PFR SPTS No. 10328

Monitoring nitrate loss under vineyard soils on the Wairau Plains, Marlborough

Green S, Agnew R and Greven M

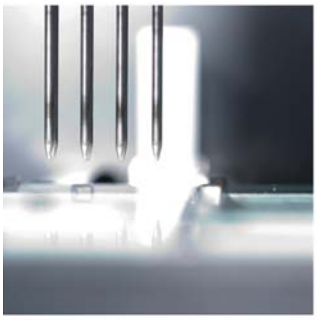
July 2014





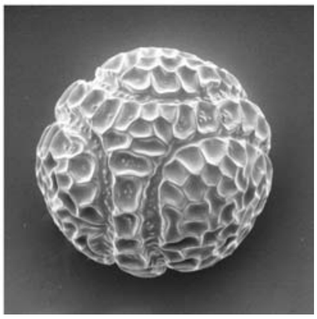










Report for:
Marlborough District Council

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Executive summary

Monitoring nitrate loss under vineyard soils on the Wairau Plains, Marlborough

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July 2014

The Marlborough District Council (MDC) is interested in gaining better understanding of the impact of land management practices on nutrient losses from the Wairau Plains. The objective of this project is to obtain data on how much nitrogen is lost beneath a typical vineyard and the impact that current land management may contribute to elevated levels of nitrate in the groundwater and local springs.

We undertook a field experiment on Motukawa Vineyard, near Raupara, and installed sets of drainage flux meters (DFMs) at Giffords Road on the Northern Wairau Plain. These devices can measure both the rate of water loss (i.e. drainage) and the rate of nutrient loss (i.e. leaching) from the vineyard. We also installed arrays of time domain reflectometry (TDR) sensors to monitor changes in soil water contents from the surface to a depth of 1.8 m. The measurements of soil water content and drainage rates have been verified against outputs from a simple tipping-bucket model of the vineyard soil water balance.

Our monitoring indicates that the average rainfall recharge from this part of the Wairau Plains has been about 290 mm per year over the past 2 years. Elevated levels of both nitrate-N (up to 5 mg-N/L) and ammoniacal-N (up to 1.5 mg-N/L) have been recorded in leachate samples from the DFMs. The highest concentrations were observed at the end of the growing season (start of the drainage season), following the first rewetting of the deeper soil profile (1.2 m) that occurred sometime after mid-May. Thereafter, the nitrate concentration of the drainage water declined below 1.5 mg-N/L, and the corresponding ammoniacal-N concentration declined below about 0.2 mg-N/L. We attribute the progressive decline in nutrient concentrations (for both nitrate and ammonium) during each drainage season (June through October) to dilution effects caused by increased drainage volumes over winter.

Our calculations of annual leaching loss show less than 4 kg/ha of nitrate-nitrogen being leached out of the top 1.2 m of the soil profile. Elevated levels of ammoniacal-N were observed in the water samples from the first winter's drainage, and this result yielded a leaching loss of 6 kg-N/ha of ammoniacal-N. Meanwhile, during the second winter of drainage, ammoniacal-N concentrations were much lower so that only 1 kg-N/ha of ammoniacal-N was leached during the second winter. We expect the results from the second season to be more typical for a grape vineyard since ammonium is not normally as mobile as nitrate with respect to vertical movement through the soil profile. These leaching losses are very low compared with the impacts from other land uses that have been reported around New Zealand.

During the past 2 years, we have experienced two 'dry' summers and two 'wet winters'. Initial results from this DFM study are not yet sufficient in duration to capture a full range of drainage losses because we have had reasonably similar rainfall totals over both years of the trial. It

would therefore seem prudent to continue the field trials for a longer period (certainly a few more years) in order capture a more diverse set of representative weather and growing conditions.

A preliminary examination of the linkage between land use and the quality of the groundwater was made by comparing the nitrate concentrations in drainage water, as collected by the DFMs, against corresponding nitrate concentrations of water samples from the nearby MDC monitoring well at Wratts Road (No. 3009). That comparison indicated a significant attenuation (1:10) and a lengthy time delay (185 d) between nutrient losses from the vineyard and nutrient appearance in the groundwater sampling site located some 2.4 km away.

The experimental data collected here, in combination with a more detailed modelling effort, will eventually be used to provide an estimate of the total nutrient input into the groundwater system of the entire unconfined aquifer area. That modelling will be carried out elsewhere, during a second stage of this project, whereby nutrient drainage rates will be compared with observations of concentrations in downstream groundwater for the purpose of calibrating this new flow and contaminant transport model. That model will enable MDC to accurately account for the impact of land applications of nutrient, as required by the National Policy Statement (NPS) on Freshwater, and to simulate the impact of land surface interactions with downstream ground water quality.

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1 Introduction

In New Zealand, as in other developed countries, there is increasing concern that nitrate losses originating from different agricultural activities are resulting in a contamination of the surface and groundwater resources. As a consequence of these concerns, a large body of research has been carried out to quantify potential nitrate losses from a range of productive land uses.

Nitrogen typically appears in groundwater, in the form of nitrate, and is monitored for health and environmental reasons. Excessive levels of nitrate in drinking water[1] have been linked with blood disease in infants (commonly known as 'blue baby syndrome'). From an environmental perspective, elevated levels of nitrate are also a good indicator of general groundwater degradation. In addition, groundwater that is rich in nitrate also has the potential to elevate nutrient levels in the surface water it drains into.

Nitrate contamination of groundwater in Marlborough is not thought to be a major problem at present. While a few nitrate hotspots have been observed in the past, e.g. west of Renwick, at Rarangi, and in the lower Fairhall/Brancott catchment, these have been attributed to historic dairy and arable farming activities. Nowadays, grape vineyards are the predominant land use activity (Figure 1). Viticulture generally uses very low rates of nitrogen fertiliser compared with other agricultural and horticultural practises. So the potential leaching losses are expected to be relatively small. On the other hand, grape growers also adopt widespread use of irrigation onto typically shallow soils. This practice could increase the amount of nitrate-N moving downwards through the soil profile and thereby increase the risk of contamination to the groundwater.

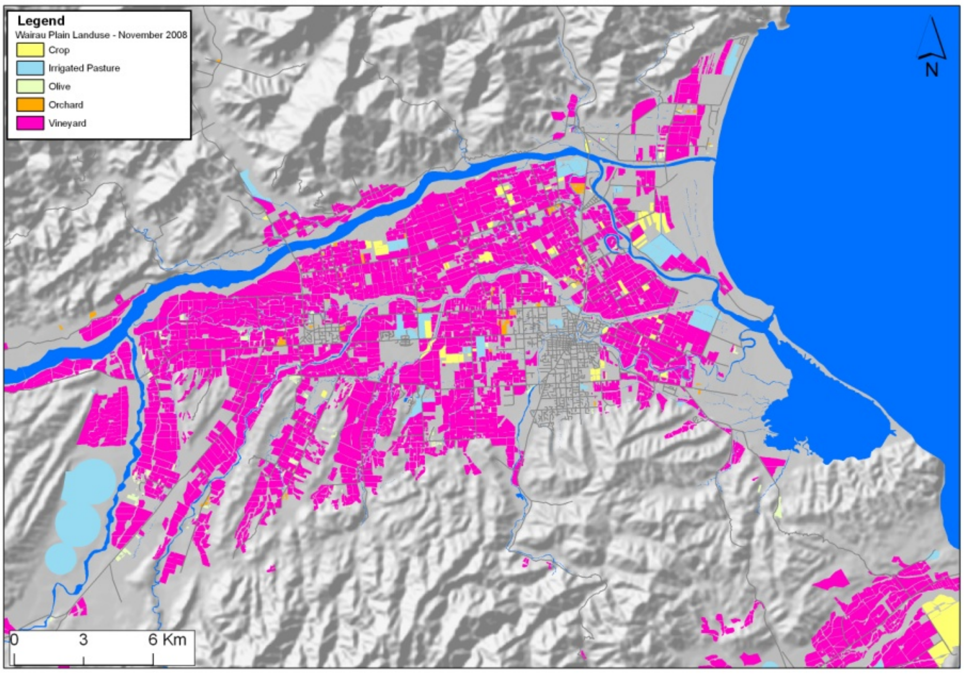

Figure 1: Land use activity on the Wairau Plains, Marlborough, is dominated by viticulture (shown in pink). A field site has been set up at Giffords Road to monitor nitrate leaching beneath the vineyards (location shown by the ⊗ marker of Figure 3).

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[1] The health-related drinking water guideline is 11.3 milligrams per litre (https://www.mfe.govt.nz/publications/water/nz-drinking-water-standards-00.html)

The Marlborough District Council (MDC) is a guardian of the region's precious water resources. They recognise the importance of understanding the linkages between activities on the land surface and the quality and quantity of the receiving ground and surface water bodies. As part of the National Groundwater Monitoring Programme, the MDC takes monthly water samples from the region's wells, and they also monitor the state of their rivers and streams (Figure 2). Over the past two decades, the Council has also invested time and money into research to better understand their groundwater since both the rural and urban communities depend on a reliable supply of high quality water for domestic, agricultural and industrial purposes.

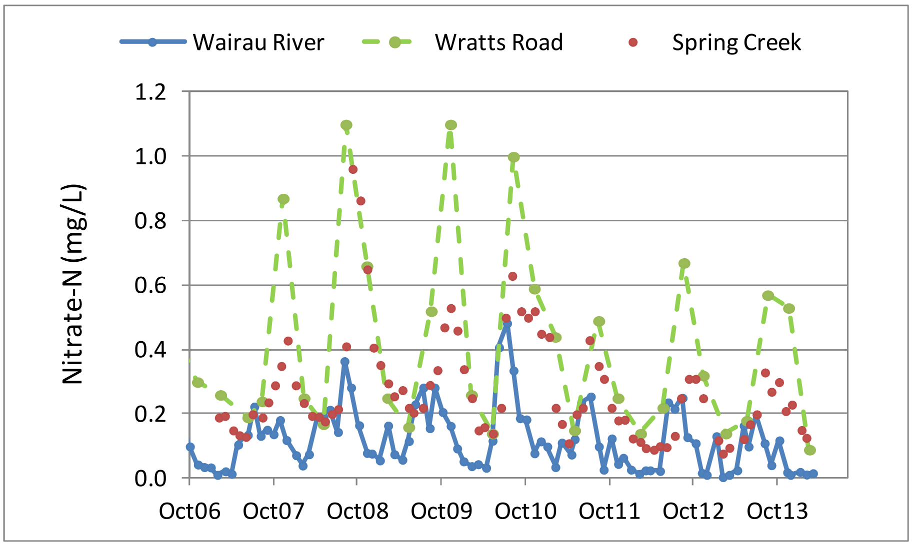

Figure 2. Measured groundwater nitrate-nitrogen concentrations in water samples taken from the Wairau river, the Wratts Road Well (No 3009) & Spring Creek at the Floodgates (data supplied by Peter Davidson, Marlborough District Council). These nitrate levels are less than 10% of the current drinking water standard.

