ROMA: A NOVEL LABORATORY APPLIANCE TO QUANTIFY HOW WATER REPELLENCY AFFECTS SOIL WATER DYNAMICS

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Introduction

Soils are normally thought to wet readily under rainfall or irrigation. In hydrophobic (water-repellent) soils, wetting is inhibited, resulting in reduced infiltration rates in severe cases by several orders of magnitude. The environmental impacts of this phenomenon include enhanced run-off, which can contribute to flooding; accelerated soil erosion by water; enhanced preferential flow and associated leaching of nutrients and pesticides (Aslam *et al.* 2009); and reduced seed germination and crop growth (Doerr *et al.* 2000). A large number of agricultural areas in New Zealand have hydrophobic soils, with associated economic and environmental consequences which are still unclear. A recent survey across the North Island of New Zealand covering all soil orders under pastoral land-use found that most soils exhibit SWR when dry out below the critical water content (Deurer *et al.* (2011).

Only a few studies have attempted to quantify the influence of SWR on run-off, directly. Therefore, we developed a laboratory-scale run-off measurement apparatus (ROMA). The ROMA was designed to assess the influence of SWR on the run-off behaviour of an undisturbed soil slab (460 mm long x 190 mm wide x 50 mm deep) subject to run-on at a specified rate. ROMA allows the separate and simultaneous collection of run-off and drainage water. The equipment can simulate run-on at different intensities (e.g. 40-65 mm/hr) to a slab at variable slope angles (15-30^0). In the experiment we compare, the run-off resulting from the run-on of water and of ethanol solution. Due to its low surface tension, ethanol solution is not affected by SWR and serves as the reference. The aim of this study is to evaluate the technical performance of the ROMA and to quantify the impact of SWR on surface run-off from two different soil types at a laboratory scale.

Methods

Evaluation of the technical performance of the ROMA

We conducted all run-off experiments with water followed by a fully-wetting liquid, namely a 30% (v/v) ethanol solution. We determined the molarity of the ethanol solution necessary to overcome the impact of SWR on infiltration via a preliminary study. We found that a 30% (v/v) ethanol solution was needed to ensure soil hydrophobicity had no influence on the penetration rate of the liquid.

We then evaluated that the run-on rate of both water and the ethanol solution was equivalent to a rainfall rate of 60 mm/h. We also measured the run-off rates and expected them to be identical to the run-on rates, as these experiments were run without soil slabs. We achieved a

60 mm/h run-on rate for water and the ethanol-water solution by using the following materials and settings (Figure 1), which were then also used in the experiments:

- 20G 1-inch needles (BD PrecisionGuide™ Needle, Australia)
- Pressure head for water with a height of 12 cm and with 27 cm for the ethanol solution
- Soil-slab was placed at a 20° slope

We evaluated the performance with these settings in multiple consecutive experiments, separately for water and the ethanol solution. The duration of each test was one hour, identical to the duration of the actual run-off experiments with soil slabs. In three tests, the run-on volumes of water or ethanol solution from each needle were collected at 10-minute intervals. In eight tests, the run-off volumes of water or ethanol solution were collected at 10-minute intervals.

After calibrating the ROMA for constant water and ethanol solution run-on rates, experiments were conducted with soil slabs placed in a perforated tray that was set to a 20^{o} slope (explained later). The homogeneity and reproducibility of flow rates produced by ROMA were confirmed by running repeated run-on tests in between any consecutive run-off experiments with soil slabs. These tests were conducted without soil slabs.

