



Assessment of spatial and temporal variability in soil moisture using multi-length TDR probes to calibrate Aquaflex sensors

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Abstract

Despite subtle variations in soil moisture (SM) across a paddock, irrigation scheduling in New Zealand dairy farms is solely based on the SM monitored at a single location, primarily using an Aquaflex soil moisture sensor at a specified root depth. This study aimed to address this issue by assessing the “effective” root depth of a pasture, calibrating the Aquaflex soil moisture sensor and evaluating the spatial and temporal variability of SM. Twenty non-weighing lysimeters and 1 Aquaflex with 2 sensors installed 125-m away from the lysimeters on the same paddock were utilized for the study. TDR probes with 200-, 500- and 900-mm lengths were installed vertically adjacent to the Aquaflex and the lysimeters for monitoring spatio-temporal variability in SM, and calibrating the Aquaflex. A dry down experiment was performed for investigating the root depth of the pasture. All TDR probes responded to wetting and drying events, with varying SM measurements both vertically and horizontally, due to variations in soil type at different locations, indicating a need of SM monitoring at different locations in the paddock for irrigation scheduling. There was a strong linear relationship between the Aquaflex and TDR probes readings, which can be used to calibrate the Aquaflex and improve its reliability for measuring soil moisture and in turn irrigation needs. Over the dry down period, out of the total moisture change in the 0–900-mm soil profile, 96% was contributed by 0–500 mm, indicating that the significant root depth of the pasture lies on the top 500-mm soil profile. Findings of the study can contribute to better irrigation scheduling and to conserve water.

Introduction

Improvement in agricultural water management practices is vital for increasing food production and contributes towards the global objective of food security (KC 2008, 2011; Schultz et al. 2007). Improved food production can contribute to diminish poverty, as there is a direct link among water, food and poverty (KC et al. 2017; Schultz et al. 2009). In addition, better use of available land and water resources can contribute to safeguard environmental deterioration (Anthony and KC 2017; KC et al. 2018a, b, c). Efficient use of water resources is possible by adopting irrigation scheduling that accounts for existing soil water content in the plant root zone (Cape 1997; KC et al. 2018b), as irrigation water demand has the largest share in total water demand. The scheduling requires monitoring of soil water status in the plant root zone (Allen et al. 2011; KC et al. 2016).

Soil moisture is the key component of the soil water balance, both on small and large agricultural farms, and contributes substantially to crop yield and the availability of nutrients (Cape 1997; Tromp-van Meerveld and McDonnell

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2006). Therefore, maintaining adequate soil moisture levels in the root zone could be a practical strategy for conserving water and improving agricultural production (George et al. 2000). Soil moisture driven irrigation scheduling contributes to improving irrigation effectiveness (Srinivasan and Duncan 2011), for which proper soil moisture information is essential for estimating actual crop water needs (Cape 1997; Chandler et al. 2004; Van Housen 2015).

Spatial variability of soils caused by differences in vegetation, topography, soil type and non-uniform water input, and the spatial and temporal variability of water content in the soil is a reality throughout farms (Barringer et al. 2016; Hedley et al. 2010; Hedley and Yule 2009b). In fact, soils are heterogeneous, both physically and chemically, and a complex porous medium (Seyfried and Murdock 2001). This indicates that soil moisture measured at one location might not always represent the water content at other locations or the entire farm. Therefore, several measurements of soil moisture at different locations representing the area to be irrigated are essential (Jacobs et al. 2004).

With increasing water scarcity and pollution problems associated with over-irrigation and waterlogging, the issue of proper soil moisture sensor placement to better represent given soil characteristics is also increasing (Evelt 2016). Some previous studies in New Zealand have shown the benefits of using multiple sensors across a farm for soil moisture monitoring and applying variable rates of irrigation water (Hedley et al. 2010).

Time domain reflectometry (TDR) is one of the widely used tools for measuring soil water content in the field. TDR determines the soil water content from the dielectric properties of soils (Jones et al. 2002; Skierucha et al. 2012). Based on the travel time of an electromagnetic signal passing through parallel probes buried in the soil, the bulk dielectric constant¹ is estimated, which is then converted to water contents (Blonquist et al. 2005; Chandler et al. 2004). TDR has been accepted as a practical technique for non-destructive, repetitive and in-situ measurement of the water content in the soil profile (Robinson et al. 2003; Skierucha et al. 2012).

A combination of short and long TDR probes is needed to determine spatio-temporal variability of the soil water content in a farm (Miyamoto et al. 2001; Young et al. 2000). Installing different soil moisture sensors at one location can help to evaluate and compare the responses of the different sensors to variable wetting and drying events (Paige and Keefer 2008). Young et al. (2000) used 200-, 400-, 600-, and 800-mm TDR probes and also came to a similar conclusion that “a combination of short and long probes improves the estimate of percolation”. Field experiments by Miyamoto

et al. (2001) with 100-, 200-, 300-, and 450-mm TDR probes, installed vertically from the soil surface, also demonstrated that the TDR technique with multi-length probes is an effective method for measuring soil water distributions at different depths.

Aquaflex (Streat Instruments., Ltd, Christchurch, New Zealand) is one of the widely used soil moisture measurement devices in New Zealand dairy farms. It consists of 3-m-long dual-core wires which are joined at the end to form two complete loops for signal transmission. The device is buried in the soil. By calculating the pulse delay time (time delay transmission-TDT) of an electrical signal sent along the transmission line installed in the soil, the dielectric constant is estimated based on which average soil moisture content around the Aquaflex length is measured.

