GROUNDWATER ABSTRACTION FROM THE WAIRAU PLAINS, MARLBOROUGH

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Abstract

The Marlborough District Council (MDC) is currently seeking to define the volumes of water used for irrigation of wine grapes. This information is needed to establish sustainable limits for groundwater abstraction. A measurement and modelling approach was adopted for this task. The measurements included seasonal irrigation records (November to April) and soil moisture readings from a large number of monitor sites (> 300 vineyards) between the years 2004 and 2011. The modelling was carried out using Plant & Food Research's SPASMO model (Soil Plant Atmosphere System Model) that simulates the daily water and nutrient balance for a given land use, soil type and microclimate.

Daily values of irrigation, determined from both the measurement and the modelling approaches, were summed up on a monthly basis to generate two estimates of water take from each aquifer zone under the Wairau Plains. There was good agreement between the two approaches. Our analysis revealed large differences in irrigation use across the plains that could be explained by differences in soil water-holding capacity and summer rainfall. More importantly, we found that grape growers, on average, are using substantially less water than they have been allocated on a seasonal basis. These findings will enable the Council to draw conclusions about current water allocation policies and to assess the sustainability of water takes for irrigation of wine grapes cf. aquifer recharge of the Wairau Plains.

Keywords: soil water balance, irrigation allocation, drainage flux, modelling

Introduction

Pastoral farming, horticulture and viticulture are major land use activities in the rural landscape. These activities are becoming increasingly reliant on irrigation over the dry summer months. Recent intensification has led to an increase in volume of water being used for irrigation, and a rise in the number of resource consents that are granted by local and regional councils. The main source of irrigation water is typically from surface water takes (i.e. lakes, rivers and streams) or from wells that tap into the groundwater. Furthermore, water harvesting and water storage options are being considered to provide for security of water. Often the water supplies are also used as sources of drinking water for both stock and domestic purposes. Thus, it is vitally important for the nation's economic prospects, and the population's health and well being, that farmers and land users develop sustainable farming practices that will secure the quality and quantity of the region's groundwater resources.

Grape vineyards are the dominant land use in Marlborough and their irrigation represents a major abstraction of groundwater from the Wairau Plains. At present, the Marlborough District Council's (MDC) irrigation records for vineyards are incomplete. They are seeking to define the volumes of water used for wine grape production. This information is needed to establish sustainable limits for ground-water abstraction.

Plant & Food Research (PFR) are working with the MDC to determine, via measurement and modelling, just how much water is being used for the irrigation of wine grapes on the Wairau Plains. For these calculations, we have used the MDC's GIS database of the current land area under vineyard production, and combined it with soils data from Landcare Research's fundamental soil layers and daily climate data from NIWA's virtual climate network (Fig. 1). Our task was to define actual water takes, for vineyard irrigation, from each aquifer zone.

