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Irrigation REPORT

GUIDELINES FOR REASONABLE IRRIGATION WATER REQUIREMENTS IN THE OTAGO REGION

PREPARED FOR
Otago Regional Council

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EXECUTIVE SUMMARY

The purpose of this report is to present the approach and results to update guidelines for the Otago Region's reasonable daily and seasonal irrigation water requirements. This project was completed by Aqualinc Research Limited (Aqualinc) in consultation with ORC and with inputs from stakeholders.

The project was undertaken in the following stages:

> Stage 1: Review of previous ORC irrigation guidelines (Aqualinc 2006) and the scoping of work required through stakeholder consultation.
>
> Stage 2: Development of the final irrigation guidelines as presented in this report using water balance computer modelling for a range of climatic, soil, crop and irrigation management parameters.

Stage 1 aimed at identifying the shortcomings and concerns of the previous irrigation guidelines through consultation with irrigation water users and industry representatives. The consultation process laid the foundations to develop the scope for the Stage 2 of the project. In addition, the stakeholder consultation was also valuable in gathering parameters necessary for water balance computer modelling.

Stage 2 was dedicated to developing reasonable irrigation requirement values for crops and pasture. Aqualinc's water balance computer model, Irricalc was used for crops, and CSIRO's AusFarm model was used for pasture.

Both models use the principles developed by Food and Agriculture Organization (FAO) of the United Nations for daily soil moisture water balance modelling (Allen et al., 1998).

Both models used either NIWA's virtual climate station (VCS) climate data, or climate station data directly. VCS data is available at a 5 km by 5 km grid across the region. Aqualinc considers that data on a 5 x 5 km grid provides reasonable guidance of daily and mean annual rainfall for a given location.

The crops that are modelled include pasture, grapes, stonefruit (represented by apricots and cherries) and market garden vegetables (represented by a crop rotation of potatoes and cabbages). The water requirement modelling was carried out for five soil plant available water (PAW) classes that cover the potential range of PAW values within the Otago Region. The model outputs, therefore, can be used for any PAW in the Otago region without need to re-run the model if future high resolution soil surveys determine different soil water characteristics than what is available presently.

The water balance modelling has been carried out for 42 irrigation seasons (1972 to 2014). Peak daily demand (mm/day), peak monthly demand (mm/month) and mean, 80 percentile, 90 percentile and maximum annual demand (mm/year) for a combination of climate (location), soil, crop and irrigation systems are provided.

The irrigation guidelines for reasonable water use in the Otago Region have been developed using internationally accepted water balance computer modelling. The computer model have been field verified in a wide range of soil and climate conditions in New Zealand. On that basis, the guideline values presented in this document and associated electronic files for different soil-crop-climate and irrigation management combinations are appropriate for determining reasonable water allocation limits for irrigation in the Otago Region.

LIST OF ABBREVIATIONS

amsl	Above mean see level
ASM	Available soil moisture
ET	Evapotranspiration
m	Metre
mm	Millimetre
mm/d	Millimetres per day
mm/month	Millimetres per month
PAW	Plant available water
PET	Potential evapotranspiration

LIST OF ACRONYMS

FAO	Food and Agriculture Organization
NIWA	National Institute of Water and Atmosphere
NZFSL	New Zealand Fundamental Soils Layer
ORC	Otago Regional Council

GLOSSARY

Crop coefficient (k_c)	Relates the amount of water lost through evapotranspiration by the relevant crop to the reference evapotranspiration value. The crop coefficient is determined by dividing the evapotranspiration for the crop being studied by the evapotranspiration for the reference crop; i.e., evapotranspiration for the studied crop ÷ reference evapotranspiration (dimensionless).
Evapotranspiration (ET)	Combined water lost by soil evaporation and crop transpiration (mm/day).
Field capacity	Maximum level of soil water available for plant extraction after gravitational drainage from a saturated condition falls to a rate that is insignificant (i.e., generally a rate of ≤ 1 mm/day) (dimensionless, often expressed as a percentage of the depth of the soil profile).
Irrigation system capacity	Depth of irrigation water applied ÷ minimum return period (mm/day).
Irrigation field application efficiency	Average depth of water retained within the root zone ÷ average depth of water applied on a farm through an irrigator during a single irrigation event. Losses include wind drift, interception losses, run-off, and deep drainage from a farm (dimensionless, often expressed as a percentage). Field application efficiency does not include the efficiency of the conveyance system i.e. water losses in the conveyance system. In piped irrigation systems, water losses in the conveyance system are

	negligible making field application efficiency equal to irrigation system efficiency. However, in canal irrigation systems, irrigation efficiency includes both conveyance and field application efficiency.
Plant Available Water (PAW)	PAW reflects the soil water reservoir of the crop that is available for the crop to use (mm). It is the soil moisture available between the field capacity and wilting point.
Readily Available Water (RAW)	The soil water reservoir available to the crop above which wilting or stress in the crop does not occur. Often assumed to be about 50% of PAW.
Reference ET (ETo)	ET of reference crop (grass). A reference crop is defined as a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered.
Return period	Minimum time between irrigation events in the same location (days).
Water stress reduction coefficient (k_s)	The water stress reduction factor is a function of the soil water status in root zone. k_s equals 1.0 when the soil water content in the root zone is within the readily available water content, and then k_s reduces linearly down to a value of zero at permanent wilting point (dimensionless).
Permanent wilting point	The point at which soil water is no longer available for plant extraction, assumed to be at -1,500 kPa. (Dimensionless, often expressed as a percentage of the depth of the soil profile).

1 INTRODUCTION

Irrigation is a growing consumptive use of water in the Otago Region. The consented irrigated area within the region is estimated to have doubled to approximately 168,000 ha between 2000 and 2010 (Aqualinc, 2010a)[6]. Otago Regional Council (ORC) is responsible for allocating reasonable volumes of water for efficient use for irrigation in the region.