The Council has developed a groundwater flow model which shows the Wairau River water is generally flowing in an easterly direction through the adjacent Wairau Aquifer that resides under land that is mostly in viticulture (Figure 3). The Spring Creek, and other Wairau Plain freshwater springs represent an up-welling of groundwater that is directly connected to the Wairau Aquifer. Although the contribution of current land-use remains largely unclear, any nutrient losses from these productive lands could have the potential to contaminate the springs which are highly valued by the local community. Thus, it is vital, for planning and consenting purposes, that the MDC has a good understanding of the carrying capacity of the Wairau Plain's land-based activities in terms of the dilution or assimilative capacity of the average groundwater flows.

The Council has contracted The New Zealand Institute for Plant & Food Research Limited (Plant & Food Research) to quantify, via measurement and modelling, the amount of nitrate nitrogen leaching beneath a grape vineyard. To achieve this task, Plant & Food Research has installed an array of drainage flux meters (DFMs) at Giffords Road on the Northern Wairau Plain (the location is indicated in Figure 3). These DFM devices can measure both the rate of water loss (i.e. drainage) and the rate of nutrient loss (i.e. leaching) from the vineyard.
The methodology had been perfected in other areas of New Zealand and was introduced in Marlborough to quantify the baseline influence of existing land uses on the valuable water

resource underlying the Wairau Plain, and for modelling the consequences of potential future land use conversion.

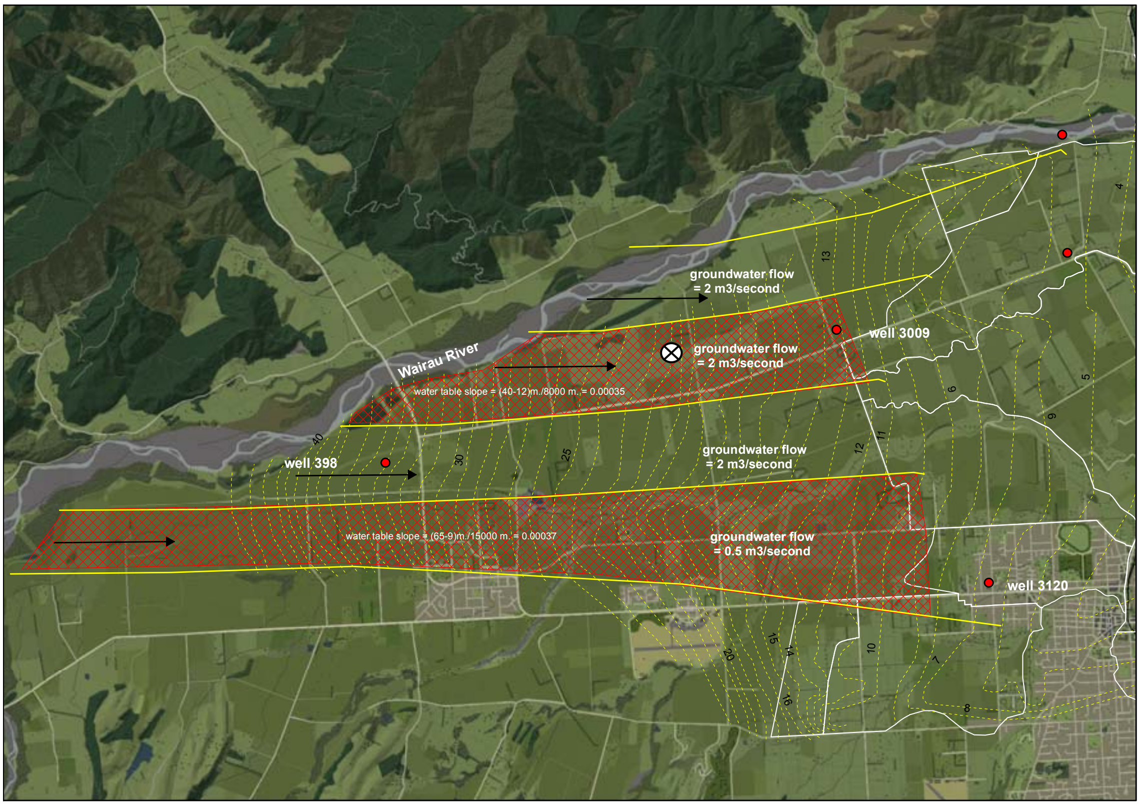

Figure 3: A schematic of the average groundwater flow through the Wairau Aquifer. The arrows show the flow is in an easterly direction. The red markers indicate the Marlborough District Council's monitoring wells. Well No. 3009 is located approximately 2.4 km to the west of where the pilot study of nitrate leaching is being undertaken on the Gifford's road site (marked with an ⊗). This figure was supplied by Peter Davidson of MDC.

The establishment of this trial site, in May 2012, pre-empted central government's amendments to the National Policy Statement (NPS) on Freshwater relating to its quality which require regional councils to account for land applications of nutrients by 2024. The MDC's goal is to use the results from this monitor site to contribute to MDC's response to the NPS by quantifying the nutrient losses on the Wairau Plain. Since viticulture is the main land use activity, it means that evaluating the potential for nutrients to end up draining through the soil profile, and into the water table, can be verified at this single trial site.

The purpose of this report is to summarise the preliminary results of the DFM trial. The experimental data collected here, in combination with a detailed modelling effort, will eventually be used to provide an estimate of the total nutrient input into the groundwater system of the entire unconfined aquifer area. That modelling will be carried out elsewhere, during a second stage of this project whereby nutrient drainage rates will be compared with observations of concentrations in downstream groundwater for the purpose of calibrating flow and contaminant transport models.

2 Research Scope

This research is divided into three main tasks.

- Part 1 involves describing the vertical (downwards) leaching process from the soil surface to beyond the depth of the main roots of the grape vineyard.
- Part 2 involves describing the local connection between nitrate being lost directly beneath the vineyard and the nitrate that is appearing in the local groundwater at a certain time.
- Part 3 involves describing the horizontal transport and attenuation of the nitrate as it is entrained as Wairau Aquifer flow between the Giffords Road DFM trial site and the Wratts Road well (No. P28w/3009) or Spring Creek at the floodgates.

2.1 Stage-1 (preliminary) findings

In the first instance, Plant & Food Research has been contracted to provide the following:

- A summary of preliminary results of the DFM trial and a discussion of the implication of what the results tell us about land-use impacts and groundwater interactions. This work will be presented to the Council at the 24 July 2014 meeting and will be the focus of this report.
- Develop a simple spreadsheet-based model to predict the changes in nitrate-nitrogen concentration at the MDC monitoring well 3009 (Wratts Road) and Spring Creek at the floodgate using the concentration arriving at the water table at the upstream DFM site in Giffords Road as input (Figure 2).
- Provide brief notes on how the model was developed, the derivation of flow parameters and the level of uncertainty of the forecasts.
    a. Discuss the attenuation of the nitrate concentration and what the lag in concentrations tells us about horizontal groundwater or vertical travel times.
    b. Comment on whether the leachate is likely to be seasonal or accumulate over more than a single season.

2.2 Stage-2: development of a ground water-surface water interactions model

The next stage of this work will be to develop a more detailed model of the land-groundwater interactions, in two-dimensions, to incorporate other land uses and to factor in historical climate. At present Marlborough has a land area of about 2,500 ha between Spring Creek and Wairau River recharge reach which is mostly in vineyard. Questions such as “What would be the increase in nitrate-nitrogen concentration in Spring Creek if vineyard was converted to arable farming?” is something that the MDC planners are wanting to pose and answer.

In assessing the Wratts Road and Spring Creek data, Plant & Food Research will provide expert advice on whether the nitrate-nitrogen effects are likely to originate from fertiliser and natural nutrients from the previous years or whether there is an accumulation over several seasons. In other words, is there a legacy of “old” nitrate from past decades still to arrive at water table from mixed farming over the period between the 1930s and the 1980s? We have done similar work in the past to explain elevated levels of nitrate under a sheep feed lot in the Hawke’s Bay (Rosen et al. 1995).

As part of this Stage-2 work, Plant & Food Research will also use the DFM and soil moisture data, in combination with nutrient concentration data from the Council's own monitoring wells, to develop and refine a software tool that MDC will then be able to use to calculate rainfall recharge to groundwater. This model, verified against experimental data from the field, will help MDC to separate rainfall from Wairau River recharge to the aquifer. Soon after our Stage-1 work is complete, Plant & Food Research and MDC will develop up a specification for the Stage-2 modelling which is expected to be completed by the end of July 2015. Having a tool linking the likely nitrate concentration of Spring Creek with the upstream land uses will allow MDC to predict the maximum carrying capacity of the Wairau Plain based on a maximum threshold. This ceiling nitrate level is currently being defined by MDC staff. The observed physical relationship between nutrient use and nitrate in Spring Creek water can then be applied to running scenarios to test the acceptable level of future land-use intensification.

3 Materials and methods

Tools to estimate the unsaturated water-flux density, J_W (mm/d), and nutrient flux density, J_N (mg/m^2/d), are needed to quantify water and nutrient transport within the soil's 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 in some fashion, 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).

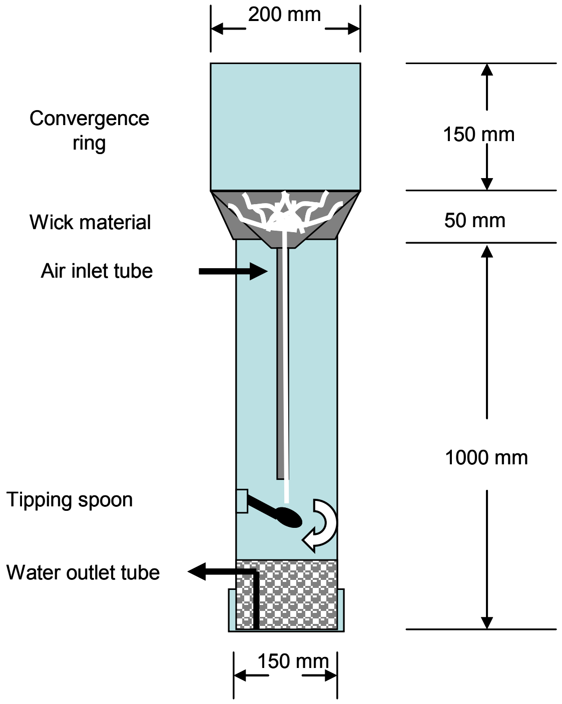

Figure 4: Passive wick lysimeter to monitor water and nutrient fluxes. Some of Plant & Food Research's DFMs have tipping spoons to monitor drainage rates. The ones used at trial site at Giffords Road do not have the spoon device.

3.1 Flux meter design and installation

Plant & Food Research has built large number (>600) of passive-wick drainage-flux meters (DFMs) to monitor water and nutrient losses under productive land. The basic device 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 4). A nearly-fixed tension on the soil is maintained using an inert wicking material made from fibreglass (Holder et al. 1991). A hanging water column is created, and drainage water is pulled out of the lysimeter while the lower soil-boundary is "passively" maintained at a pressure that is less than atmospheric, so the soil stays unsaturated. The degree of unsaturation depends upon the wick length, the flux rate, and the soil type (Zhu et al. 2002).

The instantaneous drainage flux (mm/hr) can be measured automatically with a tipping spoon device that collects water draining from the fibreglass wick, or the drainage volume can also be recorded manually in order to calculate an average drainage rate (mm/d). The wick "passively" controls the pressure head in the soil at a value approximately equal to -50 cm (i.e. the length of the wick). A soil-filled control tube is placed directly above the wick to minimize divergent or convergent flow. The control tube can contain either an intact or a repacked soil column. Typically the device is buried well below the root zone depth (Figures 5–8) and drainage water is collected in a subterranean reservoir where it can be extracted using a vacuum pump (Figure 9) and then analysed for nutrients and co-contaminants.