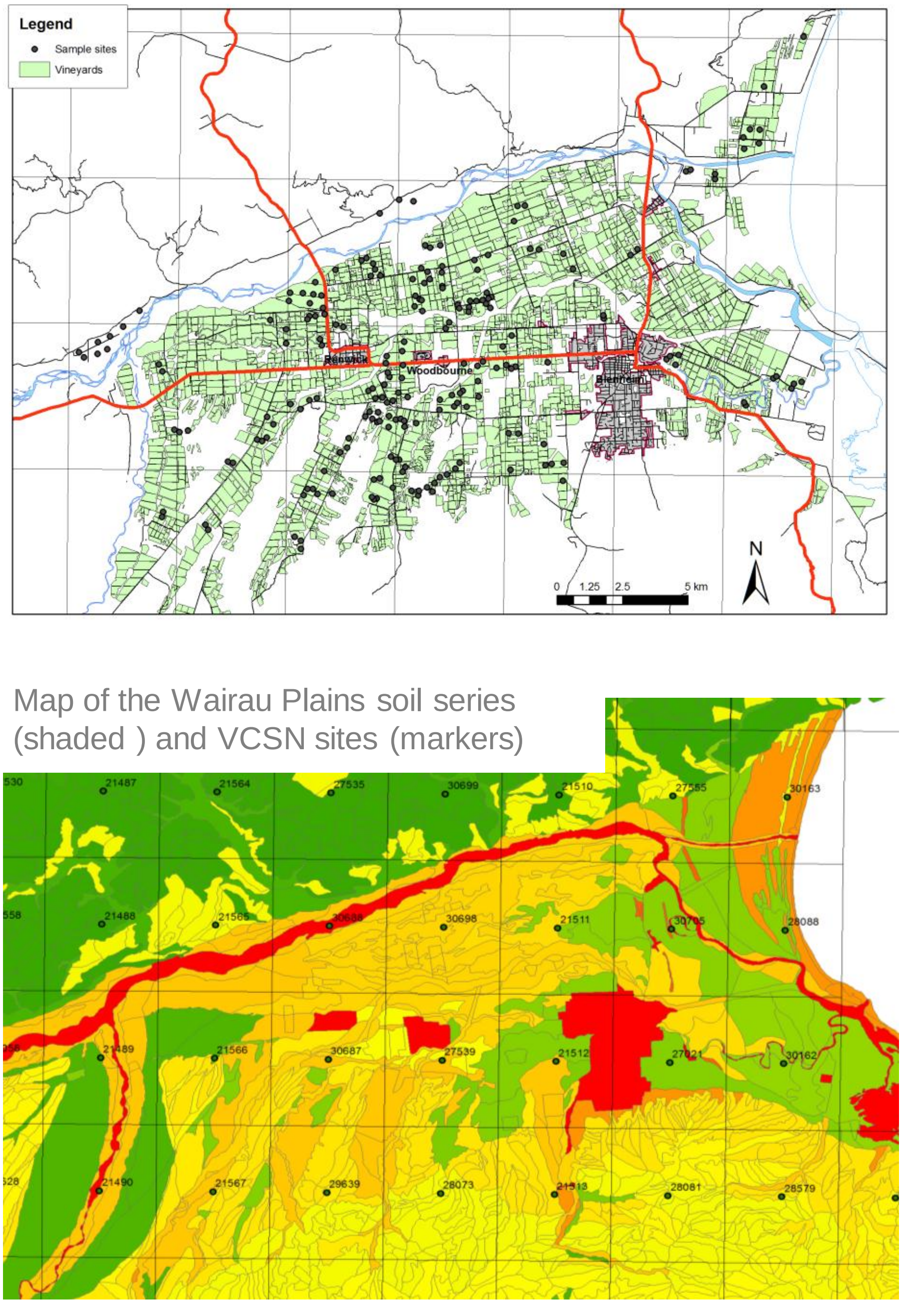

Figure 1. The top panel shows a map of the Wairau Plains, with vineyard areas indicated by shaded areas and monitored sites shown by markers (data were provided by Fruition Horticulture). The bottom panel shows soil series as shaded polygons (*source*: Landcare Research's Fundamental Soil Layers database); the markers represent individual stations on NIWA's Virtual Climate Station Network (VCSN). Daily climate data (1972-2011) were downloaded for each climate station using the Cliflo software (www.cliflo.niwa.co.nz).

Materials and Methods

Calculations of crop water use at the vineyard scale

SPASMO calculates the soil water balance of each vineyard by considering inputs (rainfall and irrigation) and losses (plant uptake, evaporation, runoff and drainage) of water from the root-zone. Irrigation is applied on the basis of need, when the root-zone water deficit exceeds a given threshold value. Vineyard water use depends on three factors: the atmospheric demand for water that is defined by the local microclimate; the green leaf area; and the response of the leaves to their aerial and soil environment. When soil water becomes limiting, the actual vine water use will decline as the leaf stomata close in response to increasing water stress. The degree of water stress will depend (approximately) on the fraction of readily-available soil water that has been extracted from the root-zone soil.

A standard crop-factor approach is used here 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. 1998). The reference evaporation rate, ET_O [mm d^{-1}] is first calculated using the equation:

$$ET_0 = \frac{\frac{s}{\lambda}(R_N - G) + \gamma \frac{900}{(T + 273)} u_2 (e_s - e_a)}{s + \gamma\,(1 + 0.34 u_2)} \qquad \text{Eq. [1]}$$

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. Equation [1] defines the potential rate of evaporation from an extensive surface of green grass, of a short, uniform height, that is actively growing, completely shading the ground, and not short of water. For routine calculations of crop transpiration, the following equation is used:

$$ET_C = K_C . ET_O \qquad \text{Eq. [2]}$$

Here K_C represents a dimensionless 'crop factor' that can vary between about 0.1 (young vines with small leaf area) and about 0.5 (vigorous vines with large leaf area). In past work, we have used sap flow sensors in the vine trunk to obtain a direct measure of K_C via the ratio of actual transpiration loss (i.e. daily sap flow) to the potential evaporative demand. Figure 2 shows an example of the seasonal water use of grapevines from Marlborough. In this case, the basal crop factor at mid-season is about 0.45, although it varies over the season in proportion to the development of green leaf area (Green et al. 2008).

Irrigation volumes are largely established by crop demands, ET_C, and soil water availability. The timing of irrigation, on the other hand, depends on the grower's irrigation strategy. Currently, many growers aim to have plenty of soil water over flowering, then they gradually reduce soil water through to véraison (i.e. fruit ripening), and finally they seek to impose a mild water-stress from véraison through until harvest. SPASMO incorporates a component for the crop phenology (i.e. timing of events such as budburst, flowering, véraison or maturity, and harvest) to help to schedule an appropriate irrigation strategy (Fig. 3).

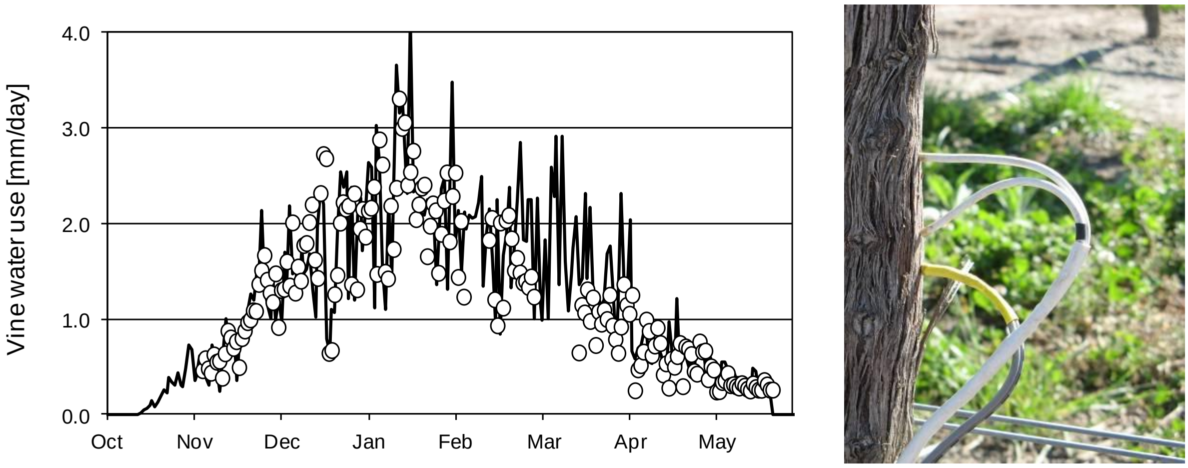

Figure 2. Sap flow sensors have been used to measure the actual water use (ET_C, symbols) of the grapevines in Marlborough. The basal crop factor (K_C, vines only) was calculated from the ratio of ET_C to ET_O. The value of K_C is about (~0.45) for these grapevines because of the sparse leaf canopy.