In order to achieve this, ORC commissioned Aqualinc Research Limited (Aqualinc) to develop guidelines values for reasonable water requirements to efficiently irrigate a range of crops under different climatic and soil conditions for all potentially irrigated areas in the Otago region.

The basis of the request comes from Policy 6.4.0 A in the Regional Plan – Water for Otago, which became operative on the 1 March 2016. The Plan states:

"To ensure that the quantity of water granted to take is no more than that required for the purpose of use taking into account:

(a) How local climate, soil, crop or pasture type and water availability affect the quantity of water required; and

(b) The efficiency of the proposed water transport, storage and application system."

While the meaning of "reasonable" can be debated, the basis on which the guidelines were developed was generally as follows:

- For pasture, to ensure average annual pasture production loss due to soil moisture deficits was less than 0.5%.
- For crops, to maintain soil moisture above 50% of PAW for at least 90% of the time.

In preparing the guidelines, we have used and documented a range of assumptions. Under those assumptions, the guideline values will be suitable for most water users. There will be exceptions, and water users can provide site-specific information if they wish to do so and have that information assessed by ORC to see if different rates are justified.

The report builds on the existing 2006 Water Requirements Guidelines (Aqualinc, 2006)[1], and presents the approach and findings of the project to define peak daily, monthly and annual (seasonal) irrigation water requirements based on crop, climate and soil characteristics in the region.

2 SOIL-WATER BALANCE MODELLING

2.1 Modelling approach

A paddock-scale daily soil water balance modelling approach using historical climate data was used to calculate reasonable irrigation water requirements for crops. As recommended by Food and Agriculture Organization (FAO) of the United Nations, daily soil moisture water balance modelling is the internationally accepted method for calculating irrigation requirements (Allen *et al*., 1998)[2]. This method has been field-verified both internationally and in New Zealand, and has been shown to successfully model what occurs on-farm.

A description of soil water balance modelling is presented in Appendix A.

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[1] Aqualinc (2006). Water Requirements for irrigation throughout the Otago Region. A report prepared for Otago Regional Council by Aqualinc Research Ltd, Report No L05128/2, October 2006.

[2] Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). "Crop evapotranspiration: Guidelines for computing crop water requirements". FAO Irrigation and Drainage. Paper No. 56. Rome.

2.2 Climate time-period covered

Model simulations were run using historical daily climate data from 1 June 1972 to 31 May 2014, covering 42 irrigation seasons.

A list of the actual climate stations used for rainfall and evapotranspiration (ET) for the modelling is provided in Appendix B.

2.3 Irrigation management

Irrigation management information is given in Appendix C. The most common irrigation system that is used for irrigation of each crop type is modelled, which is described under different crop types in Section 5.

2.4 Irrigation application uniformity

One of the primary aims of irrigation is to apply irrigation water as uniformly as possible to increase the effectiveness of application. The uniformity of application varies considerably between systems and how they are configured (e.g. sprinkler type, number and size of nozzles, arrangement of sprinklers, working pressure). The variability of irrigation system application uniformity has been represented by Christiansen's uniformity coefficient (CU) (Christiansen, 1942)[3].

3 AREA CLASSIFICATION

The land area of the Otago region was divided into four main zones based on geographical distribution and climatic conditions, primarily evapotranspiration and temperature. This zonation enabled the use of more representative climate data for determining irrigation water requirements for different areas within the region. These four zones were further divided into rainfall sub-zones using mean annual rainfall (MAR), as irrigation demand is primarily dependent on rainfall.

Further description of the area classifications is presented in the following sections.

3.1 Area zonation

The Otago Region stretches from coastal areas to high country (i.e. high altitude). The climatic conditions also vary considerably, primarily due to the geographic and altitude variation. For this reason, the region was divided into four zones, as shown in Figure 1.

The four zones are:

1. Central and Lakes District;
2. Coastal and South Otago;
3. Maniototo;
4. North Otago.

[3] Christiansen J.E. (1942): Irrigation by Sprinkling. California Agriculture Experiment Station Bulletin, No. 670.

The climate data used for the study is described in Appendix B.

