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MONITORING THE SOIL WATER BALANCE AND DRAINAGE LOSSES FROM KIWIFRUIT ORCHARDS IN THE BAY OF PLENTY REGION

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Abstract

The New Zealand kiwifruit industry faces the prospect of limits being imposed on the use of water for irrigation. Currently there is almost no data available to assess the soil water balance (SWB), and in particular the drainage losses below the root-zone of kiwifruit orchards. To fill this knowledge gap, Zespri Group Limited has contracted The New Zealand Institute for Plant & Food Research Limited (PFR) to undertake a series of field studies on a range of orchards in the Bay of Plenty region.

PFR has installed instrumentation on seven kiwifruit orchards. Our equipment includes flow meters for irrigation volumes, time-domain reflectometry sensors (TDR) for soil water contents, passive-wick flux meters (DFM) for drainage and weather stations for local microclimate. The seven sites cover a range of representative kiwifruit orchards including the two main kiwifruit varieties (*Actinidia chinensis* var. *deliciosa* 'Hayward' and *Actinidia chinensis* var. *chinensis* 'Zesy002' Gold3), the two predominant soil types (allophanic and pumice) and different irrigation management including some non-irrigated orchards. The data loggers are equipped with IP-modems to enable real-time access to the soil moisture and climate data.

This project is expected to develop the first comprehensive dataset for kiwifruit, comprising a quantified seasonal water balance across a range of soils and climates. This data will enable robust development and validation of models with which irrigation limits will be determined. Having good models should allow better management of water on orchards. In this paper we will describe the field set-up and present preliminary data on the SWB.

Introduction

The National Policy Statement for Freshwater Management (NPS-FM 2014, MFE 2014) directs all regional councils to undertake catchment level regulation of parameters affecting the quantity and quality of their ground and surface water resources. The Bay of Plenty Regional Council (BOPRC) are currently in the process of developing their freshwater management plan in response to the NPS-FM. This plan will set limits on nutrient discharges to the environment as well as limits on the volumes of water that can be used for irrigation. Modelling and reliable scientific data are needed to inform the policy-making process (van Daalen et al, 2002).

Under the NPS-FM, the New Zealand kiwifruit industry now faces the prospect of limits being imposed on irrigation volumes and nutrient losses, particularly nitrogen and phosphorus. Such regulations could have an economic impact on the kiwifruit industry, especially if a restriction on inputs leads to a significant drop in production. It is imperative, then, that the impacts of any regulation and limit setting with regard to irrigation and fertiliser use are known well in advance. Currently there are almost no data available to assess drainage losses below the root-zone of kiwifruit orchards. To fill this knowledge gap, Zespri Group Limited has contracted The New Zealand Institute for Plant & Food Research Limited (PFR) to undertake a series of field studies on seven orchards to quantify the soil water balance (SWB). This study takes a dual 'measurement and modelling' approach to quantify the losses and to provide solutions.

Materials and Methods

Site selection

PFR has been commissioned to install instrumentation on seven orchards that represent a range of kiwifruit operations in the Bay of Plenty region (Figure 1). These orchards were chosen to include the following characteristics:

- Two main kiwifruit cultivars of *Actinidia chinensis* var. *deliciosa* 'Hayward' and *A. chinensis* var. *chinensis* 'Zesy002' Gold3
- Two ages of vines: Established (full cropping, extensive leaf canopy, well-developed, and a deep root system) and new plantings (limited root system)
- Two predominant soil types — allophanic and pumice
- Different rainfall amounts — average and above average
- Different irrigation management regimes (including non-irrigated).

