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THREE YEARS OF DRAINAGE FLUXMETER MEASUREMENTS UNDER A VARIABLE RATE CENTRE PIVOT – HOW DO THEY RELATE TO SOIL, CLIMATE AND IRRIGATION?

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Abstract

This paper reports a study conducted at Massey University No. 1 Farm, Palmerston North. The aim of the study was to understand the relationship between predicted drainage volume and the drainage volume measured by passive-wick tension flux meters in the field, and how these volumes relate to soil, climate, and irrigation.

The study area has a centre pivot with variable-rate irrigation (VRI) control to ensure optimum use of water resources on two water management zones. The site was cropped with peas, beans, and spring wheat over the 3-year measurement period. Twelve drainage flux meters (DFMs) were installed around the centre pivot in the Manawatū fine sandy loam. The tops of the meters were installed at 60 cm depth and they were positioned around 3–4 m apart in four replicated plots (three per plot). Drainage samples were collected at regular intervals over the 3-year period using a custom-designed pump, and the volumes were measured and converted to millimetres of drainage. The available water-holding capacity (AWC) of the soil was measured in the laboratory using standard methods. Other data collected included climate and crop management information.

The measured drainage was compared with amounts predicted by the FAO-56 Penman-Monteith soil water balance model, and although both measured and predicted amounts followed the same trends, the measured drainage was found to be greater. We hypothesise that the design and tension created by the flux meters caused more drainage to be collected than predicted and that this drainage may have been captured from a larger soil volume than the ‘sample’ soil volume encased in the flux meter. We, therefore, used a least-squares regression model to adjust the measured drainage volumes to fit the theoretically predicted values.

On this basis, the total amount of drainage over the 3 years was 786 mm. Both rainfall and irrigation had significant effects on the drainage pattern. The wetter growing season of the bean crop (210 mm rain) led to an increase in drainage volume compared with the drier growing season of the pea crop (146 mm rain) with similar water demands. Besides, real-time soil water monitoring enabled further reduction of drainage compared with model-based scheduling in both pea and bean crop trials. In a wheat trial, during the third year of trials, drainage was reduced from 129 mm to 114 mm by irrigating at irrigation thresholds determined at 0.4 AWC compared with 0.6 AWC, without negative impact on yield.

Key words: drainage flux meters, drainage volumes, soil water balance, sensor networks, variable-rate irrigation

Introduction

Precision agriculture technologies, such as variable rate application of irrigation water and the use of management zones for improved management of soil spatial variability, coupled with good farm practices can help reduce farm inputs, improve nutrient use and profit, and help minimise water applied, drainage losses, and nutrient losses from farms (Hedley 2015; Drewry et al. 2019).

Variable-rate irrigation (VRI) systems have been shown to reduce drainage and nutrient losses compared with uniformly applied irrigation water on dairy farms (McDowell 2017) and cropping farms (Hedley et al. 2009; Hedley 2015; El-Naggar et al. 2019). However, there is a need to improve our knowledge of field measurements of drainage from VRI systems under cropping, as previous work has largely been modelled rather than measured (e.g. Hedley et al. 2009).

Passive-wick drainage flux-meters (DFM) have been used to measure drainage from soils in field conditions (e.g. Gee et al. 2009; Norris et al. 2017). Gee et al. (2002, 2009) investigated the design and application of DFMs and explained that proper matching of wick length and control tube height to the soil pressure conditions expected during typical drainage events will improve the performance of the passive wick units (Fig. 1). A design advantage over other lysimeters is the use of the control tube above the wick to minimise either convergent or divergent flow, which would change drainage volume measurements from those actually occurring in the undisturbed soil profile. An additional advantage of the passive wick fluxmeters is that drainage water can also be sampled for its chemical characterization.

The aim of our study was to understand the relationship between soil water balance model predicted drainage and the drainage measured by DFMs in the field, and how these volumes relate to soil, climate (especially rainfall), and variable-rate irrigation treatments.