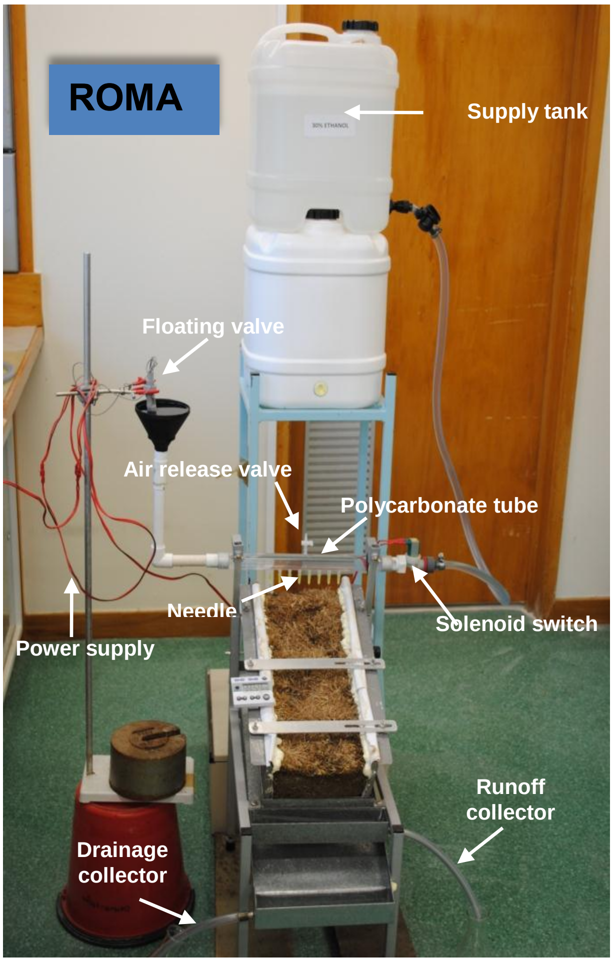

Figure 1. Run-off measurement appliance (ROMA) in operation.

Setting up the run-off experiments with ROMA

A soil slab is collected in the field and shaped to the chosen dimensions (460mm long x 190mm wide x 50mm deep) in order to fit in a perforated tray. Side plates and rubber liners are put on either side of the sample, and clamping bars tighten the whole installation. We also used rubber-foam liners and expanding foam between the soil slabs and the side plates to prevent any side leakage during the run-off. The perforated 'soil sample tray' can be adjusted to different angles, and an 'infiltration flow tray' is installed under it to collect the leached water below a soil depth of 50cm. An infiltration flow trough (drainage collector), and an overland flow trough (run-off collector), can respectively collect the drained and run-off of water, or ethanol, during the experiment (Figure1). For the experiments we collected several soil slabs at the end of summer 2010/11 from two sites in Taranaki and Hawkes' Bay. These soils belong to the soil orders Organic and Recent, respectively, and in a survey we had previously identified that both the degree and persistence of SWR were high.

Soil sampling and soil slabs preparation: Samples of bulk topsoil (depth, 0-50 mm) and six undisturbed soil cores (45 x 50 mm inner diameter) were collected at the end of summer 2010/11 at each of the 2 sites (n=12). The topmost 30-40 mm of the mineral soil was sieved (< 2 mm) prior to analysis. Undisturbed soil slabs (3 replicates) were randomly collected near the soil sampling sites, transported to the laboratory. We cut the pasture on the slabs to a height of 0.5 cm, air-dried, and then weighed the soil slabs in the laboratory before starting the experiments.

Measurement of soil properties and SWR: We measured the bulk density and volumetric soil water contents, using standard methods. Soil organic carbon (SOC) content was determined by the Dumas method for %C and %N using a 'Leco Truspec' instrument. In addition, soil samples were analysed for pH using a Hanna HI 9812 pH meter. The potential (pot) and actual (act) persistence of SWR was measured with the water drop penetration time (WDPT) test (Doerr 1998). The degree of SWR was determined using the molarity of ethanol-droplet (MED) test and the results were quantified in the form of the contact angles (CA) between the drop of the aqueous ethanol solution and the soil surface (Roy and McGill 2002).

Initial and boundary conditions for each run-off experiment: A soil-slab was placed at a 20° slope and water or ethanol was applied at a 60-mm/h run-on flow rate to the top end of the soil slab. Each run-off experiment lasted for 60 minutes. Firstly, for each site, three experiments with three soil slabs were conducted using water. The soil slabs were allowed to dry at room temperature and were weighed daily until the weight was equal to the initial weight (before starting the run-off experiments) of the slabs. We then used the same three slabs, using the ethanol solution as run-on liquid. The total volumes of run-off and drainage were measured in 5-min intervals.