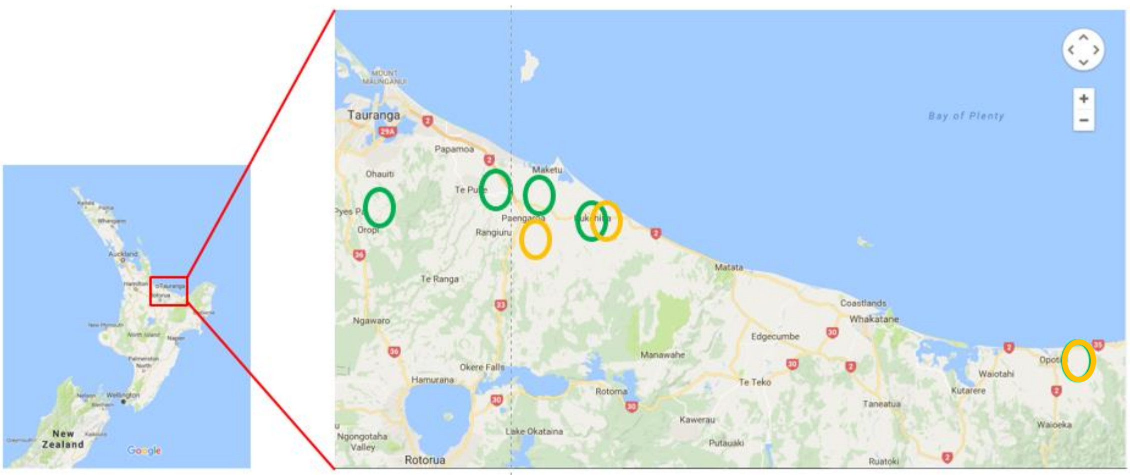

Figure 1. The location of the seven kiwifruit orchards that are hosting the Zespri Group Ltd monitoring sites in the Bay of Plenty region. A green symbol represents an *Actinidia chinensis* var. *deliciosa* 'Hayward' orchard and a yellow symbol represents an *A. chinensis* var. *chinensis* 'Zesy002' Gold3 orchard.

Prior to the commencement of this study a number of growers were contacted by Zespri and asked to host a study site. The soil type from each orchard was first identified using the software tool S-MAP (Landcare Research) and satellite images from Google Earth (GE) were used to locate the orchard boundaries and to properly align them with the S-MAP images (Figure 2). The microclimate, and in particular the annual rainfall total, was also assessed using data from the National Climate Database from the National Institute of Water and Atmospheric Research (NIWA).

Figure 2. The left panel shows a Google Earth image of the orchard on Old Coach Road, near Te Puke. The right panel is the corresponding SMAP image which identifies the soil as Turang_8 (a composite of 60% Ohinepanea loamy sand and 40% Paengaroa sandy loam). The yellow rectangle identifies the location of the experimental site.

Weather data

A standard weather station was set up at each of the monitoring sites to record hourly values of global shortwave radiation (R_G, W/m2), air temperature (T_A, °C), relative humidity (R_H, %), and rainfall (R_F, mm). At three sites (only) we are also recording the wind speed (U, m/s) using a three-cup anemometer. These instruments are placed at a height of approximately 2 m above the canopy, except for the air temperate and humidity sensor which is placed just beneath the canopy. The following instrumentation is being used:

- A shortwave sensor (Licor model LI200) for R_G
- A screened temperature and humidity sensor (Vaisala model HMP60) for T_A and R_H
- A tipping-spoon rain gauge (Pronamic model 100.054) for R_F
- A three-cup anemometer (Maximum model Type 40) for W_S

These sensors are connected to a Campbell data logger (models CR10X and CR1000, Campbell Scientific, USA) to record hourly averages (R_G, T_A, R_H, W_S) and hourly totals (R_F). The loggers are powered by a 12 V 25 AHr sealed lead-acid (SLA) battery that is recharged by a 20 W solar panel. An IP modem is used to transmit data from the logger to a Host FTP site that is providing near real-time updates of the data. Scott Technical Instruments (Hamilton) are providing the service to download and archive all of the ‘raw data’. PFR are compiling the datasets and carrying out analysis and interpretation of the results.

For the purpose of modelling, additional climate data from Te Puke and Opotiki have been downloaded from the National Climate Database (www.cliflo.niwa.co.nz). These data are being used to estimate daily rates of evapotranspiration which is an essential part of modelling the SWB and assessing the behaviour of our DFM devices.

Soil Water Content

Arrays of time-domain reflectometry (TDR) sensors were installed at each site to measure the spatial and temporal dynamics of soil water content (SWC) in the root-zone soil. A combination of sensor types has been employed in this project (Figure 3).

On three of the orchards, multiple sets of 30 cm long TDR waveguides (model CS616, Campbell Scientific, USA) were installed vertically into the soil. The sensor depths varied from the soil surface down to 160 cm at approximately 40 cm depth intervals. The probes were grouped in sets of three in order to generate a profile measurement of SWC. A total of 10 TDRs were installed in each orchard, this being the maximum number of spare channels on the data logger (model CR10X, Campbell Scientific), with the remaining analogue channels being assigned to monitor T_A and R_H.