Figure 5: Peter Davidson from the Marlborough District Council (MDC) is augering a hole in the middle of the alley between vines at Motukawa vineyard near Raupara, Blenheim. The hole was carefully excavated in 10 cm increments with each soil sample being placed into an ordered set of plastic buckets. Once the DFM was inserted into the 2.4 m deep hole, then each soil sample from the buckets was then repacked to approximately the same volume (density) to maintain the order of the soil layers.

In May 2012, MDC purchased a total of twelve DFMs and placed them into a single vineyard (Motukawa) beside Giffords Road near Raupara. Six of the DFMs were placed in the row under the vines and the remaining six DFMs were placed in the inter-row between the vines. Drainage volumes from these devices have been collected during the past 2 years, and samples were sent away (to Hills Laboratories, Hamilton) for analysis of mineral nitrogen (in the form of ammonium and nitrate) plus other contaminants. Some of the raw data from these DFM devices is presented in Appendix A.

Once every 4 to 6 weeks, the DFMs have been emptied by MDC staff and the drainage volume (V_D, cm^3) has been recorded. The corresponding drainage flux of water (D_W, mm/d) over the time interval (Δt, day), is calculated as:

$$D_W = V_D / A\,\Delta t \times 10 \qquad \text{Eq. [1]}$$

where A (=285 cm^2) is the cross-sectional area of the DFM, and the factor of 10 is a unit conversion (from cm to mm). The corresponding leaching flux of nutrients (L_N, kg/ha/d) is calculated as:

$$L_N = D_W C_N / 100 \qquad \text{Eq. [2]}$$

where C_N (mg/L) is the average nutrient concentration, and the factor of 100 is a unit conversion (from mg/m^2 to kg/ha).

Figure 6: Steve Green from Plant & Food Research is preparing a drainage flux meter (DFM) for installation into the soil at Motukawa vineyard near Raupara, Blenheim. The top 20 cm of this DFM has been filled with soil from a depth of 1.0–1.2m.

3.2 Soil water content measurements

Changes in water content of the vineyard soil have been measured using time domain reflectometry (TDR) probes inserted vertically into the soil profile, at different depths and at different locations within the root zone. Data were collected using a multiplexed TDR system (Campbell TDR100 with SDMX50 multiplexers, Campbell Scientific Instruments, Logan, USA) combined with arrays of waveguides (30 cm long) that were constructed at Plant & Food Research workshops in Palmerston North. Figure 10 shows an example of one array of TDR probes.

Figure 7: This photograph is looking down into the hole where a drainage flux meter (DFM) is being installed. The top of the convergence ring is at a depth of 1.0 m. Soil from this hole was originally collected at 10 cm depth increments. These samples were placed into plastic buckets, and then repacked into the hole, in the same order and at a similar density to the original soil profile. Despite careful packing, some setting down period (perhaps the first winter) is expected.

Figure 8: Marc Greven (Plant & Food Research) is burying sample tubes from the drainage flux meters (DFMs) that are located in the alley way between the vines at Motukawa vineyard near Raupara, Blenheim. The clear tube is used to extract a water sample from the base of the DFM. The coloured (red) tube is used as an air inlet.

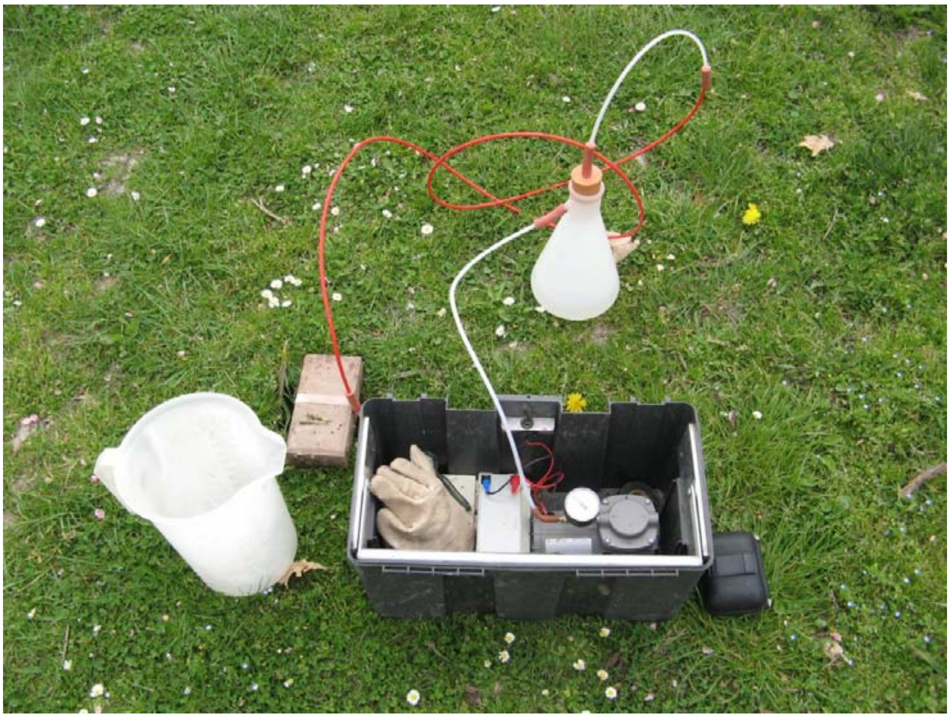

Figure 9: Drainage meters were emptied once every 4–6 weeks, depending on rainfall and soil water contents, using a suction pump connected to a 5L conical flask. Water samples collected in the flask were sent to Hill's Laboratory Ltd for an analysis of mineral nitrogen (nitrate and ammonium) as well as other co-contaminants.

Figure 10: An array of 30cm long TDR (time domain reflectometer) waveguides that are being used to measure changes in the soil water content to a depth of 1.8 m beneath the vineyard. A 10 cm diameter hole was augured to the correct depth, then the TDR probe was inserted into the hole, with the 3-wire waveguides being placed into undisturbed soil.

Six profiles of soil water content were obtained from the experimental site. The measurements extended from the soil surface to a depth of 1.8 m, at 30 cm depth increments. Some of the TDR probes were placed either directly under dripper and therefore under a ‘wet spot’, and others were placed away from the drippers and therefore under a ‘dry spot’. The remainder of the TDR probes were located in the alley way between the vine rows and well outside the influence of any irrigation events. The goal of these TDR data is to provide continuous, reliable measurements of the soil water content in order to verify a model of the soil water balance. This is important data when it comes time to test our model of nutrient transport.

The total amount of water in the root zone soil is calculated via a simple linear average of soil water contents at the different spatial locations and soil depths. Soil water contents are recorded at daily intervals (midnight) using a data logger (Campbell model CR1000, Campbell Scientific Instruments, Logan, USA) powered by a 12V battery and recharged using a 20W solar panel. A cellphone modem is being used to interrogate the data logger and the data are being downloaded at 1- to 2-week intervals. There were very few issues with batteries and modems at the experimental site and so we now have an almost continuous record of soil water content data spanning two complete years.

Towards the end of this Stage-1 project, additional soil moisture data were obtained from Fruition Horticulture. These data comprised weekly measurements of irrigation and soil water content obtained using neutron probes (Troxler model 4300). The additional data were measured manually, once per week during the irrigation season, using a hand-held probe inserted into an access tube installed in the vine row, next to but not directly under one of the emitters. The neutron probe data spanned the depths 0.2–1.1 m (i.e. not the top 20 cm of the soil profile). These additional soil water contents, as measured in a different part of the vineyard, were used during the testing phase of our rudimentary model that allows us to verify data from the DFMs. This model is described in Appendix B.

4 Experimental results from the trial site at Giffords Road

4.1 Changes in soil water contents and drainage volumes

In this section we present data showing seasonal changes in the average soil water content at different root zone depths (Figure 11), as measured using six profiles of TDR probes inserted vertically into the soil to a depth of 1.8 m. We also examine corresponding cumulative values for the amount of water draining below the root zone (Figure 11), as measured using all twelve DFMs installed at a depth of 1.2 m below the soil surface. The temporal plots of soil water content (*SWC*) are presented in order to (1) demonstrate root uptake activity, (2) define upper and lower bounds on *SWC* on this irrigated vineyard, and (3) to help with our interpretations of the drainage data. Where possible, outputs from our tipping-bucket model of the soil water balance (Appendix B) are also used to verify and comment on the performance of the DFMs.

Firstly, we examine the measured changes in *SWC* under the vineyard. Irrigation scheduling for the vineyard site was carried out by Fruition consultants who also monitored changes in soil water contents on other blocks within the same vineyard (Greg Dryden, pers. comm.). Fruition's irrigation strategy resulted in soil water contents of the surface layers remaining between 30 and 40% on a volume basis (Figure 11). Meanwhile, we recorded negligible drainage over the irrigation season (November–March) so the irrigation was deemed to be very efficient by matching irrigation volumes to crop water needs and delaying irrigation whenever rainfall occurred.

Our soil water content data are consistent with root-uptake extending beyond the depth of the DFM devices, and possibly beyond a depth of 180 cm, although the greatest root uptake activity tends to be near the soil surface. The deeper soil layers, at 180 cm, appear to extract water throughout the summer and early autumn period and they do no rewet until after May in both years.

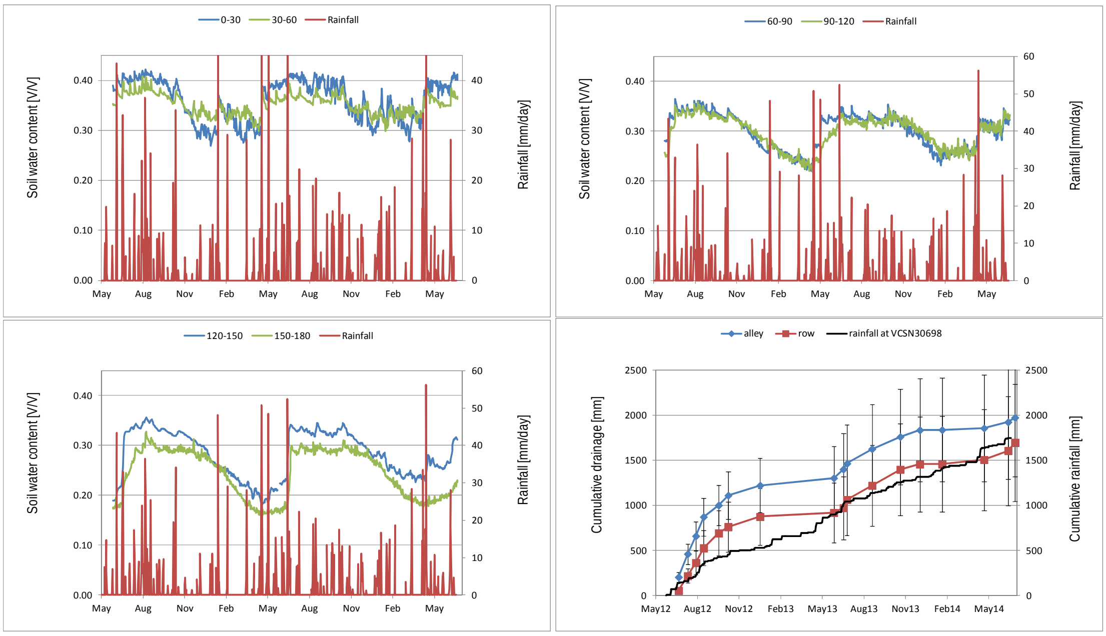

Figure 11: A time series of soil water contents as measured by an array of Time-Domain Reflectometer (TDR) waveguides installed in the soil under a grape vineyard at Giffords Road, near Raupara. Values in each legend indicate the depth of the TDR waveguides. Rainfall data were sourced from the virtual climate station network (Agent No. 30688; www.cliflo.niwa.co.nz). The lower right hand panel represents the average cumulative drainage from all six drainage flux meters (DFM) that are located in the alley and in the rows of the grape vines.