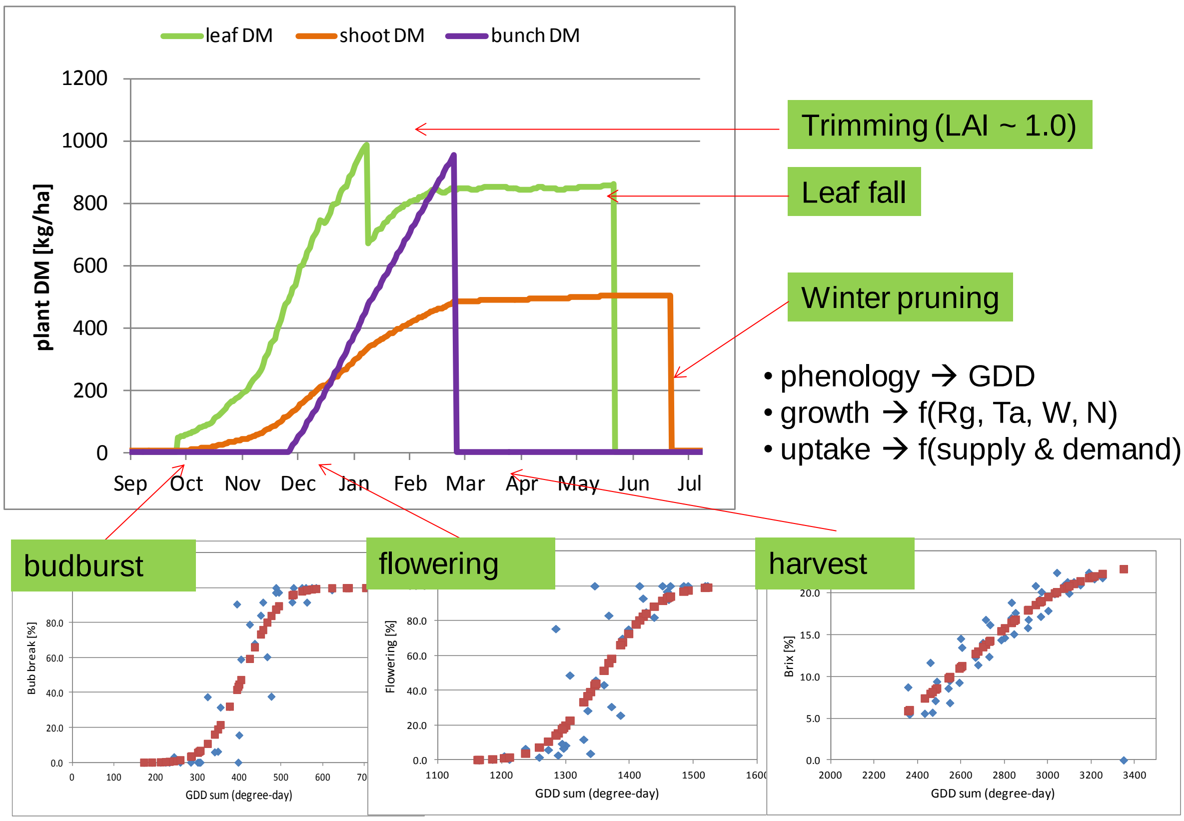

Figure 3. SPASMO includes components for crop phenology (i.e. budburst, flowering and harvest) that help to establish dry-matter allocation (DM), and irrigation management of the grapevines. The bottom panels show data sourced from regional grape trials in Marlborough (blue symbols) compared against predictions from SPASMO (red symbols). The data were provided by Alistair Hall (PFR, pers. comm.).

Soil properties at the vineyard scale

SPASMO requires a detailed set of soil physical and hydraulic properties to calculate the soil water balance. These properties are available from Landcare Research's public database for the Fundamental Soil layers. They include soil texture (sand, clay and stone content), water-holding capacity, drainage class, potential root depth and stone content. Our software uses a functional form for the soil's water retention curve, obtained by fitting each set of water retention data (i.e. the TP, FC and WP points discussed in Fig. 2) to the van Genuchten (1980) equation of the form:

$$\Theta = \frac{\theta - \theta_R}{\theta_S - \theta_R} = \left[\frac{1}{1 + (\alpha h)^N} \right]^M \qquad \text{Eqn [4]}$$

Here S and R refer to saturated and residual values of the soil water content (θ) and the parameters α, N and M (=1-1/N) are fitting parameters that determine the 'shape' of the curve. The non-linear routine SOLVER in Microsoft® Excel® was used to determine each of the fitting parameters for more than 20 different soil series found on the Wairau plains. The relative hydraulic conductivity (K_R) is also needed for the water balance calculations. This is described using the equation:

$$K_R = K(h)/K_S = \Theta^{1/2}\left[1 - \left(1 - \Theta^{1/M}\right)^M\right]^2 \qquad \text{Eqn [5]}$$

where $K(h)$ is the hydraulic conductivity at a water potential h, K_S is the hydraulic conductivity at saturation, Φ is the relative water content and M is the corresponding fitted parameter for Eqn [4]. Examples of the water retention curves are shown in Figure 4.