On the other orchards, multiple sets of 60, 120 and 200 cm long waveguides (Tranzflo NZ Ltd, Palmerston North, NZ) were inserted vertically into the soil to provide an integrated measure of the average SWC along the depth of the wave guides. Two types of TDR devices (Tektronix TDR1502C & Campbell TDR100) and two types of data loggers (Campbell CR10X and CR1000) were employed. A total of 15 waveguides were used at each site and they were connected to the TDR instrument using a number of high-frequency multiplexers (SDMSX-50, Campbell Scientific).

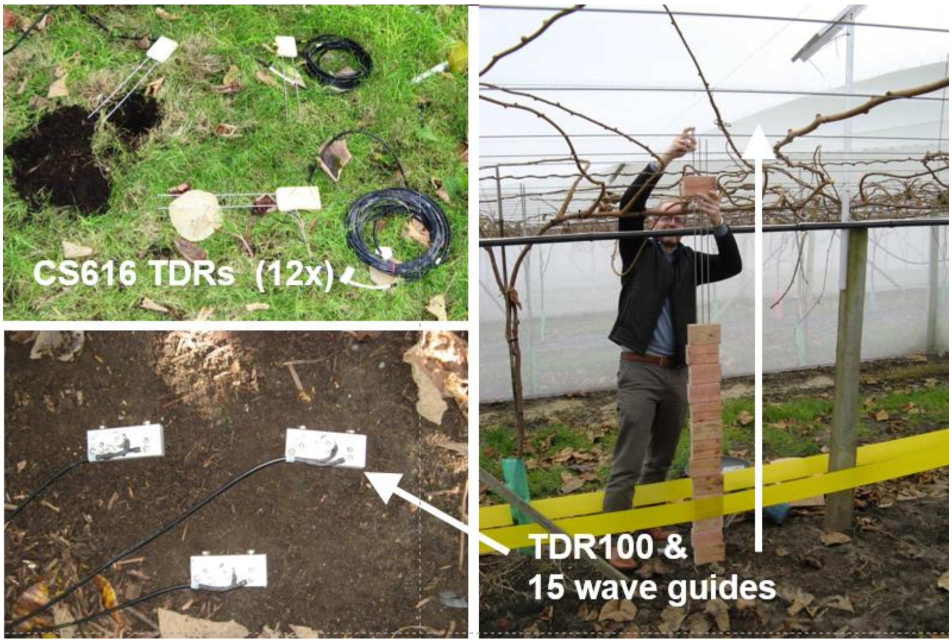

Figure 3. Time domain reflectometry (TDR) probes were installed in each orchard to record changes in volumetric soil water content (SWC, %). On three orchards, an array of CS616 sensors (Campbell Scientific, USA) was used to measure profiles of SWC to a depth of 1.6 m, at 40 cm depth increments. On the other four orchards, either a TDR100 device (Campbell Scientific, USA) or a TDR1502C device (Tektronix, USA) was used to obtain an integrated measure of the average soil water content over the waveguide depth of 60, 120 and 200 cm. The right panel shows David Armour from Zespri, Mt Maunganui, installing some of the 2 m long TDR waveguides.

TDR sensors respond to the dielectric properties of the soil and their measurements are strongly influenced by a number of factors including soil water content and soil organic matter. A standard calibration factor is often used to convert a TDR-measured value of the apparent dielectric, K_A, to a volumetric measure of SWC (Topp et al. 1980; Anon, 2007). This procedure works adequately for most mineral soils. However, for pumice soils from the Bay of Plenty we have recently observed the standard calibration for a CS616 sensor results in SWC values that are low by about 40% (Figure 4). A similar discrepancy between measured and actual values of SWC is expected in allophanic soils which are also relatively high in soil organic matter. At the time of writing this paper, the 'correction factor' for the TDR sensors used in this study was undetermined. Preliminary data presented here are based on the calibration curve of Figure 4 which has been applied as a correction factor.