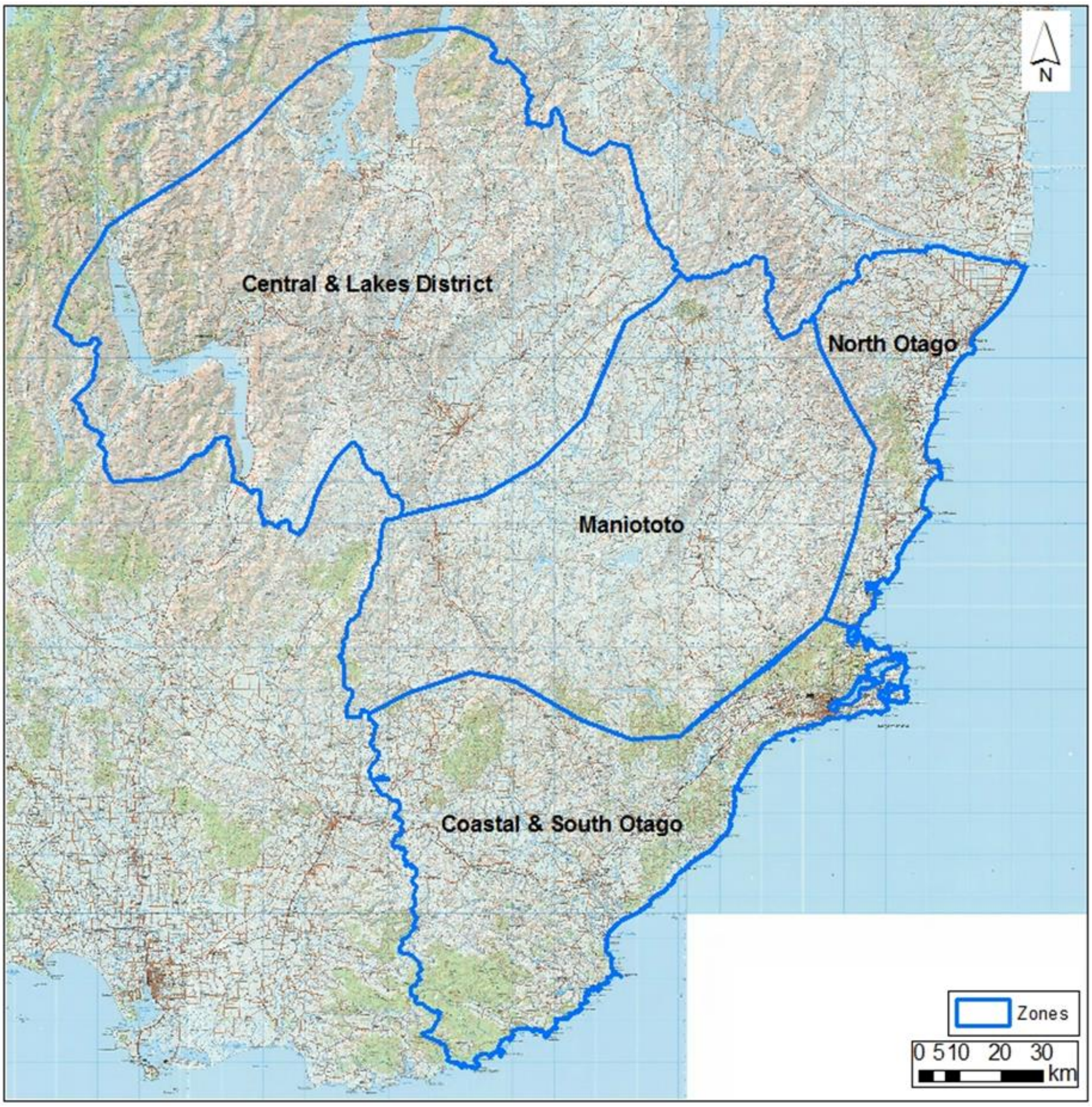

Figure 1: Geographical zones used for the study.

3.2 Sub-Zonation using Mean Annual Rainfall (MAR)

Mean annual rainfall (MAR) is highly variable within the region, as shown in Figure 2. The four zones (Section 3.1) were further divided into 11 climate classes based on MAR. These classes represent eleven 100 mm rainfall bands ranging from 300-400 to 1300-1400 mm/year.