Very few studies have directly compared the performance of different soil moisture sensors under field application (Paige and Keefer 2008). A comparative evaluation of TDR and Aquaflex soil moisture sensors carried out in a heterogeneous soil is not understood well. In addition, there is a lack of field studies to estimate the “effective” root depth of pasture that is used for irrigation scheduling. The “effective” root depth of pasture considered for irrigation planning has substantial implications in estimating irrigation requirements.

Therefore, this study aimed at: (1) assessing the “effective” root depth of pasture for irrigation estimation; (2) calibrating the Aquaflex soil moisture sensors based on TDR probes for better irrigation scheduling; and (3) evaluating the spatio-temporal variability of soil moisture for proper accounting of soil variability and crop water needs. The “effective” root depth of pasture was estimated by the field assessment of changes in soil water content measured from an Aquaflex soil moisture sensor and TDR probes. A comparison of Aquaflex and TDR soil moisture measurements helped to calibrate Aquaflex sensors by TDR probes. TDR probes were installed across the farm to monitor spatial and temporal variability in soil moisture measurements.

Materials and methods

Experimental site and equipment setup

Field experiments were conducted at Lincoln University Dairy Farm (LUDF) (40.26 S, 172.44 E), located in Canterbury, South Island, New Zealand (Fig. 1) during the period 29 May 2015 to 10 October 2015.

The LUDF is a 160-ha pastoral farm consisting of two blocks totalling 21 paddocks with 11 paddocks in the North block and 10 paddocks in the South block. Hereafter, in this paper, the north block paddocks are denoted as N for “North”, followed by the respective paddock number (e.g.

¹ The dielectric constant is the capacity of a non-conducting material to transmit electromagnetic waves or pulses (Charlesworth 2005).

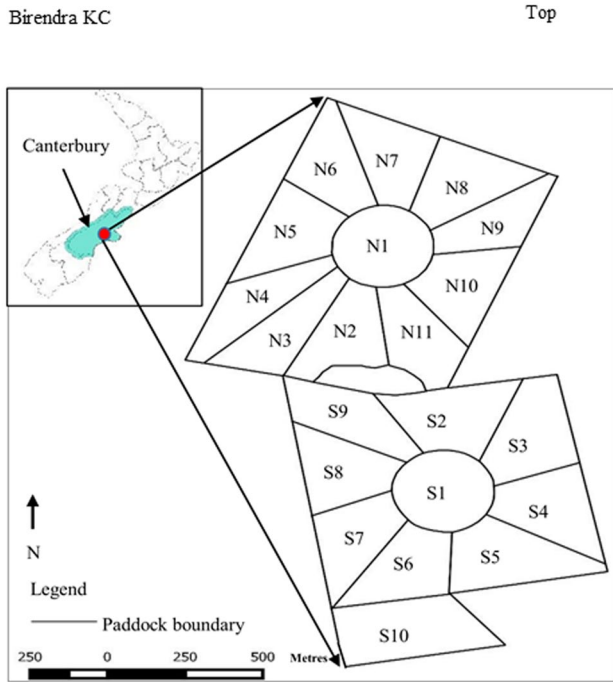


Fig. 1 Location of Lincoln University Dairy Farm in Canterbury, New Zealand. N and S stand for the ‘north’ and the ‘south’ block, respectively

Vegetation in LUDF is perennial ryegrass pasture (*Lolium perenne*) which is the main pasture grass for providing major nutrients to dairy cows in New Zealand (Lee et al. 2010; Monaghan et al. 2008). The average annual rainfall and reference evapotranspiration recorded at Broadfield weather station located at 3 km north-east of LUDF were 609 and 939 mm, respectively (National Institute of Water and Atmospheric (NIWA) 2015). On an average, 450 mm of irrigation water is applied per annum by three different irrigation systems: center pivot (80% area), long laterals (15% area) and K-lines (5%). The center pivot supplies water to the farm at a rate of 5.5 mm per day.

There was a pre-existing Aquaflex soil moisture sensor installed in paddocks N7 for monitoring soil moisture content (% of the volume) for irrigation scheduling. The Aquaflex was located at the fence line that divides adjacent paddocks (fence between N6 and N7), which is the common way of soil moisture sensor installation in New Zealand dairy farms. This minimizes disturbance to the equipment due to animals. The Aquaflex was within a sandy loam soil containing stones. The Aquaflex comprised of two soil moisture sensors, one is installed in inclination from the soil surface to 200-mm soil depth, covering the active root zone (top sensor), and the other is installed horizontally below the active root zone (500 mm)