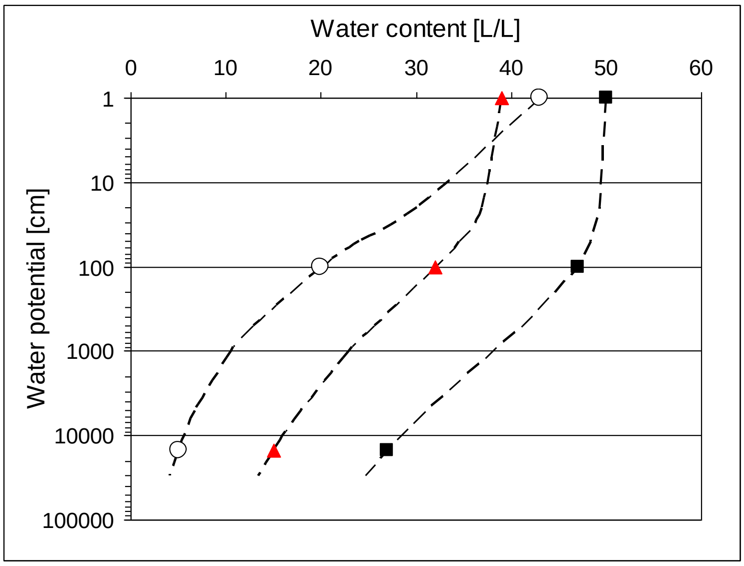

Figure 4. Water retention properties for sand (open circle), silt loam (red triangle) and silty clay (black square). The soil's field capacity (FC) is given by the water content at a potential of -100 cm. The soil's wilting point (WP) is defined by the water content at a potential of -15000 cm. The refill point for irrigation (RP) is typically at a potential of about -1000 cm, although RP does vary over the season to match the grower's irrigation strategy (see Fig. 6).

Calculations of vineyard water use at the regional scale

Approach 1: Grower records

The first approach is based on measurements. Here, we used irrigation volumes and soil moisture readings recorded by Fruition Horticulture (FH) from a large number of monitor sites (> 300 vineyards) between 2004 and 2011 (Fig. 1). Vineyard records (weekly values) were first grouped according to aquifer zone and soil series. Then weekly irrigation volumes from each vineyard were summed up on a monthly basis, and averages (mm/day) were scaled (L/s) according to the total vineyard area (ha) above each aquifer zone. This scaling provided one estimate of the monthly and annual water takes. With this scaling, we did not make a distinction for grape variety, irrigation strategy or vine age and vigour; rather, we gave an equal weighting to each vineyard data set.

Approach 2: Desktop modelling

The second approach is based on modelling. Here, we used our SPASMO model to simulate irrigation demand for a range of locations (i.e. climate grids) and soil types across each aquifer zone. SPASMO works on a daily basis, at the paddock scale, and all model outputs for the soil-water balance are expressed in terms of mm/day. Climate records (1972-2011) were assembled on a 5-km grid using NIWA's Virtual Climate Network of stations (Fig. 1). Within each 5-km grid, a GIS map of the Fundamental Soil Layers (Landcare Research) and a GIS map of the vineyard property boundaries were used to determine the land area and corresponding soil series under each vineyard. A profile of the soil's physical and hydraulic properties, needed for the modelling, was deduced using data from the New Zealand soils database (NZSDB, Landcare Research). Local values for the crop factor, K_C, of wine grapes were derived from >10 years of experimental data from Sauvignon vines in Marlborough (Fig. 2). A standard irrigation strategy was adopted for all simulations (as described by Fruition Horticulture). The vines were irrigated according to need (i.e. non-stressed) from budburst up to flowering. Deficit-irrigation (reducing soil moisture) was then imposed between fruit-set and véraison, and a mild water stress was maintained until harvest.

For the purpose of calculation, model outputs from SPASMO (irrigation, mm/day) were grouped according to aquifer zone, climate zone, soil series and vineyard area. Irrigation volumes associated with each aquifer zone were then summed up on a monthly basis. Statistics of irrigation use (mm/month) were scaled (L/s) according to the total vineyard area (ha) above each aquifer zone. This scaling provided a second estimate of the monthly and annual water takes. It accounted for variation in soil and climate but did not consider other factors (vine age, variety, irrigation strategy, ground-water depth).

Results and Discussion

Water use at the vineyard scale

The seasonal dynamics of soil water content (0-100 cm) for three contrasting soils from the Wairau Plains, Marlborough, are shown in Figures 5 and 6. In each case, the grower's strategy results in a gradual depletion of soil moisture throughout the growing season. A significant water deficit (i.e. the difference between field capacity and the current soil moisture content) is developed, ranging from 100 mm on the lighter soils to 175 mm on the heavier soils. There is good agreement between the model calculations of soil water content and the neutron probe data from these Marlborough vineyards. In addition, we have grouped the data into heavy, medium and light textured soils, and then averaged the calculations over each year. Model outputs of annual irrigation demand are similar to the actual amounts being applied in these vineyards (Fig. 7). This good agreement provides further support that outputs from SPASMO, at the vineyard or enterprise scale, are both realistic and reasonable.

