to the upper soil surface only. Tanks were packed from above to bulk densities similar to that seen on site (Table 4.1), with soil of varying water repellency. Soil was wetted either by adding moisture to the soil surface under laboratory conditions or by natural rainfall events when placed outdoors. Tanks were weighed twice daily at 0900 and 1700 hours and weights recorded to the nearest 0.1 g. Evaporative losses in millimetres of moisture calculated from the net weight change divided by soil surface area. Flow pathway locations, evident from sharp changes in soil colouration when wetted, were outlined on the sides of the tank with a marker pen following infiltration events so that subsequent spread or drying would be readily apparent. Soil tanks were also photographed periodically from both sides to record flow pathway locations.

To expose soil to ambient weather conditions and produce internal temperature regimes comparable to field conditions, tanks were placed outside during daylight hours. Tanks were stored in two arrays of 5 tanks each, placed side to side with the base and outer sides of the array covered with a layer of 20 mm insulation foam to minimise heat transfer through the outer edges. Tank positions within the array were rotated daily in order to average the effects of insulation. Soil surfaces were left open and uncovered.

Three tanks were instrumented with ECT temperature sensors (Decagon Devices, Inc), installed at depths of approximately 5, 15 and 30 cm from the soil surface. Temperature
readings were manually recorded using a hand reader at each weighing and periodically during the day.

Potential evaporation and rainfall data were sourced from a nearby weather station at Floreat, Perth, Australia operated by the Department of Agriculture and Food, Western Australia (Foster, I. Personal Communication).

Infiltration and evaporation were measured from tanks packed with either uniform or layered soil in different phases of the experiment. Methodology during these phases is discussed in more detail below.

4.2.3. Uniform Soil Tanks

Evaporation from soil columns packed with soil of uniform repellency was recorded in summer, during a period from February to March. The uniform soil phase functioned as a relatively simple initial dry run, during which soil was wetted artificially under laboratory conditions, and placed outside during an extended period of maximum evaporative demand. Tanks were stored inside overnight in a temperature-controlled laboratory. Three tanks were packed with soil from each of the high and medium water repellency classes respectively, and two tanks each with soil of the low and non-water repellent classes (see Table 4.2). In the case of the wettable soils, one tank was packed with fine river sand, and the other with wettable B-horizon soil from the primary field site.

Tanks were wetted by ponding 100 mL of water on day 0 and 24 of the study, equivalent to 5 mm depth of rain, and left to settle indoors overnight before the main monitoring period commenced.

4.2.4. Layered Soil Tanks

Following the uniform soil experiments, tanks were emptied and repacked with surface layers of decreasing water repellency over a wettable B-horizon sublayer, approximating the variation seen in the field. Evaporation was monitored during autumn and winter, so that soils could be wetted by natural precipitation events, with tanks left outside throughout the
experiment. Scheduling during this phase was consequently dependent on ambient weather conditions, with evaporation periods limited by time between significant rain events.

Six soil tanks were initially packed with water repellent layers extending to 10, 20 or 30 cm over a wettable sublayer, with two replications each. Water repellency within these layers varied from the high water repellency class at the surface to the low repellency immediately over the wettable sublayer, in an arrangement similar to the pattern of varying water repellency with depth observed in the field (Figure 4.1). Two additional control tanks contained only wettable soil. Precise depths of each water repellent layer in each treatment is given in Table 4.2.

**Table 4.2.** Depths of soil layers of each water repellency class in each 40 cm tank, for all phases of the experiment. Where tanks contained layers of two or more soil types, layers were ordered to decrease in water repellency with depth.

<table>
<thead>
<tr>
<th>Tanks</th>
<th>High Repel.</th>
<th>Medium Repel.</th>
<th>Low Repel.</th>
<th>Wettable (0M)</th>
<th>Beach Sand (0M)</th>
<th>Temperature Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uniform Soil Tanks (10 tanks)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR1-HR3</td>
<td>40 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 tank</td>
</tr>
<tr>
<td>MR1-MR3</td>
<td>40 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 tank</td>
</tr>
<tr>
<td>LR-1, LR-2</td>
<td></td>
<td></td>
<td>40 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR-1</td>
<td></td>
<td>40 cm</td>
<td>1 tank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS</td>
<td></td>
<td></td>
<td>40 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Layered Soil Tanks, April-May (8 tanks)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-1, 30-2</td>
<td>3 cm</td>
<td>12 cm</td>
<td>10 cm</td>
<td>10 cm</td>
<td></td>
<td>1 tank</td>
</tr>
<tr>
<td>20-1, 20-2</td>
<td>2 cm</td>
<td>9 cm</td>
<td>9 cm</td>
<td>20 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-1, 10-2</td>
<td>1 cm</td>
<td>4 cm</td>
<td>5 cm</td>
<td>30 cm</td>
<td></td>
<td>1 tank</td>
</tr>
<tr>
<td>0-1, 0-2</td>
<td></td>
<td></td>
<td>40 cm</td>
<td></td>
<td></td>
<td>1 tank</td>
</tr>
<tr>
<td><strong>Layered Soil Tanks, June (6 tanks)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td></td>
<td>5 cm</td>
<td>35 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-2</td>
<td></td>
<td>5 cm</td>
<td>35 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-1</td>
<td></td>
<td>15 cm</td>
<td>25 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-1, 15-2</td>
<td></td>
<td>7.5 cm</td>
<td>7.5 cm</td>
<td>25 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-3, 0-4</td>
<td></td>
<td>40 cm</td>
<td>1 tank</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These tanks were placed outside in late April and wetted by a rainfall event of approximately 8 mm over two days. After 11 days of drying, a larger rainfall event of 48 mm
caused water to pool at the base of the tanks, after which monitoring was discontinued and the tanks emptied.

Six tanks were refilled with dried soil for a second phase of monitoring in June, again including two control tanks filled with wettable soil, as well as four containing water repellent surface layers. As soil layers of 10-30 cm had not produced clear differences in net evaporation rates during the previous monitoring period, tanks were repacked with shallower surface layers of only 5 or 15 cm, using soil of medium to low water repellency only (see Table 4.2). Tanks were again placed outside on the 15th of June and their weights monitored over 3 days of sporadic rainfall totalling around 18 mm followed by 4 days of drying. Monitoring was concluded following a second very large rainfall event in excess of 60 mm over several days, and tanks were emptied.

4.3. Results

4.3.1. Infiltration into wettable soils

Infiltration into wettable soils was characterised by roughly horizontal wetting fronts (Figure 4.2B). Limited preferential flow was sometimes observed in wettable soils, typically in the form of shallow regions of irregular wetting of up to 0.1 m in depth extending slightly beneath the deepest extent of the main front. More significant preferential flow was observed in tanks 0-1 and 0-2, which served as wettable controls to the layered soil tanks monitored during the April-May period, with flow pathways extending up to 0.2 m in 0-1 after the first 8 mm rain event, and preferential flow reaching the base of the tank in both 0-1 and 0-2 after the latter 48 mm rain event after 11 days of drying. It is considered possible that the degree of preferential flow in these tanks may reflect some undetected residual or subcritical water repellency in B-horizon soil used during this stage. Evaporation rates from tank 0-1 were consequently lower than those from 0-2 during April-May monitoring. Evaporation from tank 0-1 nonetheless remained substantially higher than that recorded in any tank containing highly water repellent surface layers.
4.3.2. Infiltration into uniform water repellent soil

Distinct preferential flow pathways of at least 0.15 m in length developed in all soil tanks containing high (HR) and medium (MR) water repellency soil after the first laboratory wetting with 5 mm of moisture, as well as in one of the two tanks containing low (LR) water repellency soil. Infiltration into all three MR tanks occurred as a single, narrow (<50 mm wide) pathway extending to the base of the tank. However, pathways were comparatively shallower in the HR soil tanks, reaching maximum depths of only 0.15-0.25 m. Infiltration was also slower in HR tanks, taking up to 5 hours to reach a depth of 50 mm, as compared to less than 1 hour for all MR tanks. Maximum pathway depths per wetting and per tank are shown in Table 4.3. Most pathways in HR and MR tanks recurred at the same locations after the second wetting, propagating substantially faster in HR tanks than during the first wetting, taking less than 15 minutes to reach 50 mm after the second wetting. New pathways not observed on the first wetting also appeared in some tanks.

Pathway formation in LR soil was more variable, reaching a depth of 0.16 m in tank LR2 following the first wetting, but only 0.10 m following the second. In LR1, distinct pathways
were observed only after the second wetting. Some redistribution of moisture was apparent after the first 24 hour period in LR and MR tanks, with pathways continuing to spread gradually for over a week, particularly at their deepest extent. For comparison, similar behaviour was also apparent in moisture sensor data recorded at the field site (Rye and Smettem, 2015) where readings at some sensors were observed to reach their maximum only more than 48 hours after some rain events (unpublished data). In comparison, pathways in HR treatment tanks did not exhibit substantial spreading after the first 48 hours.

 Preferential flow pathways visible through the side of the tank in both uniform and layered water repellent soil were often, though not universally, visible on both sides of the tank, indicating that pathways extended through the centre of the soil column at these locations.

Table 4.3. Maximum pathway depths observed in all tanks during summer phase over two wettings, in tanks containing 0R (wettable), LR (low water repellency), MR (medium repellency) or HR (high repellency soil). Figures indicate the number of tanks which had visible pathways reaching the specified depths.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Tanks (x2 wettings)</th>
<th>Maximum pathway depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.25-0.40</td>
</tr>
<tr>
<td>OR</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>LR</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>MR</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>HR</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

4.3.3. Infiltration into variably water repellent soil

Narrow flow pathways of typically 0.02-0.10 m in width appeared within 10-20 mm of the soil surface in all tanks containing water repellent surface layers. Pathways in most tanks spread laterally on encountering wettable soil layers at depth, with spread often continuing for several days after rainfall ceased (compare Figure 4.2A, Figure 4.3A). The tendency of infiltrating moisture to spread laterally on reaching wettable soil was most apparent in the June batch, which were packed with shallower water repellent layers which transitioned
abruptly from LR to wettable soil beneath. Flow pathways in these tanks all reached their maximum width directly beneath the maximum extent of the water repellent soil layer, with maximum widths equal to the full width of the tank in tanks 5-1 and 5-2 after 18 mm of rainfall. Tanks in the May batch, containing water repellent layers of 10-30 cm deep, were packed to generate a more gradual decrease in water repellency with depth (Table 4.2), and received only 8 mm of rainfall after the first May event, generating maximum lateral spread of typically between ½-¾ of the tank width in all tanks.