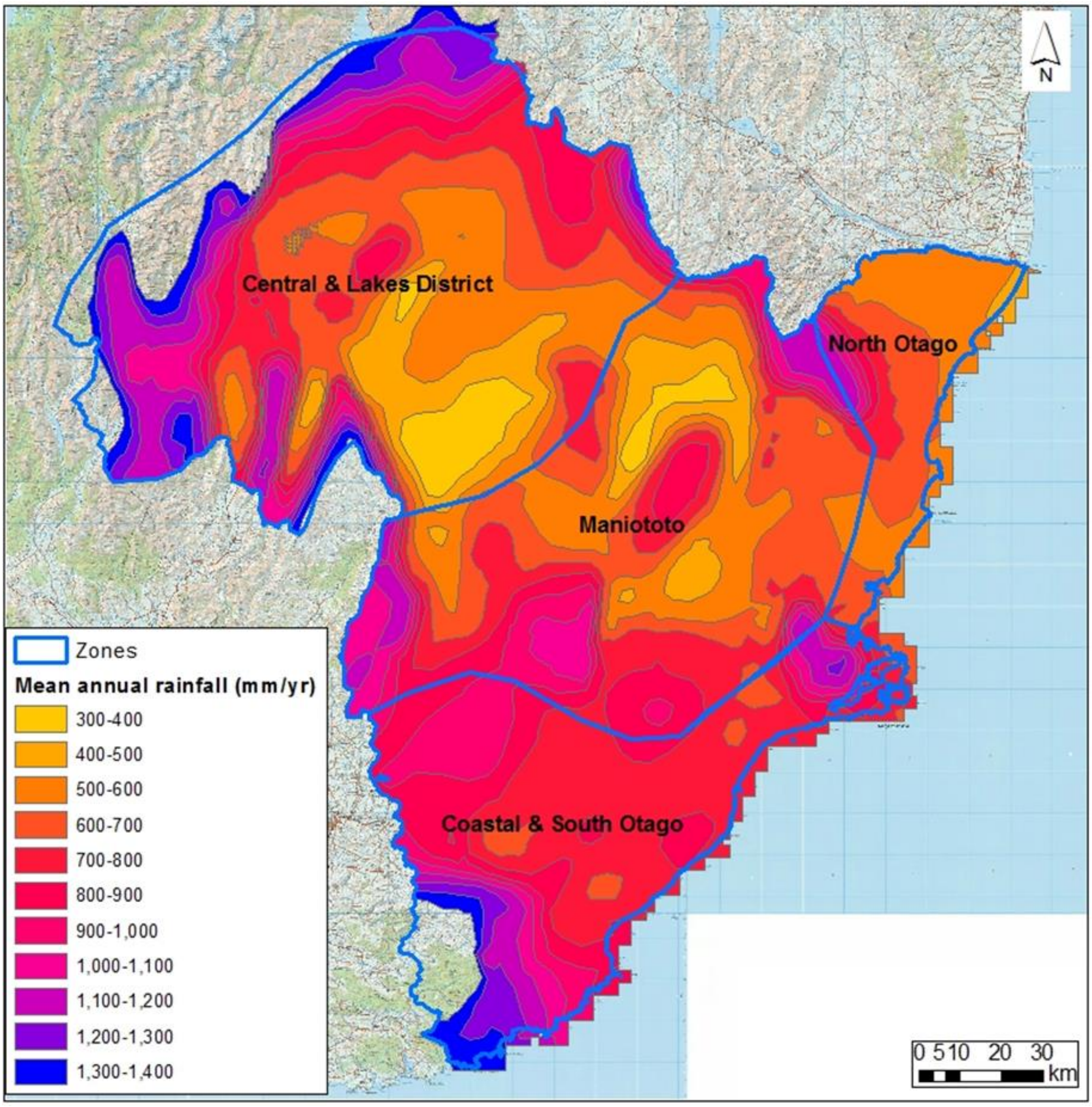

Figure 2: Distribution of mean annual rainfall (MAR) within the region

3.3 Irrigable Areas

The potential irrigable areas have been selected primarily based on MAR, land slopes and elevation. Based on the recent irrigation developments in the region, most irrigation activities in the future probably will occur on land slopes less than 15º. We recognise that some grapevines are currently planted on slopes exceeding 15º, but the area is likely to be small. In addition, it is unlikely that irrigation will be necessary or practical at elevations greater than 600 m amsl due to the cool climate and difficulty in accessing water at a viable cost at those heights, but again, they are not precluded.

The irrigation of land areas that receive mean annual rainfall of more than 1,200 mm/year (i.e. high rainfall areas) are unlikely to be economic to irrigate. Therefore, these areas were also excluded. The isolated land areas that may be too small in size to realistically develop for irrigation are also excluded.

In addition to the more readily irrigable areas, marginal irrigable areas have also been identified. The criteria used for selecting most likely irrigable and marginally irrigable areas is summarised in Table 1. The land areas that meet the criteria listed in Table 1 for irrigable areas and marginally irrigable areas are shown in Figure 3 and Figure 4 respectively.

Table 1 : Criteria for selecting irrigable and marginally irrigable areas

Parameter	Likely irrigable area	Marginally irrigable area
Mean annual rainfall	<1,200 mm	<1,400 mm
Slope	<15°	<20°
Elevation	<600 m amsl	<800 m amsl
Isolated areas	<500 ha excluded	<500 ha excluded

While small contiguous areas less than 500 ha have been excluded from the mapping of likely and marginal irrigable areas, the water requirement guidelines can be equally applied to small areas.