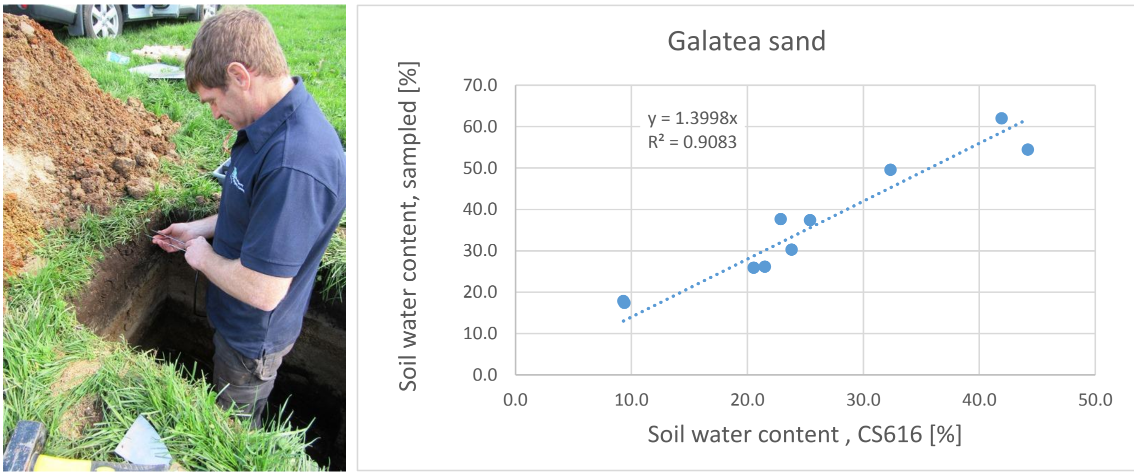

Figure 4. Scott Mahupuku from the Bay of Plenty Regional Council carries out a field calibration of a CS616 time-domain reflectometry (TDR) sensor (Campbell Scientific, USA)) on Galatea sand. Steel cores were inserted beside the TDR waveguide to determine the soil's bulk density and volumetric water content (Green & Mason, 2017).

Drainage fluxes

Estimates of the unsaturated water-flux density, J (mm/day), are needed to quantify water movement within the vadose zone. One approach is to use lysimetry (Allen et al. 1991) where a quantity of soil water is captured in a buried container and the volume is measured over a given period of time.

A wide range of lysimeters can be employed including pan lysimeters, wick lysimeters and tension lysimeters, each with their own advantages and disadvantages (Gee et al. 2009). In this project we are using a basic device that is similar to that of Gee et al. (2002, 2003), consisting of a convergence tube, a funnel, a hanging wick and a subterranean reservoir (Figure 5).

The drainage flux is measured automatically with a tipping spoon device that collects water draining from the fibreglass wick. The device is buried at a depth of 220 cm, leaving the top part of the funnel sitting at a depth of 120 cm which is the assumed measurement depth.

The cross-section of the DFM, through which the drainage water flows, has an area A = 314 cm^2. Periodically, we empty the device and record the drainage volume as V (cm^3) after a time Δt (day). The corresponding drainage rate, D, is computed as:

$$D = 10 * (V/A) / \Delta t \text{ (mm/day)} \qquad \text{Eq [1].}$$

The value of 10 is a unit conversion from cm to mm. Individual DFMs are pumped out, one at a time, with the water samples being collected into a 2 L or 5 L measuring cylinder. The total volume is recorded and so the total drainage rate is quantified.