![Image](image.png)

**Figure 4.3.** Change in pathway shape after 8 mm rainfall and 11 days of drying in tank 10-2 (A) and flooding of tank 20-1 (20 cm water repellent layer) following 48 mm of rainfall that concluded the April-May monitoring period (B). Black lines show initial pathway shapes marked after the first rain event.

Although surface layer thickness clearly influenced moisture distribution, it had no obvious effect on maximum pathway depth over the 0.4 m tank depth. Maximum depths by treatment for all tanks containing layered soil are shown in Table 4.4. Pathway width through water repellent soil layers was not obviously affected by water repellency in most cases, though significant spread in LR regions was observed in tanks with the deepest water repellent layers (tanks 30-1 and 30-2).

The May and June monitoring periods were concluded after unusually large rainfall events of 48 mm and 60 mm respectively, both of which resulted in moisture pooling in the base of tanks, visibly wetting most or all of the wettable soil layers from the bottom of the tank up
(Figure 4.3B). As tank geometry was clearly influencing wetting patterns after rain events of such magnitude, monitoring was discontinued at this point. Pathways often recurred in the same places established during the previous rain event in patterns similar to those noted in related literature (Liu et al., 1994; Ritsema et al., 1998a; Täumer et al., 2006), but new pathways were also established in some locations (Figure 4.3B). Although wetted fractions of water repellent zones increased during these events, visible wetting patterns in all tanks showed that the majority of moisture had been routed to wettable subzones, while water repellent surface layers remained primarily dry (Figure 4.3B).

Table 4.4 Maximum pathway depths observed in all tanks containing layered soil during the April-May and June monitoring periods, in tanks containing water repellent surface layers from 0 to 0.3 m maximum depth. Figures indicate the number of tanks which had visible pathways reaching the specified depths. Note that June tanks contained only soil of low-medium classes, while April-May tanks contained highly water repellent surface layers – see Table 4.2 for details.

<table>
<thead>
<tr>
<th>Water repellent layer depth (m)</th>
<th>Period</th>
<th>Tanks</th>
<th>Tank maximum pathway depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>To base</td>
</tr>
<tr>
<td>0</td>
<td>May-June</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>0.05</td>
<td>June</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0.10</td>
<td>April-May</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0.15</td>
<td>June</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0.20</td>
<td>April-May</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0.30</td>
<td>April-May</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

4.3.4. Evaporation from Uniform Soil Tanks

Cumulative evaporation was calculated by monitoring changes to net weight of each soil tank over 22 days of drying following the first wetting, and a further 10 days of drying following the second wetting (Figure 4.4). Average daily potential evaporation was 8.3 mm in the drying period following the first wetting, and 7.1 mm after the second, with maximum diurnal soil temperatures ranging between 38-55°C at the 5-cm depth, attenuating to maxima 30-40°C at the 15 and 30 cm depths. Tank weights typically increased slightly
overnight due to condensation onto cooling soil, resulting in the sawtooth drying rates shown in Figure 4.4 and temperatures uniformly returned to 22-23°C while stored in the laboratory overnight.

**Figure 4.4.** Change in net soil moisture (mm) through time for all soil tanks during February-March summer evaporation experiment. Tanks designated as containing wettable soil (OR, RS), low repellency soil (LR1-2), medium repellency soil (MR1-3) or high repellency soil (HR1-3). See Table 4.2 for detailed tank designations.

Daily evaporative losses were consistently higher in tanks containing wettable soil, with both tanks 0-1 and 0-2 losing more than 90% of the initial 5 mm of added moisture within the first three days, as compared to losses of 60% or less from all tanks in the medium to high water repellent category. Within two days after the first wetting there were no longer any visible traces of wetting in tanks containing readily wettable soils. Net evaporation in both tanks containing wettable soil slightly exceeded the initial 5 mm application by the end of observations, indicating that a small quantity of moisture absorbed while soil cooled in the laboratory after drying had also been lost (see Table 4.1 for initial moisture contents).

Moisture retention in the low water repellency tanks was more variable, with some moisture still visible in LR2 after the first 22 days of drying, and in LR1 after the second 10
day period. By contrast, results from LR1 following the first wetting and LR2 following the second wetting closely approximated those in the wettable soil tanks.

At the conclusion of the first 22 day drying period, visible trace moisture also remained near the base in each of the four tanks with the lowest values for net evaporation by weight. These tanks included the three MR tanks, and one HR tank (HR3). Evaporation from these tanks varied between 2.78 and 4.17 mm, as compared to between 4.65 and 5.30 mm in tanks which appeared dry. Trace moisture was also still visible in all tanks in the medium and high categories at the conclusion of the second drying period.

4.3.5. Evaporation from Layered Soil Tanks

Soil tanks received 8 mm of rain over the first 24 hours of the May measurement period. Evaporation was monitored for an 11 day period before a second rain event occurred, totalling 48 mm over a period of five days and flooding the base of most soil tanks, after which weighing was discontinued. Average daily potential evaporation was 3.5 mm during this period, with maximum 5 cm soil temperatures in the range of 25-36°C. Cumulative evaporation figures from the time of the first weighing after rainfall concluded are shown in Figure 4.5.

Rates of evaporation here varied more substantially between the two wettable soil tanks (0-1 and 0-2) than over other measurement periods, attributed to the development of some preferential flow in tank 0-1. By the end of the 11 day drying period there was no longer any visibly darkened damp soil in tank 0-2 and tank weight had fallen slightly below that recorded before rainfall commenced, while tank 0-1 retained 48% of its maximum moisture as recorded immediately after rainfall ceased at the end of the same period. However, both wettable soil tanks recorded considerably greater cumulative evaporation than all tanks with water repellent soil layers, the latter retaining between 68% and 80% of their maximum recorded moisture by weight after 11 days. Results did not suggest that the depth of the water repellent surface layer made any appreciable difference in net evaporative losses or maximum flow pathway depth.
In light of these results, six of the eight tanks were repacked with dry soil in shallower water repellent layers (see Table 4.2) and placed outside for a second measurement period in June. Sporadic rainfall of 18 mm occurred over days 1-3 of monitoring, followed by a single, large rain event in excess of 60 mm in under 24 hours on the ninth day of study, again flooding the base of several soil tanks. Cumulative evaporation recorded over the five-day period separating these events is shown in Figure 4.6, from the time of maximum recorded moisture onwards. Potential evaporation during this period averaged 1.6 mm per day, with maximum diurnal soil temperatures between 20-25°C.

![Cumulative evaporation graph]

**Figure 4.5.** Change in net soil moisture (mm) during April-May evaporation for soil tanks containing water repellent surface layers of 30 cm (30-1, 30-2), 20 cm (20-1, 20-2), 10 cm (10-1, 10-2) and 0 cm (0-1, 0-2) in depth. Detailed packing schemes for all tanks are outlined in Table 4.2.

After five days of drying, tanks with water repellent surface layers contained between 1.3 and 1.9 times more moisture than tanks with only wettable soil. Moisture loss in tank 15-1, which contained a 15-cm layer of LR soil, was considerably higher than that in the remaining three tanks with water repellent soil layers; but no similar variation was evident in tank 5-1, which similarly contained LR soil. As such, no consistent advantage to tanks with deeper water repellent layers or stronger water repellency was evident from these results.
Figure 4.6. Change in net soil moisture for all soil tanks during the winter evaporation phase. Tanks contained water repellent surface layers of 15 cm (15-1, 15-2) 5 cm (5-1, 5-2) or 0 cm (0R-1, 0R-2). Detailed packing schemes for all tanks are outlined in Table 4.2.

4.4. Discussion

4.4.1. Infiltration patterns

Results show a clear association between water repellency and preferential flow, with visible flow pathways forming within 10-20 mm of the surface in all soil tanks with medium to highly water repellent surface layers (MED > 1.2 M). Comparable flow pathways were observed in some tanks filled with uniform low water repellency soil (MED 0.4-1.2 M) during the first experimental phase, and were rare in wettable (0 M MED) soil. Results from the uniform soil tanks monitored over the extended summer evaporation period highlighted the importance of path length in controlling evaporative loss during periods of maximum potential evaporation, with all tanks with pathways extending to at least 0.15 m retaining between 33% and 65% of added moisture after 5 days of drying, compared to less than 5% retained in tanks containing wettable soil. Visible trace moisture remained present after the
maximum 3 week evaporation period only in tanks where moisture reached depths greater than 0.2 m.

However, higher water repellency did not necessarily generate deeper flow pathways. Although average pathway depth increased with repellency across the wettable, low and medium categories, high water repellency soil produced shallower pathways and more variable evaporation rates than those seen in medium repellency tanks. Pathways were also slower to form and wider in very strongly water repellent soil, and the greater resistance to wetting appears to have limited pathway propagation relative to that observed in medium water repellency tanks.

Where soil was layered such that water repellency decreased with depth, wetting patterns were broadly consistent with the structure outlined by Ritsema & Dekker (1995), where wettable subsoil beneath the water repellent layer forms a ‘redistribution layer’ where preferential pathways spread and merge, resulting in rapid drainage of pathways above the wettable interface (Ritsema et al., 1998b). Layered soil tanks from the May and June monitoring periods had water repellent layers of 0.05-0.3 m in depth, similar to or shallower than those observed before the start of autumn rainfall in the field, transitioning to wholly wettable soil beneath. Visual evidence of redistribution in these sublayers was distinct, with pathway widths often increasing markedly on reaching layers of wettable soil. Pathways in these tanks regularly reached their maximum widths immediately or shortly below the deepest extent of the water repellent soil layer, allowing narrow pathways through the layer above to spread laterally up to the full width of the tank. Even after the much larger rain events in excess of 40 mm that concluded the monitoring periods in May and June, wetting patterns showed that water repellent soil layers remained predominantly dry, with the overwhelming majority of moisture successfully routed beneath (Figure 4.3B).

Visible preferential flow was occasionally present in tanks containing only wettable soil, and appears to have influenced evaporation rates in at least once case during the April-May monitoring period. Samples of soil retrieved from the B-horizon at the primary field site was occasionally found to be slightly water repellent, and it is possible that soil used in this phase was initially slightly or subcritically water repellent (Lamparter et al., 2006; Tillman et
al., 1989) when collected, at levels difficult to detect using the standard MED test in 0.2 M increments. After wetting and redrying prior to the June monitoring period preferential flow was no longer observed.

