Journal of Hydrology (NZ) 55 (2): 135-142, 2016

NOTE

A pilot investigation into soil water movement in shallow subalpine soils

Josephine A. Cairns and Sarah M. Mager

Department of Geography, University of Otago, PO Box 56, Dunedin
Corresponding author: josephine.cairns@otago.ac.nz

Abstract

A pilot study was undertaken in the Saint Marys Range, Canterbury, New Zealand to assess how soil moisture varies with depth in a shallow subalpine mineral soil. Observations of soil moisture over a three-week period showed the top 35 cm of the profile to respond to both drying and wetting cycles, but at depths greater than 60 cm there was little change in volumetric water content. At field capacity the potential available water depth was 62 mm, over a 300 mm soil profile. Infiltration rates between 10 and13 mm hr^{-1} (high for a silty loam) reflect the rocky fragments contained in the soil.

Keywords

soil moisture, TDR, infiltration rate, tussock grasslands

Introduction

Tussock grasslands are an important source of runoff to lowland catchments due to their low transpiration rates and efficient water use, thus most of the precipitation that occurs over this vegetation type becomes streamflow (Mark and Dickinson 2003; Mark, 1975); yet little is known about the variations in soil moisture under this vegetation. The majority of past investigations into soil moisture to one metre depth in New Zealand soils have focussed on pastoral soils rather than soils with endemic vegetation (Bretherton *et al.*, 2010). In this study, the field site exemplified conditions that have not been investigated in previous soil moisture research in New Zealand, specifically native subalpine tussock vegetation and a mineral soil. Additionally, hill country soils are subject to reworking by slips resulting in buried and mixed soil horizons that are atypical of traditional soil stratigraphic profiles. Disturbed layers within the soil stratigraphy have likely created preferential flow pathways that may differ to a more traditional undisturbed soil profile. The aim of this pilot study was to quantify the response time and vertical distribution of soil moisture as well as the infiltration rate of water in a tussock hillslope setting.

There are numerous methods for quantifying soil moisture including gravimetric analysis and in situ probes (e.g., time domain reflectometry (TDR), capacitance and neutron probes) (Mittelbach *et al.*, 2012). Previously, methods such as neutron probes were used to measure soil moisture at depth; however, these have largely fallen out of favour due to safety concerns and are increasingly being replaced by capacitance probes, which have their own limitations. For this pilot study, the use of an array of TDR probes at different depths layers (e.g., Hawke and McConchie 2011) was preferred to the other methods, as this allowed for continuous, in situ measurement of soil moisture movement whilst removing the need to auger instillation holes. Infiltration can be directly measured by double ring infiltrometers, or calculated from rainfall and soil moisture data (Hillel, 1998). Calculating infiltration from rainfall and soil moisture data was selected for this study due to the field conditions during the experimental time frame, as the presence of partial snow cover interfered with the direct measurement of infiltration at the site.

Methods

A pilot study was undertaken at the Awakino catchment in St Marys Range, South Canterbury (44.7742ºS; 170.3358ºE). The field site is at 1009 m above sea level and is dominated by tall snow tussock on an extremely steep (37.5%) north westerly facing slope. The field site soil is a very shallow silty loam, with a stone percentage between 5 and 70% and clay composition ranging from 5 to 35% (Landcare Research, 2015).

An array of six TDR soil moisture sensors and an automatic weather station were installed from 13 to 30 August 2016. The automatic weather station measured wind speed and direction, air and ground surface temperature, relative humidity, incoming and outgoing radiation, and precipitation at 10-minute intervals. The TDR array comprised six Campbell Science CS616 probes installed horizontally at 10, 21, 31, 48, 60 and 70 cm depths from the surface, at approximately 10 cm intervals, as determined by the substrate rock fragments (Fig. 1). The TDRs measured dielectric constant at 10-minute intervals and automatically converted it to volumetric water content (VWC). The instruments were installed one day prior to the start of the experimental period, without a settling time, similar to the methodology utilised for portable TDR studies (Brocca *et al.,* 2012).

The VWC for each TDR was expressed as an equivalent water depth, with an observed mean tussock root depth of 35 cm:

$$Wr = 1000\theta Z$$

where *Wr* is soil water content of the root zone expressed as a depth (mm), 1000 is average soil water water content for the root zone expressed as a equivalent depth per unit soil depth [mm(water)/m(soil depth)], is average volumetric water content in the root zone (m^3/m^3) and is TDR depth (m) (Raes *et al.,* 2012).

The depth, duration and intensity of rainfall was determined to calculate wetting fronts, which are a measure of the delay between the start of precipitation and soil moisture increase at each depth in the profile, and the amount of precipitation required to initiate a response at each depth in the soil moisture profile.