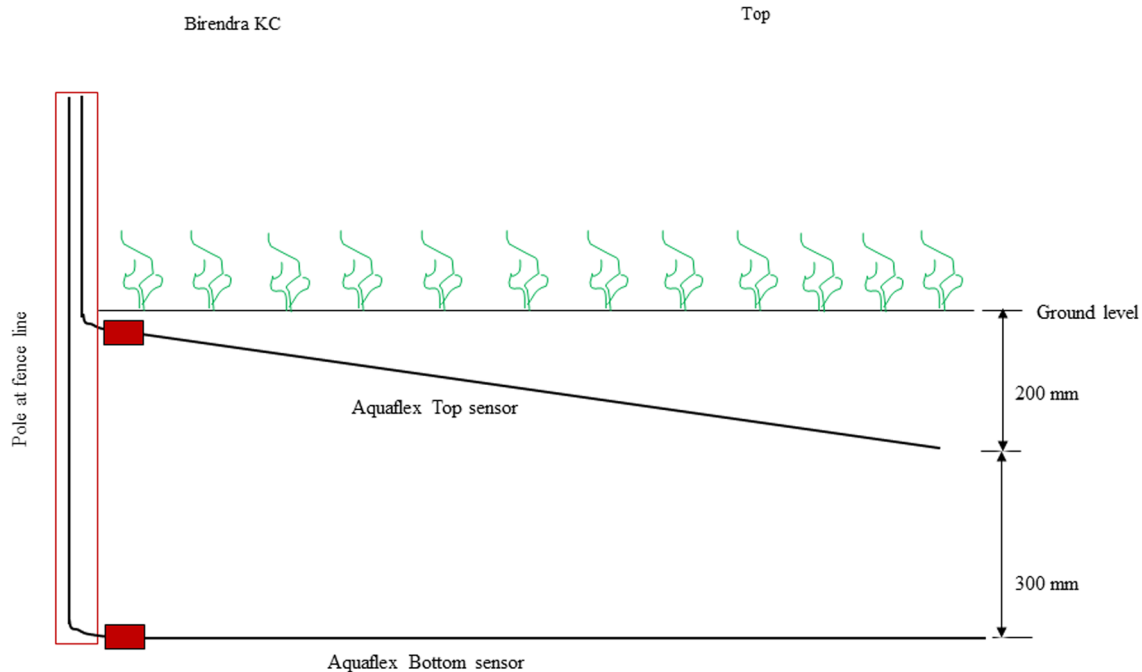
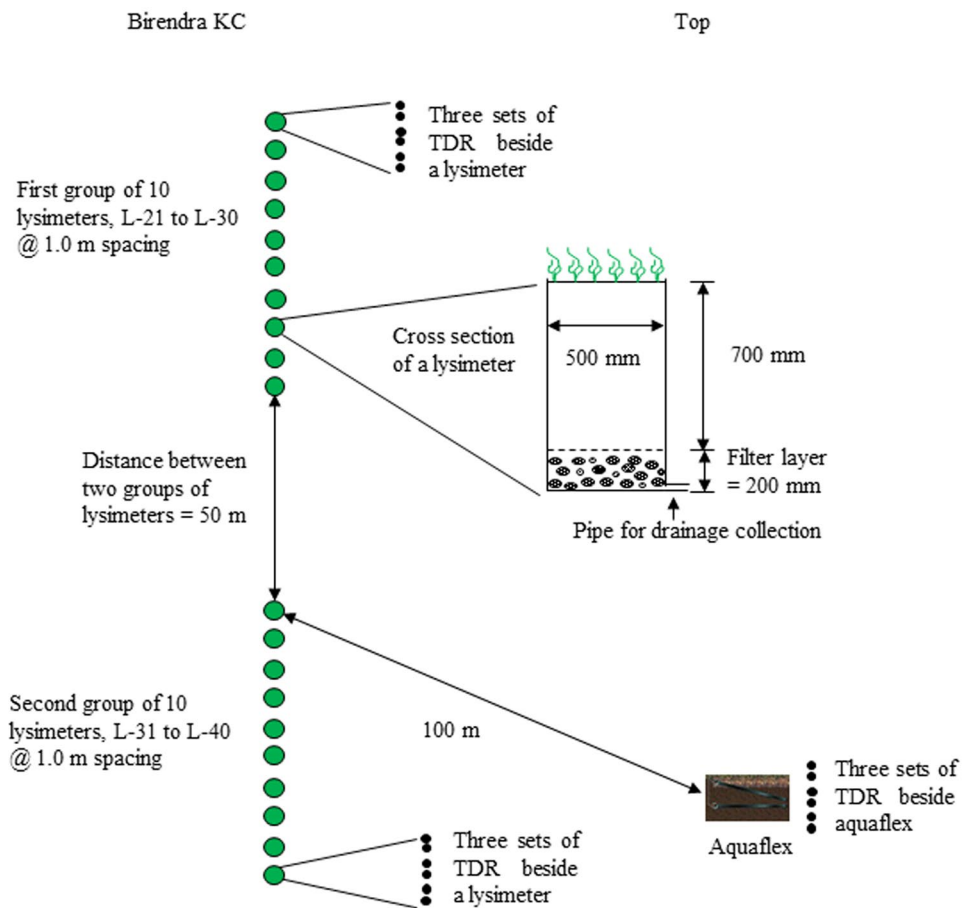


Fig. 2 Schematic representation of Aquaflex installed on LUDF. Source: (KC et al. 2018a)

N1, N2 and so on), and the same for the south block paddocks but with a letter S for “South”.

(bottom sensor) (Fig. 2). Soil moisture readings from the top sensor are used to decide on irrigation trigger points,

Fig. 3 Equipment setup in the field (LUDF) with cross-section view of a lysimeter. Source: (KC et al. 2016, 2018a)



and soil moisture readings from the bottom sensors are used to monitor drainage.

Twenty non-weighting lysimeters had been installed in the middle of N7 to monitor nutrient leaching through percolation following the methods described in Cameron et al. (1992). To represent different soil textures, the 20 lysimeters had been installed in two groups with 10 lysimeters (L-21–L-30) within silty loam soils and 10 lysimeters (L-31–L-40) within sandy loam soils. Distance between the two groups of lysimeters was 50 m with adjacent lysimeters in each group being 1 m apart. The Aquaflex was 100 m away from the first lysimeter in the second group (Fig. 3). These 20 lysimeters and the Aquaflex installed on paddock N7 were utilized for the study.