Results and Discussion

Technical performance of the ROMA

Figure 2 shows that the run-on rates of the individual needles for water and the ethanol (30% v/v/) solution were constant. Within each experiment, the maximum deviations of the 10-minute intervals did not exceed 1.5 and 1.78% for water and the ethanol solution, respectively. The minimum deviations were 0 and 0.06% for water and the ethanol solution. In addition, the reproducibility of the experiment was high. The standard error for the 10-minute intervals was on average only 0.39% of the mean for the water run-on rate, and 0.5% of the mean for the ethanol solution run-on rate.

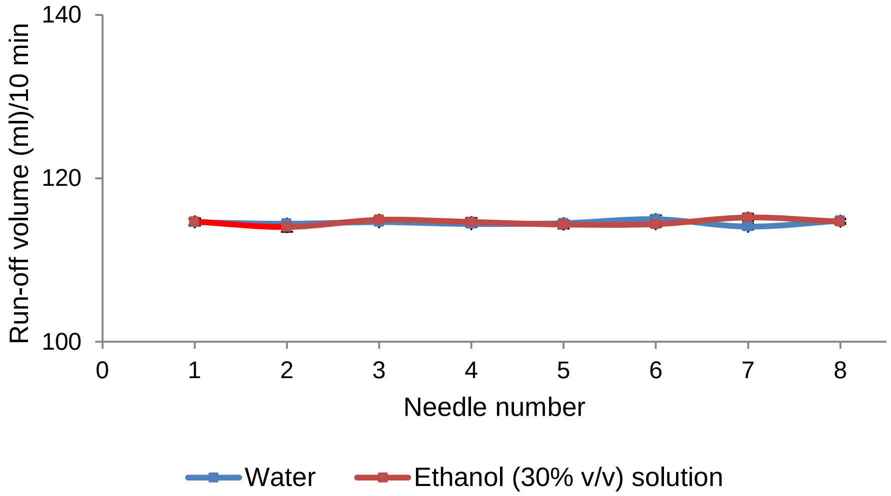

Figure 2. Reproducibility of ROMA run-on rates during 60-minute experiments using water or an ethanol (30% v/v) solution. The bars denote the standard errors of the measurements (n=3).

Figure 3 shows that the run-off rates for water and the ethanol solution were constant during the duration of an experiment. Within each experiment, the values of the 10-minute intervals deviated by 0.01% (minimum) to 0.83% (maximum) for water and by 0.08% (minimum) to 0.9% (maximum) for the ethanol solution. In addition, the reproducibility of the experiment was high, as the standard error for the 10-minute intervals was on average only 0.2% of the mean for the water run-off rate and 0.21% of the mean for the ethanol run-off rate.

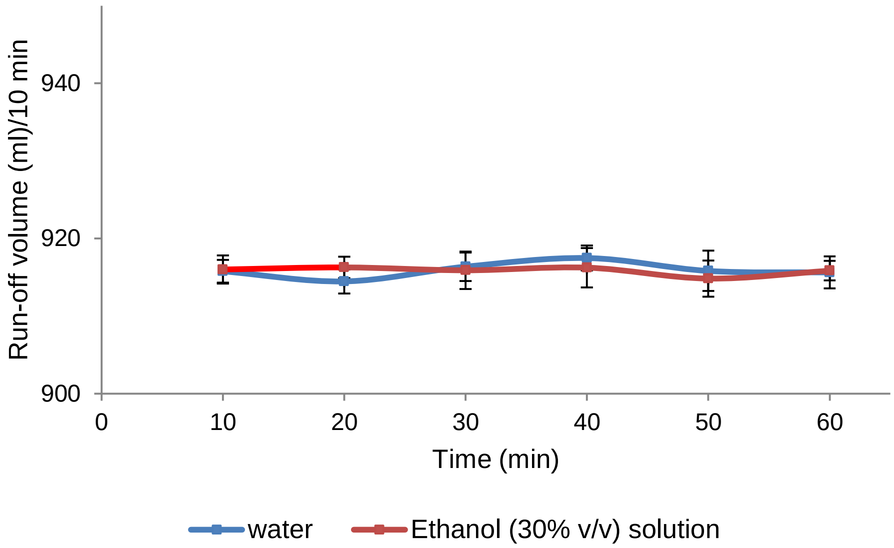

Figure 3. Reproducibility of ROMA run-off rates during 60-minute experiments using water or an ethanol (30% v/v) solution. The bars denote the standard errors of the measurements (n=8).