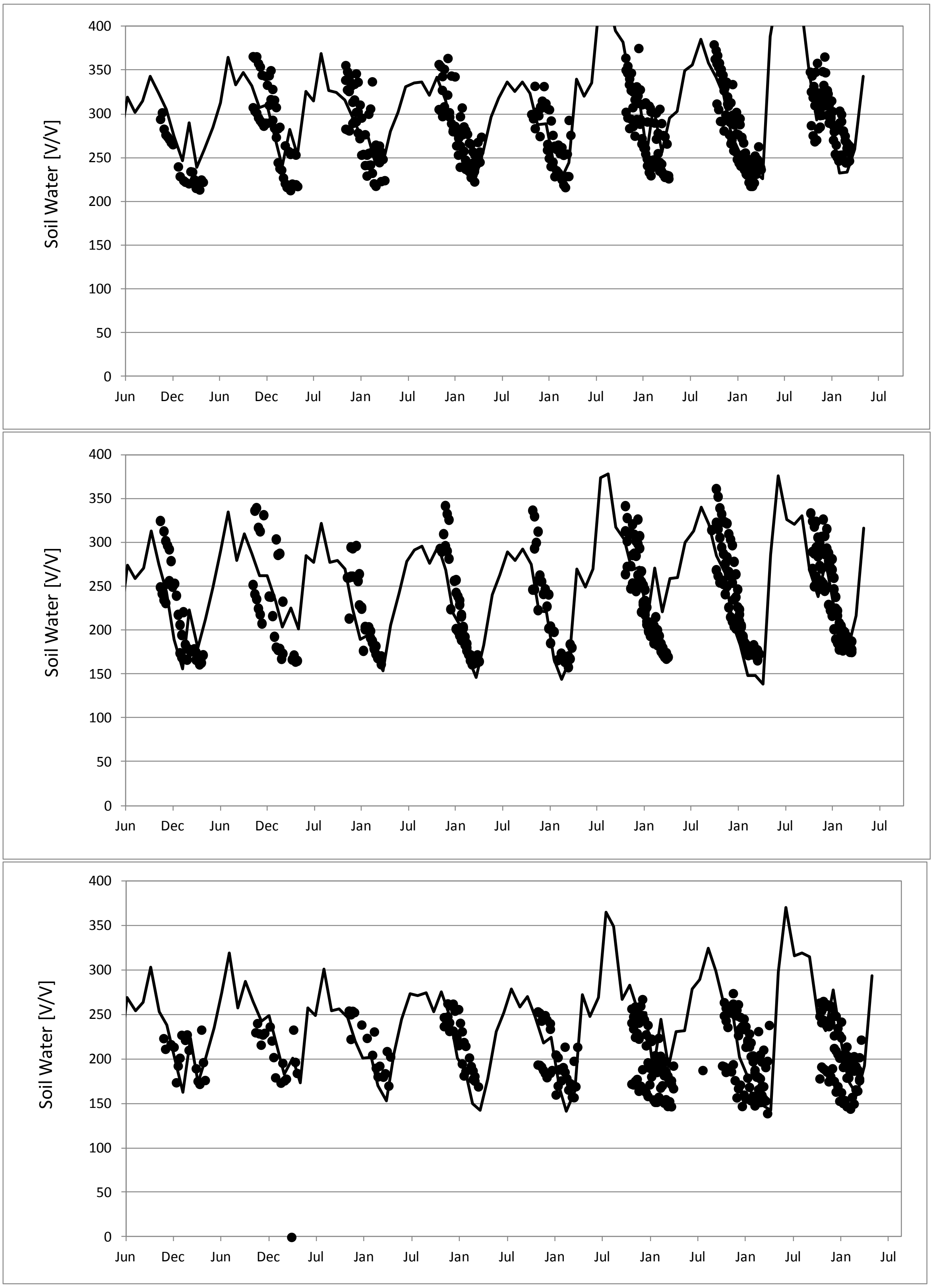

Figure 5. The dynamics of soil moisture (0-100 cm depth) from Marlborough vineyards on a Renwick stony silt loam (top panel), a Wairau silt loam (middle panel) and a Raupara gravelly sand (bottom panel). The markers represent neutron probe measurements taken by Fruition Horticulture. The lines represent model outputs from SPASMO at the beginning of each month.