As soil organic matter content typically peaks in near surface regions, water repellency distributions at sites across the world have frequently been reported to decrease with depth in a manner similar to that observed at our field site, transitioning to wettable over some distance of the order of decimetres. Although water repellency distributions may thus be explained as a relatively simplistic product of decaying leaf litter and other plant material, results from this study suggest that the resulting field distributions may be remarkably well-engineered to favour moisture conservation, relative to either stronger or weaker alternatives. Tanks containing uniform, strongly water repellent soil to depth produced generally shallower flow pathways and no obvious improvement in moisture conservation relative to those containing only moderately repellent soil. Shallow or less well-graded water repellent layers of 0.15 m or less examined during the June monitoring period produced shallower average infiltration depths than those with layers up to 0.3 m during May monitoring, despite June tanks receiving twice as much rainfall during the first days of measurement. The relatively small number of replications present in this study precludes detailed statistical analysis, however, soil tanks packed with water repellent layers of 10-30 cm produced the most consistent recorded reductions in evaporation rates over 4 days of drying, with net evaporation consistently reduced by 70-80% compared to wettable controls. By comparison, 4 day net evaporation was reduced by only 35-40% in some tanks containing deep, uniformly water repellent soil, or tanks containing only shallower water repellent layers monitored during June.

4.4.2. Relevance to Seasonal Field Conditions

In the field, water repellency has been observed to vary on a seasonal cycle, decreasing during winter as flow pathways spread and water repellent compounds are leached from the soil, to be re-established during summer when the soil dries out. Past authors have noted that water repellent soil layers likely confer particular value in conserving moisture
after isolated rain events during periods of summer drought, when potential evaporation rates and moisture stress will be at their annual peaks (Cammeraat and Imeson, 1999; Robinson et al., 2010). That soil water repellency itself is at a peak during summer likely magnifies these benefits. Conversely however, the annual net advantages to moisture conservation, particularly with regards to deep storage and net groundwater recharge, may be limited by the fact that repellency will tend to break down through the period where the majority of rainfall occurs.

Evaporation figures recorded from uniform soil tanks, which were monitored during a prolonged period of summer drying, highlight particularly the benefit of soil water repellency in conserving any moisture received during periods of maximum daily potential evaporation. Tanks containing uniform water repellent soil were able to retain up to 45% of added moisture for three weeks after a simulated wetting event of only 5 mm, while wetting soils lost 80% or more within the first 24 hours.

In the layered soils examined during the June monitoring period we found that even greatly reduced water repellent soil layers (maximum depth 5-15 cm, compared to maximum depths close to 30 cm seen in the field) are able to confer a measurable advantage with respect to moisture conservation. These results may suggest that some evaporative benefit may persist through the winter season. Rye and Smettem (2015) demonstrated that preferential flow may persist throughout autumn and winter in years of average or below average rainfall, with complete water repellent breakdown occurring only in years of substantially greater rainfall totals. As such, evaporative reductions generated by water repellency may be able to counterbalance the impact of reduced moisture availability during below-average rainfall years.

4.5. Conclusions

Rates of evaporative loss recorded during all phases of this study provide evidence that water repellent soil layers are capable of reducing evaporative moisture loss by promoting deep preferential flow. Tanks containing water repellent soils retained substantial trace
moisture even after three weeks of summer drying, while wettable soils lost all added moisture within the first 2-3 days. Tanks with water repellent surface layers also lost less water to evaporation following rain events in autumn and winter, retaining at least 1.5 times more moisture than wettable controls after 5 days of drying in winter, and over 2 times more moisture after 11 days of drying in autumn. Post-rainfall moisture distributions in soils with strongly water repellent surface layers minimise moisture storage in the shallowest layers where it is most susceptible to evaporation, channelling the majority of moisture deep into the soil, where it will be more effectively protected.

Water repellent surface layers are particularly beneficial in conserving moisture following isolated summer rain events, when water repellency, moisture stress and potential evaporation rates coincide at their annual peaks. The advantage of deep water repellent layers is less pronounced during autumn and winter, though the establishment of strong, deep water repellency during summer may prolong the persistence of such layers through winter, during which period water repellency gradually breaks down.
5. Seasonal variation of subsurface flow pathway spread under a water repellent surface layer

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 effective in diverting flow to deeper layers in periods where significant rain events were separated by dry periods of at least a week, but less
effective 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.

5.1. 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; Petter 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 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., 1998a), 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 (eg. 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., 1998a), 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, enabling 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., 1997). 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, Kobayashi and Shimizu, 2007).

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 & 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 greater than 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.
5.2. Materials and Methods

5.2.1. 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 0M, whereas extremely water repellent soil may be above 4.0M). Soil at the field site is classified as yellow-phase Karrakatta sand (Salama et al., 2001) or as Dystric Xerosamments under the U.S. system of soil taxonomy (Soil Survey Staff, 2014), consisting of highly water repellent dark brown topsoil (MED test 2.5-4M) transitioning to a non-repellent (0M) yellow sand B-horizon at a typical depth of 10-25cm (Figure 5.1). 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 the main winter rainfall period between May and September (Australian Bureau of Meteorology, 2012).

![Figure 5.1. Water repellency variation with depth at the experimental field site](image)

96
5.2.2. Instrumentation

Soil moisture was recorded using 20 SISOMOP sensors (SImple SOil Moisture Probe) (Hübner et al., 2010), inserted horizontally into the wall of a 1.5 m long trench at depths of 5 and 15 cm. The trench was backfilled after installation. Precipitation was measured on site using a commercially-available ECRN-100 rain gauge and recorded using an EM5b data logger from Decagon Devices. Data from all devices was recorded on a 5 minute interval for the complete trial duration, excluding some short periods of battery outage or other equipment faults. Recorded data was retrieved manually on a weekly basis. Other environmental data including potential evaporation was sourced from a Department of Agriculture weather station located 500 m to the west of the experimental site, which also provided supplemental rain data during periods of on-site equipment failure (I. Foster, personal communication, 2012).

5.2.3. The Effective Cross Section

The Effective Cross Section (ECS) is a metric introduced by Täumer et al. (2006) to quantify the area share of flow pathways in terms of the minimum fractional cross-section of soil which can be said to account for 90% of total flow.

To calculate both the ECS and the new MR metric, we quantify soil moisture response to rainfall in terms of the maximum increase in soil moisture ($\Delta O_{l,s}$) reported by any particular moisture sensor (at position $s$ in layer $l$) during a distinct rain event (Equation 5.1), plus up to 5 hours after the last recorded rainfall to allow for delayed travel time or pathway spread following small events. Here a ‘layer’ corresponds to a specific sensor depth (5 or 15 cm at our installation).

$$\Delta O_{l,s} = O_{l,s}(t_{\text{max}}) - O_{l,s}(t_0) \quad (5.1)$$

Where $O_{l,s}$ = observed soil moisture reported by sensor at horizontal location $s$ in layer $l$, $t_0$ = start time of rain event and $t_{\text{max}}$ = time of maximum moisture content.
To calculate the ECS, fractional contributions $f_{l,s}$ from each sensor to the total change in moisture across that layer are calculated (Equation 5.2).

$$f_{l,s} = \frac{\Delta O_{l,s}}{\sum_{s=1}^{s=n} \Delta O_{l,s}} \text{ with } \sum_{s=1}^{s=n} f_{l,s} = 1$$  \hspace{1cm} (5.2)

For a soil layer containing $n$ sensors, each individual sensor represents an area share of $\frac{1}{n}$.

The resulting $f_{l,s}$ values are ranked in descending order, and their cumulative sum plotted against the corresponding cumulative area share. The resulting data is fitted to the beta function (Equation 5.3) so that the minimum area fraction associated with 90% of cumulative change in moisture $f_{l,s}$ may be determined. A more detailed account of this process as applied to the Floreat site is published in Rye and Smettem (2015).

$$p(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}$$  \hspace{1cm} (5.3)

($\alpha > 0, \beta > 0, 0 \leq x \leq 1$)

In a perfectly wettable soil, the ECS is expected to be exactly 0.9, whereas in a soil where flow pathways account for only a small fraction of soil cross-sectional area, the ECS may be only 0.2 or less (Täumer et al., 2006). As an established metric for changes in flow under water repellent conditions, the ECS is here used as a comparison point for the new Modified Response metric, and as an independent indicator of the periods during which flow conditions on site best approximated uniform flow for 1-D model calibration purposes.

5.2.4. Modelling Vertical Water Fluxes

Simulation modelling of vertical water fluxes was performed using Hydrus1D (Šimůnek et al., 2009). The objective of modelling efforts was to produce infiltration and soil water profile data for a 'base case' scenario representing the study site under wettable conditions. To ensure similarity to on-site conditions, rainfall input to the model was sourced directly from the on-site rain gauge. Potential evaporation data from the nearby Department of Agriculture weather station, calculated using the Penman-Monteith equation, was input to the model in hourly increments. Individual Hydrus1D simulations were run on a per-rain
event basis, taking average recorded soil moisture immediately prior to each event as initial conditions.

Table 5.1. Initial estimates and calibrated soil hydraulic parameters for two layered Hydrus1D simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Soil Horizon</th>
<th>$\theta_r$ (m$^3$/m$^3$)</th>
<th>$\theta_s$ (m$^3$/m$^3$)</th>
<th>$\alpha$ (m$^{-1}$)</th>
<th>$n$</th>
<th>$K_s$ (m/hr)</th>
<th>$l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial estimates</td>
<td>A (0-10 cm)</td>
<td>0.006</td>
<td>0.42</td>
<td>1.2</td>
<td>1.1</td>
<td>0.05</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>B (10 cm +)</td>
<td>0.006</td>
<td>0.41</td>
<td>1.1</td>
<td>1.4</td>
<td>0.24</td>
<td>1.0</td>
</tr>
<tr>
<td>Calibrated</td>
<td>A (0-10 cm)</td>
<td>0.006</td>
<td>0.42</td>
<td>1.2</td>
<td>0.61</td>
<td>0.05</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>B (10 cm +)</td>
<td>0.008</td>
<td>0.41</td>
<td>1.8</td>
<td>0.60</td>
<td>0.24</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Soil hydraulic properties were parameterised for the A and B horizons using the Brooks-Corey model in Hydrus1D. Specific hydraulic parameters for both layers were estimated from soil moisture data collected on site at a late stage of water repellent breakdown and inverse fitted against the corresponding rain and evaporation records using Hydrus1D’s inverse fitting routines. To identify periods suitable for calibration, the ECS was employed as an indicator of the degree to which site conditions best approximated uniform flow. A first-estimate for some soil parameters calibrated during the fitting process, including saturated hydraulic conductivity ($K_s$), saturated moisture content ($\theta_s$) and the Brooks-Corey $\alpha$ and $n$ parameters (Table 5.1) were obtained from a previously published source examining yellow-phase Karrakatta sands under Banksia woodland (Salama et al., 2001). To accommodate the inclusion of rain events occurring during summer, where initial soil moisture was very low, the residual moisture content ($\theta_r$) input to the model was constrained to be less than the minimum recorded value (approximately 0.6% moisture by volume).