The repeated run-on tests (n=3, without soil slabs) in between any consecutive run-off experiments with soil slabs confirmed the homogeneity and reproducibility of flow rates produced by ROMA. For water, the deviations from the expected cumulative run-off ranged between 0.01 and 0.3%, and for the ethanol solution between 0.04 and 0.2%.

In conclusion, the ROMA was thoroughly tested. Therefore, we have developed a robust and reproducible method which performs at a high standard with methodological errors below 1%.

Run-off experiments with ROMA

Soil properties and SWR of the experimental sites: Table 1 provides an overview on generic soil properties of the two sites selected for our experiments. It also gives the SWR measurement parameters of these soils. The soil organic carbon (SOC) content was significantly higher for the Organic Soil (21.9%) than the Recent Soil (13.2%). The bulk density and pH did not differ much between two soils (Table 1). With regard to the potential persistence and degree of SWR, the Organic Soil was significantly higher than the Recent Soil. These results are in well agreement with our previous survey (Deurer *et al.* (2011) in the same sites. In our survey, organic carbon (and nitrogen) content was positively correlated with SWR.

Table 1. Soil properties and SWR of the soil orders Organic (Taranaki) and Recent (Hawke's Bay) under pastoral land-use (top 4 cm of the soil) used for the run-off experiments. Values in rows followed by different letters are significantly different ($P \le 0.05$)

Properties	Recent Soil	Organic Soil
Contact angle (°)	96.9 (±0.4)b	103.54 (±0.3)a
WDPTpot (s)	2500 (±254)b	13860 (±1499)a
WDPTact (s)	1(±1)b	5490 (±623.6)a
Volumetric water content (%)	56.4 (±2.5)a	27.2 (±0.4)b
Organic carbon content (%)	13.2 (±0.8)b	21.9 (±0.8)a
Organic nitrogen content (%)	1.2 (±0.1)a	1.4 (±0.1)a
C/N ratio (-)	11.2 (±0.4)b	16 (±0.2)a
pH (KCl) (-)	4.5 (±0.1)a	4.7 (±0.1)a
Bulk Density (g/cm^3)	0.67 (±0.01)a	0.63 (±0.02)a

Run-off and drainage of water and ethanol solution: The run-off and drainage volumes of water or the ethanol solution collected at each sampling time are illustrated in Figure 4. The relatively small standard errors at individual sampling times (0.7 to 9.8%) that we derived from the three replicated soil slabs indicate both a good reproducibility of our experiments, and a small variability between slabs.

The experiments with the ethanol solution as run-on liquid reflect the wetting-up behaviour of a hydrophilic soil. The first important thing to notice for the experiments with the ethanol solution is that no run-off occurred from both soils (Figure 4). Therefore, it did not exceed the infiltration capacity of any of these soils. This is a direct proof that SWR was the only factor generating run-off at both sites. Secondly, the basic shape of the drainage curve was comparable for all soil types. It can be explained by the wetting-up behaviour of a sloped, hydrophilic and air-dried soil slab: run-on infiltrates into the soil and starts filling up the pores which can hold water against gravity. Once field capacity is reached, which happens - with our experimental set-up of simulating run-on at the upper end of the soil slabs - first at the upper end of the soil slab, drainage starts. During the experiment, the wetting front travels down the slope and successively fills up the field capacity of the entire soil slab. At the same time, the volume of the liquid in the soil slab, where field capacity has been reached, increases, and in turn, drainage increases over time. The increase in the rate of drainage may continue until the end of the experiment, as 60 minutes may not be enough to reach field capacity in the entire soil slab.

We conducted the soil slab run-off experiments with water under identical initial soil and hydraulic conditions to those of the experiments with the ethanol solution. Water did generate run-off from both soils. For both soils, the first run-off was measured within the first five minutes of the experiments, indicating that run-off started immediately and was clearly due to SWR as opposed to saturation-excess runoff.