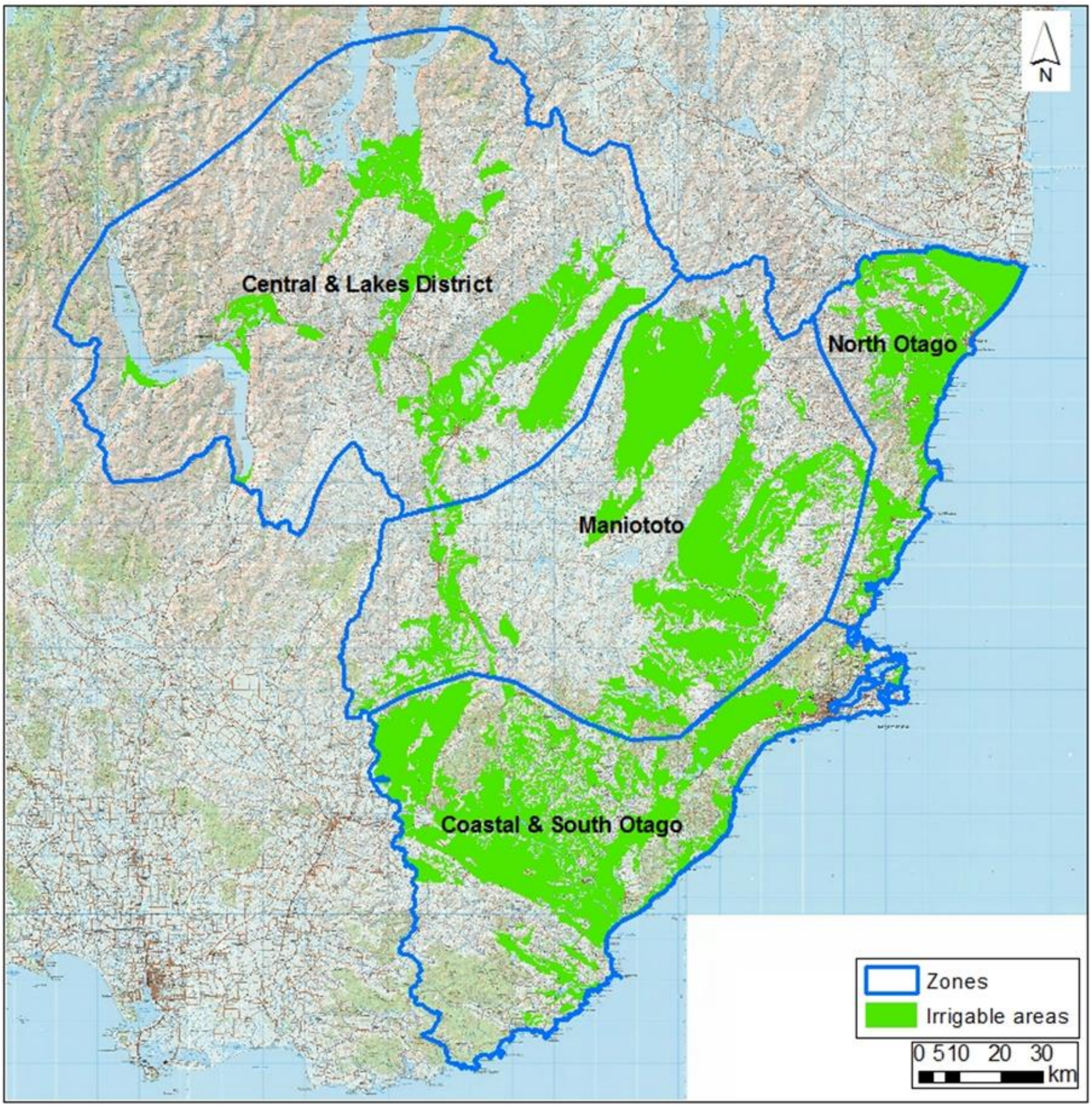

Figure 3: Likely irrigable areas

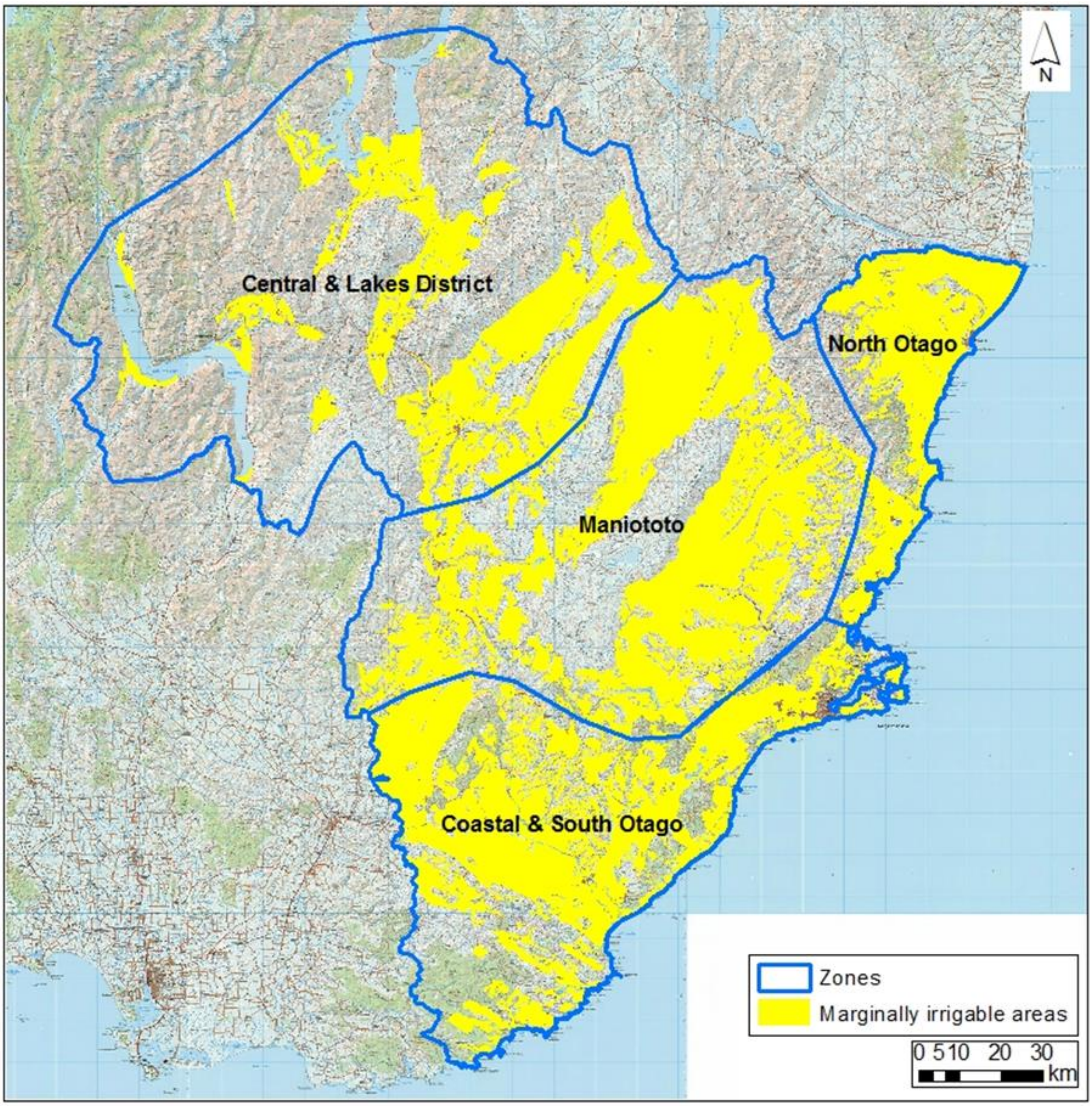

Figure 4: Likely irrigable areas and marginally irrigable areas combined

Based on the above analysis, the total irrigable areas (i.e. including marginally irrigable area) under each MAR band for the four zones were developed. The irrigable areas under each MAR band are shown in Figure 5.

The resulting land area by zone and MAR band is summarised in Table 2. However, to be pragmatic and minimise the number of combinations needed to be modelled to determine reasonable irrigation demands, the total areas that are relatively small (or can be approximated through another MAR band) were excluded from the final analysis. The combinations that were excluded are shown in 'blue' text in Table 2.

We recommend that the irrigation water demands for the excluded bands are allocated water using the values of the closest MAR band that is modelled for the zone. For example, the irrigation demand for the MAR 950 mm within 'Central & Lakes District' can be determined based on the values of the MAR 850 mm of the zone.

The selection process has resulted in a total of 21 combinations of MAR-Zone for soil-water balance modelling in the Otago region.