The rate of the wetting rate front progressing through the soil profile was determined as the time taken at each TDR depth for the sensor to record a 1% increase in VWC from the onset of precipitation. The pace of the wetting front through the soil profile was then converted to an infiltration rate, by multiplying the VWC by the soil depth to get water depth in mm. The calculated infiltration rate is limited by the precipitation rate, so may not reflect the maximum infiltration rate of the soil, but rather an infiltration rate at the end of winter when filled soil storage is high. Evapotranspiration was determined using the FAO 56 Penman-Monteith equation (see Allen *et al.*, 1998) for a tussock land surface, using crop input variables of bulk stomatal resistance of 158 s m^{-1} and a leaf area index of 3 as determined by Campbell (1989).

Results

During the construction of the TDR pit, the soil was observed to have a disturbed profile, without the distinct layers usually found (Fig. 1). Gravel fragments were interspersed irregularly through the substrate and the reworked nature of the soil prohibited the

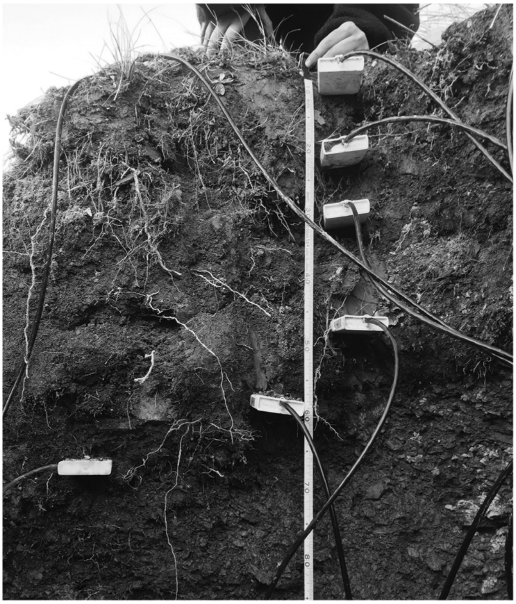

Figure 1 – Soil profile indicating locations of the 6 TDR probes in the Awakino field site.

construction of a standard soil description as would usually be included here (e.g., Milne, 1995). Bulk density samples were collected; however, due to the confused nature of the profile rock fragments made this process less than ideal. Bulk densities of 1.5 $g\,cm^{-3}$ for the uppermost 10 cm and 1.9 $g\,cm^{-3}$ for the 20-30 cm layers were calculated, along with porosity values of 42% and 28%, respectively, for these layers.

Intermittent rainfall occurred from 23 to 27 August, with a total of 21 mm of rain over the 5 days, varying from 1.4 to 6.2 $mm\,d^{-1}$, and a mean intensity of 0.25 $mm\,h^{-1}$ (Table 1). Given the low rainfall depth and intensity, we have assumed that all rainfall infiltrated and that overland flow was not a factor during the experimental period. The highest VWC consistently occurred at 60 cm depth, with an average of 35% (Table 1; Fig. 2). The 10 cm depth probe had the lowest VWC, of 17%, with the other probes ranging between 19 and 28%. Evapotranspiration fluctuated throughout the experiment, with a maximum value of 1.0 $mm\,d^{-1}$ on 29 August and a minimum of 0.0 $mm\,d^{-1}$ on 24 August. Soil moisture gradually decreased for the first 10 days of the experimental period, during which time no precipitation occurred and evapotranspiration was between 0.92 and 0.58 $mm\,d^{-1}$, with the days of higher evapotranspiration generally resulting in a greater decrease in soil moisture, particularly in the upper 21 cm of the soil profile (Fig. 3). Soil moisture responded slowly to the precipitation, with an increase of 1% in VWC at 10 cm depth occurring 10 hours after precipitation onset. A 4% increase in VWC from the onset of precipitation took 40 hours at 10 cm depth. The wetting front moved down the soil profile, with a 1%

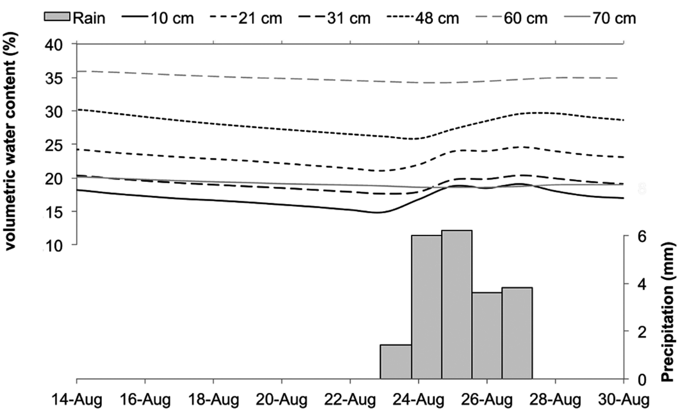

Figure 2 – Daily average volumetric soil moisture content from depth array of TDR probes, with daily rainfall totals shown.