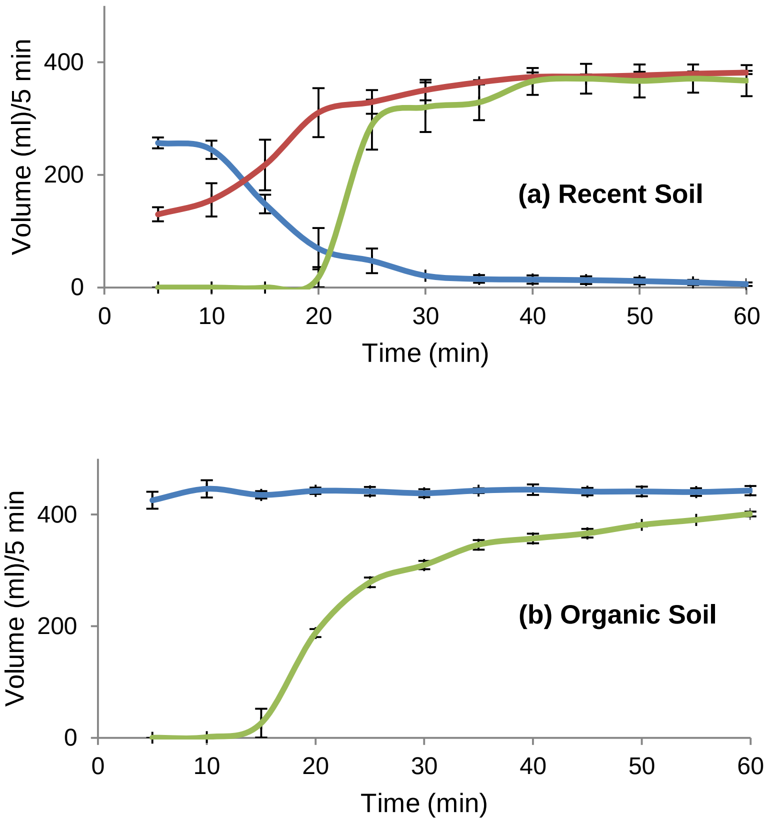

Figure 4. Run-off and drainage of water and of the ethanol (30% v/v) solution for (a) Recent Soil and (b) Organic Soil. The bars denote the standard errors (n=3).

In the Recent Soil, when the field capacity was reached in the upper part of the soil slab, about 10% of the run-on rate of ethanol solution drained after 21 minutes. This time was less than 5 minutes for the experiment with water. The much earlier drainage when water was used highlights the low capacity of topsoil suffering from SWR to store water. The wetting-up behaviour of the Organic Soil was similar to that of the Recent Soil in the experiments with the ethanol solution but, no drainage was measured during the water run-off experiment. In the run-off experiments with water, the maximum run-off coefficient for Recent Soil was 56% and occurred within the first five minutes. The run-off rate declined then rapidly. After 25 minutes only 10% of the run-on was translated into run-off. For the Organic Soil and in the experiments with water, the run-off rate was very high (93-97% of the run-on rate) throughout the entire experiment (Figure 4). It appears that the Organic Soil remains more vulnerable to SWR than the Recent Soil. The SWR persistency of Organic Soil lasted more than 3 hours, and had a very high contact angle of more than 103° (Table 1) which reflects its severe hydrophobic character.

For the Recent Soil, the persistence of SWR was measured as 42 minutes. Accordingly, we expected the run-off rate to be constantly high until this time. However, in the ROMA run-off experiment, we found much earlier (after 10 minutes) reduction of the run-off rate. The persistence of SWR determined by the WDPT test analyses soil properties of a very small point-like sample, but the persistence of SWR has a large spatial variability. On the other hand, the ROMA run-off test with a soil slab is a larger scale run-off prediction in comparison to the WDPT test scale.

Conclusion

Our laboratory results have demonstrated once again that SWR is important in New Zealand pastures and gives a sense of the economic and environmental consequences that this phenomenon induces in terms of agriculture. We have developed a robust and reproducible laboratory method to quantify the impact of SWR on run-off. The ROMA run-off experiments with soil slabs revealed that the Organic Soil was more vulnerable to SWR than the Recent Soil. We identified difficulties around the accuracy and meaningfulness of the persistence of SWR determined with the water drop penetration time (WDPT) test, which measures the persistence of SWR at a single point. In contrast, our ROMA experiments integrate the spatial variability of SWR of an undisturbed soil slab. In addition, the method is faster for extremely hydrophobic soils once the ROMA is set up. We are currently analyzing if our soil slab experiments are representative of larger scale run-off behaviour on the field.

Acknowledgements

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