During the early winter period, the top 1.0 m of the soil profile under the grape vines has returned to field capacity because of decreasing evaporative demands combined with a return of autumnal rains. During the months June to October, our deepest TDR probes showed evidence of very wet sub-soils, presumably associated with a rise in the groundwater levels. In terms of drainage volumes, we actually measured more drainage than rainfall over the winter periods (Figure 11), and this result seems very unlikely in these free-draining soils. Clearly, some DFMs have collected far more drainage than is actually occurring since the measured cumulative drainage (as measured by all 12 DFMs) has approximately matched the net rainfall over the 2 years of the study.

We are drawn to the conclusion that some of the DFMs may have been ‘flooded’ (i.e. they have drawn in more water than would be expected during ‘normal’ drainage events). While this ‘flooding’ is partly attributed to the elevated SWCs during the winter period, our results also suggest there is likely to be a short-term settling in period for the DFM devices. For example, the raw data (Appendix A) indicate that half of the DFMs have taken a while to resettle (6–12 months) following the initial packing of the soil. This result means that the first winter’s drainage is likely to be over-estimated. Similarly, while most drainage data for the second year appears to be a more realistic, there are still two or three DFMs that are generating far too much drainage. These DFMs should eventually settle down, perhaps over the coming winter, and we will be keeping a close watch on the drainage volumes collected by those devices.

Meanwhile, we will need to use modelling both to verify what is meaningful DFM data and to discard any data from other DFMs that are deemed to be ‘flooded’ or still settling in. It should be noted that flooded DFMs generally produce lower nutrient concentrations (cf. Tables A1–A3) and so their data could also compromise our DFM-based estimate of nitrogen leaching.

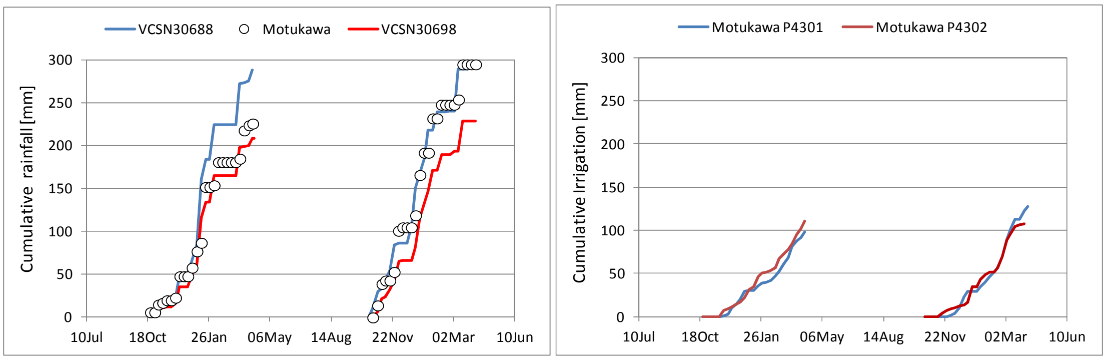

Figure 12: Cumulative totals for the rainfall (left panel) and irrigation (right panel) recorded at the Motukawa vineyard, near Raupara, during the irrigation season (November–March) for the 2013 and 2014 harvest years. Data from Motukawa were provided by Greg Dryden, Fruition Horticulture. Virtual rainfall data (Agent Nos 30688 & 30698) were downloaded from the National Institute of Water and Atmospheric Research (NIWA) Cliflo database (www.cliflo.niwa.co.nz).

4.2 Developing the model framework

For the purpose of modelling, we have used actual weekly volumes of irrigation, as recorded by Fruition Horticulture, and we have used synthetic (virtual) climate data (Figure 12). The reason for using virtual climate, as opposed to actual climate data, is that the vineyard has only recorded rain falls during the irrigation period. In order to evaluate our drainage data from the DFMs, we need a complete record of daily climate since that is one of the main climate inputs to the model. There are two virtual-climate stations (VCS) within 2 km of the Motukawa vineyard (i.e. Agent Numbers 30688 & 30698). Cumulative rainfall totals from the vineyard, as recorded by Fruition Horticulture during the irrigation season, are intermediate between the two virtual rainfall totals, although there is up to 70 mm difference between the three sets of cumulative rainfall. This discrepancy in rainfall indicates there is probably quite a large rainfall gradient on the northern parts of the Wairau Plain.

We first constructed a simple spreadsheet of the soil water balance, based on Eqns A1–A14 from Appendix A. The mid-season value of $K_{C,mid}$ was set equal to 0.45 for the grape vines, which is consistent with previous measurements of vine sap flow recorded in the Seaview vineyard (Green et al. 2009). We then ran the calculations to model daily changes in soil water content, using soil hydraulic properties 'tuned' to match what we had measured with our TDR probes in the top 1.2 m of the soil profile. The calculations used actual irrigation records obtained from the vineyard, and they used daily climate data from the nearest virtual climate station (Agent No 30698).

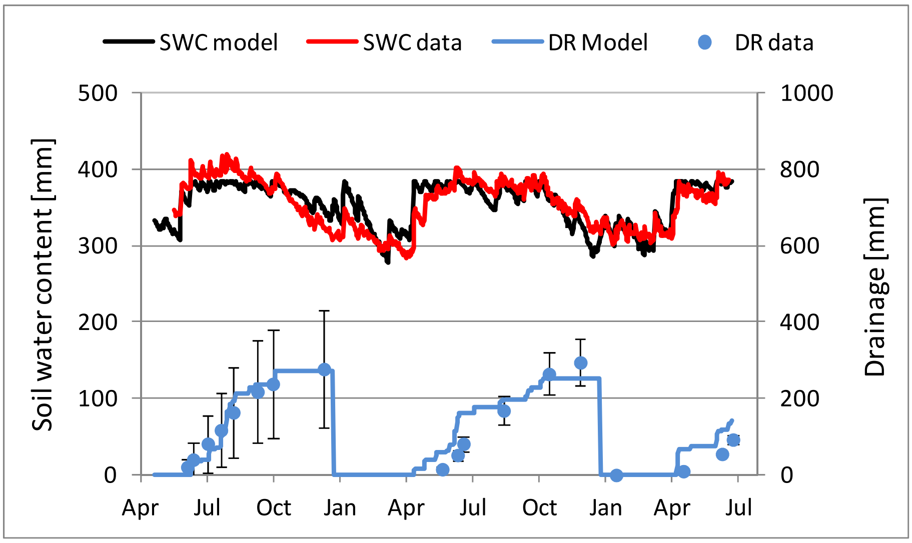

Figure 13: The seasonal pattern of water content (SWC) in the top 1.2 m of the soil profile under the Motuawa vineyard, near Raupara, as measured by time-domain reflectometry (TDR) and as modelling using a simple tipping-bucket approach. Cumulative totals for the drainage (DR) have also been modelled and measured (DR data). These results are for the 2013 and 2014 harvest years. Virtual climate data (Agent No. 30688) has been used for the modelling, and this was downloaded from the National Institute of Water and Atmospheric Research (NIWA) Cliflo database (www.cliflo.niwa.co.nz). More scatter is observed in drainage during the first winter because we were able of use data from fewer of the DFMs at the start of the experiment (see text for details).

A reasonable agreement was achieved between our model outputs for the seasonal dynamics of soil water content and our TDR data (Figure 13). This is partly because we have 'tuned' the model by setting the soil' field capacity to match our measurements. In terms of model inputs, the fractional areas of the bare soil (herbicide strip) and the percentage value of the effective rainfall are key model parameters which required a guess and correct approach to obtain the 'best fit' model outputs. However, when we scrutinized all components of the soil water balance calculations, and set realistic values for each parameter value, then we were able to reproduce a reasonable time series for average drainage losses over the two years period (Figure 14), providing we ignored data from those DFMs that was deemed to either be flooded or still settling in (Appendix A identifies those DFMs). During the first winter season we accepted data from only four of the DFM devices; for the second winter season we accepted data from eight of the

DFM devices; and now we are accepting data from 10 of the 12 DFM devices. It is possible that the other two DFMs are still settling down.

The fact that we are now seeing similar results between measured and modelled drainage rates partially validates our use of a simple modelling approach for the soil water balance.
The weighting factors used to accept, or reject, drainage data from particular DFMs can now be applied to the nutrient concentration data in order to estimate firstly the average nutrient concentration of the drainage water and secondly the cumulative nutrient leaching losses. The concentration data are shown in Figure 14 and the cumulative leaching losses (January to January) are shown in Figure 15, respectively.

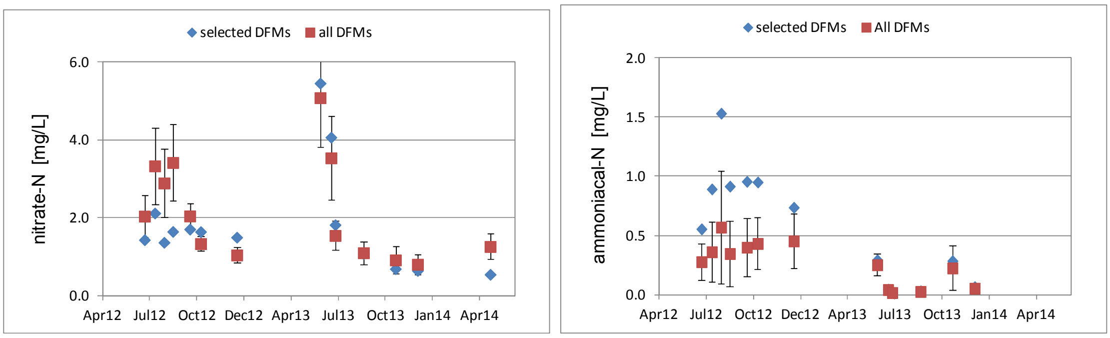

Figure 14: The seasonal pattern of the average mineral-nitrogen concentration in samples of drainage water collected from an array of drainage flux meters (DFMs) installed in the Motukawa vineyard, near Raupara. Error bars (+/- one standard error) are only displayed for the average from all twelve DFMs.