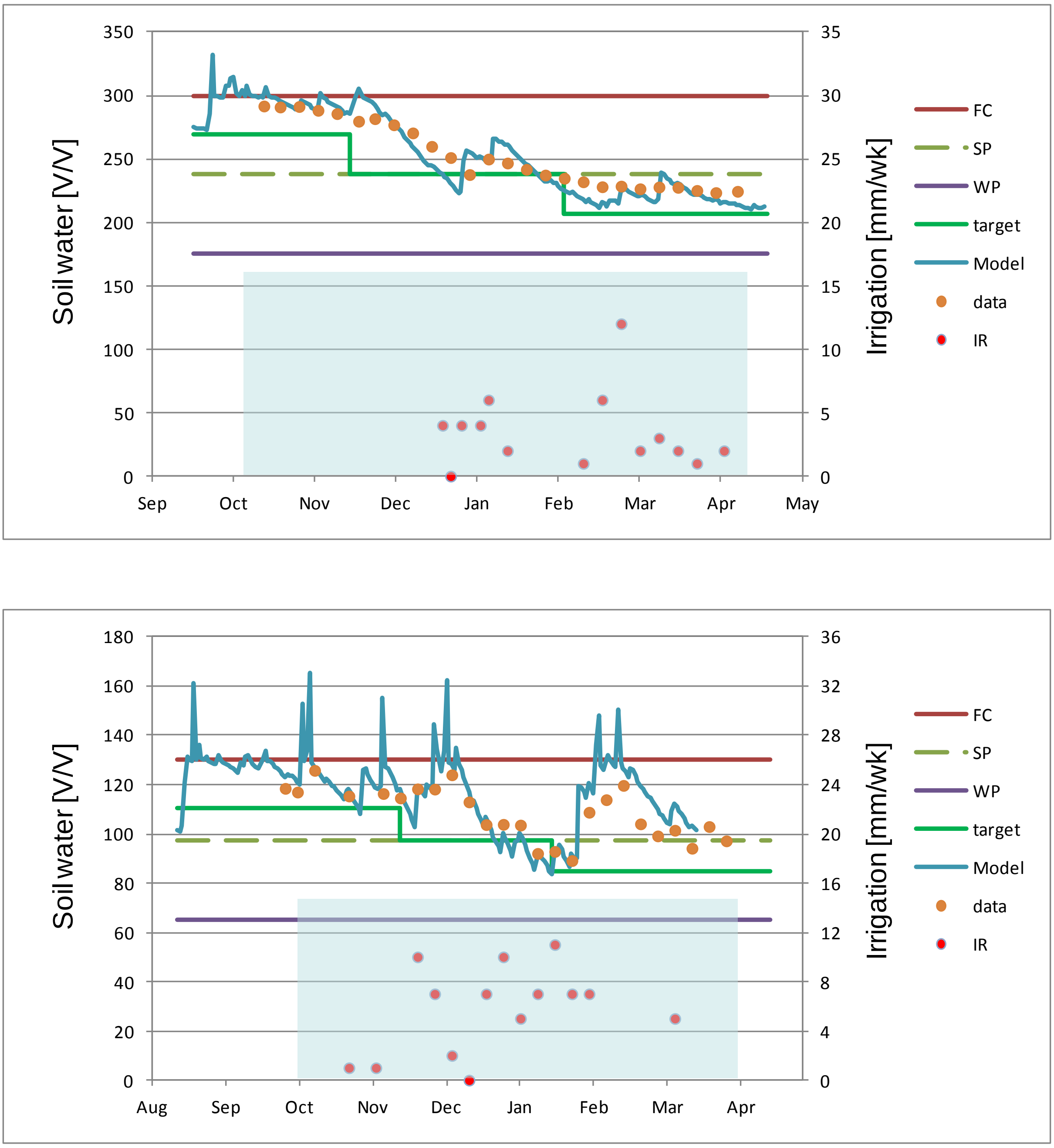

Figure 6. The dynamics of soil moisture (0-100 cm depth) from Marlborough vineyards on a Wairau silt loam (upper panel) and a Fairhall stony silt loam (bottom panel). The upper symbols in each panel (orange markers) represent neutron probe data taken by Fruition Horticulture. The lower symbols in each panel (red markers) represent the amount of irrigation applied each week. The green line (decreasing stepwise) represents the irrigation strategy. The fluctuating line (blue) represents model outputs from SPASMO for each day of the growing season. The shaded region (blue) represents the current water allocation from the MDC. Growers are using much less water than they have been allocated over the growing season.