In New Zealand, some farms have lysimeters installed for monitoring nutrient leaching. The most common lysimeter networks are the regional council lysimeter networks, which generally have soil moisture sensors installed within the lysimeters, or adjacent to the lysimeters (Duncan et al. 2016). However, lysimeters installed on LUDF have no soil moisture sensors (KC et al. 2019). As the lysimeters and the Aquaflex were within different soils, differences in soil moisture between the Aquaflex and lysimeters are expected. It is because agricultural farms experience both subtle and

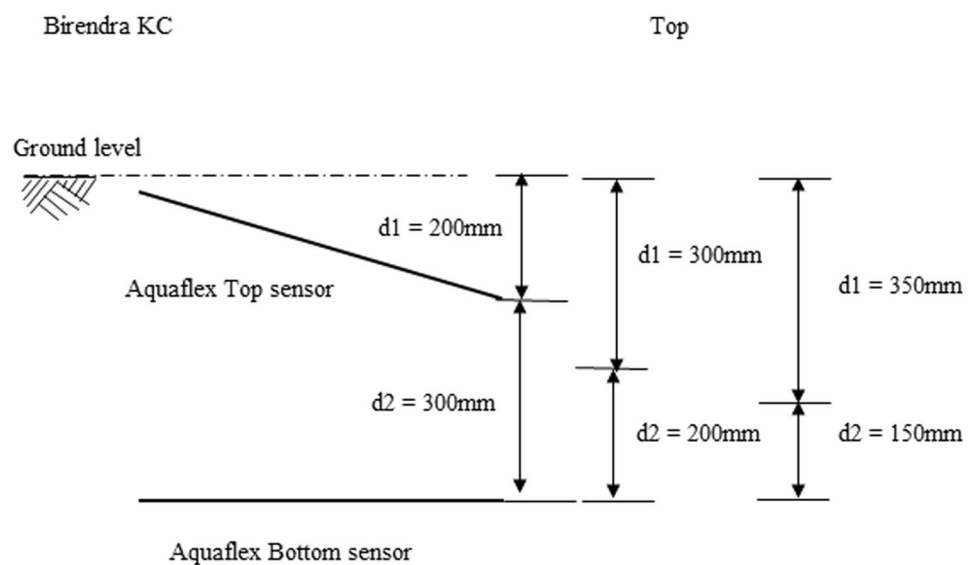
sharp changes in soil type across the farm and down the soil profile. In fact, soil moisture may change even within 1.0-m distance (Allen et al. 2011).

To assess spatial and temporal variability in the soil moisture measurements, three sets of TDR probes with 200-, 500- and 900-mm lengths and 5-mm diameter were installed vertically from the soil surface beside the lysimeters and Aquaflex so that both sensors are within the same location (Fig. 3). Each set consisted of two parallel stainless steel rods. A vertical probe installation was chosen to minimize soil disturbance on the farm. Each set of probes was installed at 100-mm spacing, with individual probes in one set being 50 mm apart. The distance between a lysimeter and its corresponding TDR probes was 1.0 m.

Calibration of the Aquaflex by TDR

Aquaflex soil moisture sensor and TDR probes measure soil water content by sending an electromagnetic pulse through the soil. The Aquaflex soil moisture sensor consists of a 3-m-long, dual-core wire. The two wires are joined at the end to form two complete loops for signal transmission. Both ends of the wire are connected with the Aquaflex sensor, which sends an electrical pulse along the first transmission

Fig. 4 Schematic representation of the top and bottom soil moisture sensors in Aquaflex, and 500-mm soil depth division into two parts under three combinations



line that returns back through the second transmission line. Soil moisture is determined by measuring the time taken by the pulse to travel along its sensor cable. The more the amount of water around the sensor cable the longer is the travel time of the electrical pulse. Thus, Aquaflex works based on the time delay transmission (TDT) principle. It measures average soil moisture over a 3-m length and in a 25-mm cylindrical volume with an accuracy of $\pm 2\%$.

The TDR probe works based on the time domain reflectometry (TDR) principle, i.e., soil water content is estimated based on the travel time of an electromagnetic signal passing through probe buried in the soil (Blonquist et al. 2005). An electrical signal applied to the waveguides travels along their length and is reflected back from the end of the probe to the TDR control unit. The more the amount of water around the TDR probe, the shorter is the travel time of the electrical pulse, as dielectric constant for water is far greater (80) compared to that for soil (4) and air (1). It measures average soil moisture in a 30-mm cylindrical volume with an accuracy of $\pm 1\text{--}2\%$.

Before Aquaflex soil moisture sensors were calibrated by TDR probes, the TDR probes were calibrated in the laboratory via the gravimetric method, with soil collected from three locations, beside two blocks of lysimeters and Aquaflex. Three soil samples were collected from each location totalling nine soil samples during dry and wet periods. Before collecting the soil samples, soil moisture was measured using TDR probes. The gravimetric soil water content was obtained by oven drying the sample at 105 °C for 24 h. The dry bulk density (ρ_b) of soil was calculated by taking an intact soil core.

Aquaflex soil moisture sensors were calibrated by TDR following a two-step approach. In the first step, soil moisture of the 500-mm soil column (θ_{500}) was estimated using

Aquaflex top and bottom sensors readings. For this, the following weighted relationship was used (KC et al. 2016):

$$\theta_{500} = \theta_1 \times \frac{d_1}{500} + \theta_2 \times \frac{d_2}{500}, \quad (1)$$

where θ_{500} is the soil moisture of 500-mm soil column, d_1 is the top soil depth covered by the Aquaflex top sensor reading (θ_1), and d_2 is the bottom soil depth covered by the Aquaflex bottom sensor reading (θ_2).