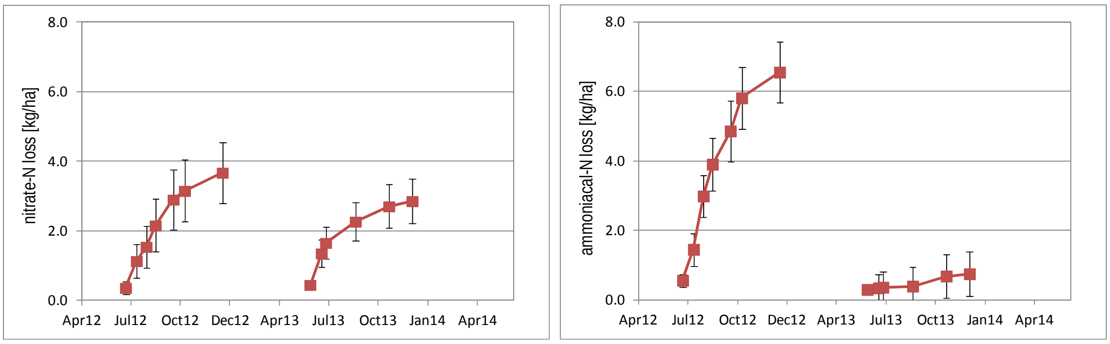

Figure 15: The seasonal pattern of the average mineral-nitrogen concentration in samples of drainage water collected from an array of drainage flux meters (DFMs) installed in the Motukawa vineyard, near Raupara.

Elevated levels of both nitrate-N (up to 5 mg-N/L) and ammoniacal-N (up to 1.5 mg-N/L) were recorded in leachate samples from the DFMs (Figure 14). The highest concentrations were observed at the end of the growing season (start of the drainage season), following the first rewetting of the soil profile to the depth of the DFMs. A rewetting of the deeper soil profile, beyond a depth of 1.2 m, did not occur until late June of the first year and late April of the second year of observations. Thereafter, some 1–2 months later, the nitrate concentration of the drainage water declined below 1.5 mg-N/L, and the corresponding ammoniacal-N concentration declined below about 0.2 mg-N/L, at least for the second season of measurements. The steady decline in nutrient concentrations (for both nitrate and ammonium) during each drainage season (June–October) may be associated with dilution effects cased by larger drainage volumes.

Our calculations of the cumulative nitrogen leaching losses, for both nitrate and ammoniacal-N, are shown in Figure 15. Over both calendar years, we calculated that less than 4 kg/ha of nitrate-nitrogen had leached out of the top 1.2 m of the soil profile. We also observed elevated levels of ammoniacal-N in the water samples from the first winter's drainage, and this meant that a total of 6 kg-N/ha of ammoniacal-N was recorded as being leached out of the top 1.2 m of the soil profile during the first winter. Meanwhile, during the second winter of drainage, ammoniacal-N concentrations were much lower and so we calculated that only 1 kg-N/ha, in the form of ammoniacal-N, had leached during the second winter.

We speculate that the elevated levels of ammonium observed during the first winter of drainage could either be the result of the repacking process, enhancing mineralization, or they could equally be a result of the winter-grazing by sheep (at 60 animals per ha) for 1–2 weeks in May. We expect the results from the second season to be more typical for a grape vineyard since ammonium is not normally as mobile as nitrate with respect to vertical movement through the soil profile.

5 Discussion of the field experimental results

The Motukawa vineyard has proved to be an excellent experimental site in terms of access and security. The measurements of soil water content and drainage rates have been verified against outputs from a simple tipping-bucket model of the vineyard soil water balance. Our monitoring indicates that the average rainfall recharge from this part of the Wairau Plains has been about 290 mm per year over the past 2 years.

Our DFM data indicate the annual nitrate-N leaching losses, measured at a depth of 1.2 m under the Motukawa vineyard, are of the order of 3–4 kg NO_3-N/ha. This is very low compared with the impacts from other land uses that have been reported around New Zealand. For example, we have measured an annual leaching loss of 10–12 kg NO_3-N/ha under apples and peaches in the Hawke's Bay (Green et al. 2012), Herath et al. (2014) reported an annual leaching loss of 28 kg NO_3-N/ha under a potato crop in the Manawatu; Parfitt et al. (2009) reported mean annual leaching losses of approximately 30 kg NO_3-N/ha from hill country grazed by sheep; Thomas et al. (2005) reported annual leaching losses in the range of 12–45 kg NO_3-N/ha under arable crops in Canterbury; Cameron et al. (2014) reported nitrate losses of 43 kg NO_3-N/ha losses under a dairy farm in Southland; and De Klein et al. (2010) and Monaghan et al. (2013) reported annual nitrate losses in the range of 39–119 kg NO_3-N/ha from a wintering support farm. Such a wide spread in leaching losses associated with different land use activities is partly due to the intensity of farming, i.e. more or less fertilizer or irrigation or animals, although soils and climates also play an important role.

The DFM data are starting to show clear evidence of a seasonal trend both in the nutrient concentrations and drainage losses. As expected, most of the drainage has been observed during the wetter months, between April and September, while there has been negligible drainage, so far, over the period between October and March. In terms of the soil water balance, the year (July to July) can be broadly separated into two periods: an irrigation season that spans the period October through March, and a drainage season that spans the period April through September.

Seasonal rainfall is quite variable from year to year (Appendix A: Table A5). Some years, a significant amount of rainfall has occurred during the irrigation season (Appendix A: Tables A5 & A6). For example, almost 700 mm of rainfall was recorded during the spring and summer of 2002. Such a large amount of rainfall would have rewet the soil profile and most likely resulted in drainage and leaching of mobile nutrients, such as nitrate. On the other hand, there have also been other years when very little rainfall was recorded during the irrigation season, e.g. 2001 where just 123 mm of rainfall was recorded. In that year a lot more irrigation would have been required and the winter recharge of drainage would most likely have been delayed by a couple of months.

Rainfall during both irrigation seasons, spanning the 6 months from October and March, was about 82% of the long-term average, whereas rainfall during the corresponding drainage season, spanning April through September, was about 120% of the long-term average (Table 1). In other words, we have collected data from two 'dry' summers and two 'wet winters'. Initial results from this DFM study are not yet sufficient in duration to capture a full range of drainage losses because we have had reasonably similar rainfall totals over both years of the trial. In addition, some of the DFMs may still be settling down after installation so we do not yet have a complete picture from all of the DFMs. We also have an as yet unexplained result, i.e. a difference in ammoniacal-N loss between years 1 and 2 of the experiment. It would therefore seem prudent to continue the trial for a longer period (certainly a few more years) in order capture a more diverse set of representative weather and growing conditions. A continuation of the DFM trials is even more important when we examine the linkage between land use impacts and groundwater quality, as explained below.

Table 1. Seasonal rainfall statistics calculated from daily rainfall totals recorded by the National Institute of Water and Atmospheric Science (NIWA) for the Virtual Climate Network Station (Agent No. 30688) which is close to the Motukawa Vineyard, near Raupara. The irrigation season runs from October to March, and the drainage season runs from April to September. LTA is the long-term average rainfall (mm). The other values in the Table represent the fraction of the LTA.

Year	Irrigation season Oct–Mar	drainage season Apr–Sep
LTA	433	534
2012	1.26	1.18
2013	0.82	1.20
2014	0.81	

In general terms, any mobile nutrients that drain beyond the grasp of the more-active surface roots also have the potential to eventually move further downwards, through the soil profile, posing an increased risk of contamination to the groundwater.

The remaining task for this Stage-1 report is to examine the relationship between activity on the land surface, i.e. that leads to nitrate leaching directly under the grape vineyard, and the quality of the receiving groundwater. This can be done by comparing the nitrate concentrations in drainage water, as collected by the DFMs, against corresponding nitrate concentrations of water samples taken from the well. This comparison is shown in Figure 16. Nitrate-N concentrations in well water show a large seasonal fluctuation with values in the range of 0.1–1.1 mg/L, and the concentrations are lower, by a factor of about 10, than the corresponding concentrations observed in the drainage samples. Furthermore, the well water concentrations are greatest in the summer whereas the DFM concentrations are greatest in the winter. So there is a significant attenuation and a lengthy time delay between nutrient losses from the vineyard and nutrient appearance in the groundwater.

From the outset, we expected to see attenuation combined with a time delay when comparing samples from the DFM with groundwater. This is because the DFMs are directly under the vineyard, at a depth of just 1.2 m and the well is located about 2.4 km away. The Wairau Aquifer flows under the vineyard, at a depth of between 2 and 4 m, in an easterly direction past the sample well and towards the coast (Figure 3). This degree of attenuation and time delay will be related to aquifer flow volumes, dilution and mixing processes, and/or the distance between the source and the sample site for groundwater (Well No. 3009).

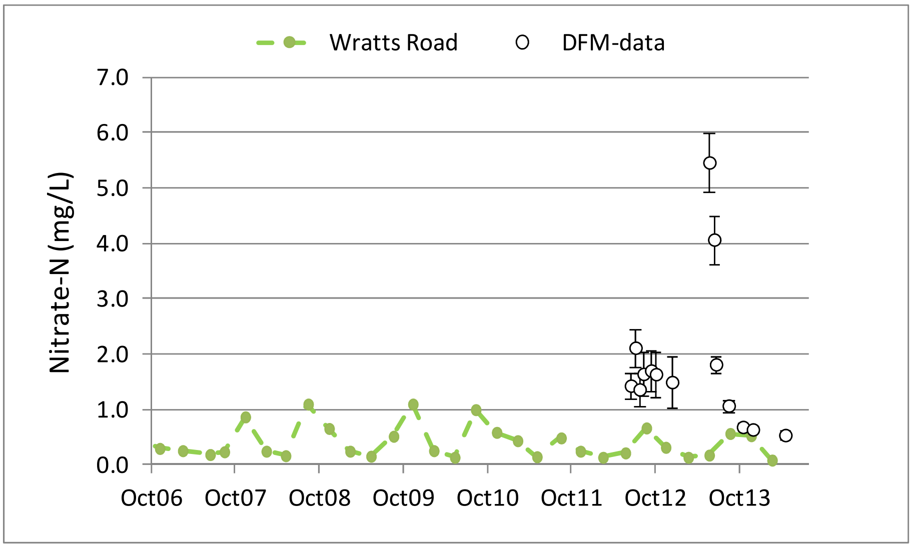

Figure 16. A time series of nitrate-N concentrations (mg/L) measured in water samples taken from the Wratts Road well (No. 3009) and from the drainage flux meters (DFMs) located under the Motukawa vineyard, near Raupara. The DFM data represent the average n (+/- one standard error) calculated for water samples collected from between four to ten devices buried at a soil depth of 1.2 m. The Wratts Road data represent spot measurements of water samples taken from the well, which is about 2.4 km away from the DFM site an in the down flow direction of the Wairau Aquifer.

A very simple empirical approach, using a time delay and attenuation model (TDA), can be used to simulate the groundwater concentrations as:

$$C_G(t + \Delta\tau) = \propto C_L(t) \qquad \text{Eq. [3]}$$

where t is the time (d), $\Delta\tau$ is the time delay (d), C_G and C_L are the respective concentrations of nitrate in the drainage water (from the DFM) and the groundwater (from the well) and $\propto$ is an attenuation factor. Figure 17 shows a very good fit of this simple model to the actual data. The corresponding parameter values are: $\alpha = 10$ and $\Delta\tau = 185$ d. This result implies that the combined dilution and mixing effects are of the order of 1:10 and that the transport time for a ‘plume of nutrients’ to travel the distance of 2.4 km, from under the vineyard and into well, is of the order of 6 months.