Methods

Site and soil details

The study was conducted at the Massey University arable trial plots at No.1 Farm, Palmerston North. The study area has a centre pivot with variable rate control that irrigates two management zones. The area was divided into two management zones based on soil type. Zone 1 soil is classed as a Manawatū fine sandy loam and Zone 2 is classed as a Manawatū silt loam. This paper reports on Zone 1 only, as drainage volume collection is incomplete for Zone 2. The Manawatū fine sandy loam is classified as a Fluvial Recent soil (Hewitt 2010). It is classed as a deep, free draining soil with high value for multiple uses (Land Use Capability Class 1).
The site was cropped with peas, beans, and spring wheat over the 3-year period.

Drainage flux meters and drainage sampling measurements

Twelve DFMs were constructed using the design of Gee et al. (2002, 2009), with recent applications and principles of this design included (Norris et al. 2017).

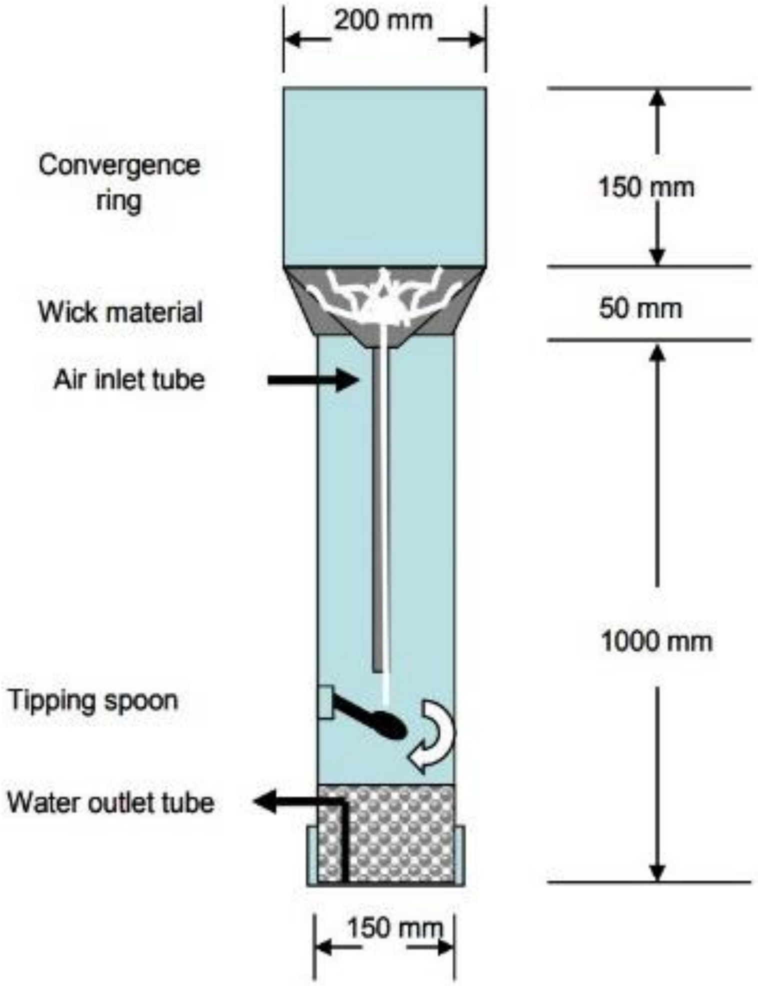

Fig. 1 Schematic diagram of a passive wick drainage flux meter (DFM).

The wick length was 60 cm and the control tube, or the so-called convergence ring (Fig. 1), was approximately 15 cm in height. Each meter was installed so that its top was at least 60 cm below the soil surface, and soil was repacked into its original layers above the DFM at installation. The DFMs were installed 3–4 m apart (Fig. 2) into four replicated plots in the Manawatu fine sandy loam soil. Drainage volumes were collected regularly using a customized pumping system (Fig. 3).