To test the most representative soil depth for Aquaflex top and bottom sensor readings, KC (2016) divided the 500-mm soil column into two depths (d_1 and d_2) in three different combinations (Fig. 4). It was found that Aquaflex top and bottom sensor readings are applicable for the top 350-mm and bottom 150-mm soil profile, respectively. Therefore, in this study, $d_1 = 350$ mm and $d_2 = 150$ mm were applied to the above weighted relationship (Eq. 1).

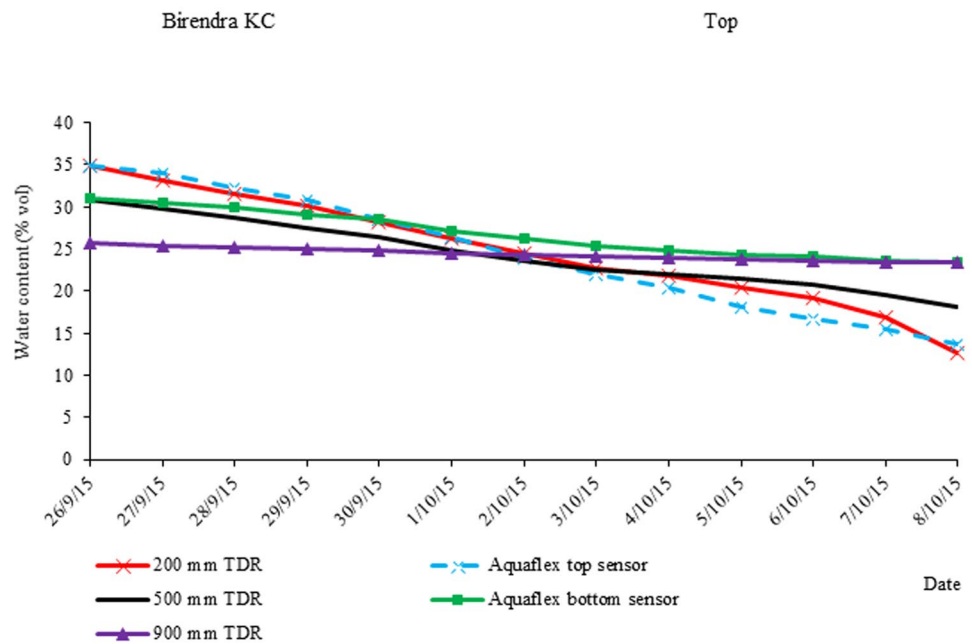
In the second step, a relationship between θ_{500} and 500-mm TDR readings was investigated. The adopted approach of soil moisture calculation using a weighted mean of Aquaflex top and bottom sensors readings was in agreement with Paige and Keefer (2008).

Results

Optimum root depth

Soil moisture sensors need to be evaluated over a range of conditions including natural wetting and drying sequences (Paige and Keefer 2008). To determine how different probes, respond under no water input regime, a dry down experiment was performed for 13 days starting on 26th Sep 2015 before

Fig. 5 Changes in average soil moisture readings from 200-, 500- and 900-mm TDR installed beside the lysimeters, and Aquaflex top and bottom sensor readings over 13 days dry down experiments commencing from 26 September 2015



the start of the irrigation season, because daily water input (irrigation and precipitation) complicates the soil moisture drainage process (Young et al. 2000).

All TDR probes responded to wetting and drying events, with varying soil moisture (SM) observed both vertically and horizontally. The amplitudes of the daily fluctuations in SM measurements were noticeably higher for 200-mm TDR and Aquaflex top sensors with relatively lower fluctuations for 500-mm TDR and Aquaflex bottom sensors. However, 900-mm TDR showed only minor fluctuation in average SM values (Fig. 5).

Over the 13 days' time period, average water content (% vol) from 200-mm TDRs showed 22% reduction, from 35% at the beginning of the dry down experiment to 13% by the end of the experiment. The top sensor of the Aquaflex (200 mm) also showed a similar reduction in average water content (% vol), with 21% reduction over the experiment period, from 35 to 14%. Over the same time period, average water content (% vol) from 500-mm TDR reduced by 13%, from the average water content of 31% at the beginning of the dry down experiment to 18% by the end of the experiment. The bottom sensor of the Aquaflex (500 mm) showed 8% reduction in average water content, from 31% at the beginning of the dry down experiment to 23% by the end of the experiment. However, average soil moisture records from 900-mm TDR reduced only by 3%, from 26 to 23%.

Variability in soil moisture measurements across the paddock increased with soil depths. Among the three TDR probes tested, the 200-mm TDR showed the least variability in SM measurement across the paddock with relatively higher variability for the 500-mm TDR. There were no significant differences between SM variability across the farm

as measured from 200- and 500-mm TDR. However, the 900-mm TDR showed noticeably high variability in SM measurement.