5.2.5. Model Calibration

The ECS metric was used to identify periods where field data best approximated uniform flow for model calibration. Values for the highly water repellent 5-cm layer were prioritised at this stage of analysis, as these demonstrated consistently stronger seasonal trends and
less variability across consecutive events than those for the 15-cm depth. Both average soil moisture and ECS values reached annual peaks in August or early September in all years of study, after some months of gradual increase through autumn and winter.

2013 was considered a poor candidate for model calibration, due to the failure of one of the five recording nodes early in the year, reducing the number of reporting sensors by 4. Of the years remaining, 2012 appeared to represent the year in which pathway spread during early autumn and winter was most rapid, possibly due to an unusually wet preceding summer, which may have limited the period suitable for re-establishing strong water repellency (Rye and Smettem, 2015). Moisture contents in the 5-cm layer had exceeded those at 15 cm by early June of 2012, as compared to August or September in 2010-2011, while 5-cm ECS values of 0.7 or greater were associated with every significant rain event recorded between the 6th June and the 17th September inclusively. A 35 day period from the 1st August to the 4th September 2012, comprising seven consecutive rain events with 5-cm ECS>0.73, was selected for model calibration.

Hydrus1D’s built-in inverse fitting routine was used to optimise soil parameters to match observed depth-averaged soil moisture contents recorded during the calibration period. Rainfall and initial soil moisture inputs were also sourced from field site records. Brooks Corey parameters determined by this process are shown in Table 5.1.

5.2.6. Calculation of the Mean Modified Response

Output from the Hydrus model provided a baseline against which divergence of observed wetting patterns from expected behaviour could be quantified. Observed and modelled results were compared on a per-event basis, where a distinct rainfall event was defined as a period having a total rainfall of at least 3 mm, preceded by a dry period of at least 12 hours, and resulting in an increase in simulated soil moisture of at least 2% volumetric moisture content at the shallower sensor depth. Events matching these criteria were simulated as individual Hydrus1D runs, taking the average site moisture at each sensor depth as initial conditions.
As previously described for the ECS, calculations take the maximum change in soil moisture recorded during an event ($\Delta O_{l,s}$) as a raw measure of soil response to rainfall. Using modelled rather than observed field data, we define $\Delta M_l$ as in Equation 5.4:

$$\Delta M_l = M_l(t_{\text{max}}) - M_l(t_0)$$  \hspace{1cm} (5.4)

Where $M_l$ = modelled soil moisture response in layer $l$, $t_0$ = start time of rain event and $t_{\text{max}}$ = time of maximum moisture content.

Where infiltration is dominated by preferential flow, the moisture content reported by any particular sensor will vary depending on the fraction of its sensitive volume which intersects flow pathways. A sensor located entirely within a flow pathway may report moisture substantially greater than $\Delta M$ for that layer; however, if flow pathways are narrow, the modelled response $\Delta M_l$ will be greater than the observed response $\Delta O_{l,s}$ at most sensor locations $(s)$. To scale for the effects of rain event magnitude on relative responses in the first soil layer, $\Delta O_{l,s}$ is divided by modelled response (Equation 5.5).

$$MR_{l=1,s} = \frac{\Delta O_{l=1,s}}{\Delta M_{l=1}}$$  \hspace{1cm} (5.5)

The resulting metric expresses site response relative to modelled predictions of uniform wetting on a scale ordinarily varying from 0-1, with 0 representing no response to rainfall, and a 1 representing average wetting which matches modelled 1D wettable profile predictions. Values greater than 1 would indicate that observed increases in soil moisture exceeded model predictions, which may occur within flow pathways due to channelling and concentration effects.

At depth, changes in soil texture and repellency may act to further modify flow pathway areas established in soil layers above. While uniform infiltration will typically produce decreasing $\Delta M$ in deeper layers (Figure 5.2A), the relative diameter of flow pathways may either decrease (Figure 5.2B) or increase (Figure 5.2C) with depth in response to changing water repellency and other factors. To quantify these effects, the change in response
relative to the layer above will be more representative than the absolute value at that depth.

![Diagram of moisture distribution](image)

**Figure 5.2.** MR values for some hypothetical moisture distributions representing A. Perfectly wetting 1-D wetting profile (Hydrus 1D), B. Fingered flow for a water repellent soil, and C. Fingered flow for a water repellent soil with decreasing repellency with depth.

Scaling by differences in \( \Delta M \) between the layers rather than by absolute \( \Delta M \) at depth also allows the inclusion of small rain events which would wet only the uppermost layers of an evenly wetted soil (producing \( \Delta M = 0 \) at depth), but which may reach greater depths in water repellent soil due to preferential flow. Taking the response at the soil surface \( (l=0) \) as 0, this Modified Response can then be calculated for both layers according to Equation 5.6.

\[
MR_{l,s} = \frac{\Delta O_{l,s} - \Delta O_{l-1,s}}{\Delta M_{l} - \Delta M_{l-1}} \quad (5.6)
\]
A modified response (MR) value can be calculated for any sensor location. However, to summarise site behaviour across a large sensor array, we will discuss MR values primarily in terms of the Mean Modified Response by layer (Equation 5.7).

\[
MMR_i = \frac{\Delta O_i - \Delta O_{i-1}}{\Delta M_i - \Delta M_{i-1}} \tag{5.7}
\]

Here layer 1 refers to soil at the 5 cm sensor depth, and layer 2 to the 15 cm sensor depth.

Note that if modelled and observed responses see the same proportional increase or decrease between two consecutive layers (ie, if \( \Delta O_{i-1} / \Delta O_i = \Delta M_{i-1} / \Delta M_i \)) then the metric as formulated will return the same MR value for both soil layers, with \( MR_i = MR_{i-1} \). Where MR values differ between the layers, the difference provides an indicator of whether flow pathway sizes have increased or decreased relative to expectations.

In water repellent soils, MR values for deeper soil layers will often be less than those near the surface, indicating that responses diverge from model predictions with depth due to bypass flow, which may allow moisture to reach deeper layers before sufficient rain has occurred to thoroughly wet surface layers. In some cases, MR values for these layers may be negative, indicating that, while the model predicted decreasing rainfall responses with depth, observations recorded greater responses in the deeper layer than in the surface region (Figure 5.2C). In practice, this may occur where decreasing water repellency at depth allows pathways to spread, increasing the region of intersection with soil moisture sensors.

5.3. Results

5.3.1. Sensor Data

Moisture contents recorded simultaneously across the field site showed significant variability during most periods of the study, consistent with infiltration patterns dominated by preferential flow. Though results indicated that soil surrounding some sensors remained dry during some isolated rain events in summer or early autumn, all sensors had recorded
some response to rainfall by May at the latest in each year of study. Moisture data suggested that most sensors intersected with flow pathways over only some partial fraction of their sensitive length, with this fraction spreading gradually through the year. Site averaged responses by layer for all four years of record are shown with daily rainfall totals in Figure 5.3.

Contrary to modelled 1D predictions, both absolute moisture contents and increases in moisture in response to rain were sometimes greater at the 15-cm depth during summer and some autumn periods. However, by late winter of all years, differences between the two layers had reversed, with moisture and responses at 5 cm steadily increasing as pathways spread, until responses at 5 cm exceeded those at 15 cm (Figure 5.3). By contrast,
responses at 15 cm showed no obvious trends in most years. Although average moisture contents between events increased in both layers, average responses did not increase at 15 cm, and in some cases appeared to decrease as pathways spread in the layer above (Figure 5.3).

Variability within layers remained considerable, with responses at some sensors (particularly those located primarily or entirely within flow pathways established early in the year) more obviously influenced by individual rain event magnitude than broader seasonal trends. However, for most sensors, annual maxima were recorded late in winter, regardless of event magnitudes in this period. Variability among sensors in the same soil layer generally decreased as average moisture across the layer cross-section increased.

In some cases, moisture contents at particular sensors were found to reach a local maximum only hours after the end of a rainfall event, suggesting moisture continued to be redistributed as flow pathways spread. Similar patterns of gradual flow pathway spread, continuing some hours after wetting of the surface has ended, have previously been observed during the wetting of soil tanks containing similar layered water repellent soil (Rye and Smettem, 2017).

Non-sequential depth responses (i.e. rain events for which sensors in the 15-cm layer reported a response at least one recording interval before a response occurred at 5 cm) were sometimes evident in sensor data in summer and early autumn, but responses and local peaks more often appeared to be simultaneous (Figure 5.4A). By late winter, as pathways spread in the upper layer, clear increases in moisture at 15 cm were more frequently delayed, occurring only one or more recording intervals after an increase in moisture at the shallower depth (Figure 5.4B).

5.3.2. Vertical Flux Modelling Results

A comparison of modelled and observed soil moisture during two 2011 events is shown in Figure 5.4, one in autumn and one in late winter. Simulated soil moisture exceeded observed site data during most rain events, particularly for the upper 5 cm soil layer (Figure
5.4A), with the discrepancy generally decreasing as the autumn-winter season progressed. Conversely, average field moisture at 15 cm sometimes exceeded that modelled, particularly during the early hours of the event (Figure 5.4A). By late winter or early spring, average moisture contents closely approximated modelled predictions during most years (Figure 5.4B).

![Figure 5.4](image)

Figure 5.4. Observed and modelled data from two events in 2011, illustrating early and late stages of repellency breakdown. Shaded regions indicate standard error margins for field data. A: 17-18 May, B: 3-4 September.

5.3.3. Mean Modified Response and Effective Cross Section Results

Although broad seasonal patterns are evident in site averaged responses (Figure ), considerable scatter is introduced by the variability of rain event intensity and duration. Seasonal trends may be better resolved by scaling responses by model predictions using the MMR metric (Figure 5.5). Here values close to 100% indicate that site data closely approximated modelled wettable soil responses, whereas values close to 0% indicate that little or no response to rainfall was observed. Effective Cross Section values, adapted from Rye and Smettem (2015), are provided for comparison for each year.

Trends in both metrics are broadly comparable, with both MMR and ECS values increasing through winter of all water years. However, ECS values reached an apparent maximum at
around 0.8-0.85 in most years of recording, while MMR values often continued to increase during the same period, reaching their annual maximum later in the season. This suggests
Figure 5.5. MMR (left) and ECS (right) results for 5cm and 15 cm for all water years
that the ECS may be relatively insensitive to changes occurring in late stages of water repellent breakdown.

Discrepancies between observed and modelled data were more pronounced at depth, producing MMR values at 15 cm significantly lower than those at 5 cm during most rain events. During autumn and spring-summer rain, this regularly translated into negative MMR values at 15 cm. This highlights the fact that sensor data recorded an increased response ΔO₁ at 15 cm where the model predicted a decreased response ΔM₁ relative to the layer above, inverting model predictions. Broad trends nonetheless remained highly comparable and well correlated in both soil layers. Annual variation in MMR values is considered to be overall consistent with a gradual decrease of water repellency through winter, followed by steady reestablishment during the warmer months from late September to March.