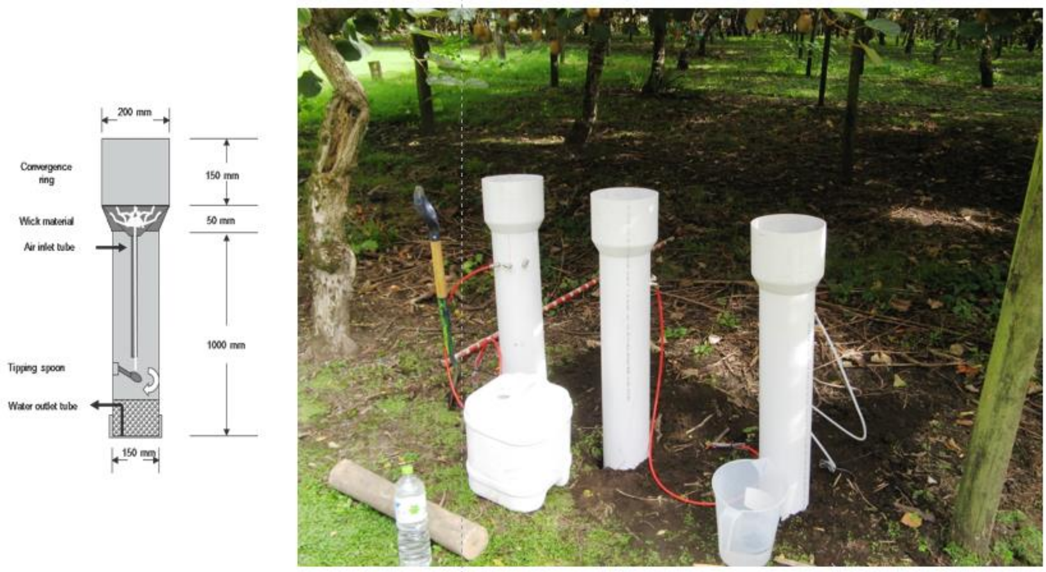

Figure 5. A photograph of three drainage flux meters (DFM) being prepared for installation on an *Actinidia chinensis* var. *deliciosa* 'Hayward' orchard near Te Puke. The left panel is a schematic of the device (DFM20, Tranzflo NZ Ltd), showing the fibre-glass wick that drains water through a tipping spoon near the base of the unit. The tipping spoon is connected to a data logger to record the drainage events. Water samples accumulating in the reservoir of the DFM are drawn to the surface through a clear tube (labelled as the water outlet tube), using a 12 V vacuum pump that connects to the red tube (labelled as the air inlet tube). The device is buried in a hole of 220 cm depth, leaving the top of the device at a depth of 120 cm which is the assumed measurement depth. Soil is repacked into the hole to match the original density.

RESULTS

The soil water balance

In this project, we have measured some, but not all, of the components of the SWB. In particular, we have explicit measurements of:

- The inputs of water to the soil profile from rainfall and irrigation
- The changes in the amount of water in the soil profile from the water content
- The outputs from the soil profile from drainage losses

The remaining components of the SWB, which we have not measured, include:

- Outputs of water from the soil via plant water uptake and soil evaporation
- Losses of water from the orchard system as interception and run-off of rainfall

Modelling is used here to: (1) generate estimates for the remaining components of the SWB, and (2) evaluate the performance of the DFMs as they are settling in. The SWB of each orchard is shown in Figure 6, along with a comparison between measured and modelled values of the SWC in the top 120 cm of the soil profile, which is just above the DFMs. The SWC data come directly from the TDRs, which has no settling-in period. A 'local calibration' has been applied to the TDR data in accordance with the curve of Figure 4. The modelling was carried out using a simplified spreadsheet version of the water balance component of Soil Plant Atmosphere System Model (SPASMO; Green 2011), compiled in Excel™.

In general, by using a consistent set of input-parameters and local climate data, we have been able to simulate SWCs that are very close to actual TDR data. This good agreement gives us added confidence in the plant water-uptake part of the calculations, since the modelled rate-of-change of SWC matches closely with the measured decline from early December.

Model outputs of SWC at the Maketu (MAK) site, which is non-irrigated, do not appear to be quite as good compared with the other sites. Our calculations show a little more water missing from the root-zone (0 to 1.20 m) than is measured by the TDRs. There may be a simple reason for this discrepancy. All of our simulations assume a 'standard' root depth of z_R = 1.2 m for kiwifruit. This may not be the case for the vines at the MAK site, which are mature 'Hayward' vines. As it happens, we can get an almost exact match (data not shown) between data and model outputs if we assume a much deeper root zone and set z_R = 2 m. We are drawn to the conclusion that the active root-system at the MAK site is likely to be much deeper than 1.2 m. Root sampling to a depth of 2.0 m is planned to occur during the next stage of this project.

Figure 6 also compares measured and modelled drainage rates in order to assess the performance of the DFMs. The DFMs are deemed to have a good performance only if the measured drainage rates are close to the modelled drainage rates. That is not to say the modelled drainage rates are exact, since there are many parameters that can affect the outcome. They are, however, likely to be close to the right answer since measured SWCs are closely matched to the model outputs. The results are summarized as follows:

- On the basis of our SWB modelling, we believe that the DFMs from the Te Puke (BAY) site have already settled in, and they are already providing a good measure of drainage. There are a few 'flooded' DFMs at this site, but we have omitted their data from our measurement and modelling comparison.
- The DFMs at four other sites, namely Maketu, Opotiki (OPK), Pyes Pa (PYE) and Paengaroa (PNG), are still settling in. The timing of the drainage events coincides approximately with the model outputs, and both are responding to the large rainfall events. However, the absolute values of drainage from these DFMs are still much lower than our modelled results.
- The DFMs at the OCR and PUK (Pukehina) sites do not appear to be working very well at all. Since July 2016 we have recorded only a small sample volume yet we expect, via modelling, for there to have been more than 320 mm of drainage at those sites (Table 2). The OCR and PUK sites are interesting for at least two reasons: they are the sites with the greatest slope (about 1:10), so we expect highest rates of run-off, and there has been major re-contouring of the natural soil affecting soil properties.