The information provided by this DFM trial is likely to be only suitable to address issue of nutrient accounting by the NPS, providing the land area remains in grape production. Continuing the trial across more years will provide additional data, under different climate conditions, and this is important for addressing the impact of rainfall on the actual leaching losses. With the current set of DFM data, obviously we cannot address impacts of other soil types. That would require a more expansive array of DFMs, or a more complex modelling approach, such as could be offered by Plant & Food Research’s SPASMO (Soil Plant Atmosphere Systems Model).

In reality, the linkages between activities on the land surface and groundwater quality are far more complex than Eq. 3 suggests. There are multiple diffuse sources of nutrient loss, originating from each of the neighbouring properties, and there will also be multiple delays associated with different travel distances between those properties and the sample well. A far more detailed model is also needed to encompass the complex nature of a patchwork of different land-use activities. With the simple model of Eq. 3 we cannot expect to accurately extrapolate our measured data to predict the likely leachate rate from other land uses on the Wairau Plain, such as Dairying or cropping. Firstly, we do not have the measured drainage concentrations (the C_L values) under those land uses and secondly, the actual nutrient loads are likely to be much higher, as discussed above.

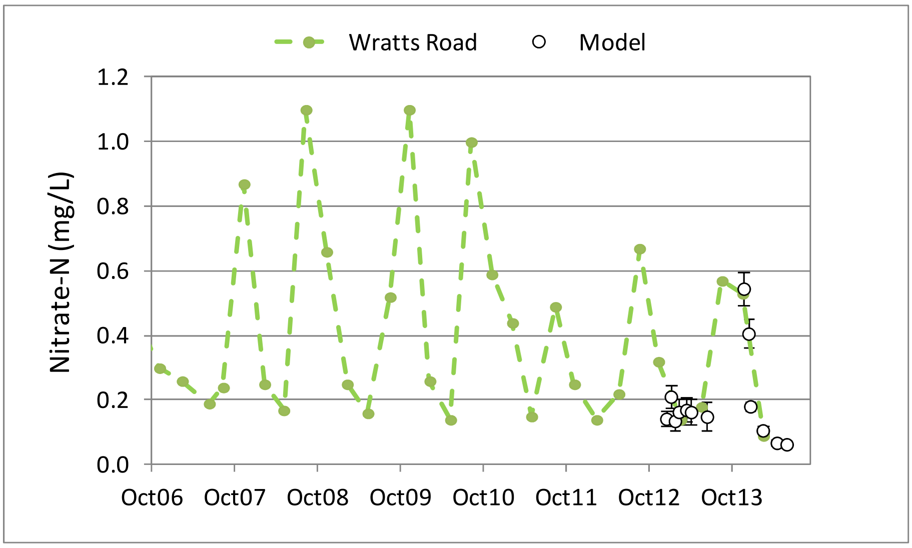

Figure 17. A time series of nitrate-N concentrations (mg/L) measured in water samples taken from the Wratts Road well (No 3009). The open symbols represent a simple attenuation and time-delay model (Eq. 3) that uses concentration data from drainage flux meters (DFMs) located under the Motukawa vineyard, near Raupara.

Stage-2 of this project is expected to combine model outputs from SPASMO, i.e. daily water and nutrient fluxes from a wide range of land-use activities, with a three-dimensional analytical model of groundwater concentrations under the Wairau Plains. This new analytical model will need calibration and tuning, e.g. using historical records of nutrient concentrations obtained from the region's many sampling wells. The eventual goal is to develop a model that can make forward predictions of the likely impact of current, and future, land-use activity on groundwater quality across the Plains. Once tuned, the same model will also be able to make backwards predictions, e.g. of the likely leachate loading and land use that corresponds with a certain water quality target in a downstream groundwater fed stream such as Spring Creek. If the model planned for Stage-2 is successful, then the MDC will also be able to accurately account for the impact of land applications of nutrient, as required by NPS on Freshwater. Such a tool will enable Council to simulate the impact of land surface interactions with downstream ground water quality.

6 Acknowledgements

This project was funded by Marlborough District Council under Contract No. 30840. We are grateful to Mr Philip Neal for allowing us to work on his Motokawa vineyard near Raupara. We also thank Fruition Horticulture (Mr Greg Dryden) for providing soil data and the irrigation records that have been used to calculate the vineyard water balance

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Appendix A. Raw data from the drainage flux meters

Table A1. Records of drainage volumes (cm^3) collected from each of the drainage flux meters (labelled 1A to 6R) installed at a soil depth of 1.2 m under the grape vines at the Motukawa vineyard near Raupara, Marlborough. Sites with a name ending in 'R' are located under the row of grapes while sites with names ending in 'A' are in the alley way between rows of grapevine. The DFMs were installed on the 12/5/2012. Those samples with a volume exceeding 6000 cm^3 are likely to be flooded. Some of the first year's winter drainage is likely to be compromised as the soil inside the DFMs resettles following the installation and repacking procedures. Two of the DFMs (4A and 6R) still appear to be giving too much drainage even after 2 years of settling time.

total volume	Site											
Sample Date*	1A	1R	2A	2R	3A	3R	4A	4R	5A	5R	6A	6R
14/06/2012	2000	100	4000	500	6200	150	12500	0	3200	2500	7200	5200
22/06/2012	940	2680	3900	1300	7000	180	13000	0	5000	5100	8800	1070
12/07/2012	1100	5620	5580	3100	11000	820	12800	220	6400	9300	11500	11800
30/07/2012	860	4400	3500	2500	7900	860	12300	245	5000	7100	7800	12300
16/08/2012	1300	4300	5100	3100	6300	1150	12700	270	6100	10100	8500	11900
18/09/2012	1260	4750	3100	3400	6600	1650	1260	475	4500	9000	7500	11800
9/10/2012	440	1860	700	1380	2600	460	12000	300	2300	2400	2500	6600
18/12/2012	580	3800	640	2100	3600	1600	9200	610	3700	5100	3100	8100
29/05/2013	0	400	50	340	500	180	12300	240	1850	4200	740	2900
19/06/2013	100	1150	0	750	2400	1080	11000	210	2700	5300	2100	1640
27/06/2013	310	1060	290	650	1800	640	6300	150	1750	5300	1700	9100
21/08/2013	920	4150	880	1900	4800	2600	15000	520	5200	8500	3600	12100
22/10/2013	1000	4950	750	2100	5200	3200	9200	640	5600	10300	3600	12200
4/12/2013	310	1600	450	890	1280	1030	9300	360	1430	2100	1200	5000
22/01/2014	0	0	5	10	0	10	480	15	10	10	10	150
24/04/2014	0	0	0	220	0	100	3400	0	0	2800	0	6100
16/06/2014	0	1440	0	1040	1220	1320	8400	150	2000	5800	1200	9100
1/07/2014	0	1600	100	550	1310	680	5120	100	1420	4600	1440	9550

Table A2. A weighting matrix was used to accept (value = 1) or reject (value = 2) data from each of the drainage flux meters (DFM) installed, at a soil depth of 1.2 m, under the grape vines at the Motukawa vineyard near Raupara. Sites with a name ending in 'R' are located under the row of grapes while sites with a name ending in 'A' are located in the alley way between the rows of grapevines. It is possible that DFMs 4A and 6R will never settle down.

- **Year-1 refers to the first calendar year of records (June 2012 to December 2012).**
- **Year-2 refers to the second calendar year (January 2013 to December 2013).**
- **Year-3 refers to the third calendar year (January 2014 until the present).**

Site	1A	1R	2A	2R	3A	3R	4A	4R	5A	5R	6A	6R
year 1	1.00	0.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00
year 2	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00
year 3	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	0.00

Table A3. Records of nitrate-nitrogen (mg/L) concentration of water samples from each of the drainage flux meters (labelled 1A to 6R) installed at a soil depth of 1.2 m under the grape vines at the Motukawa vineyard near Raupara, Marlborough. Sites with a name ending in 'R' are located under the row of grapes while sites with names ending in 'A' are in the alley way between rows of grapevines. The upper and lower quartiles are represented by UQ and LQ, respectively. Values exceeding the UQ are shaded.

Analyte Name	Nitrate-N	LQ	0.65	median	1.24	UQ	2.50

Sum	Site											
Sample Date	1A	1R	2A	2R	3A	3R	4A	4R	5A	5R	6A	6R
22/06/2012	2.4	1.0	7.3	1.5	1.2	1.8	1.2		0.9	0.9	1.6	2.6
12/07/2012	2.7	1.0	13.1	1.6	2.3	1.5	6.2	2.7	2.6	1.1	3.8	1.4
30/07/2012	2.2	0.6	10.8	0.8	1.6	1.1	5.9	1.4	2.5	1.2	5.5	1.2
16/08/2012	2.6	0.7	9.5	0.7	1.4	1.3	9.1	1.9	2.7	1.7	8.1	1.3
18/09/2012	2.5	0.6	4.2	0.7	1.2	1.8	2.3	1.8	2.5	2.4	0.9	3.6
9/10/2012	2.3	0.5	2.1	0.5	1.0	2.1	0.7	1.7	1.6	1.6	1.1	0.8
18/12/2012	1.8	0.6	0.9	0.3	0.3	2.5	0.1	1.4	1.1	1.6	0.9	1.2
29/05/2013		7.7	15.5	5.1	4.8	8.1	0.8	6.4	0.5	3.1	1.1	2.9
19/06/2013	10.0	4.8		6.6	0.5	9.3	0.5	4.6	0.4	1.1	0.5	0.7
27/06/2013	1.9	1.7	2.4	3.2	0.1	2.3	1.1	4.1	0.3	0.8	0.3	0.3
21/08/2013	0.9	0.8	0.8	1.8	0.2	0.9	0.6	3.4	0.6	2.6	0.3	0.3
22/10/2013	0.7	0.5	0.5	0.7	0.1	0.8	0.1	2.3	0.4	4.3	0.2	0.4
4/12/2013	1.1	0.5	0.7	0.4	0.2	1.0	0.1	1.5	0.2	3.3	0.3	0.5
24/04/2014				1.8		3.0	0.3			0.6		0.6

Table A4. Records of ammonical-nitrogen (mg/L) concentration of water samples from each of the drainage flux meters (labelled 1A to 6R) installed at a soil depth of 1.2 m under the grape vines at the Motukawa vineyard near Raupara, Marlborough. Sites with a name ending in 'R' are located under the row of grapes while sites with names ending in 'A' are in the alley way between rows of grapevines. The upper and lower quartiles are represented by UQ and LQ, respectively. Values exceeding the UQ are shaded.