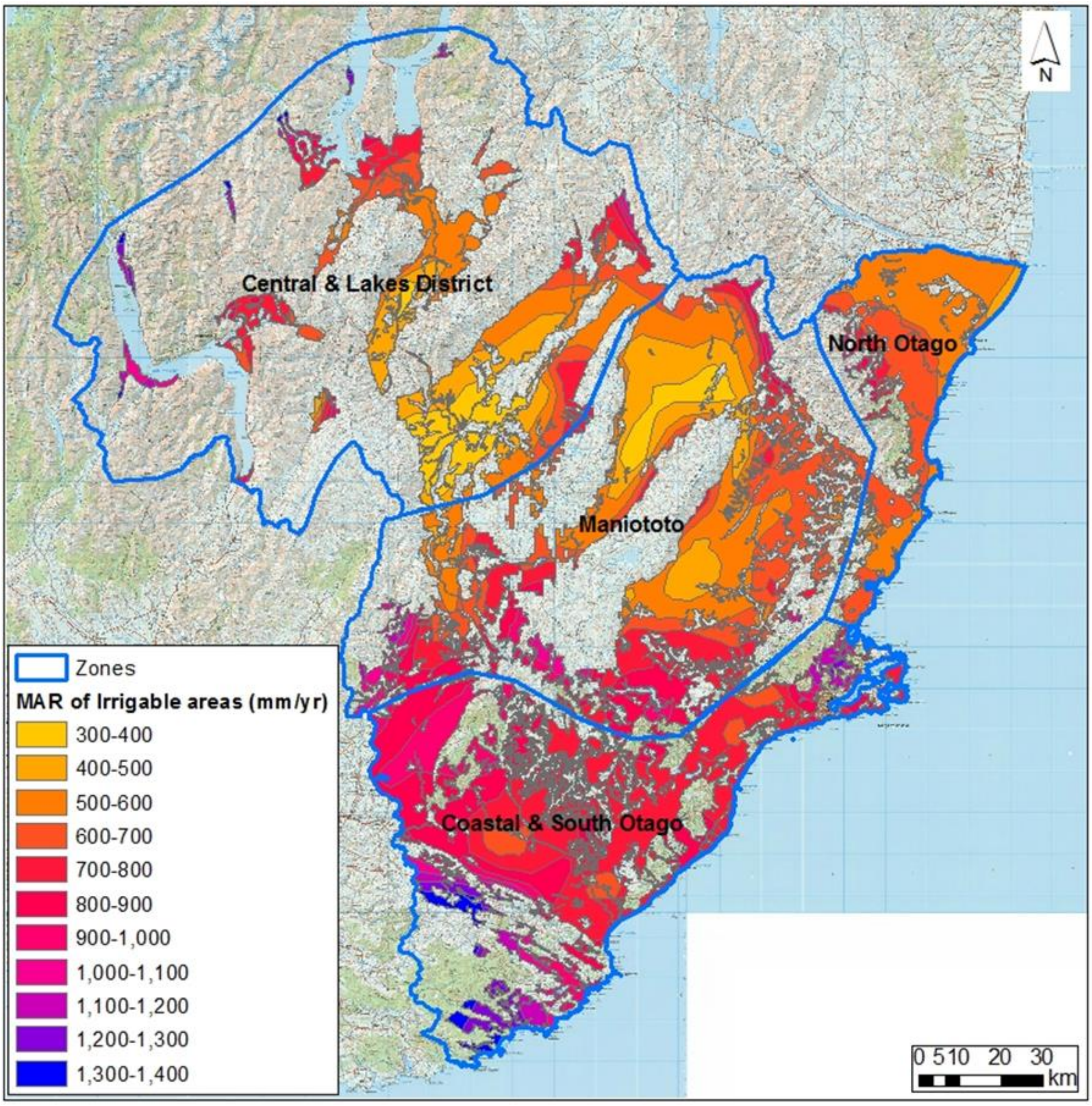

Figure 5: Distribution of MAR for Irrigable areas

Table 2: Irrigable area within each MAR band and zone (ha). Blue text values excluded from modelling.

Mean annual rainfall band (mm/yr)	Irrigable Area (ha)			
	Central & Lakes District	Coastal & South Otago	Maniototo	North Otago
350	32,562		18,560	
450	47,763		65,046	3,765
550	66,757		113,227	72,283
650	44,025	17,468	102,726	52,785
750	36,149	144,313	59,655	5,912
850	6,651	86,758	40,279	2,131
950	2,659	40,006	14,028	597
1,050	3,884	9,441	9,571	
1,150	3,225	13,042	2,599	
1,250	2,426	12,068		
1,350	1,232	8,045		

4 SOILS

The key soil property for irrigation is plant available water (PAW). PAW is the amount of water that a soil can store that is available for plants to use. By definition, soil PAW is the amount of water available to the plant (usually defined in millimetres depth) between the states of field capacity and permanent wilting point.

We have not specified soil types or provided soil maps for any location. We have specified up to six soil PAW classes for various crops. These were 40, 60, 90, 120, 150 and 200 mm.

Soils data to determine the relevant PAW classes for the study was mostly obtained from the S-map database (Landcare, 2014)[4]. PAW data is available for 30 cm, 60 cm and 1 m depths from the S-map database. Soil PAW varies considerably from location to location within the Otago region. The S-Map database shows that PAW for 1 m depth ranges from <10 mm to 450 mm, for different soils within the region.

Given the same soil, PAW differs between crops because different crops have different rooting depths and the ability to access water from different depths. Therefore, it is important to determine a representative soil-water reservoir depth for each crop type and estimate the PAW. The PAW classes used for different crops are listed in Appendix C. As S-map coverage is not available for all irrigable areas, another soils database/s such as the New Zealand Fundamental Soils Layer (FSL) (Landcare, 2000)[5] needs to be used to obtain soil information for the areas where the coverage is currently unavailable.

We have provided guidance on using S-Map and FSL soil information to obtain PAW values, but recognise that irrigators may have better site-specific data than either of those sources.

Irrigation water requirements were calculated for all PAW classes for each crop for a given location, except for vegetables in North Otago, where PAW was limited to 120 mm and 150 mm. Availability of irrigation water requirements for all PAW classes for irrigable areas allows ORC to extract water use

[4] Landcare (2014). https://smap.landcareresearch.co.nz/, produced by Landcare Research New Zealand Ltd.
[5] Landcare (2000). "New Zealand Land Resource Inventory version 2". GIS spatial data produced by Landcare Research New Zealand Ltd.

requirements from the Guidelines without the need for additional model runs if better soils information becomes available in the future.