Values of both the ECS and MMR for events occurring at the end of winter from late August onwards represent a less stable transitional period, and spring trends overall were more variable than those through winter, particularly in years where winter rainfall patterns persisted beyond September. In 2013, regular rainfall events continued at an average rate of 2.8 mm per day until late October, extending the usual winter trends without obvious interruption. Similarly, although winter rainfall ceased in September of 2011, an unseasonably large series of rain events occurred between 18th October to 8th November, totalling 88 mm. A sharp increase in both MMR and ECS values during this period suggests this rainfall was sufficient to trigger a return to winter breakdown patterns, interrupting the usual pattern of spring recovery.

The varying breakdown rates in different water years may be better compared by plotting metric values against cumulative winter rainfall for that year, or antecedent rainfall recorded over a set period prior to the event. An analysis of ECS values associated with this dataset using this methodology was previously published in Rye and Smettem (2015). Good correlation was found between ECS for the 5-cm depth and both cumulative rain from the start of winter, and 90 day antecedent rainfall (Table 5.2), though antecedent rainfall was found to be more useful in explaining differences between the different years, as this
measure was better able to account for differences resulting from the unusually short, intense winter season of 2011 (Rye and Smettem, 2015).

**Table 5.2.** Linear regression statistics for ECS at 5 cm and 15 cm against cumulative winter rainfall, antecedent winter rainfall, and antecedent soil moisture recorded during the breakdown phase (March-September) of all years of study

<table>
<thead>
<tr>
<th>Depth</th>
<th>Year</th>
<th>90 day antecedent rainfall</th>
<th>Cumulative rainfall</th>
<th>Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slope</td>
<td>Const.</td>
<td>R²</td>
</tr>
<tr>
<td>ECS 5 cm</td>
<td>2010</td>
<td>1.34E-03</td>
<td>0.35</td>
<td>76.1%</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>1.32E-03</td>
<td>0.30</td>
<td>86.0%</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>9.40E-04</td>
<td>0.52</td>
<td>70.6%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>1.12E-03</td>
<td>0.37</td>
<td>69.1%</td>
</tr>
<tr>
<td>ECS 15 cm</td>
<td>2010</td>
<td>1.23E-03</td>
<td>0.38</td>
<td>54.5%</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>1.24E-03</td>
<td>0.28</td>
<td>81.9%</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>4.07E-04</td>
<td>0.55</td>
<td>12.6%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>6.88E-04</td>
<td>0.49</td>
<td>31.6%</td>
</tr>
</tbody>
</table>

**Table 5.3.** Linear regression statistics for MMR at 5 cm and 15 cm against cumulative winter rainfall, antecedent winter rainfall, and antecedent soil moisture recorded during the breakdown phase (March-September) of all years of study

<table>
<thead>
<tr>
<th>Depth</th>
<th>Year</th>
<th>120 day antecedent rainfall</th>
<th>Cumulative rainfall</th>
<th>Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slope</td>
<td>Const.</td>
<td>R²</td>
</tr>
<tr>
<td>MMR 5 cm</td>
<td>2010</td>
<td>1.84E-03</td>
<td>-0.05</td>
<td>83.0%</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>1.71E-03</td>
<td>-0.04</td>
<td>91.9%</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>2.65E-03</td>
<td>-0.05</td>
<td>88.3%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>1.51E-03</td>
<td>0.08</td>
<td>76.2%</td>
</tr>
<tr>
<td>MMR 15 cm</td>
<td>2010</td>
<td>2.03E-03</td>
<td>-0.65</td>
<td>77.7%</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>1.76E-03</td>
<td>-0.25</td>
<td>89.8%</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>3.63E-03</td>
<td>-0.38</td>
<td>85.6%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>1.65E-03</td>
<td>-0.23</td>
<td>66.9%</td>
</tr>
</tbody>
</table>
MMR values likewise correlated well with both cumulative and antecedent rainfall (Table 5.3), though best fits were found with a slightly longer antecedent period of 120 days. Relationships for both metrics and both sensor depths with antecedent rainfall are shown in Figure 5.6. Although precise relationships varied year to year, the strength of correlations of both metrics rainfall highlights the importance of regular rainfall in driving water repellent breakdown.

**Figure 5.6.** Relationships between MMR (left) and ECS (right) with antecedent winter rainfall, for all rainfall years, in each soil layer.
Values for the 5- and 15-cm depths were also substantially inter-correlated for both metrics (Table 5.4). However, whereas ECS values for the 15-cm layer correlated poorly with rainfall during most years of record, MMR values maintained strong correlations with rainfall at both sensor depths (compare Table 5.2, Table 5.3). The particular value of MMR results in analysing behaviour at this depth will be further discussed below.

**Table 5.4.** Linear regression statistics for 15-cm MMR against MMR at 5 cm for all years of study.

<table>
<thead>
<tr>
<th>Year</th>
<th>MMR Slope</th>
<th>MMR Const.</th>
<th>MMR R²</th>
<th>ECS Slope</th>
<th>ECS Const.</th>
<th>ECS R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>9.31E-01</td>
<td>0.58</td>
<td>68.4%</td>
<td>8.44E-01</td>
<td>0.12</td>
<td>73.2%</td>
</tr>
<tr>
<td>2011</td>
<td>9.85E-01</td>
<td>0.22</td>
<td>94.0%</td>
<td>8.78E-01</td>
<td>0.03</td>
<td>83.0%</td>
</tr>
<tr>
<td>2012</td>
<td>1.27E+00</td>
<td>0.00</td>
<td>90.0%</td>
<td>6.47E-01</td>
<td>0.18</td>
<td>42.5%</td>
</tr>
<tr>
<td>2013</td>
<td>1.18E+00</td>
<td>0.16</td>
<td>77.6%</td>
<td>7.20E-01</td>
<td>0.20</td>
<td>63.0%</td>
</tr>
</tbody>
</table>

MR values calculated for separate sensors sometimes, though not consistently, showed smooth, progressive breakdown patterns comparable to the average trends reflected in Figure 5.5. An example of typical variability among individual MR values at three sensors in 2013 is shown in Figure 5.7. Here, relatively steady, gradual breakdown throughout the season was apparent at sensor S1, whereas responses at S2 remained negligible until mid-July, after which rapid breakdown occurred through the rest of the year. Sensor S3 represents an outlier at which evidence of early breakdown in March and April actually recedes to negligible responses through June, after which pathways were rapidly re-established following a week of heavy rain (> 50 mm total) in July. The apparent reestablishment of localised water repellence in this region through June was sufficient to influence ECS values for 2013, which actually decrease in this period, though MMR values for the same period were not obviously affected (Figure 5.5).
Figure 5.7. Individual MR results for 3 sensors at the 5-cm depth during 2013

5.4. Discussion

5.4.1. Subsurface Pathway Spread

The ability of shallow soil water repellency to limit moisture storage in the surface layers, where it is most readily lost to evaporation, may be key to its ecological significance. It has been suggested that deep preferential flow, such as that favoured by water repellency, may be a major contributor to groundwater recharge in arid environments (Jaramillo et al., 2000; Scott and Lesch, 1997; Stephens, 1994), and that water repellence may be particularly beneficial in conserving moisture following isolated summer rain events or during periods of drought (Cammeraat and Imeson, 1999; Robinson et al., 2010). Net annual effects on evaporation may, however, be limited by the fact that water repellency breaks down during the period where the majority of rainfall occurs (Rye and Smettem, 2017).
Periods in our dataset in which moisture contents were low in surface soil but increased with depth are of particular interest in regards to moisture conservation. Not only do these periods represent the greatest deviations from the behaviour expected of a 'normal' evenly-wetting soil, but the spread of flow pathways in redistribution zones at depth allows for rapid drainage from narrow infiltration paths above (Ritsema et al., 2005, 1993), further reducing matric pressure near the surface, and producing a dry barrier region to evaporation (Rye and Smettem, 2017). Most significant are the subset of rain events associated with negative values of 15-cm MMR, as these indicate an increased rainfall response at depth, independent of antecedent moisture, in circumstances where 1D modelling predicted the opposite (ie. decreased response with depth).

A few periods in the data record were associated with not only negative MMR values at 15 cm, in the range of −20% to −50%, but unusually large discrepancies between MMR values for the two layers, which were otherwise usually similar (Table 5.4). The most significant such period occurred in autumn of 2010 (Figure 5.5), producing discrepancies between 5 and 15-cm MMR values which persisted until the cessation of winter rain. As wetting patterns recorded in this period represent maximum divergence from the model, it is tempting to attribute them to heightened water repellence produced by the unusually long, hot summer which preceded autumn 2010, having a total October-February rainfall of only 38 mm (Rye and Smettem, 2015). However, a comparably severe summer preceding 2011 (Oct-Feb rainfall 64 mm) produced only slightly negative 15-cm MMR values, whereas several events with MMR < −20% did occur in autumn 2013 despite a much wetter preceding summer (Oct-Feb rainfall 107 mm). Large gaps between 5- and 15-cm MMR values were also associated with several events in spring and summer of 2011 and 2012 (Figure 5.5).

Based on analysis of the rainfall record, we theorise these unusually strong relative subsurface responses are instead produced by periods characterised by heavy or moderately heavy rain events, sufficient to raise moisture contents (and thus produce some breakdown) in the less water repellent region at depth – but separated by intervals of at least a week of dry weather. It is likely that intervals of this length were sufficient to allow
some reestablishment of water repellency at the shallower sensor depth, as has occasionally been reported following comparable dry periods at other sites (Crockford et al., 1991; Keizer et al., 2008). However, periods of the order of a week are insufficient for the drying front to penetrate deep into the subsoil, as it does during the prolonged summer drying period, and soil at the lower sensor depth retained significantly more moisture between events, at lower maximum diurnal temperatures, and thus it is unlikely water repellence in this zone would have recovered to a comparable degree. Large, well-spaced events may thus produce patterns of transient breakdown near the surface but persistent breakdown at depth. At the onset of later events, this would allow narrow pathways through the surface region to drain quickly into the subsoil, rather than spreading close to the surface, magnifying differences between the soil layers. Patterns of this nature would be consistent with MMR values for those periods.

All periods associated with 15-cm MMR < -20% were specifically characterised by moderately large and relatively isolated rain events, with median gaps between significant rain events (>5 mm) of more than 8 days. By contrast, the median gap between similar rain events during winter 2011 and 2012 was only 4 days, which may have precluded opportunity for surface soil to dry. Rainfall events in summer 2010 were not associated with 15-cm MMR < 0%, as, although well-spaced, events in this period were consistently small (<5.5 mm), and thus may have been unable to produce significant pathway development at the 15-cm depth.