Analyte Name	NH4-N	LQ	0.018	median	0.047	UQ	0.119

Sum	Site											
Sample Date	1A	1R	2A	2R	3A	3R	4A	4R	5A	5R	6A	6R
22/06/2012	0.34	0.07	0.05	0.08	0.03	1.80	0.03		0.06	0.54	0.03	0.03
12/07/2012	0.18	0.02	0.60	0.04	0.01	0.25	0.08	3.10	0.02	0.02	0.01	0.01
30/07/2012	0.12	0.02	0.32	0.02	0.01	0.20	0.04	5.80	0.02	0.12	0.09	0.08
16/08/2012	0.10	0.05	0.12	0.02	0.02	0.14	0.13	3.40	0.01	0.06	0.07	0.04
18/09/2012	0.45	0.19	0.34	0.07	0.11	0.21	0.08	3.10	0.02	0.09	0.06	0.09
9/10/2012	0.73	0.20	0.73	0.14	0.13	0.24	0.06	2.70	0.07	0.09	0.08	0.03
18/12/2012	0.08	0.04	1.80	0.05	0.52	0.43	0.01	2.40	0.05	0.03	0.04	0.01
29/05/2013		0.02	0.81	0.86	0.10	0.36	0.07	0.03	0.44	0.05	0.03	0.01
19/06/2013	0.07	0.09		0.16	0.01	0.01	0.02	0.02	0.04	0.02	0.01	0.02
27/06/2013	0.02	0.04	0.02	0.04	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01
21/08/2013	0.01	0.06	0.05	0.11	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
22/10/2013	0.06	0.03	2.30	0.06	0.01	0.01	0.03	0.04	0.05	0.06	0.01	0.04
4/12/2013	0.25	0.01	0.12	0.07	0.02	0.08	0.02	0.01	0.02	0.01	0.01	0.01
24/04/2014				0.09		0.12	0.04			0.05		0.01

Table A5. Seasonal rainfall statistics calculated from daily rainfall totals recorded by the National Institute of Water and Atmospheric Science (NIWA) for the Virtual Climate Network Station (Agent No. 30688) which is close to the Motukawa Vineyard, near Raupara. The shaded cells indicate the timing of observations from the study site. The rainfall totals are grouped into season: October–December (OND), January–March (JFM), April–June (AMJ) and July–September (JAS). The annual total is summed over the months July–July. The irrigation season runs from October to March, and the drainage season runs from April to September.

Harvest Year	Seasonal Rainfall Total					Rainfall Probability of Exceedance				
	OND	JFM	AMJ	JAS	Jul-Jul	OND	JFM	AMJ	JAS	Jul-Jul
1973	138	72	140	217	556	90	95	93	73	98
1974	202	81	321	432	821	67	93	24	7	71
1975	231	339	349	276	1350	60	10	19	44	7
1976	242	222	235	357	976	52	29	64	24	45
1977	271	215	243	285	1087	33	33	62	41	38
1978	273	53	270	400	881	31	98	43	15	60
1979	175	299	276	260	1151	76	12	36	54	21
1980	367	261	451	233	1339	12	17	5	68	10
1981	235	134	276	236	878	57	74	33	66	62
1982	325	136	277	213	974	19	69	31	76	48
1983	116	97	309	414	735	93	90	26	12	86
1984	350	222	163	264	1149	14	31	88	51	24
1985	309	350	248	264	1171	26	7	57	49	19
1986	274	378	195	272	1112	29	5	83	46	33
1987	169	179	272	185	892	81	60	40	78	57
1988	326	227	85	238	822	17	26	100	63	69
1989	208	206	207	245	858	64	45	71	61	64
1990	178	126	205	309	754	74	79	76	34	83
1991	237	109	101	338	756	55	86	98	29	81
1992	144	192	103	341	777	88	50	95	27	76
1993	249	274	390	139	1254	50	14	12	95	12
1994	179	169	198	424	685	71	67	79	10	95
1995	270	401	441	372	1536	36	2	7	17	2
1996	315	245	197	332	1129	21	19	81	32	26
1997	255	207	219	170	1012	43	43	69	83	43
1998	100	171	251	515	692	100	64	55	2	93
1999	399	207	256	245	1377	5	40	50	59	5
2000	373	230	327	222	1175	7	24	21	71	17
2001	113	9	190	107	534	95	100	86	100	100
2002	496	195	254	165	1052	2	48	52	88	40
2003	181	109	276	181	731	69	88	38	80	88
2004	165	230	264	286	841	83	21	45	39	67
2005	262	212	160	150	921	38	36	90	90	55
2006	107	179	283	147	720	98	57	29	93	90
2007	251	119	247	166	764	48	83	60	85	79
2008	256	123	233	504	778	40	81	67	5	74
2009	314	182	206	294	1206	24	52	74	37	14
2010	217	135	451	360	1097	62	71	2	22	36
2011	254	131	379	134	1125	45	76	14	98	29
2012	371	174	262	368	941	10	62	48	20	52
2013	145	209	394	246	1116	86	38	10	56	31
2014	173	180	368		966	79	55	17		50

Table A6. Seasonal rainfall statistics (mm) calculated from daily rainfall totals recorded by the National Institute of Water and Atmospheric Science (NIWA) for the Virtual Climate Network Station (Agent No. 30688) which is close to the Motukawa Vineyard, near Raupara. The shaded cells indicate the timing of observations from the study site. The irrigation season runs from October to March, and the drainage season runs from April to September.

Year	Rainfall total (mm) Irrigation season	Drainage season	Rainfall Probability of Excedance	
	Oct–Mar	Apr–Sep	Oct–Mar	Apr–Sep
1973	211	357	98	93
1974	283	752	90	10
1975	570	625	21	27
1976	465	592	43	32
1977	487	528	36	46
1978	326	670	81	20
1979	474	536	40	39
1980	628	684	12	17
1981	369	512	62	54
1982	461	490	48	63
1983	213	723	95	15
1984	572	427	19	83
1985	659	512	7	56
1986	652	467	10	66
1987	348	457	71	68
1988	552	322	26	95
1989	414	451	50	73
1990	304	515	83	49
1991	346	439	76	78
1992	335	444	79	76
1993	523	529	31	44
1994	348	622	74	29
1995	671	813	5	2
1996	560	529	24	41
1997	461	389	45	90
1998	271	767	93	7
1999	606	501	14	59
2000	603	549	17	37
2001	123	297	100	100
2002	691	420	2	85
2003	290	457	86	71
2004	395	551	52	34
2005	474	310	38	98
2006	287	430	88	80
2007	370	413	60	88
2008	379	737	57	12
2009	496	501	33	61
2010	352	811	69	5
2011	385	514	55	51
2012	545	630	29	24
2013	354	639	64	22
2014	353		67	

Appendix B. Modelling crop water use

A measurement and modelling approach has been used here to determine crop water use, drawing upon results from previous MDC funded research (Green et al. 2002, 2008, and 2011). In theory, transpiration from the grape vines depends on three factors:

- The atmospheric demand for water that is defined by the local microclimate
- The green leaf area of the transpiring crop, and the understory (grass and bare soil)
- The crop's response to the aerial and soil environment.

A standard crop-factor approach is used to calculate the daily water use of the grapevines based on guidelines given by the Food and Agriculture Administration (FAO) of the United Nations (Allen et al. 1999). A reference evaporation rate, ET_O [mm d^{-1}] is first calculated using the equation:

$$ET_O = \frac{\frac{s}{\lambda}(R_N - G) + \gamma \frac{900}{(T+273)} u_2 (e_s - e_a)}{s + \gamma\,(1 + 0.34 u_2)} \qquad \text{Eq. [B1]}$$

Here R_N [MJ m^{-2} d^{-1}] is the net solar radiation, G [MJ m^{-2} d^{-1}] is the ground heat flux, T [^{o}C] is the mean air temperature, e_s [kPa] is the saturation vapour pressure at the mean air temperature, e_a (kPa) is the mean actual vapour pressure of the air, u_2 [m s^{-1}] is the mean wind speed at 2 m height, s [Pa $^{o}C^{-1}$] is the slope of the saturation vapour-pressure versus temperature curve, γ [66.1 Pa] is the psychometric constant, and λ [2.45 MJ kg^{-1}] is the latent heat of vaporisation for water. Our calculations are based on daily values of local weather data that have been downloaded from the National Institute of Water and Atmospheric Research (NIWA) Cliflo database (www.cliflo.niwa.co.nz). The nearest stations to the Motukawa vineyard are VCSN Agent Numbers 30698 & 30698.

Equation [B1] defines the potential rate of evaporation from an extensive surface of green grass cover, of a short, uniform height, that is actively growing, completely shading the ground, and not short of water. The value of ET_0 is commonly referred to as the 'Potential ET'. The transpiration of a grape vine is related to, but not necessarily the same as, the Potential ET. In this case, for routine calculations of crop transpiration, the following equation is used:

$$ET_C = K_C . ET_O \qquad \text{Eq. [B2]}$$

Here K_C represents a dimensionless 'crop factor' that can vary between about 0.1 (young vines with small leaf area) and about 0.6 (vigorous vines with large leaf area) depending on vine spacing and canopy leaf area (Green et al. 2011).

A1. Fitting the seasonal crop factor

For grape vines, the value of K_C is not a constant. Rather, K_C reflects changes in ground cover and, in particular, changes in canopy leaf area and over the growing season. For the purpose of modelling the soil water balance, we use a simple linear representation to describe and construct the crop coefficient curve based on three values: those during the initial stage ($K_{C,ini}$), the mid-season stage ($K_{C,mid}$) and the end of the late-season stage ($K_{C,end}$).

Figure B1 presents an example of how the crop factor curve was developed for grapes, using daily values of sap flow and daily calculations of local values for ET_O. Here, the mid-season value of K_C was set at 0.45, as determined from sap flow measurements at Seaview (Green et al. 2009). The value of K_C was assumed to be zero prior to budburst (typically October 5; Table B1) since the vines will then have no leaves. A linear interpolation was applied between budburst and full leaf canopy, which typically occurs around January 1. Thereafter, the crop factor was held constant until a few weeks before harvest, which typically occurs mid-April. A linear interpolation was then applied from harvest until leaf fall, which typically occurs mid-May. For all other times, we assume K_C equals zero because the grapevines are deciduous.

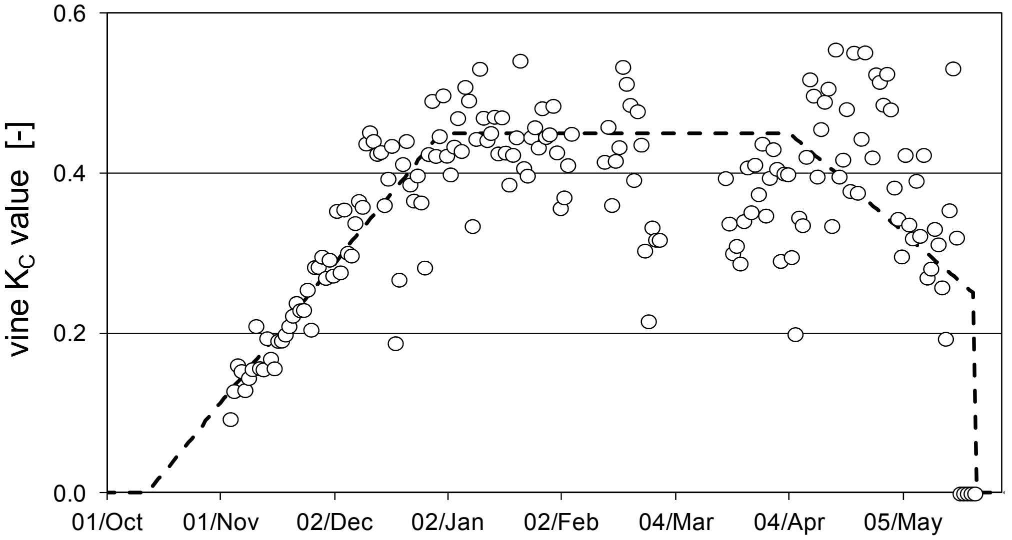

Figure B1. The basal crop factor (symbols) for grapes at Seaview vineyard, Marlborough, as calculated by dividing the measured sap flow (mm/day) by the regional potential evapotranspiration (*ET*) (mm/day). The broken line is a schematic of the crop factor that has been used to calculate by the soil water balance from climate data. Data are for 2006/07 growing season.

