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Repellency-induced runoff from New Zealand hill country under pasture: A plot study

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ABSTRACT

Soil water repellency is a common phenomenon which develops when surface soils become dry in summer and autumn. It is claimed that repellency is likely to result in a lower infiltration rate and a concomitant increase in surface runoff, particularly on slopes. This study quantifies the effect of water repellency on runoff from a series of small plots on a range of slopes (20° and 30°) and aspects (N, S and E) in a hilly landscape in the south-east of the North Island of New Zealand. The plots (1 m wide and 2 m long) were set up to capture runoff via a slotted PVC pipe and measure it using tipping bucket apparatus: at each of the slope/aspect locations there were duplicate plots. A meteorological station was also established at the site along with TDR probes to measure soil moisture down to 300 mm depth. When moist, the soil at the site had a very high infiltrability (> 1.5 mm/min). On nine occasions, runoff was measured (ranging from 1 to 59% of rainfall) when the soil surface was dry and rainfall was intense (greater than 0.1 mm/min). However, during the two-year study period, this repellency-induced runoff equated to only 5% of the total rainfall. Furthermore, the infiltration rate of initially dry, repellent soil (ranging from 0.2 to 0.6 mm/min) partly recovered over a ten-minute period (0.6–1.0 mm/min) and, with sufficient rainfall, repellency completely disappeared within two days. The transitory nature of water repellency was confirmed in an experiment on large soil slabs conducted in the laboratory where repellency-induced runoff was observed to largely disappear over a period of 30 min. Overall, it is concluded that soil water repellency does not play a major role in the soil water balance of the hill country at the study site.

1. Introduction

Soil water repellency is a common and much-studied phenomenon (Dekker et al., 2005). Deurer et al. (2011) found that 98% of the 50 North Island of New Zealand pasture soils they studied became hydrophobic when dry. As in many other studies, they used the Water Drop Penetration Time (WDPT) and Molarity of Ethanol Droplet (MED) tests to identify repellency. Both these tests measure the time taken for the absorption of a drop of liquid, usually into a small sample of sieved soil. While useful for exploratory investigations, the drop-size scale of the WDPT and MED tests disqualifies them from contributing useful information about what happens at larger scales in the field.

In an extensive review, Doerr et al. (2000) states that among the major hydrological impacts of repellency are "increased overland flow, …. enhanced streamflow responses to rainstorms, and enhanced total stream flow". In an earlier review, Wallis and Horne (1992) similarly suggested that the "influence of repellency upon runoff…. deserves more attention, considering both the on-site and downstream consequences." However, there are few studies of such impacts, particularly on soils under pasture.

The study that comes nearest to addressing the effect of repellency on runoff from pasture soils in a detailed manner is that of Jeyakumar et al. (2014) which used the runoff measurement apparatus (ROMA) that they developed. They brought large rectangular slabs of intact soil under pasture into the laboratory, let the slabs dry out, then set them on a 5–20° slope and applied liquid at the top of the slope via eight hypodermic needles at a rate of 1 mm/min (if averaged over the area of the slabs). They applied both water and a 30% v/v water-ethanol solution. Measurements included runoff from the slabs and drainage through the slabs as a function of time. For three of the four New Zealand soils studied, they found similar runoff rates after the first five minutes of 56%, 57% and 64% of the water application rate, dropping to 10% of the application rate after 25, 42 (Recent soils) and 51 min (Gley soil). The fourth soil was an organic soil which became highly

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repellent, with more than 90% of the applied water lost as runoff over the 60 min of the experiment. There was no runoff at all from all four of the soils when the water-ethanol mixture was applied, confirming that it was repellency causing the runoff. Their paper suggests that initially, repellency can cause over half of a heavy rain event to be lost as runoff, although after an hour of further wetting this repellency-induced runoff has effectively stopped. However, the ROMA apparatus differs from the field situation in two important aspects; the manner in which the water is applied, and the soil depth. It is not clear how these differences affected their results. The issue of scale also remains. Would a larger area of soil behave similarly?

A field study by Gillingham and Gray (2006) avoided the uneven water application and shallow soil depth problems mentioned above, and was on a larger scale. They installed twelve, 4 m long runoff collector troughs in a hill country catchment. The runoff went into containers (200 L) and was measured manually after each runoff event. They also measured topsoil water content at monthly intervals. The runoff collection area above each trough was not delineated, so their results can only be interpreted in a general way. Over the 20 months of their study they observed just four larger runoff events and eight smaller ones. They state that “volumes of runoff were highest in the period from early summer to late autumn and inversely related to soil moisture content”, suggesting that repellency was the major mechanism producing this runoff.

A third study pointing to the occurrence of repellency-induced runoff from hill country under pasture is that of Bretherton et al. (2010) which focussed on a soil water balance. On three occasions over the two-year period of the study, substantial runoff was measured from rainfall events which occurred when water balance calculations indicated that there was less than 2.5 mm of available water in the top 50 mm of soil. It is probable that most of this runoff was due to repellency.