Water balance components of the seven kiwifruit orchards are summarised in Table 1, for the nine month period between July 2016 and February 2017. In most years there would normally be very little drainage for the next three months. This is because growers would be trying to maintain a reduced soil moisture level in order to increase the fruit dry matter (DM) content between now and through until harvest. Following the recent heavy rainfalls at the end of February, there is unlikely to be further need for irrigation before harvest.

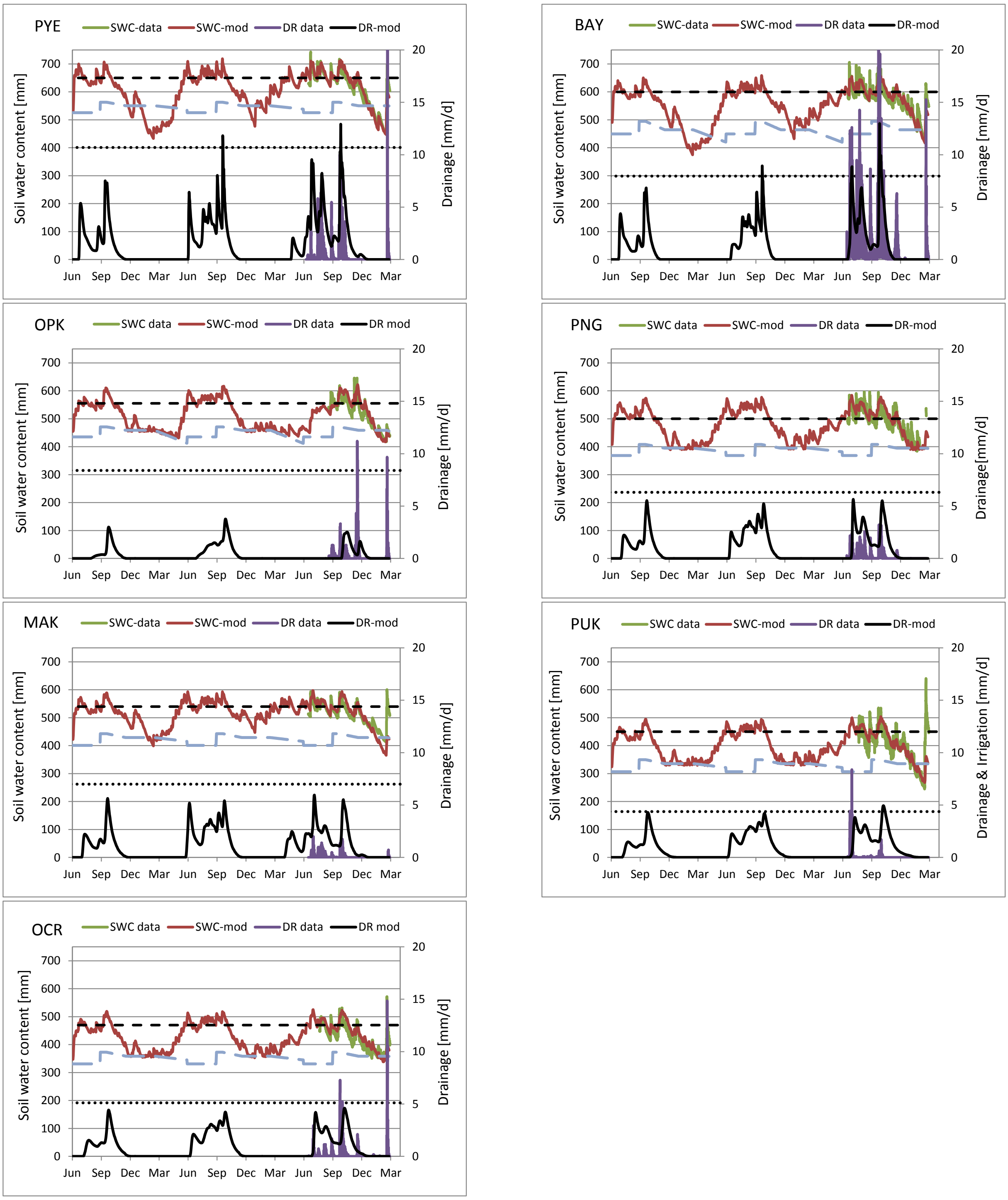

Figure 6. The soil water content (SWC, 0–120 cm depth) and the drainage (DR at 120 cm) at seven kiwifruit orchards that are hosting the Zespri Nutrient Loss experiments in the Bay of Plenty region. The site names are as follows: BAY is near Te Puke, PYE is Pyes Pa, OPK is Opotiki, PNG is Paengaroa, MAK is Maketu, PUK is Pukehina, and OCR is Old Coach Rd.

Table 1. Components of the soil water balance (SWB) from seven kiwifruit orchards that are hosting the Zespri Group Ltd experiments in the Bay of Plenty region. The site names are: BAY is near Te Puke, PYE is Pyes Pa, OPK is Opotiki, PNG is Paengaroa, MAK is Maketu, PUK is Pukehina, and OCR is Old Coach Rd. The components are: RF is rainfall, IR is irrigation, DR is drainage, RO is run-off, ET_C is the total crop transpiration, including water loss from the alleyway. These are model estimates (mm) for the period July 2016 and February 2017. The code is: H is *Actinidia chinensis* var. *deliciosa* 'Hayward', G is *A. chinensis* var. *chinensis* 'Zesy002' Gold3, A is allophanic soil, and P is pumice soil.

Jul-Feb	RF	IR	DR	RO	ET_C	Code
*OPK	735	103	97	86	745	GP
PYE	1110	0	509	142	631	HA
BAY	1125	0	438	214	655	HA
**MAK	687	0	332	79	572	HA+P
PNG	894	168	339	228	691	GP
PUK	991	218	362	281	752	GP
OCR	868	155	323	243	657	HP

*OPK – this site was started at the end of winter 2016.