Although negative 15-cm MMR values sometimes occurred in autumn, none were associated with the first rain events of the season. The 2010 season, which produced the longest series of negative 15-cm MMR on record, began with two exceptionally large but well-spaced rain events of the order of 50 mm each, which preceded the start of data recording, occurring on the 22nd March and 13th of April. Although precise sensor data is not available for these events, they may have provided ideal conditions to raise moisture contents in the subsurface, and prime the system for later observed behaviour. An examination of individual MR values during these periods shows that pathways at specific sensor locations occasionally shrunk or receded where rain events were well-spaced (one
such instance is shown in Figure 5.7 above), which supports the presumption that some degree of short-term, localised water repellent reestablishment was possible.

The patterns here identified suggest a 'threshold' rainfall frequency required for persistent breakdown of surface water repellency of less than 8 days. Though the full magnitude of impacts on net annual evaporative loss remain to be determined, these results support the theory that water repellency is likely to be best suited to conserving moisture received during isolated summer events, or well-spaced events in years of less frequent rainfall.

Building upon the premise that relative rates of breakdown in different soil layers may differ based on variations in the annual rainfall regime, we may also propose an explanation for an anomaly in ECS data during winter 2012 (Figure 5.5). Values for the 15-cm layer during this period were unusually low, averaging 0.07 less than those in the layer above, as compared to differences of less than 0.03 in all other years. This indicates that responses at this depth remained unusually variable throughout winter, despite the rapid breakdown evident in the surface layer above. It is possible that 2012 thus represents a year in which rapid pathway spread in the surface layer limited the fraction of moisture which reached the deeper layer, in turn limiting breakdown and pathway spread in this layer. If so, 2012 may represent a year in which the water repellence of the subsoil served to trap a greater fraction of moisture near the surface, relative to the results of previous years.

Surprisingly, ECS data shows little evidence of the impact of the less water repellent subsoil, though pathway spread at this depth this should theoretically produce an increase in 15 cm ECS relative to the 5 cm layer above. Instead, ECS results reflect only slight and inconsistent differences between the soil layers during autumn 2010 and other periods of interest identified using the MMR (Figure 5.5). A further analysis shows that differences between the layers appear to have been obscured in ECS values for this dataset because responses often increased with depth by similar ratios among vertically aligned sensor pairs at different locations, thus relative area shares maintained a similar fit to the beta function at both depths.
The ECS, being dependent upon calculations of the relative contribution of each sensor to a ‘total’ response, does not lend itself so readily to analysis of the difference in response between soil layers, which may be simultaneously positive and negative at different locations in the same horizontal plane. Overall, the ECS may be poorly suited to reflect changes in pathway share occurring at below the sensor length scale.

5.4.2. Seasonal and Climactic Factors

Seasonal trends identified in our dataset, particular those for the shallower 5 cm sensor depth, are remarkably strong (Table 5.2, Table 5.3). In introducing the ECS concept, Täumer et al. (2006) analysed the correlation of antecedent soil moisture and other environmental variables with ECS data over 20 rain events across a 1 year period at a water repellent study site in Berlin, reporting that only 35% of variation could be explained by antecedent moisture contents alone. By contrast, correlation of ECS values from the Perth field site with antecedent moisture alone explains 59% of variation among 112 events at the shallower sensor depth, with even greater correlations produced when data was limited to the main breakdown period of a single year (Table 5.2).

Although correlations with antecedent moisture content were significant for both the ECS (Table 5.2) and MMR (Table 5.3), we have chosen to focus instead on relationships with antecedent rainfall, as (despite considerable inter-correlation between antecedent moisture and rainfall variables) correlations with rainfall were significantly stronger in most periods. That rainfall was able to explain more variation in metric values suggests that flow pathway sizes were affected not merely by antecedent moisture (which typically correlated better with shorter antecedent rainfall periods than did MMR values) but by an extended wetting history of soil at that location. In particular, antecedent rainfall totals are likely better able to reflect the influence of factors such as extended periods of partial saturation (Doerr and Thomas, 2000; Urbanek et al., 2015), and opportunities for leaching of hydrophobic substances (Arye et al., 2007; Hardie et al., 2012; Ritsema et al., 1998a) which have been previously found to be significant in generating persistent breakdown of water repellency.
Several additional factors are considered likely to have contributed to the strength of the trends evident in this data, including a short recording interval (5 minutes) and a shallow minimum sensor depth of only 5 cm. Not only were trends in this layer more distinct than those for deeper soil, the capture of responses in this layer was found to be essential in identifying patterns at the less water repellent 15-cm depth, as trends in this layer became apparent only when considered relative to data from the layer above.

The Mediterranean climate of the Perth region, characterised by a hot, dry summer and a cool, wet winter, has likely also contributed to the strength of the seasonal trends identified in this dataset. Previous sensor studies such as that of Täumer et al. (2006) have been primarily limited to temperate or oceanic climates, where rainfall is more evenly distributed throughout the year. A review of the literature shows that although water repellency is recognised as a common phenomenon in Mediterranean climates (e.g., Gabarrón-Galeote et al., 2013; Imeson et al., 1992; Lozano et al., 2013; Zavala et al., 2014), such climates have not been the subject of previous long-term sensor studies of this kind. Nonetheless, the strength of the trends here identified suggest that similar locations may provide a valuable opportunity for further investigation into the factors which influence rates of water repellent breakdown in the field, with the potential to generate schemes providing real predictive power based on weather data alone.

5.4.3. Choice of calibration period

In this study, we have used a one-dimensional model calibrated to match observed field data during a specific calibration period to produce the second 'base case' dataset required to calculate the MMR metric. Although this period was selected to represent the greatest degree of water repellent breakdown identifiable using the existing ECS metric, ECS trends differed between the two layers (see discussion in section 5.4.1 above), thus it is unlikely that ideal wettable characteristics were perfectly represented by this period.

In order to assess the sensitivity of our results to the suitability of this calibration period, two additional model calibrations were performed, using data from late 2010 and 2011 respectively. Both calibrations produced MMR values > 100% for late 2012 (Figure 5.8),
which indicate that observed responses substantially exceeded those predicted by the model. However, other key trends, such as correlation with cumulative rainfall, and relative values at 5 and 15 cm for the various years of study, were substantially preserved by both alternative calibrations. We conclude that the MMR appears to provide a degree of independence from the calibration method or soil parameters used to generate the simulated dataset, provided it is correctly interpreted as a relative, rather than absolute, metric.

![Comparison of MMR results for 2012 at 5 cm when recalculated based on three different soil parameter sets, derived from two alternative calibration periods in 2010 and 2011, in addition to the original calibration (2012).](image)

**Figure 5.8:** Comparison of MMR results for 2012 at 5 cm when recalculated based on three different soil parameter sets, derived from two alternative calibration periods in 2010 and 2011, in addition to the original calibration (2012).

### 5.5. Conclusion

By comparing observed soil moisture variation in a water repellent field soil to a simulated dataset representing uniform wetting conditions, we have quantified how soil responses to rainfall are modified when infiltration is dominated by preferential flow. Use of the resulting MMR metric to examine moisture sensor data from a field site with strongly water repellent
topsoil revealed strong seasonal trends, broadly comparable to those revealed by the existing ECS metric, which quantifies preferential flow in terms of cross-sectional wetting variability. However, the MMR results provided additional insight into some aspects of flow modification obscured using the ECS alone.

In particular, MMR values demonstrated the effect of shallow water repellency, which can result in elevated moisture contents in the subsurface, where it is effectively sequestered against evaporative loss. Analysis of MMR values revealed that observed wetting patterns were most successful in diverting moisture to deeper soil layers in periods where large rain events (> 5 mm) were separated by dry periods of a week or more. These conditions appear to have led to persistent water repellent breakdown in deeper soil layers, while allowing time for surface soil to dry between events, limiting pathway spread following later rain events. Conversely, during a year in which regular rainfall through autumn and winter followed a relatively mild summer, results indicated that water repellent effects may have broken down in surface regions while persisting at depth at some parts of the site. Overall, these observations indicate that variations in inter-annual rainfall regime affect the resulting pattern of water repellent breakdown and emergent flow pathway characteristics. Results also provide evidence to support the theory that water repellency may be particularly effective in conserving moisture in years of relative drought, or following isolated summer rain events.

The MR metric can also be used to compare rates of non-wetting breakdown at individual sensor locations within a site, thus providing a greater degree of precision than existing metrics such as rainfall effectiveness or non-sequential depth response. This may be especially useful for interpretation of data from sites at which only limited numbers of sensors are available.
6. Summary

6.1. Metrics for the spread of flow pathways in water repellent soils

A major component of work reported in this thesis has been the analysis of soil moisture sensor data from four years of recording at a water repellent field site, where infiltration is dominated by preferential flow for the majority of the year. Two metrics have been used to analyse seasonal variation in this data – the existing Effective Cross-Section metric, which quantifies variation among sensors installed at the same depth, and the new Mean Modified Response metric, which quantifies sensor data by comparison to a simulation representing the same soil in a hydrophilic state.

It should be noted that both metrics are inherently better suited to examining change during periods of water repellent breakdown than periods of reestablishment, as both the ECS and MMR are calculated from short-term soil moisture increases following rainfall. In summer, water repellence is expected to increase as soil dries. However, metric values can be quantified only during rain events, which are infrequent, and will serve to interrupt underlying trends. As such, in attempting to identify seasonal trends, we have focused on data recorded during the autumn and winter breakdown periods of each year of study.

Although strong seasonal trends were demonstrated by both metrics, trends were overall stronger for our site when analysed using the MMR metric (Chapter 5), giving improved correlations over the ECS metric with antecedent or cumulative seasonal rainfall. MMR values also produced best fits with a longer antecedent period (120 days for MMR versus 90 days for ECS), reflecting the greater sensitivity of the MMR metric to changes in soil responses which occurred late in the breakdown season. By this stage ECS values and average soil moisture readings between events had largely stabilised.

The MMR metric was especially useful in analysing changes occurring in the 15-cm layer, as the spread of flow pathways in the less water repellent soil at this depth was found to be poorly reflected by measures of flow uniformity alone. Consequently, ECS values for the 15-
cm depth tended to correlate poorly with environmental variables (Chapter 3) and were of less use in identifying how breakdown rates varied with depth (Chapter 5). To identify meaningful trends in subsoil data, it was necessary to consider how rainfall responses varied relative to those in the layer above, rather than relative to responses elsewhere in the same layer. These considerations have been explicitly incorporated into MMR calculations, and are discussed in more detail in section 6.2 below.