We have also listed the minimum and maximum trigger levels that we have assumed for the soil water balance model.

For example, the minimum value for grapes is 67% of the PAW – for a 50 mm PAW soil, it would be 33.5 mm, or a 16.5 mm deficit.

The maximum we have used is 90%, which on a 50 mm soil would be a deficit of 5 mm. We leave a small gap to accommodate both rainfall storage and non-uniform application of water, which helps to minimise wastage (as per the policy objective in the Plan).

In practice, there is nothing to stop irrigators using different trigger and refill points to those we have assumed for modelling. Irrigators could choose to refill to 100% all of the time, but would be losing some water due to non-uniformity and would not be able to utilise as much rainfall. That could lead to exceeding annual demands in extreme years.

5 CROPS

Reasonable water requirements have been modelled for the most commonly irrigated crops in the region. These include pasture, viticulture, stonefruit (represented by cherries, apricots) and vegetables (represented by potatoes, cabbages). The following sub-sections outline the parameters used for each crop type.

5.1 Pasture

Pasture irrigation accounts for about 80% of all irrigation water use in the region (Aqualinc, 2010a)[6].

Irrigation is a major factor in increasing the reliability of pasture production, thus it has a high overall economic value for the region. It is important that the effect of peak water shortfalls on pasture production or on potential production loss is taken into account in determining reasonable water requirements for pasture. For that reason, the modelling criteria for determining reasonable irrigation demand was that peak daily water demand, which is deemed as reasonable, should not result in more than a 0.5% average annual pasture production decrease as compared to production under an unlimited water supply.

Generally, it is unrealistic and uneconomical to design an irrigation system to meet maximum daily demand. Farmers are usually prepared to take some risk of not meeting full demand for short periods. Therefore, using 0.5% average annual pasture production decrease, which is a small amount, may be conservative. However, Aqualinc considers that it is an appropriate level to use in developing irrigation guidelines for a region.

For the purpose of this study, pasture was assumed to have a constant crop coefficient (kc) of 0.95 throughout the year (reflecting grazed or harvested pasture), and a constant soil depth of 600 mm. Five PAW classes (for 600 mm depth) were modelled, as listed in Appendix C. The irrigation management parameters (e.g. irrigation triggers) are also given in Appendix C. A coefficient of uniformity (CU) of 70%, which is representative of typical spray irrigation systems, was used for pasture.

[6] Aqualinc (2010a). Update of water allocation data and estimate of actual water use of consented takes – 2009-10. A report prepared for Ministry for the Environment by Aqualinc Research Ltd, Report No H10002/3, October 2010.

The AusFarm simulation model, developed by CSIRO Australia, was used for pasture modelling. AusFarm has been field-verified both internationally (Moore et al., 2004)[7] and in New Zealand (Aqualinc, 2010b)[8]. AusFarm uses a number of climate parameters (rainfall, ET, temperature, solar radiation and vapour pressure) to estimate daily pasture production.

5.2 Viticulture

The irrigated area of grapes, compared to pasture, is relatively small in Otago (Aqualinc, 2010a)[6], but is of high value.

Viticulture requires less irrigation water than pasture (at a comparable location), because grapes have lower actual ET and tolerate higher soil moisture deficits than pasture.

A paddock-scale daily soil water balance model, Irricalc was used to calculate the irrigation requirements for grapes. The crop coefficient (kc) for grapes was assumed to gradually vary from 0.25 in winter to 0.7 in summer.

Note that FAO 56[9] Table 17 recommends a kc of 0.65 for wine grapes in areas with average wind speeds of 2 m/s and minimum relative humidity of 45%. Given that Central Otago probably tends to have lower relative humidity, the kc used for the modelling was increased to 0.7.

According to Williams (2001)[10], kc is approximately 0.017 x % shade area (measured beneath the vines at solar noon). A kc of 0.7 corresponds to a noon shaded area of about 40%.

Grapes are largely irrigated using drip irrigation systems that have higher application uniformity than spray systems. Therefore, a CU of 90% was used. Assuming a density of 2,500 vines per hectare and 8.8 litres/day/vine, a peak daily demand of 22,000 litres/day/hectare or 2.2 mm/day, was used.

The daily volume we recommend as required to meet the soil moisture criteria is 2.42 mm/day over the vineyard area. On a planting density of 2500 vines per hectare, that works out at 9.7 litres per plant per day. If planting density was 2200 vines per hectare, it would be 11 litres per plant per day.

We recommend a soil water reservoir of 900 mm be used for grapes because grapes generally have deep rooting systems. With a deeper soil water reservoir as compared to pasture, six soil PAW classes were modelled. These PAW classes along with the relevant irrigation parameters are given in Appendix C.

The irrigation criteria for determining the daily irrigation demand for grapes was that available soil moisture (ASM) should be retained above 40% of PAW for 90% of the time (based on an October-April irrigation season). Note that this criteria is applied to all of the days arising from all irrigation seasons over the years of climate record. It means that in some individual irrigation seasons, the 90% criteria will be violated, but in most seasons, it will be met or exceeded.

We have used 40% for grapes (which would be a deficit of 30 mm in a 50 mm PAW soil) as a check on the daily volumes to ensure that in extreme years, soil moisture does not get too low too often. In the Central and Lakes District, soil moisture could get marginally below 40% for 2% of the time, so easily exceeds the irrigation criteria. Soil moisture always remains well above permanent wilting point.

While FAO 56 suggests an increase in crop factor for higher average wind speed and lower relative humidity than the standard values used in Penman-Monteith, there are several factors that impact on actual ET and therefore allocation rates. Relative to our estimates, some parameters result in an increase in demand and others a decrease.

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[7] Moore, A.D., Salmon L. and Dove, H. (2004).The whole-farm impact of including dual-purpose winter wheat and forage brassica crops in a grazing system: a simulation analysis. New directions for a diverse planet: Handbook and Abstracts for the 4th International Crop Science Congress, Brisbane, Australia: 153.