Table 1 – Mean daily volumetric water content (VWC) at each TDR as well as the daily rainfall total and evapotranspiration (ET) rate

Date	10 cm (%)	21 cm (%)	31 cm (%)	48 cm (%)	60 cm (%)	70 cm (%)	Rain (mm)	ET (mm d^{-1})
13/08/16	18.5	24.2	20.5	29.8	35.4	19.9		
14/08/16	18.2	24.2	20.4	30.2	35.9	20.1		0.80
15/08/16	17.7	23.8	19.9	29.7	35.8	20.0		0.81
16/08/16	17.3	23.5	19.6	29.1	35.6	19.8		0.74
17/08/16	16.9	23.1	19.3	28.6	35.3	19.6		0.83
18/08/16	16.7	22.8	19.0	28.1	35.2	19.4		0.70
19/08/16	16.4	22.6	18.7	27.7	35.0	19.3		0.83
20/08/16	16.0	22.2	18.5	27.3	34.9	19.1		0.85
21/08/16	15.7	21.8	18.2	26.9	34.7	19.0		0.58
22/08/16	15.2	21.4	17.9	26.5	34.5	18.9		0.92
23/08/16	14.9	21.1	17.6	26.2	34.4	18.8	1.4	0.54
24/08/16	16.8	22.0	17.9	25.9	34.2	18.6	6.0	0.04
25/08/16	18.8	24.0	19.7	27.3	34.2	18.6	6.2	0.38
26/08/16	18.5	24.0	19.8	28.5	34.4	18.6	3.6	0.13
27/08/16	19.1	24.6	20.4	29.6	34.7	18.7	3.8	0.75
28/08/16	18.0	24.0	19.9	29.6	35.0	19.0		0.74
29/08/16	17.3	23.4	19.4	29.1	34.9	19.0		1.04
30/08/16	17.0	23.1	19.1	28.6	34.9	19.0		0.24
Average	**17.1**	**23.1**	**19.2**	**28.2**	**34.9**	**19.2**	**21**	

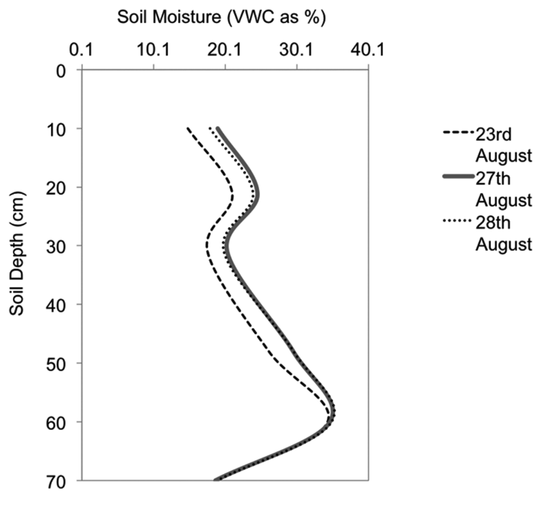

Figure 3 – Soil moisture (VWC %) across the depth profile, with values plotted for the first and last days of the precipitation event, as well as the day after the culmination of the precipitation event.

increase in VWC occurring 38 hours into the rainfall event at 48 cm depth and 79 hours at 60 cm depth. A preliminary examination of the daily data compared the VWC from a 6-point average, compared to a 3-point average from the top 30 cm, and from a single point measurement at 30 cm. Over the three week period, a 3-point VWC average underestimated the 6-point VWC average by 13–19%. Similarly, comparison of the single point VWC at 30 cm underestimated the 6-point VWC average by 19 to 25%.

The infiltration rate was determined to be equivalent to 10 mm hr^{-1} at 10 cm and 13 mm hr^{-1} at the 21 to 48 cm depths (Table 2). The rate of soil moisture reduction tapered off down the profile, with the highest value of 0.0035 VWC per day occurring at 10 cm (equivalent to 0.015 mm hr^{-1}). Initially, the mean soil moisture was highest at 60 cm depth (13–22 Aug), equivalent to 1.58 mm, and lowest at 10 cm depth, with 0.76 mm (Table 3). The same pattern held during the precipitation event (23–27 Aug), with a low of 0.79 mm at 10 cm depth and a high of 1.54 mm at 60 cm depth.