The corresponding drainage flux of water (D_W, mm/d) over the time interval (Δt) was calculated as:

$$D_w = V_D / A\ \Delta t \times 10 \qquad \text{Equation [1]}$$

where V_D is the recorded drainage volume (cm^3), A is the cross-sectional area of each DFM (cm^2), and the factor of 10 is a unit conversion (from cm to mm) (Green et al. 2013).

Fig. 2 Installing the flux meters. Once the DFM was inserted into the hole, the soil was repacked layer by layer.

Fig. 3 Pump designed to collect drainage from DFMs

Irrigation Trials

The soil had four replicated plots (20 m × 10 m) used for each of the crop trials during the 3-year period, with three DFMs installed into each plot. During the pea and bean trials, three replicated drainage volumes were collected from each of the four plots, and the plots were split into two replicated irrigation treatments.

The pea and bean trials compared soil water balance (SWB) scheduling (two replicated plots) with soil water sensor-based scheduling (two replicated plots). In the wheat trial, drainage volumes were collected from two replicated irrigation treatments that corresponded to irrigation at thresholds of 40% (soil water deficit of 50 mm) and 60% (soil water deficit of 64 mm) available water content (AWC). The threshold for irrigation timing was estimated using soil water measurements, collected hourly in the field using a distributed wireless soil water sensor network, during the irrigation season.

For the SWB method, a daily time-step water balance model was developed. This model used daily weather data derived from a local climate station (http://cliflo-niwa.niwa.co.nz/), located 50 m from the trial site, to calculate the daily ETo (reference evapotranspiration), ETc (crop evapotranspiration) and SWD (soil water deficit) values.

For the sensor-based method, El-Naggar et al. (2019) provide details of the wireless sensor network- (WSN) based method used to monitor soil water using frequency domain reflectometry probes (SM300- DeltaT, Burwell, UK) and how they are calibrated for the specific soil type. The SM300 probes were calibrated in a weekly basis by taking three undisturbed soil sample replicates of known volume (intact cores) close to the sensor probes (about 1–3 m distance) at depths of 0.10, 0.20, 0.30, and 0.40 m. The soil volumetric water content was determined by multiplying the gravimetric water content by the measured bulk density (El-Naggar et al. 2019).

The SM300 probes were installed horizontally for each plot at 4 depths, i.e. 0.10, 0.20, 0.30, and 0.40 m, and connected using a WSN developed by Ekanayake and Hedley (2018) to provide a direct continuous measurement of the water content at 1-hour intervals. This is referred to as the sensor method in this paper. For the pea and bean trials, irrigation was scheduled at a specified SWD and this was compared with irrigation to two other plots at the same specified soil water deficit but estimated using a soil water balance model approach. In the wheat trial the WSNs were used to schedule irrigation and compare drainage losses from plots irrigated at trigger points of 0.4 and 0.6 AWC.

Drainage samples were collected over a 3-year period (May 2016 – July 2019) using a custom-designed pump at regular approximately monthly intervals and the volumes were measured.

A least-squares regression model was used to adjust the measured drainage volumes to fit the model predicted values where necessary. This was considered the most appropriate method to find the best fit between the two sets of data and aligns with the procedure used by Norris et al. (2017) to verify that drainage volumes were realistic.

Soil physical measurements

The available water holding capacity of the soil is a measure of the capacity of the soil to store water for plant use. The AWC was measured using standard methods (–10 to –1500 kPa) in the Manaaki Whenua – Landcare Research soil physics laboratory in Palmerston North (Gradwell & Birrell 1979). (https://www.landcareresearch.co.nz/resources/laboratories/soil-physics-laboratory/services-offered/tests)

Results

Although both measured and predicted amounts of drainage followed the same trends, the measured drainage was found to be much greater (Fig. 4). We hypothesise that the tension in the DFMs caused more drainage to be collected than predicted, as drainage flux was not being confined to one-dimensional vertical flow. This is likely due to a combination of the wick length being too long and the height of the convergence ring being too short (Gee et al. 2002, 2009). We therefore used a least-squares regression model to adjust the measured drainage volumes to fit the model predicted values (Fig. 4), following similar procedures adopted by Norris et al. (2017).