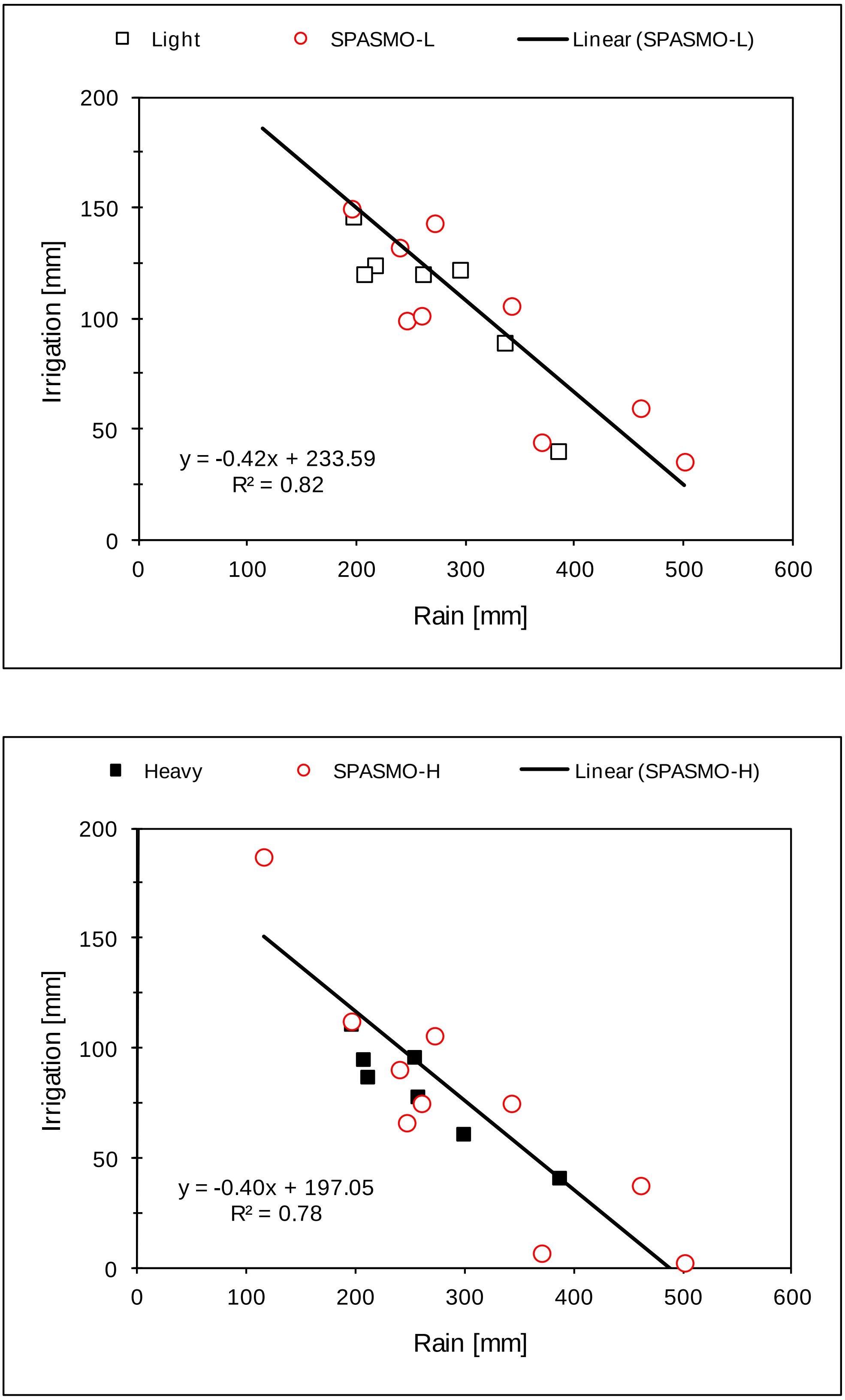

Figure 7. The relationship between irrigation need and seasonal rainfall (November-April) as measured on light (top panel) and heavy (bottom panel) soils, and as calculated with SPASMO (open circles). Data for this comparison were supplied by Fruition Horticulture.

About 80% of the seasonal variation in irrigation need is explained by rainfall during the irrigation season. The relationship appears to be almost linear, suggesting that growers understand the need to adjust their irrigation to account for rainfall. A regression line through the model outputs shows about 40% of the summer rainfall is effective (i.e. as indicated by the slope of the regression line). This is because small daily rainfall totals (i.e. < 5 mm) barely wet the soil and are therefore largely ineffective at rehydrating the root-zone soil. Figure 7 shows a general trend for less irrigation to be used on heavier soils and for less irrigation to be used in wetter growing seasons. This latter result helps to confirm good irrigation management is being adopted on the monitored vineyards.

Calculation of water takes from each aquifer

For each aquifer zone, and for the whole of the Wairau Plains, we have calculated the monthly irrigation takes (m^3/s) from grower records and from the desktop modelling using SPASMO. The results are expressed in terms of an average with a standard deviation and an upper quartile (75%) for each month of the irrigation season (November to April). Grower records span the years 2004-2011 and include observations from between 4 and 199 vineyards (fewer monitor sites on the smaller aquifers) from each aquifer zone. For the purpose of this calculation, all vineyard data were equally weighted across a wide range of vineyard ages (young, developing, established), varieties (Cabernet, Chardonnay, Pinot gris, Pinot noir, Riesling and Sauvignon blanc), irrigation strategies (developing, conservative, standard, young) and soil types. Model outputs, on the other hand, are based on daily simulations spanning the years 1972-2011, and they consider only an established Sauvignon blanc vineyard with a standard irrigation strategy and a typical vineyard management. Figures 8 and 9 show our calculations of water take from the Wairau and Southern Valleys aquifers, respectively.

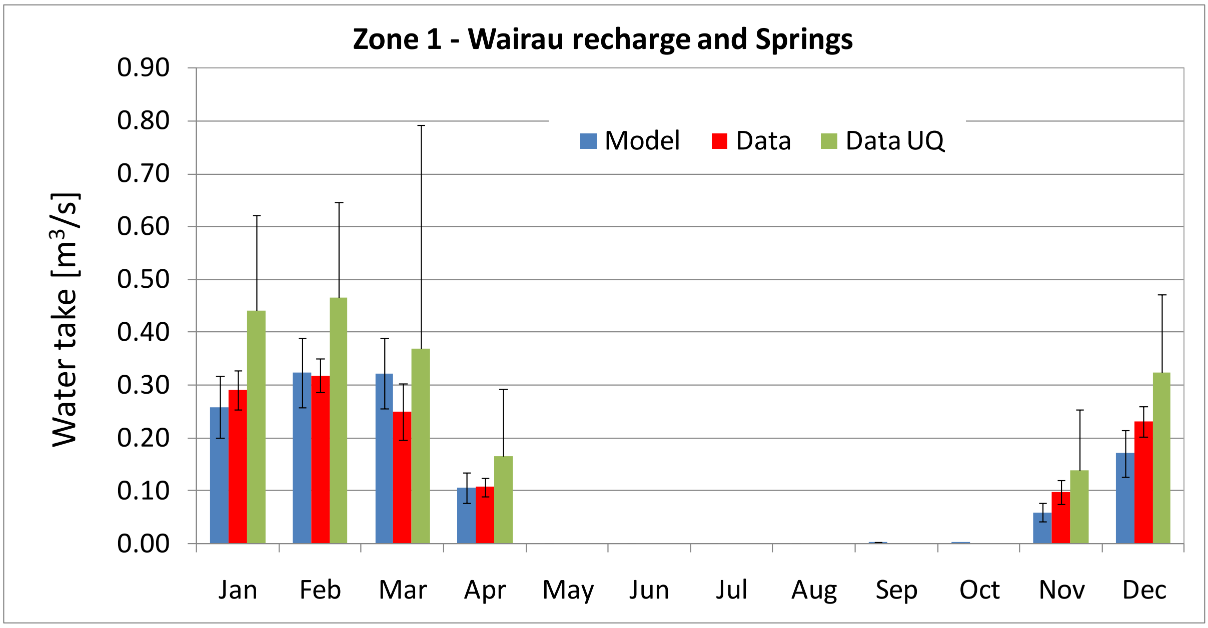

Figure 8. Model calculations of average water takes from the Wairau Recharge and Springs aquifers. The upper quartile (UQ) values are based on climate data from 1972-2010. Data records are from between 80 (2004) and 170 (2011) monitored sites (Fruition Horticulture).