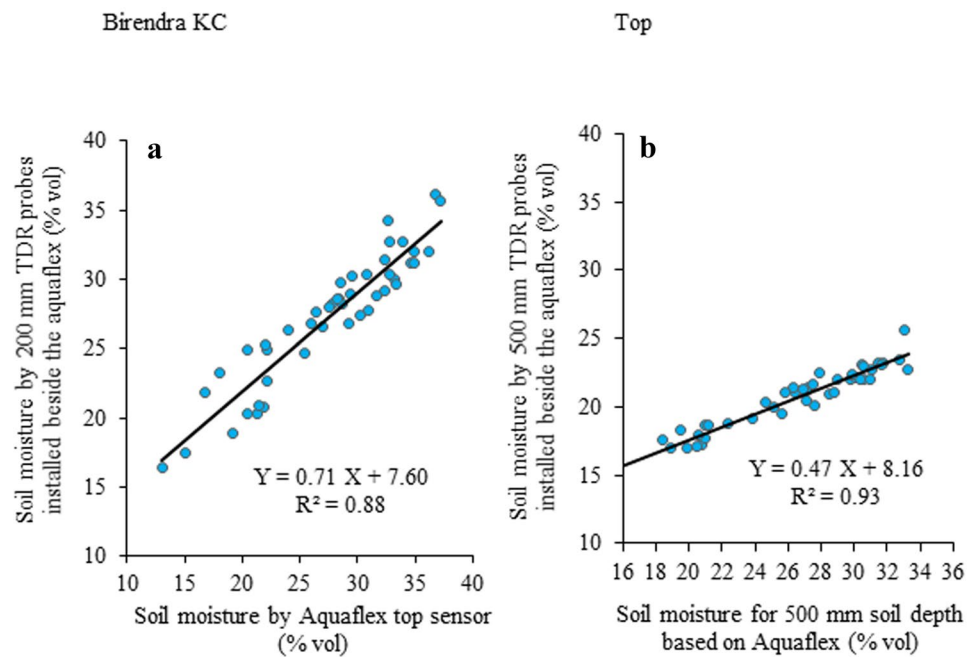
Among three different soil profiles (0–200 mm, 200–500 mm, 500–900 mm), total soil moisture changes were the highest for 0–200 mm followed by 200–500 mm. Total soil moisture changes from 500 to 900-mm the soil profile were minimal. Over the dry down period, out of the total water change in the 0–900-mm soil profile, 66% was contributed by 0–200 mm, 30% by 200–500 mm, and 4% by 500–900-mm soil profile.

Until the 5th day of the dry down experiments, daily water change from 0- to 200-mm soil profile was around 5 mm, which might have been enough for the evapotranspiration. However, after that period, daily water change from 0- to 200-mm soil profile dropped below 5 mm (for example 3.5 mm on 8th day and 2.4 on 11th day), which might have not been enough to meet potential evapotranspiration and the crop might have extracted additional water from the deeper layers.

Evaluation of the Aquaflex results

There was a very strong relationship between soil moisture measured from the gravimetric method and TDR probes with the coefficient of determination (R^2) as 0.98. This result indicate that the TDR probes measure SM accurately. Although TDR probes were calibrated with the gravimetric method, TDR probes usually do not require calibration. The waveform was measured directly to calculate the soil water content with Topp's equation. It is well known that TDR is a method to measure the soil water content without

Fig. 6 a Relationship between soil moisture (%) by 200-mm TDR installed beside the Aquaflex and Aquaflex top sensor reading, **b** relationship between soil moisture (%) by 500-mm TDR installed beside the Aquaflex and soil moisture (%) for 500-mm soil column based on Aquaflex top and bottom sensor readings



soil specific calibration (Topp 1984). However, compared to TDR probes, Aquaflex is widely used in New Zealand agricultural farms, because the cost of instrumentation and the level of user-ability associated with TDR limit its application for agricultural water management (Blonquist et al. 2005). Therefore, Aquaflex sensors require field calibration to give confidence in their accuracy (KC et al. 2016).

To investigate responses of the sensors at different levels of soil moisture content, soil water measurements were carried out intermittently, from 29 May to 10 Oct, 2015 to cover various soil moisture levels from the field capacity down to the critical point. To compare the seasonal variations of the water content profile, soil moisture was always measured at the same points. As Aquaflex measures average soil moisture over 3-m length, three sets of TDR probes were installed covering 3-m length and average soil moistures obtained from the three sets of TDR probes were compared with the Aquaflex values.

Evaluation of the Aquaflex top sensor by 200-mm TDR probes

To calibrate the Aquaflex top sensor, soil moisture readings from the Aquaflex top sensor (200 mm) were compared with 200-mm TDR values. For $SM < 20\%$ of the volume, 200-mm TDR produced relatively higher readings than the Aquaflex top sensor, while for $SM > 30\%$ of the volume the Aquaflex top sensor produced relatively higher values than the 200-mm TDR probe (see Fig. 6a). However, there were no significant differences between SM measured from TDR and Aquaflex. This variation in soil moisture measurement might

be attributed to the differences in soil moisture measurement methods of the two sensors and soil spatial variability. TDR is a point measurement technique therefore, small wetting and drying events around its rods can impact greatly on the soil moisture reading. On the other hand, Aquaflex measures average soil moisture over 3-m length, and therefore, if the water content along the sensors is not uniform, this would produce an average water content over the whole length, which can be different from the point values. However, a strong linear relationship was observed between SM recorded by the Aquaflex top sensor and the 200-mm TDR probes with a high coefficient of determination ($R^2 = 0.88$).

Evaluation of Aquaflex by 500-mm TDR probes

For this, SM estimates for 500-mm soil column using Aquaflex top and bottom sensor readings were compared with 500-mm TDR readings. For $SM < 15\%$ of the volume, 500-mm TDR produced higher readings than Aquaflex, while for $SM > 15\%$ of the volume, Aquaflex produced higher soil moisture than TDRs. However, a strong linear relationship was observed between Aquaflex and TDR probes readings with a high coefficient of determination ($R^2 = 0.93$) (Fig. 6b).