Although the ECS metric appears to be poorly suited to analysing pathway spread in shallow wettable sublayers, similar to that found at our field site, it may provide specific advantages in other applications. The ECS does provide an indicator of active flow area that can be easily visualised as the fraction of soil horizontal area responsible for 90% of flow. The ECS may additionally have potential to inform simple modelling efforts based on the use of reduction factors (Ritsema et al., 2005; van Dam et al., 1996, 1990) which have an analogous physical meaning. Additionally, the ECS can be used to quantify seasonal variation without requiring an additional dataset representing the same site in a hydrophilic state.

Conversely, whereas the ECS requires multiple, regularly-spaced readings from within the same soil layer, individual MR values (as opposed to site-averaged Mean MR results) may be calculated from a single reading per depth, allowing behaviour to be compared between multiple discrete locations across a sensor array. Similarly, the MR metric provides the means to examine preferential flow behaviour from installations taking the form of a single, vertical column of sensors, which are a widely-used means to record moisture at distributed locations in landscapes where topography makes the installation of dense arrays impractical (Blume et al., 2009). In this regard, the MR metric specifically improves on existing concepts of rainfall effectiveness or non-sequential depth responses, providing a more precise indicator of both presence and degree of preferential flow.

That the MMR metric would be able to identify such clear relationships between field data during breakdown and simulation data is an interesting result, which may be useful in future attempts to clarify the breakdown process as well as in calibrating tailored modelling solutions for water repellent sites. There is also likely considerable scope for the development of other metrics derived by comparison between field and modelled data,
which may be useful in other applications. These possibilities will be elaborated further in
the recommendations for future work below.

6.2. Soil evaporation and layering effects

6.2.1. Evaporation tanks

Soil water repellency at our field site was shallow, reaching maximum strength in the 0-5 cm
region and transitioning to primarily or wholly wettable soil at 15-30 cm depth. The
presence of wettable subsoils of this type is significant as the spread of moisture below the
water repellent topsoil may produce a counter-intuitive increase in moisture with depth,
and is believed to aid in the conservation of moisture against evaporation. Key objectives of
this thesis were to examine how layered moisture distributions at a site with a water
repellent surface layer develop, and how these patterns impact evaporation rates.

Infiltration patterns observed in our soil tanks (Chapter 4) showed that flow pathways
beneath water repellent surface layers did typically expand on encountering wettable soil,
with pathways often visibly continuing to spread in this region for some days after the event
as moisture drained from regions above. Where soil transitioned abruptly to wettable under
a relatively shallow water repellent layer, pathways spread to the full width of the wettable
layer in most tanks. Where water repellency decreased with depth over a well-graded
transition zone, some lateral pathway spread was observed even in regions of low water
repellency, of MED values of 1.2 M or less (Pathways in tanks containing deep, uniform soil
of this repellency class were also frequently wider than those in tanks in the moderate to
high repellency classes). Evaporation data from the same soil tanks confirmed that these
patterns of infiltration led to considerably lower evaporative losses than those recorded
from fully wettable soil.

Comparative spread with depth was not observed in any tank containing uniform water
repellency in either the medium or high repellency classes (1.2-4.0 M). Infiltration into
uniform WR soil instead remained confined to narrow flow pathways, retaining considerable
moisture in near-surface regions where it would be susceptible to evaporation. Although evaporation from uniform WR tanks was significantly reduced relative to that from fully wettable soil, reductions in evaporation were overall less consistent than that achieved in layered soil tanks, in which moisture could more readily drain from near-surface regions.

6.2.2. Field soil moisture data

In the field, moisture distributions comparable to those observed in the soil tanks were frequently observed, with sensors at the 15-cm depth regularly reporting both greater absolute moisture and stronger responses to rainfall than those at 5 cm, particularly during summer and early autumn (Chapter 5). As water repellency broke down during winter, these patterns gradually disappeared, with moisture contents in the 5 cm region typically overtaking those recorded at 15 cm by the mid to late winter season. Most evaporative benefits provided by the water repellent surface layer earlier in the season would similarly have dissipated by this point, as wetting patterns approached those expected for a wettable soil.

The task of analysing how these moisture patterns evolved through the season was a primarily driver behind the development of the MMR metric. Although responses at the 5-cm depth were consistently less than or equal to modelled responses, responses at 15 cm sometimes exceeded model predictions, possibly because the low water holding capacity of the highly repellent surface zone acted to funnel greater fractions of rainfall input to depth. To identify meaningful trends in sublayer responses, it must be recognised that the responses in this layer will be simultaneously affected by pathway spread within that layer, which will increase as residual water repellence breaks down at this depth, as well as by pathway spread in the layer above, which will modify the fraction of rainfall diverted to the deeper subsoil. Thus, distinct trends in data from this layer were found to be far more readily distinguished by conceptualising responses not as independent by layer ($\Delta \theta_{15cm}$) but relative to those in the layer above ($\Delta \theta_{15cm} - \Delta \theta_{5cm}$). This step was incorporated into MMR calculations.
Conceptualised in this manner, it was possible to identify strong seasonal trends in 15 cm soil responses, comparable and roughly parallel to those at 5 cm. Trends in MMR values at the two sensor depths did, however, vary sufficiently to provide new information on factors which appeared to influence relative rates of breakdown in different soil layers (specific examples of conditions which produced the greatest contrast with model predictions are discussed in more detail in the following section on seasonal variation). Though it is not yet possible to calculate exact evaporative reductions from these figures, results highlight that the breakdown of these patterns is a gradual process which may continue throughout the winter season. As such, it is surmised that some degree of evaporative benefit produced by water repellency can persist well into the winter season.

Previously, we have noted that distributions of water repellency observed at our field site appear to be remarkably well-engineered to best conserve moisture against evaporation. The strong water repellence of the surface layers is clearly beneficial in that it limits the lateral spread of moisture in near-surface regions where it is more susceptible to evaporative loss. It is also surmised that strongly water repellent surface soil will be able to maintain some degree of water repellence longer into the winter breakdown season, thus prolonging the duration of evaporative benefits. The presence of a wettable sublayer allows pathways to propagate more rapidly, reducing moisture storage and residence times in the shallow region, thus limiting opportunities for further breakdown and pathway spread near the surface (Note that infiltration into tanks containing uniform moderate to highly water repellent soil took 1-5 hours to reach depths of 5 cm, whereas moisture infiltrated rapidly into less water repellent soil – see Chapter 4 for detail).

Verboom and Pate (2006) suggest that soil water repellency reflects a means by which plants engineer their environment to their own advantage. While it is tempting to take the apparently well-engineered distribution of water repellency as evidence of evolutionary adaptation, it should be recognised that the production of hydrophobic chemicals usually provides more direct benefits to plants in environments such as this, such as by reducing moisture loss from leaves, and that the concentration of water repellence in soil surface layers may be explained by the greater organic matter content which is typical of surface
soils. Nevertheless, our data show real evidence that significant evaporative benefits are provided to extant vegetation by the soil water repellency phenomenon.

6.3. Seasonal variation and the role of rainfall regime

The four years of high-frequency soil moisture and rainfall data collected in the course of this study provide valuable insight into the effect of rainfall patterns on water repellent breakdown and reestablishment. In general, periods of regular rainfall were associated with the progressive decrease of detectable water repellent effects, whereas water repellent effects were strengthened following periods of hot, dry weather.

Data does not, for example, suggest that water repellency reached its peak only a short time after wetting commenced, as has occasionally been reported at other sites (e.g. DeBano, 1981; Oades, 1992), or that preferential flow was more likely to occur following rain events of high intensity, as has similarly been reported (e.g. Täumer et al., 2006; Lin and Zhou, 2008; Hardie et al., 2013; Wiekenkamp et al., 2016). Breakdown trends typically continued as long as regular rainfall continued, with little indication that affected features regularly reached annual 'maximum' or 'minimum' states, beyond which additional rainfall would be unable to further increase pathway share. In excess of 400 mm of rainfall appeared to be required to bring ECS values close to the effective maximum of 80%, while MMR values reached 80% of modelled predictions only after more than 500 mm total rainfall, or following 300 mm in a year following an unusually wet summer (2012). Only during one limited period from May-July of 2013 was there any evidence that pathways substantially receded at any location during the autumn-winter breakdown period (Chapter 3) affecting readings from 4 adjacent sensors out of the 20 total. Flow pathways over these sensors were subsequently re-established during a series of larger events (> 20 mm) in July, with typical seasonal trends continuing thereafter.

The specific importance of antecedent rainfall as a driver for water repellent breakdown was also demonstrated by comparing correlations between metric values and either antecedent rainfall or antecedent soil moisture. Although soil moisture has been widely
used to explain variation in indicators of water repellence in past studies, antecedent rainfall was found to produce significantly better correlations with MMR values, and typically slightly better correlations with ECS values (Chapter 5). This observation likely reflects that antecedent rainfall totals provide a better indication of soil wetting and drying history, with repeated or extended wettings producing greater opportunity to stabilise the breakdown process. If hydrophobic compounds displaced during wetting are removed as water drains, or are unable to re-establish bonds soil particles when soil dries, this would explain why moisture contents alone might be less useful as a predictor of metrics of water repellency.

Some degree of water repellence did appear to return relatively rapidly over spring drying periods of 2-3 weeks or more, as soil responses to isolated rain during late spring or summer were typically muted. However, the reestablishment of water repellence in early spring was susceptible to interruption by significant periods of spring rain, as occurred in late 2011 and 2012, resulting in rapid pathway spread if rain events continued. Where regular rainfall continued uninterrupted through spring into late October (2013), breakdown trends similarly continued without interruption. These observations support the theory that prolonged periods of hot, dry weather are necessary for the establishment of strong, persistent water repellence.

Although broad patterns of breakdown were similar in all rainfall years of study, rates of breakdown also appeared to be sensitive to interannual variations in weather regime. In descending order of importance, the following factors affecting one or both hydrophobic breakdown metrics were identified:

1. **Cumulative autumn/winter rainfall by date.** Breakdown trends began earlier in years where significant autumn rainfall occurred earlier in the season, and breakdown indicators demonstrated remarkably strong linear relationships with cumulative rainfall, typically reaching higher maxima in years of greater rainfall totals. Although rates were also affected by factors discussed below, results suggest that water repellent breakdown stage might be predicted to a reasonable degree of
accuracy using cumulative rainfall data alone (Chapter 3, Chapter 5).

2. **Total rainfall occurring during the previous summer.** In years where significant rainfall was recorded over spring and summer from October to February, the availability of the hot, dry weather necessary for strong water repellent reestablishment is significantly truncated. As a result, water repellency appears to break down considerably more rapidly in the following winter (Chapter 3, Chapter 5).