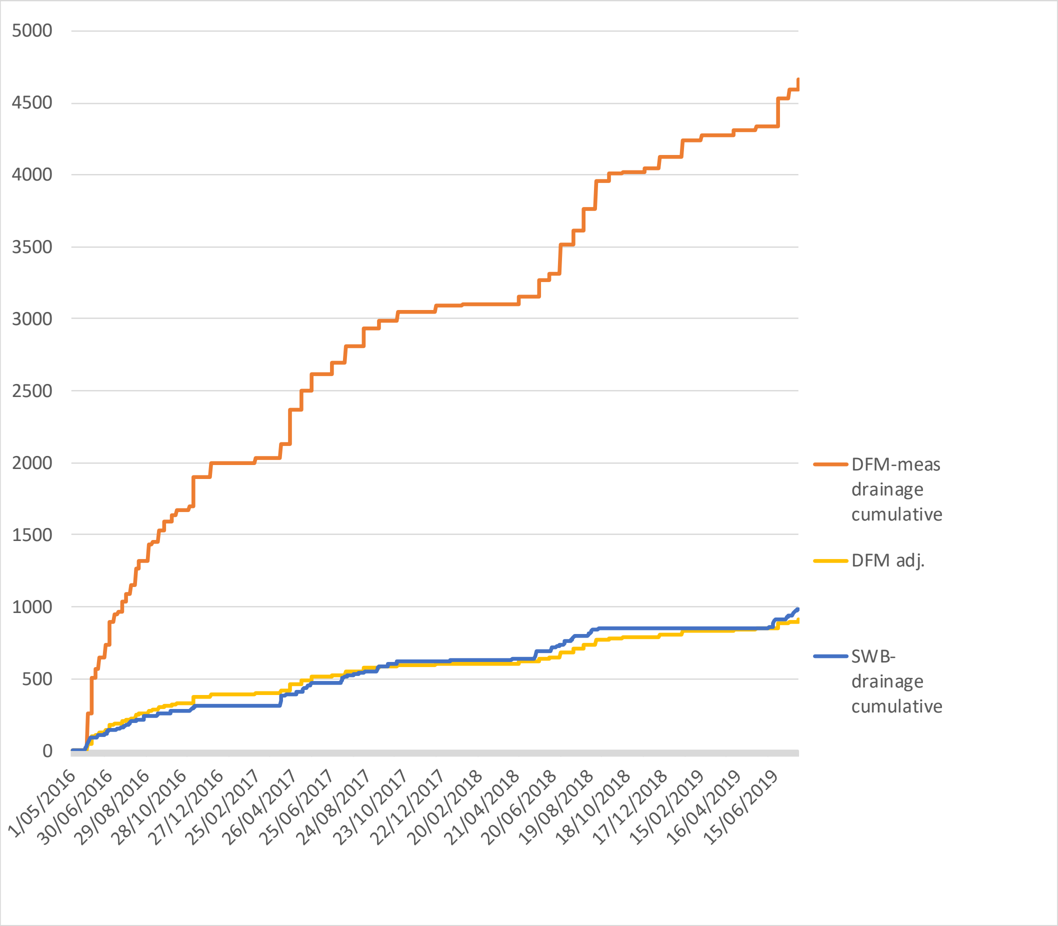

Fig. 4 Drainage flux meter (DFM) measured drainage (mm) (orange line), soil water balance modelled drainage (blue line), and DFM adjusted drainage (yellow) using a least squares regression model.

The total amount of model-adjusted drainage over the 3-year period was 786 mm. For the pea trial the soil water sensor technique reduced the drainage volume by 24 mm compared with the SWB method. In the wheat trial, less drainage was measured at 60% AWC, compared with 40% AWC. This is because more water (125 mm) was applied to the 40% AWC treatment compared with 75 mm for the 60% AWC treatment. Although less irrigation was applied to the sensor-based and 60% AWC treatment, this did not result in significant crop yield differences.