The regression equations of the trend lines shown in Fig. 6 can be used to calibrate Aquaflex by TDR. In the regression equations, Aquaflex SM values (X) are the independent variables and TDR readings (Y) are the dependent variables.

Aquaflex readings were also compared with soil moistures obtained from 200- and 500-mm TDR probes installed beside the lysimeters. The water holding capacity of the soil

beside the lysimeters was higher than around the Aquaflex, since the soil around the aquaflex was coarse-textured, compared to the soil beside the lysimeters. In addition, horizontal and vertical variabilities in the soil's bulk density and water holding characteristics also create a disparity in SM measurements at different locations (Allen et al. 2011). Further, cracks, rocks, pore size, plant roots, and texture layers are not homogenous on the farm, which affects soil's water content (Charlesworth 2005). However, there was a significant correlation between SMs measured from the two tools with a high coefficient of determination (R^2) (ranging from 0.88 to 0.93) and small P values ($\alpha < 0.05$).

Soil moisture readings from 900-mm TDRs installed at different locations were also compared where same length of probes installed at different locations showed high variations in SM measurement, both vertically and horizontally. Soil moisture recorded by 900-mm TDR probes installed besides each other showed good agreement compared to the 900-mm probes installed further apart, which might be associated with the spatial variation in soil textures. For example, the relationship between SM recorded by 900-mm TDR probes installed beside lysimeters 21 and 25 (4 m apart) showed a strong coefficient of determination with $R^2 = 0.88$, while the relationship between SM recorded by 900-mm probes installed beside the Aquaflex and lysimeter 40 (100 m apart) produced a weak relation with $R^2 = 0.49$. The coefficient of determination further weakened when probes installed at longer distances apart were considered.

On average SM beside the Aquaflex was observed as the lowest followed by the SM beside the second group of lysimeters, while it was the highest beside the first group of lysimeters. This variation in SM was associated with the soil textures in these three locations. The first group of lysimeters was installed within silty loam soils and the second group within sandy loam soils. The Aquaflex was installed within sandy loam soils containing some stones with the lowest water holding capacity.

Soil moisture measurement is highly sensitive to surrounding soil conditions. In case of the studied paddock, soil conditions were similar as in the surrounding (Whenua 2019). Any studies related to SM studies are expected to assess soil conditions in the surrounding too and discuss their potential impacts to SM in the study domain to have a more realistic picture, which was outside the scope of this paper.

Spatial and temporal variability of soil water content

This assessment incorporated the analysis of SM within the profile and between sites, and the sensor response variability of Aquaflex and TDR. Soil water contents measured from Aquaflex and 3 sets of vertical TDR probes installed

vertically at different locations are shown in Fig. 7. In the figures, L-21 means SM recorded by the TDR installed beside Lysimeter 21 and so on, while TDR-A means SM recorded by the TDR installed beside the Aquaflex. In Fig. 7a, Aquaflex implies SM reading from Aquaflex top sensor while in Fig. 7b, Aquaflex implies SM estimated for 500-mm soil column using Aquaflex top and bottom sensor readings.

All TDR probes and Aquaflex responded to individual water input, especially the shorter probes and Aquaflex top sensor responded well compared to longer probes and Aquaflex bottom sensor. Two large rainfall events at measurements no. 10 and 29 are clearly reflected in TDR and Aquaflex values. After a measurement on 27 September 2015, there was no water input (rainfall or irrigation), and therefore, SM recorded by all TDRs and the Aquaflex sensor continued their downtrend.

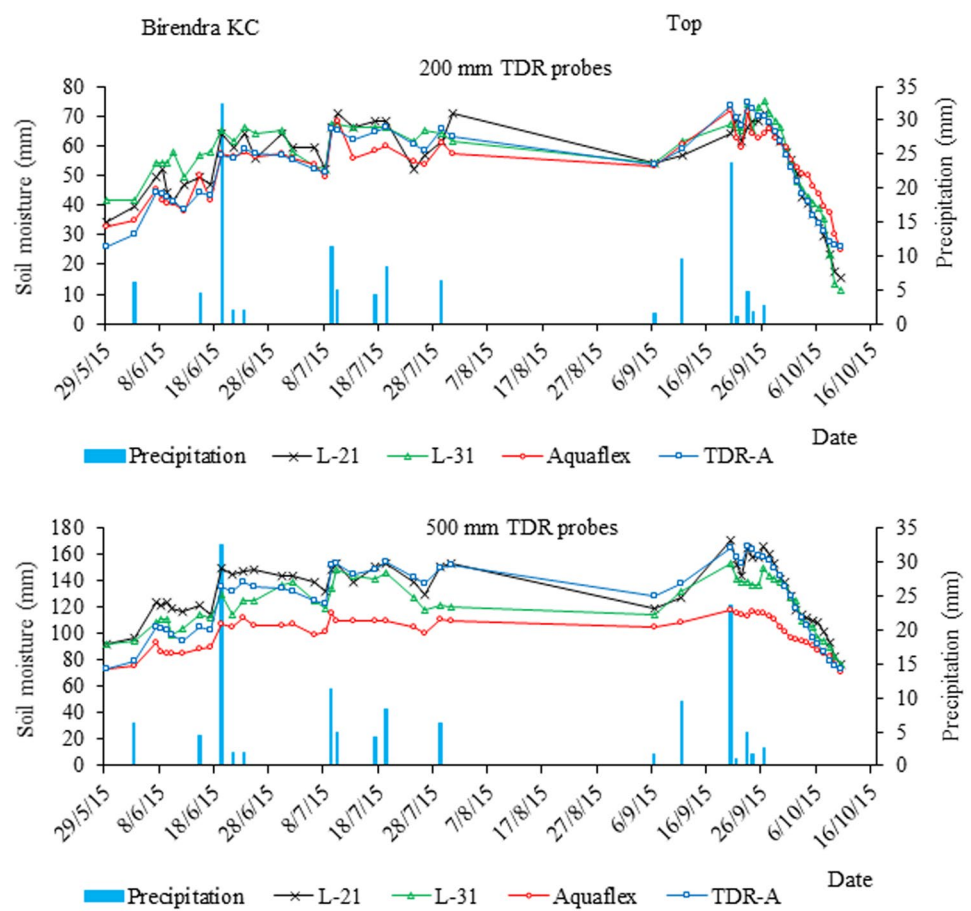
The amplitudes of the daily fluctuations in water content measurement from probes with different length were noticeably higher for the shorter probes (200 mm) and Aquaflex top sensor than those recorded by the longer probes (500 mm and 900 mm) and Aquaflex bottom sensor. In other words, the top soil was recharged and depleted in a short period of time. This reflects more root activity in the top soil and in turn higher water use from top soil than deeper soil (Parry 1994; Young et al. 2000). There was high spatial variability in inter-probe SM measurements due to variations in soil types at different locations. For example, on 10 June 2015, SM measured from 200-mm TDR besides the lysimeter 21 was 42 mm while beside the lysimeter 31 it was 58 mm. Similarly, on 24 July 2015, SM measured beside the lysimeter 21 was 52 mm while it was 62 mm at lysimeter 31. This suggests that efficient irrigation application would be complex to achieve in this situation, with the same length of probes installed on the same paddock giving different soil water contents.