**MAK – this site was missed by a large rainfall event (~125 mm) that occurred between 17 and 19 February 2017.

Table 2. Drainage from seven kiwifruit orchards that are hosting the Zespri Group Ltd experiments in the Bay of Plenty. The site names are: BAY is near Te Puke, OPK is Tablelands Rd near Opotiki, PYE is Joyce Rd near Pyes Pa, OCR is Old Coach Rd, PNG is Royden Downs Rd near Paengaroa, MAK is Maketu Rd, and PUK is MacDougall Quarry Rd near Pukehina. Data values are from the drainage flux meters (DFMs) and model values are from the water balance calculations. The collection efficiency (CE) is calculated from the ratio of the data value divided by the model value.

Drainage	BAY	OPK	PYE	OCR	PNG	MAK	PUK
data (mm)	581	87	165	86	93	39	28
model (mm)	485	95	572	324	351	351	358
CE (%)	120	92	29	27	26	11	8

The collection efficiency (CE, %) of the DFMs can be estimated from the ratio of measured drainage to the modelled amount (Table 2). While the modelled drainage rates are somewhat sensitive to the choice of parameter values, they represent the best alternative means of assessing drainage losses. So far, two sets of DFMs (BAY and OPK) are yielding the expected drainage, three other sets of DFMs (PYE, OCR and PNG) are yielding 26–29% of the expected drainage, and the remaining two sets of DFMs (MAK and PUK) are yielding just 8–11% of the expected drainage. Over time, we expect the DFMs will settle in terms of their CEs approaching 100%.

The SWB of each orchard is shown in Figure 7, in terms of the measured values of rainfall and irrigation and the modelled values of drainage and run-off. We are modelling the drainage while we wait for the DFMs settle and we are modelling the run-off because at this stage in the project we do not have any measurements of run-off. During the first 8 months of observation, total drainage losses varied between 37% (PUK and OCR) and 48% (MAK) of rainfall, while the corresponding total run-off losses varied between 28% and 11% of rainfall. Drainage and run-off are both large components of the SWB, with the former being up to two to three times larger than the latter.