Discussion

The soil moisture at the top of the soil profile was consistently lower and more responsive to precipitation than deeper in the profile. The 10 cm depth responded most rapidly to infiltration, whilst the 60 cm depth appeared to have the highest holding capacity. This layer was relatively unresponsive to inputs of precipitation, as was the 70 cm depth. The results suggest that single layer observations of soil moisture may underestimate overall water availability in a soil profile. Directly measuring soil moisture at each depth likely provides a more reasonable profile measure than a lumped single value for the profile. The time taken for any response to become

Table 2 – Infiltration rates (mm hr^{-1}) calculated from observed changes in VWC at each TDR sensor

TDR depth	10 cm	21 cm	31 cm	48 cm	60 cm	70 cm
for:						
1% increase VWC	10	13	13	13	–	–
2% increase VWC	6	8	10	11	–	–
3% increase VWC	5	7	–	–	–	–
4% increase VWC	3	–	–	–	–	–

Table 3 – Soil moisture (mm) variation over the study period at each TDR sensor

Soil depth	Mean soil moisture (mm)		
	Prior to Precipitation 13–22 Aug	**Precipitation Event 23–27 Aug**	**Post precipitation 28–30 Aug**
10 cm	25.2	26.4	26.1
21 cm	23.0	23.1	23.5
31 cm	17.3	17.2	17.5
48 cm	45.4	44.0	46.6
60 cm	38.7	37.8	38.4
70 cm	17.6	16.8	17.2

apparent at the deeper TDR locations is interesting, with no response recorded at the 60 cm depth until 79 hours after the start of precipitation. This indicates that either the precipitation depth was too low to initiate a response in the deeper layers, or that these layers are very slow to respond to precipitation. It is possible that these soil depths respond only to larger scale, seasonal changes in the hydrology of the soil; however, further work over a seasonal timeframe is required to resolve this question.

The gravel content of the study soil raises questions surrounding the accuracy of the TDR probes. The probes are optimised to work in a 'standard soil', which has both a low gravel and clay content (CS, 2016; Pumpanen and Ilvesniemi, 2005). The manufacturer's standard quadratic equation was used to convert the dielectric constant to volumetric water content. These coefficients provide accurate volumetric water content in mineral soils, which have a clay content less than 30% and bulk densities less than 1.6 g cm^{-3} (CS, 2016). On this basis, no further calibration of the TDRs was undertaken.

Typically, hill country soils are characterised as having a small water storage capacity; however, Bretherton *et al.* (2011) suggest that plant available water may occur to depths of at least 35 cm, which is a significantly deeper than an earlier reported effective root zone estimate of 15 cm (Bircham and Gillingham, 1986). Soil moisture at Awakino was observed to be responsive to rainfall at soil depths up to 48 cm; however, the most active wetting and drying appeared limited to the top 35 cm of the soil profile, concomitant with the mean rooting depth. The results show that, at field capacity, the available water content is 62 mm (over a 300 mm profile). This value is considerably higher than the 42 mm reported by Bircham & Gillingham (1986) but less than the 69 and 87 mm reported by Bretherton *et al.* (2011). The difference between the available water depths reported by Bretherton *et al.* (2011) and the Awakino study reflects the heavy clay and mineral content of the Awakino soils, which have a lower water holding capacity and porosity compared to the lower-lying silty loams studied by Bretherton *et al.* (2011) near Eketahuna in the North Island.

The infiltration rates observed at Awakino were 10 to 13 mm hr^{-1}, which is within the expected range of a steady infiltration rate for sandy and silty soils of 10–20 mm hr^{-1} (Hillel, 1998). The silty loam soil at Awakino has a high bulk density (1.5 to 2.3 g cm^{-3}) indicating a heavy soil with relatively low porosity, as well as the presence of dense rock fragments. In this instance the relatively high infiltration rates observed here (compared with standard expected values for a silty loam soil) are likely due to the rock fragments present throughout the soil profile, which act to retard ponding, and lead to greater steady state infiltration rates (Cerdà, 2001).

The majority of past soil moisture studies have been on pastoral soils, which are inherently different than the Awakino study soil, excluding the confounding factor of the reworked soils of the field site (e.g., Chang *et al.*, 2002; Jamieson, 1985; Parfitt *et al.*, 1985; McAneney and Judd, 1983) and further work is needed over a longer experimental timeframe to determine whether the soil moisture attenuation in subalpine soils is substantially different to pastoral soils. Such evidence will improve parameterisation of hydrological models for predicting runoff generation in hill country soils.