TDR probes can only sample points in a paddock, so identification of a representative location (benchmark point) for sensor installation is critical. Relying on inadequately placed equipment for SM measurement may create over or under-irrigation conditions. Soil moisture monitoring requires detailed assessment of soil water dynamics at different locations and time to select the best sensor position for irrigation onset (Hedley and Yule 2009a).

Discussion

Over the dry down experiment, out of the total soil moisture change in the 0–900-mm soil profile, 96% was contributed by the top 500-mm soil depth and 4% by the bottom 400-mm soil depth, suggesting a larger percentage of water was taken up from the top 500-mm soil profile. It can be attributed

Fig. 7 Soil water content (mm) measured from TDR installed at different locations during the period 29 May 2015 to 10 Oct 2015: **a** for 200-mm TDR, **b** for 500-mm TDR, **c** for 900-mm TDR



to evapotranspiration. Previous researchers such as Parry (1994) and Woodward et al. (2001) also indicated significantly higher water extraction rates from the shallower soil layers compared to the deeper soil layers. Higher fluctuations in daily SM measured from 200- and 500-mm TDR probes compared to those measured from the 900-mm TDR probes indicated that the 0–500-mm soil profile played a major role in evapotranspiration and the 500–900-mm soil profile played a minor role. In other words, the top soil was recharged and depleted in a short period of time. This reflects more root activity in the top 0–500-mm soil profile and in turn higher water use from the top soil than from the deeper soil (Parry 1994; Young et al. 2000). The results indicate that the significant root depth of pasture on this paddock lies in the top 500-mm soil profile. Therefore, irrigation needs to be targeted to the top 500-mm soil of this paddock. The results signify the usefulness of multiple lengths vertical TDR probes in assessing root water uptake for a farm to determine optimal root depth for targetting irrigation water supply. Previous researchers such as Young et al. (2000) and Miyamoto et al. (2001) made similar conclusions that implementation of multi-length TDR probes improves soil moisture measurement at different soil profiles.

The strong linear relationship between soil moisture measured from TDR probes (installed besides the Aquaflex) and Aquaflex soil moisture sensors indicates that the Aquaflex measures SM in the field properly. Previous study by Plauborg et al. (2005) also found that the Aquaflex is capable to reflect the dynamics of the soil water content in the field. This was also supported by the fact that the Aquaflex measured soil moisture was always between the field capacity (FC) and management allowable deficit (MAD) as intended by the farm management unit to maintain SM in this range, to reduce percolation and irrigation requirements (KC et al. 2018a). The regression relationship between Aquaflex and TDR probe readings can be used to calibrate the Aquaflex for improving irrigation scheduling.

The same length of TDR installed at different locations showed different SM measurements indicating a need to monitor SM at multiple locations for quantifying actual irrigation requirements (Hedley and Yule 2009a). Compared to 200-mm and 500-mm TDR probes, the 900-mm TDR probe showed high variability in SM measurement, indicating a significant difference in bottom soil texture across the farm. The results are in-line with those discussed in Barringer et al. (2016).

Conclusions

Application of a dry down experiment enabled the estimation of the rate of SM depletion in the pasture root zone. Results from a 13-day drydown experiment indicated that the top 500-mm soil profile contributes 96% of soil moisture changes in this farm, that is, 500 mm can be considered as “effective” pasture root depth.

Despite the differences in SM measurements by TDR and Aquaflex sensors associated with the differences in SM measurement methods and soil spatial variability, there was a strong linear relationship between Aquaflex and TDR probes readings. The strong linear relationship between Aquaflex and TDR probe readings can be used to calibrate Aquaflex and improve reliability of SM measurement and in turn better irrigation scheduling.

TDR probes showed varying SM measurements both vertically and horizontally, due to variations in soil types at different locations. This signifies the importance of SM monitoring for irrigation scheduling at multiple locations in a farm for proper estimation of irrigation needs.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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