Table B1. A simple linear interpolation is used to construct the crop coefficient curve based on three values: those during the initial stage ($K_{C,ini}$), the mid-season stage ($K_{C,mid}$) and the end of the late-season stage ($K_{C,end}$). Here D represents the Julian day (i.e. D equals one on 1 January) and the subscripts represent phenological dates: BB = budburst, CC = canopy closure (maximum leaf area), H = harvest, LF = leaf fall. By default, the value for $K_{C,end}$ equals 0.80 times K_{Cmid} to reflect a decline in leaf response as the leaves age. Other factors, such as a change in canopy leaf area due to trimming, have not been accounted for. These are the default values for each year of modelling (Appendix C).

Crop	D_{BB}	D_{CC}	D_H	D_{LF}	$K_{C,mid}$
grape	6-Oct	1-Jan	1-Apr	1-May	0.45

When soil water becomes limiting, the actual crop water use will decline as the leaf stomata close in response to increasing water stress brought on by decreasing soil-water availability. The degree of water stress will depend on a number of factors, including the fraction of readily available soil water that has been extracted from the root zone soil, root depth, and plant tolerance to water stress. Soil water availability is used as a guideline, both to estimate soil water status and to determine the need for irrigation.

A3. Calculating the soil water balance

A simple soil water balance was developed for the purpose of assessing drainage data from the DFMs. We used a simple tipping-bucket scheme that considers the soil water content, *SWC*, averaged over a specified soil depth, being a 1.2 m deep root zone. The water balance is represented by the simple sum of the inputs of water, from rainfall (RF) and irrigation (IR_a), minus the outputs (losses) of water from evapotranspiration (ET_a), drainage (DR) and runoff (RO). Small interception losses are also accounted for, as some of the day's rainfall is intercepted by the leaf canopy and subsequently evaporates without ever reaching the ground (this is discussed later). All calculations are made using a daily time step, and all variables have the dimensions of mm unless stated otherwise.

The water balance calculation proceeds as follows. Firstly, we calculate a 'temporary' value for *SWC** as the sum of yesterday's *SWC* plus today's rainfall and irrigation, minus today's actual evapotranspiration, namely:

$$SWC^* = SWC + (RF + IR_a) - ET_a \qquad \text{Eq. [B3]}$$

The value of *SWC** cannot exceed the full point, otherwise drainage and/or runoff will occur. At this stage we do not separate DR and RO in the tipping-bucket scheme. Rather, we calculate the excess amount of soil water, above the full point, and confine this to runoff and drainage losses, which are calculated as:

$$DR + RO = \max(SWC^* - FP, 0.0). \qquad \text{Eq. [B4]}$$

Thus, the *SWC* at the end of each day is calculated as:

$$SWC = SWC^* - (DR + RO). \qquad \text{Eq. [B5]}$$

This simple calculation procedure obeys mass balance and ensures the soil does not wet above field capacity. It will work best when soil water content is below field capacity, as would be expected for well-managed irrigation over a typical summer period.

In reality, all soils will temporarily wet up above *FC*, often for a few days following a large rainfall event, especially during the winter period or when excessive amounts of irrigation are applied. However, most free-draining soils will also drain back to field capacity a few days later. Furthermore, run-off is also known to be strongly influenced by rainfall intensity, soil moisture conditions, and slope, amongst other factors.

Surface runoff is predicted from daily rainfall plus irrigation, using the SCS curve number equation:

$$\begin{aligned} Q &= \frac{(R - 0.2S)^2}{R + 0.8S}, && R > 0.2S \\ Q &= 0, && R \le 0.2S \end{aligned} \qquad \text{[Eq. B6]}$$

where Q [mm] is the daily runoff, R [mm] is the daily rainfall plus irrigation, and S [mm] is the retention parameter that reflects variations among soils, land-use and management. The S parameter is related to the curve number, CN, using the SCS equation (Soil Conservation Service 1972):

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{[Eq. B7]}$$

where the constant, 254, gives S in millimetres. The average curve number can be obtained easily for any area of land-use type from the SCS Hydrology Handbook (Soil Conservation Service 1972). We have explicitly modelled runoff plus drainage with the simple tipping-bucket scheme in order to evaluate the drainage data from the DFM devices. We will compare model output against our field data (drainage and soil water content) to verify if these two approaches are consistent and therefore appropriate.

The actual evapotranspiration transpiration, ET_a, is calculated from the sum of the transpiration losses from the vines only, T_a, and evaporative losses from the understory (ground), E_G, that comprises a fractional area of grass and a remaining area of bare soil, namely:

$$ET_a = T_a + E_G \qquad \text{Eq. [B8]}$$

The actual transpiration of the vine crop (excluding evaporative losses from the understory), T_a, is related to the potential evaporative demand, ET_O, using the following relationship (modified from Eq. B2 to include a stress factor, K_S), namely

$$T_a = K_S\, K_C\, ET_O \qquad \text{Eq. [B9]}$$

where K_C is the seasonal crop-factor that accounts for changes in the green leaf-area, and K_S is a simple multiplicative factor that accounts for the effects of water stress as:

$$K_S = \max(\,0.0, \min(1.0, (SWC\text{-}WP)/(SP\text{-}WP))). \qquad \text{Eq. [B10]}$$

The factor K_S assumes a value between zero (i.e. complete water-stress with zero transpiration) and 1.0 (i.e. no water stress and maximum transpiration). In other words, we model the expression of water stress as a linear reduction in actual transpiration, T_a, as soon as the *SWC* becomes less than the stress point (SP). Other stresses such as nutrient deficiencies, heat, cold, insects and disease, have been ignored in these calculations.

Evaporative losses from the bare soil, E_S, are calculated using a simple two-stage model similar to that of Ritchie (1972). E_S is assumed to be proportional to the evaporative demand, being flux-limited (< 2.6 mm/d) for the first 2 days, and thereafter decreasing as the square-root of the time, t_L (days), since any significant irrigation or rainfall (*IR* or *RF* > 5 mm/d) has occurred. Thus, soil evaporation is modelled as:

$$E_S = \min(2.6, \min(\,1.0, (1.2\text{-}K_C)^2/\sqrt{t_L}))\, ET_O), \qquad \text{Eq. [B11]}$$

and the effect of shade from the leaf canopy is embodied in the crop factor term. Similarly, evaporative losses from the vegetative (grassed) part of the understory are modelled as:

$$E_V = \min(\,1.0, (1.2\text{-}K_C)^2\,)\, K_S\, ET_{O.} \qquad \text{Eq. [B12]}$$

In this case we make the simple assumption that the understory vegetation exhibits the same water-stress response as the vine crops. This assumption is necessary since we are using a simple tipping bucket approach that cannot separate the grass from the vines. Rather, we assume a fraction of the understory is covered in vegetation, α_V, and so the total evaporative loss from the understory (ground), E_G, is modelled as:

$$E_G = \alpha_V\, E_V + (1\text{-}\,\alpha_V)\, E_S \qquad \text{Eq. [B13]}$$

A simple spreadsheet model has been developed using Eqns B1–B13. Once parameterised, this calculation will then form part of a model that will be passed over to MDC (Peter Davidson) for use in calculating net drainage losses to the Wairau aquifer.

A4. Defining the soil water status

The following definitions have been adopted for the soil's hydraulic properties:

- Soil-water content (*SWC*, mm) is a measure of the soil's volumetric water content ($\bar{\theta}$, %), integrated (summed) over a specified depth, being a 1.2 m root zone (Δz, mm): $SWC = \bar{\theta}\ \Delta z$.
- Saturation (SAT, mm) represents the porosity of the soil spores (POR, %) multiplied by soil depth (Δz, mm). Poorly drained soils that are waterlogged are expected to be close to the SAT value during the winter.
- Full point (FP, mm) = field capacity (*FC*, %) multiplied by soil depth (Δz, mm). *FC* is a measure of the soil's volumetric water content at a matric potential of -10 kPa, averaged over a specified depth, being a 1.2 m root zone. The FP value represents the total depth of water held in the root zone soil that has recently been fully wet, by either rainfall and/or irrigation, such that all drainage has now materially ceased. The maximum *SWC* of free-draining soils is expected to be close to FP during the winter.
- Soil water deficit (SWD, mm) represents the difference between the full point and today's soil water content.
- Zero point (ZP, mm) = permanent wilting point (WP, %) multiplied by soil depth (Δz, mm). ZP is a measure of the soil's volumetric water content at a matric potential of -1500 kPa, averaged over a specified depth, being a 1.2 m root zone. The ZP value represents the total depth of water held in the root zone soil such that all plant-available soil water has been extracted and the plants have died.
- Total available water (*TAW*, mm) = the amount of water held in the root zone soil, between field capacity and wilting point: $TAW = (FC\text{-WP})\ \Delta z$
- Drought tolerance (D_{TOL}, %) is a plant-parameter that defines the fraction of *TAW* that can be extracted from the root zone soil before the symptoms of water stress begin to occur. This is a simple approximation and here we will assume $D_{TOL} = 0.5$, for both the pasture and the grapevines (Allen et al. 1998).
- Readily available water (*RAW*, mm) represents the amount of water in the root zone soil that can be extracted by the crop before the symptoms of water stress occur. The values of *RAW* are calculated from the product of D_{TOL} multiplied by *TAW*.
- Refill-point (RP, mm) represents the *SWC* when irrigation will be applied. This variable is used to set up the irrigation strategy. We have assumed a value of RP that is half-way between FP and ZP. In other words, we have set the value of D_{TOL} to equal 0.5 throughout the growing season.

Vineyard managers have some flexibility to adjust the value of RP seasonally, e.g. to mimic a deficit-irrigation strategy grapes where RP is adjusted upwards during flowering and downwards closer to harvest to improve aspects of fruit quality. Typical values of hydraulic properties of the Wairau silt loam soil series can be found in Landcare Research's online databases.

Appendix C. Grape phenology for modelling

Table C1. Grape phenology. Model outputs for the mean dates of budburst (BB), flowering, véraison (maturity), and harvest of 'Sauvignon blanc' grapes in Marlborough. Here σ represents one standard deviation (days) about the mean date. The data are from SLMACC Research Report on Climate Change (Clothier et al. 2012).

'Sauvignon blanc'		2005	2006	2007	2008	2009	2010	2011	Average	σ
Phenological stage	50% BB	5-Oct	28-Sep	8-Oct	6-Oct	3-Oct	9-Oct	13-Oct	6-Oct	5
	50% Flowering	16-Dec	5-Dec	13-Dec	10-Dec	11-Dec	20-Dec	19-Dec	13-Dec	5
	50% Véraison	24-Feb	1-Feb	17-Feb	11-Feb	17-Feb	23-Feb	14-Feb	15-Feb	8
	Harvest	4-Apr	15-Mar	27-Mar	20-Mar	2-Apr	8-Apr	25-Mar	27-Mar	9

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