Conclusions and future directions

Preliminary analysis of TDR data suggests that the hillslope soil moisture patterns at this site will provide a pertinent area for future research. TDR probes were effectively used to quantify the timing of wetting fronts, infiltration rates and water holding capacity;

however, challenges remain in the selection of field sites (both in terms of representativeness of the site, soil and hydrology and suitability of equipment). Longer-term data, potentially from a spatially-differentiated range of sites, will be required to fully resolve the analysis considered here.

Acknowledgements

The authors thank two independent reviewers for useful comments on the original manuscript; Peter Wilson and Nick Plimmer for their assistance in the field.

References

Allen, R.; Pereira, L.; Raes, D.; Smith, M. 1998: Crop evapotranspiration - Guidelines for computing crop water requirements. *FAO Irrigation and drainage paper 56*. FAO, Rome, 300(9): 51-59.

Bircham, J.; Gillingham, A. 1986: A soil water balance model for sloping land. *New Zealand Journal of Agricultural Research 29:* 315-323.

Bretherton, M.; Horne, D.J.; Scotter, D.R. 2011: Water uptake by hill country pasture – more than you think. In: *Adding to the knowledge base for the nutrient manager.* Occasional Report 24, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand

Bretherton, M.; Scotter, D.R.; Horne, D.; Hedley, M. 2010: Towards an improved understanding of the soil water balance of sloping land under pasture. *New Zealand Journal of Agricultural Research 53(2)*:175-185.

Brocca, L.; Tullo, T.; Melone, F.; Moramarco, T.; Morbidelli, R. 2012: Catchment scale soil moisture spatial–temporal variability. *Journal of Hydrology, 422*: 63-75.

Campbell Scientific (CS) 2016: CS616 and CS625 water content reflectometers. Accessed online at: https://s.campbellsci.com/documents/us/product-brochures/b_cs616.pdf.

Campbell, D. 1989: Energy balance and transpiration from tussock grassland in New Zealand. *Boundary-Layer Meteorology 46(1-2):* 133-152.

Cerdà A. 2001: Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. *European Journal of Soil Science 52(1):* 59–68.

Chang, S.; Amatya, G.; Beare, M.; Mead, D. 2002: Soil properties under a *Pinus radiata* – ryegrass silvopastoral system in New Zealand. Part I. Soil N and moisture availability, soil C, and tree growth. *Agroforestry Systems 54*: 137-147.

Hawke, R.; McConchie, J. 2011: In situ measurement of soil moisture and pore-water pressures in an 'incipient' landslide: Lake Tutira, New Zealand. *Journal of Environmental Management 92*: 266-274.

Hillel, D. 1998: *Environmental soil physics: Fundamentals, applications, and environmental considerations.* Academic Press, San Diego.

Jamieson, P. 1985: Soil moisture extraction patterns from irrigated and dryland arable crops in Canterbury. *Proceedings of the Agronomy Society of New Zealand 15*: 1-6.

Landcare Research New Zealand 2015: *Omaramara Rock Soil Report.* Accessed online at: http.smap.landcareresearch.co.nz.

Mark, A. 1975: Photosynthesis and dark respiration in three alpine snow tussocks (*Chionochloa spp.*) under controlled environments. *New Zealand Journal of Botany 13*: 93-122.

Mark, A.; Dickinson, K. 2003: Temporal responses over 30 years to removal of grazing from a mid-altitude snow tussock grassland reserve, Lammerlaw Ecological Region, New Zealand, *New Zealand Journal of Botany 41*: 655-667.

McAneney, K.; Judd, M. 1983: Pasture production and water use measurements in the central Waikato. *New Zealand Journal of Agricultural Research 26*: 7-13.

Milne, J. 1995: *Soil description handbook*. Manaaki Whenua Press, Lincoln.

Mittelbach, H.; Lehner, I.; Seneviratne, S. 2012: Comparison of four soil moisture sensor types under field conditions in Switzerland. *Journal of Hydrology 430*: 39-49.

Parfitt, R.; Roberts, A.; Thomson, N.; Cook, F. 1985: Water use, irrigation, and pasture production on Stratford silt loam. *New Zealand Journal of Agricultural Research 28*: 393-401.

Pumpanen, J.; Ilvesniemi, H. 2005: Calibration of time domain reflectometry for forest soil humus layers. *Boreal Environment Research 10(6)*: 589-595.

Raes, D.; Steduto, P.; Hsiao, T.; Fereres, E. 2012: *AquaCrop Version 4.0 Reference Manual*, Chapter 3. FAO, Rome.