Table 1: Irrigation treatments, rainfall, drainage and yield for Zone 1 in each crop trial. Analysis-of-variance (ANOVA) at *P*=0.05, Tukey's HSD were conducted to investigate significant differences in measured crop yield. The same lowercases indicate the mean difference is not significant at the 0.05 level. For further details see El-Naggar et al. (2019)

Treatments	Date	Crop	Irrigation (mm)	Rainfall (mm)	Drainage (mm)	Yield (SD) (T/ha)
VRI-SWB	15 Nov 2017 – 23 Jan 2018	Peas	120	146	66	2.44^{a} (0.01)
VRI-sensor			85		42	2.31^{a} (0.02)
VRI-SWB	8 Feb 2017 – 12 April 2018	Beans	35	210	82	1.10^{a} (0.03)
VRI-sensor			35		73	1.10^{a} (0.02)
VRI-40% AWC	25 Nov 2018 – 28 Feb 2019	Spring wheat	125	305	129	4.8^{a} (0.6)
VRI-60% AWC			75		114	4.7^{a} (0.8)

Discussion

The DFMs measured considerably more drainage than that estimated by a soil water balance model. We therefore hypothesise that the tension flux meters captured drainage from a larger soil volume than the 'sample' soil volume encased in the flux meter and so we used a least squares regression model to adjust the measured drainage volumes to fit the predicted values.

The convergence rings of the DFMs installed at this site were 15 cm in depth (Fig. 1), in contrast to the 60 cm recommended by Gee et al. (2009). The wick length of 60 cm confirmed with that recommended by Gee et al. (2009) as suitable for many conditions. However, we suggest that the wick length could have been shorter (providing less tension) and/or the convergent ring could have been deeper to better mimic field conditions. Indeed, Gee et al. (2009) discuss the importance of adjusting wick length and convergence ring height to match site specific conditions. However, in the interests of utility, choices are made in the hope that the passive tension does mimic ambient soil conditions, as we have done here.

Despite the issue of water convergence into the DFMs the trends closely matched those predicted by the soil water balance model. We were therefore able to adjust the measured drainage to fit the modelled drainage trends, and we used the adjusted values for further interpretation of crop trial results.

During the pea crop growth, real-time soil water monitoring reduced irrigation requirement and drainage water lost compared with model-based scheduling, and we hypothesise this is because the soils drained at a slightly slower rate than predicted by the soil water balance model. The spring wheat trials showed that irrigation and drainage amounts were reduced with little to no impact on yield when irrigation was scheduled at 0.6 AWC compared with 0.4 AWC.

The drainage flux meters provided a useful field check on drainage trends and timing, but their design caused larger volumes of drainage to be collected than theoretically possible, as predicted by the SWB model. Further research is required to develop a method that modifies wick length and convergence ring to meet the site specific soil conditions.

Conclusions

Although the DFMs were a useful tool for indicating when drainage is occurring, and for collecting drainage water that can also be used to measure the solute concentration of the mobile-water drainage, the measured volumes were greater than the predicted volume, therefore care is needed interpreting the results.

The two scheduling methods showed a variation in timing and quantity of irrigation, and consequently the drainage volume for the pea crop.

The use of increased deficit irrigation for the wheat crop (ie. 60% AWC compared with 40% AWC) reduced the drainage volume from these soils.

Recommendations

The DFMs are likely to have measured the correct solute concentration because they apply a tension that seeks to mimic ambient tensions, unlike suction cups which apply a far greater tension to extract the soil solution. Unfortunately, in some circumstance they do have some difficulties collecting the correct volumes of drainage because of the complex need to match the height of the convergence ring and the length of the wick to the local soil's hydraulic properties. Simplicity can sometimes create the prudent need to cross-check and validate drainage volumes.

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