Breakdown rates also appeared to be somewhat influenced by rain event spacing, presumably as significant gaps between rain events provided some opportunity for soil to dry and for some degree of water repellency to re-establish:

3. **Daily rainfall intensity.** In 2011, a year of an unusually short, intense winter season (average rainfall 4.2 mm/day), breakdown relative to cumulative rainfall was more rapid than in other years (average rainfall 3.3 mm/day or less). As such, better agreement in breakdown rates in different years was found when considering breakdown in terms of 90-120 day antecedent rainfall, as this measure could better represent variations in recent rainfall history than the cumulative winter total (Chapter 3). (Note that as both cumulative rainfall and average event frequency increased steadily through most winters, overall trends were not otherwise greatly affected.)

4. **Duration of dry periods between events.** Although the preceding factors affected breakdown similarly in both layers, gaps between events appeared to be capable of altering relative breakdown rates between the two layers. During periods where significant rain events (>5 mm) were separated by dry periods of at least a week, rainfall responses were found to be unusually pronounced at the deeper sensor depth (15 cm) but muted at the shallower depth (5 cm). We surmise that weather patterns of this nature provide sufficient rainfall for some sustained breakdown of water repellency at depth, while gaps between events were sufficient to dry surface soil and produce some limited reestablishment of water repellency near the surface.
Conversely, periods characterised by regular, small rain events may have produced persistent breakdown of water repellency in surface soil, limiting the moisture able to reach deeper layers, and thus reducing the opportunity for breakdown at greater depths (Chapter 5).

Conditions provided by this last case, where large rain events are separated by moderately long dry periods, may present the circumstances in which soil is best able to trap and conserve moisture against evaporative loss. While data is not yet sufficient for precise benefits to be estimated, the ability of water repellent surface layers to divert moisture to deeper layers has been shown to be key to its ability to minimise evaporative losses (see Section 6.2 above). These findings raise the possibility that the fraction of total rainfall retained in years where rainfall regimes produce very different breakdown patterns may differ considerably. For example, it is possible that a year like 2012, which experienced moderate total rainfall following a very wet summer, could produce lower overall deep drainage from the rootzone beneath some native bush regions than a year like 2010, in which rainfall occurred as a series of well-separated winter events following a very dry summer, despite the significantly higher total rainfall received in 2012 (676 mm total for 2012 as compared to only 555 mm total in 2010).

Overall, seasonal trends in our data were far more pronounced than those which have been reported in previous studies, particularly that of Täumer et al. (2006) who introduced the ECS metric. This likely reflects the differing climates of the two sites. The work of Täumer et al. (2006) took place near Berlin, Germany, having a continental or oceanic climate, with rainfall well-distributed throughout the year, and thus lacking the very dry Mediterranean summer characteristic of much of south-west Western Australia. The two sites differed also in the depth of the water repellent layer, which Täumer et al. (2006) reported as reaching maximum strength at around 15-cm depth, decreasing to wettable only below 35 cm deep, whereas water repellence at the Shenton Park site reached a maximum between 0 and 5 cm, reducing steadily with depth thereafter, and transitioning to wettable by around 30 cm depth.
It is also possible that the differing recording frequencies (1 hour versus 5 minutes) or the differing minimum sensor installation depth (10 cm versus 5 cm) may also have enhanced the clarity of relationships with other environmental variables identifiable in our ECS results. These factors may become useful considerations in planning of similar studies in future.

Past authors have noted that soil water repellence may influence ecosystem responses to extreme climactic events such as droughts, though opinions have differed on whether those impacts are likely to be positive (Robinson et al., 2010; Verboom and Pate, 2006) or negative (Goebel et al., 2011) in character. The results of this study indicate that drought-enhanced soil water repellency can reduce losses to evaporation in years of maximum moisture stress, thereby providing an increased resource for plant transpiration. Further research into the impacts of feedback effects associated with soil water repellency in the field could be invaluable to our ability to predict ecosystem responses to varying climate trends.
7. Conclusions

Work reported in this thesis presents considerable new insight into the seasonality of soil water repellency in a Mediterranean environment. Data collected over 4 years of study demonstrates that broadly regular patterns of breakdown recur in most rainfall years, but also that breakdown is sensitive to variations in interannual rainfall regime. Unusually wet summers limited the opportunity for the reestablishment of water repellency, leading to faster breakdown of water repellency over the following winter. Similarly, the magnitude and spacing of rain events appeared to influence the degree to which water repellence either broke down or re-established in different layers of the soil profile.

The new MMR metric, which quantifies wetting patterns by comparison to the predictions of a 1D hydrological model, was demonstrated to be a useful tool for identifying patterns in field moisture data, revealing specific features which were obscured by existing metrics for quantifying preferential flow. Taken as indicators of seasonal variation, MMR values expressed remarkably linear relationships with antecedent rainfall, raising the possibility that water repellent effects may be predicted at similar sites based on rainfall data alone. Seasonal trends identified at our site were significantly stronger than those which have been reported at comparable sensor installations in oceanic climates elsewhere in the world, which likely reflects the strong seasonality of the Mediterranean climate.

A shallow minimum sensor installation depth and high-frequency recording interval may also have contributed to the strength of the trends identified. Sensor data at the 5-cm depth was much more strongly correlated with environmental variables, particularly cumulative or antecedent rainfall. Additionally, capturing the behaviour of moisture in this layer was found to be essential to understanding responses at the 15-cm depth, which showed clear trends only when considered relative to behaviour in the layer above.

Results highlighted the significance of the vertical distribution of water repellency through the soil profile. As strong water repellency was limited to a shallow surface layer, pathways were able to spread and drain into the less water repellent soil beneath, producing average
moisture contents which often increased with depth. Evaporation experiments confirmed
that these patterns were highly effective in conserving moisture against evaporative loss,
with soil tanks containing analogous distributions of water repellency losing 65-75% less
moisture than did wettable controls over an 8 day period between rain events. Significant
reductions in evaporation were also recorded from soil tanks containing shallower water
repellent soil layers and uniform water repellent soil of varying classes. However, tanks
containing distributions of water repellency which mimicked those recorded on site were
found to be most effective at preferentially distributing moisture to deeper soil layers, and
thus reducing net evaporation.

Results from these evaporation experiments supported the supposition that water repellent
soil will aid in minimising evaporative losses following isolated summer rain events or
periods of drought, when water repellence and moisture stress coincide as their peak.
However, sensor data also suggested that the system might also be able to produce
substantial evaporative benefits in periods where rain events of significant magnitude were
separated by dry periods of at least a week, delivering significant infiltration to depth while
allowing time for surface soil to dry and re-establish water repellence between events.
Through winter, the ability of water repellent surface layers to trap moisture in deeper
layers declines as flow pathways in near-surface zones spread, but as this process is gradual,
some degree of evaporative benefit may persist well into the winter season.

A major finding is that the fraction of rainfall lost to evaporation may vary considerably in
different rainfall years due to different patterns of water repellent breakdown and
reestablishment. This in turn depends on variations in weather of that year, with potential
ramifications for net deep drainage losses and subsequent soil water availability. Further
study into this area would aid to clarify the manner in which soil will respond to varying
rainfall regimes in future, and how evaporative losses may differ depending on the degree
and distribution of water repellence present in the soil.
7.1. Recommendations for future work

In the previous chapters, we have examined the impact of water repellent surface layers on bare soil evaporation, seasonal wetting patterns at a water repellent field site, and the relationship between the recorded moisture sensor data and a one-dimensional simulation representing moisture dynamics under hydrophilic conditions, quantified using the new Mean Modified Response or MMR metric, as well as an existing metric, the Effective Cross Section or ECS.

The strength of correlations discovered between both metrics and antecedent rainfall variables is encouraging, as it suggests that rates of water repellent breakdown might be predicted to some degree of accuracy based upon rainfall data alone. Better predictions might be achieved using multiple regression techniques (as discussed in Chapter 3), incorporating other antecedent weather variables such as potential evaporation or rain event intensity, indicators of the severity of the preceding summer season, or other factors which appear to be significant sources of annual or inter-annual variation. Further work will be necessary to determine whether the same methodology would reveal similarly strong correlations when applied to data from other sites, of either similar or differing climates.

Considerable scope exists to expand the concept of the MMR metric to alternative points of comparison between modelled data and observations of preferential flow phenomena in the field. While both the ECS and MMR metrics have been designed to quantify variation between different rain events, either metric could also be adapted to quantify change occurring over the duration of a single rain event. Our own data suggest that agreement between field data and modelled predictions generally improves over the course of extended rain events, with the time of maximum moisture typically occurring later in field data than was predicted by the model. Such analysis could also shed light on degrees of partial or temporary water repellent reestablishment which occur between rain events, and the process of breakdown and pathway spread over shorter timescales.

Similarly, although the MMR has been calculated based on measures of the maximum change in soil moisture following rain, a variety of other indicators might be substituted as
points of comparison between modelled and observed behaviour. Obvious candidates include the maximum depth reached by infiltration (which may be enhanced by preferential flow), or the timings of first response to rain, or of event maxima (both of which occurred later in field data than model predictions). Finally, although we have only briefly considered the variability of individual MR values from different locations across the site, these should converge as breakdown progresses, providing the basis for another potential breakdown metric. Any of these methods might provide useful additional insight into facets of the breakdown process.

Another technique might be to use these metrics to examine scheduled irrigation events of a defined duration and intensity, which might be repeated through the year to produce a more consistent baseline than that provided by variable natural rainfall. The possibility of using the MR metric to analyse responses from a single vertical sensor column has already been raised in previous chapters, which would provide a more detailed indicator of preferential flow occurrence than has been possible using existing techniques.

As previously discussed in section 2.5, one-dimensional models may produce better representations of preferential flow using by incorporating static or dynamic flow-reduction factors, which allow the active flow area to vary with depth. The ECS metric provides a method by which active flow area may be approximated directly from sensor data, and it would be useful to establish whether model predictions might be improved by taking ECS values as reduction factors for the same rain events. While it is unlikely that the full complexity of flow in a water repellent soil could be well-represented using reduction factors alone, the prediction of simple variables of interest, such as maximum infiltration depth after rain, should be significantly improved.

The same scheme might also allow us to estimate effects on evaporation at various stages of water repellent breakdown, and by modelling evaporation during a number of rain events over the year, a first estimate of annual impacts on evaporation might be produced. This could provide considerable insight into the degree to which water repellency is able to buffer ecosystems against the effects of drought, or, for example, the impacts of the use of water repellence amelioration techniques on subsequent soil evaporation.
Although the development of models capable of accurately representing flow in water repellent soils in multiple dimensions will doubtless continue in the near future, it is the opinion of the authors that the creative use of existing and widely available modelling solutions such as those discussed above still has much to add to the field.
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140


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