In some ways, the three studies described raise more questions than answers, but all indicate that further work on repellency-induced runoff from hill country under pasture is warranted. This paper attempts to address some of these questions by reporting on repellency-induced runoff from 2 m^2 plots with the following objectives: the quantification of repellency-induced runoff as a fraction of rainfall, and the quantification of changes in the infiltration rate of a water-repellent soil during the early stages of a heavy rainfall event.

2. Site description and methodology

2.1. Site description

The runoff plots were established on a pastoral sheep and beef farm near Alfredton on the southern east coast of the North Island in New Zealand (40° 38.651′ S, 175° 53.881′ E, with an elevation of 200 m). Thirty-year (1980–2010) annual average rainfall and ten-year (1995–2005) average daily temperature values are 1234 mm and 12.5 °C, respectively. Winter climate conditions are often cold and wet, and summer rainfall is unreliable, with 12–34% of the annual rainfall falling during December through to February. Therefore, the surface soil in the area is often dry in late spring and summer. A more detailed description of the site is provided by Bretherton et al. (2010).

Plots (2 m down slope, 1 m across slope) were grouped as adjacent pairs at six locations within two sub-catchments, each plot being bordered to prevent on-flow from uphill and adjacent surface areas. The location of the plots is shown on the aerial photograph in Fig. 1. A PVC pipe with a slot cut along its 1 m length was located at the bottom of each plot to collect surface runoff (Bretherton et al., 2010). This was directed to a tipping bucket system which had been calibrated so that the volume tipped was calculated as a function of the tip rate. Plot labels describe the slope (20°, 30°), aspect (N, S, E), and whether they were on the left or right (L, R) looking uphill.

Detailed soil profile examinations on the N and S aspects revealed that the soil at the site is a mottled orthic recent soil (Hewitt, 1998) with silty clay loam texture. Pronounced mottling in the subsoil below 350 mm depth indicates impeded drainage and the intermittent presence of a perched water table. The soil was visually similar at the two aspects so would be expected to have similar hydraulic properties (and infiltration behaviour) across the site. The soil has developed from uplifted mudstones and siltstones of Tertiary and late Cretaceous age, with high erosion rates preventing the formation of a more mature soil. Soil fertility analyses (0–75 mm depth) indicated a low pH regime (5.1–5.4) with Olsen P indicating a range of fertility values (16.0–35.8 μg P/g).

The pasture was diverse (Sanches, 2009) with the grass species (83% of pasture composition) dominated by browntop (*Agrostis capillaris*), followed by crested dogstail (*Cynosurus cristatus*) and then by perennial ryegrass (*Lolium perenne*). Legumes averaged 9% of pasture composition, dominated by subterranean clover (*Trifolium subterraneum*), followed by white clover (*Trifolium repens*). The remaining pasture composition consisted of weed species.

2.2. Methodology

Four meteorological stations were installed at the research area to record; rainfall, air temperature, humidity, wind run, and short wave solar radiation at 2 m above ground level. Daily averages and/or totals were recorded for these variables, except for rainfall which was logged whenever 0.2 mm of rain fell. The primary purpose of monitoring climate variables was to enable the calculation of a daily soil water balance which will be described in a following paper. In addition to climate variables, the data loggers also recorded the runoff from the plots, as well as daily 0–300 mm depth volumetric soil water content values from Campbell Scientific (Logan, Utah) CS616 TDR probes installed in the N and S plots. During the course of the experiment the raw attenuation output from the TDR probes was calibrated against occasional volumetric water content values calculated from bulk density and gravimetric soil water content measurements at 300 mm depth, taken at 50 mm intervals. The climate data, TDR, and runoff data were logged using Campbell Scientific (Logan, Utah) CR1000 data loggers. Rainfall and runoff data are expressed as depth per unit horizontal surface area. Unfortunately, until the problem was identified and solved, the proximity of electric stock fences was responsible for frequent data losses from the loggers during the early stages of the experiment.

Bulk density values for the 0–50 mm depth of soil from each site were highly variable, ranging from 568 to 1095 kg/m^3. Bulk density increased with depth so that at 300–350 mm, a range of 1298–1563 kg/m^3 was observed. As there was no obvious correlation between bulk density and location, average bulk density values for a given depth were used to convert gravimetric water contents to their volumetric equivalents.

Water drop penetration time (WDPT) and molarity of ethanol droplet (MED) tests were not used routinely to measure water repellency, due to their small spatial resolution and the potentially high spatial variability of these measurements across the dimensions of the runoff plots. However, one set of WDPT and MED measurements was undertaken in order to assess the potential repellency of the surface soils (0–40 mm) at each of the runoff sites. The sampling and measurement techniques described by Deurer et al. (2011) were adopted. Classification of persistence class was then determined according to Dekker and Jungerius (1990) and ranged from 2 (strong) through to 3 (severe). Calculation of droplet contact angles, as described by Roy and McGill (2002), resulted in values that ranged from 95.9° through to 100.2°. All contact angles were greater than 90°, indicating that the 0–40 mm surface soils at all sites exhibited potential for water repellency. Furthermore, once established, water repellency is likely to have been strongly to severely persistent (Dekker and Jungerius, 1990).

Laboratory scale experiments employed the ROMA apparatus