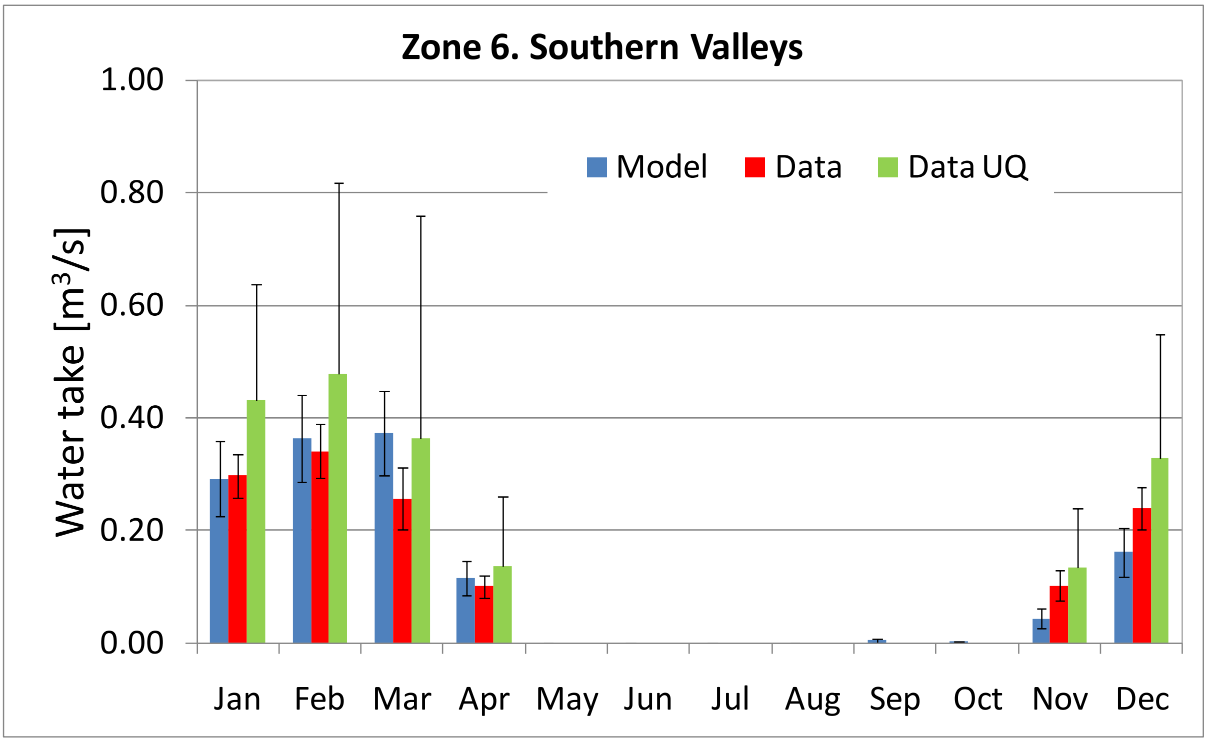

Figure 9. Model calculations of average water takes from the Southern Valley aquifers. The upper quartile (UQ) values are based on climate data from 1972-2010. Data records are from between 80 (2004) and 170 (2011) monitored sites (Fruition Horticulture).

As expected, on average, the highest water takes occur during the middle of the summer (February and March) and lower water takes occur during the shoulders of the irrigation season (November and April). We see a reasonable correspondence between measurement and modelling of the average water takes from these two aquifers (e.g. Zone 1 – Wairau Recharge and Springs section = 5050 ha; Zone 6 – Southern Valleys section = 5650 ha). These takes represent about 75% of the planted grape area on the Wairau plains. In this case we have a large number of monitor sites (>150) and a greater proportion of well established vineyards. The modelling accounts for a wide range of soil types above each aquifer, albeit limited to 'average soil properties' and mapped soil series.

Ultimately, we are trying to model the 'behaviour' of the irrigation manager – their decisions may change over time because of improved understanding of irrigation and/or changes in irrigation strategy to match market demands for fruit yields of quality. Thus, some difference between measured and modelled water take is expected since we do not have data from every vineyard on the Plains.

Conclusions

In general, model calculations of the average water take tend to be a little higher than the corresponding volumes calculated from the vineyard data, although some questions remain over how best to average and interpret the actual water use records. In both cases, we see a wide spread in monthly water takes, e.g. as shown by the upper quartiles (UQ) calculated from the vineyard data. Indeed, the maximum upper quartile is about three times the mean. The spread of model outputs is shown here only by the standard error of the mean, although more detailed statistical processing could be undertaken, e.g. a probability analysis of model outputs.

Our analysis revealed large differences in irrigation use across the plains that could be explained by differences in soil water holding capacity and summer rainfall (Fig. 7). More importantly, we found that grape growers, on average, are using substantially less water than they have been allocated on a seasonal basis (Fig. 6). These findings will enable the Council to draw conclusions about current water allocation policies and to assess the sustainability of water takes for irrigation of wine grapes versus aquifer recharge of the Wairau Plains.

Acknowledgements

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References

Allen RG, Pereira LS, Raes D, Smith M 1998. Crop Evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations, Rome, 301 pp.

Green SR, Clothier BE, van den Dijssel C, Deurer M, Davidson P 2008. Measurement and modelling the stress response of grapevines to soil-water deficits in their rootzones. Chapter 15, In Soil Science Society America Monograph "Modeling the response of crops to limited water: Recent advances in understanding and modeling water stress effects on plant growth processes", L. Ahuja et al. [Eds].

van Genuchten MTh 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil. Sci. Soc. Am. J. 44:892-898.