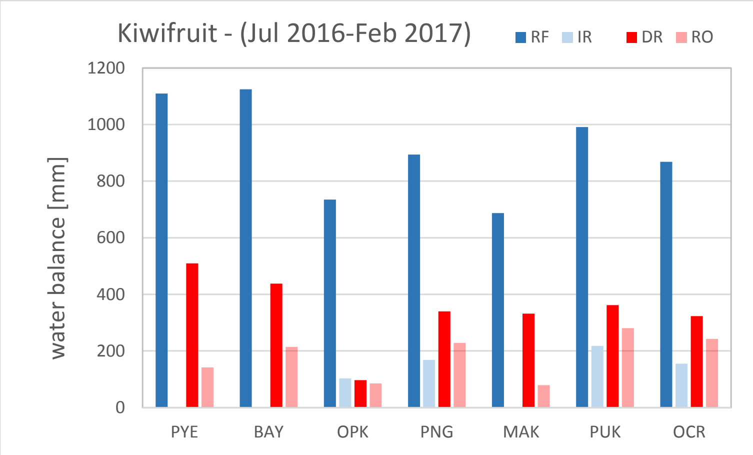

Figure 7. Components of the soil water balance (SWB) from seven kiwifruit orchards that are hosting the Zespri Group Ltd experiments in the Bay of Plenty region, as calculated using the SWB component of SPASMO (Soil Plant Atmosphere System Model). The site names are as follows: BAY is near Te Puke, PYE is near Pyes Pa, OPK is near Opotiki, PNG is near Paengaroa, MAK is near Maketu, PUK is near Pukehina, and OCR is Old Coach Rd. RF is rainfall, IR is irrigation, DR I drainage and RO is run-off.

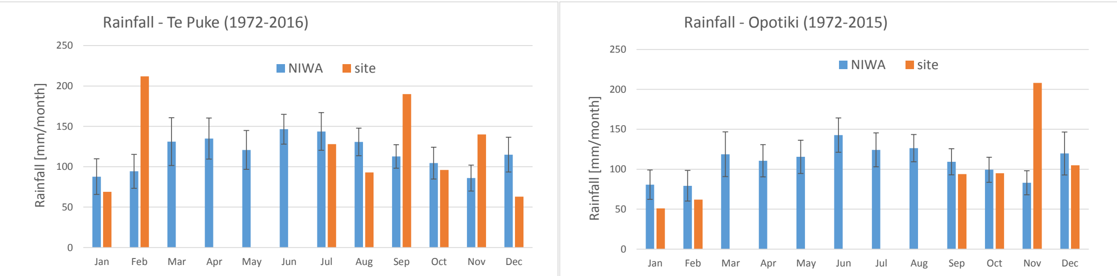

Figure 8. Monthly rainfall totals from Te Puke (top panel, SN12428) and Opotiki (bottom panel, SN1874). The blue bars represent the long-term (1972–2015) average with error bars of +/- one standard deviation (Source: www.cliflo.niwa.co.nz). The orange bars show the rainfall recorded at the Maketu site, near Te Puke (left panel), and at the Opotiki site (right panel).

A few large rain storms have travelled across the Bay of Plenty region, particularly during September and November 2016, and then again in February 2017, although they did not occur simultaneously at all sites (Figure 8). The monthly rainfall total at Te Puke was much larger than the average during the months of September and February. Otherwise, rainfall for the rest of the period was close to normal (average). On the other hand, the monthly rainfall total at Opotiki was much greater than average during November and was slightly lower than average during the months of January and February. Clearly, there have been different amounts of rainfall occurring at each site and this has led to different amounts of drainage.

Summary

The project is directly measuring the SWB of a range of kiwifruit orchards that are representative of the New Zealand kiwifruit industry. This underlying data will enable robust development and validation of models with which irrigation limits will be determined, such as SPASMO. Having good models will also allow better management of water consumption on orchards. Through a consultative process, Zespri and New Zealand Kiwifruit Growers Incorporated (NZKGI) will, in conjunction with research providers and the regional councils, develop irrigation management strategies that sustain industry growth and are underpinned by sound economic modelling supported by adequate, trusted and verified sources of experimental and modelled data. In addition, direct measurement of irrigation use on kiwifruit orchards will allow the impacts of contributing factors to be clarified. This will enable best practices to be identified so that irrigation allocation is both equitable and sustainable.

Acknowledgments

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