[8] Aqualinc (2010b). Modelling the impact of water availability on dairy profitability. Aqualinc internal research report, July 2010.

[9] Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). “Crop evapotranspiration: Guidelines for computing crop water requirements”. FAO Irrigation and Drainage. Paper No. 56. Rome.

[10] Williams, Larry E. (2001). Irrigation of wine grapes in California. Department of Viticulture & Enology, University of California-Davis, and Kearney Agricultural Center.

As the intention of the guidelines is to provide guidance to both ORC and water users on reasonable rates, if specific site conditions differ from the assumptions we have used for the guidelines, water users can provide site-specific information to help to justify different rates, if appropriate.

The irrigation water requirements for viticulture do not include any water that may be required for frost protection.

5.3 Cherries and apricots

Water requirements for stonefruit can vary considerably depending on orchard type and management practices. Cherries and apricots are considered in these guidelines, and can be used to represent the range of water demands for stonefruit generally found in Otago. Aqualinc has undertaken consultation with relevant experts to obtain the crop and soil parameters required for soil water balance modelling for these crops. The parameter values used for determining irrigation requirements for mature orchards are given in Table 3.

Table 3: Irrigation parameters for cherries and apricots

Crop	Kc(1) (initial, mid, end)	Rooting depth (m)
Cherries	0.8, 1.12, 0.85	1.0
Apricots	0.8, 1.15, 0.85	1.0

(1) From Allen *et al*., 1998. (initial, mid, end) indicate how crop water use varies during the season.
'ini' = early in season, 'mid' = mid-season, 'end' = end of season.

Five soil PAW values, (60, 90, 120, 150 and 200 mm), and six climate scenarios (MAR of 350, 450, 550, 650, 750 & 850 mm) were considered for stonefruit water requirement modelling.

The irrigation criteria was that available soil moisture (ASM) should be retained above 50% of PAW for 90% of days, based on October to April irrigation seasons. Cherries and Apricots are largely irrigated by drip and micro-spray or occasionally fixed overhead sprinkler irrigation systems that have higher application uniformity than standard spray systems. Therefore, a CU of 80% was used.

For the five PAW classes, IrriCalc was run for different irrigation application depths to determine the irrigation system capacity (mm/d) that met the irrigation criteria.

A representative diagram showing the effect of two irrigation system capacities (5 mm/d and 5.5 mm/day) on soil moisture deficits over the irrigation season is shown in Figure 6. For this particular case, an irrigation system capacity of 5.4 mm/d would be required to maintain available soil moisture above 50% of PAW for 90% of days.

Cherries will require similar amounts of water as apricots, as they both have similar crop factors and root depths.

Note that irrigation water requirement estimates do not include any water that may be required for other uses such as frost protection.

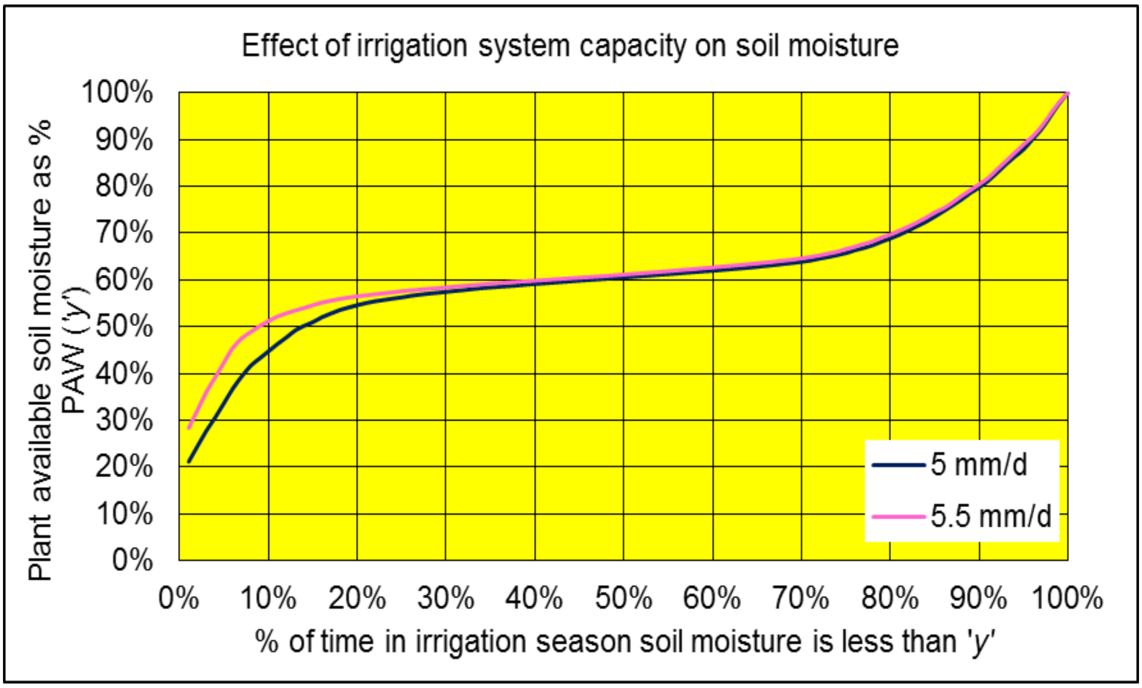

Figure 6: A representative diagram showing the effect of two irrigation system capacity rates on soil moisture over the irrigation season (October to April) for apricots

5.4 Vegetables

These guidelines have been developed for a crop rotation comprising potatoes and cabbages, as Aqualinc has been advised that these two crops are the dominant vegetables grown in the North Otago region.

Aqualinc has undertaken consultation with vegetable growers and relevant experts to obtain the crop and soil parameters required for the soil water balance modelling for these crops. In addition, Aqualinc also reviewed a number of national and international papers and reports to derive crop factors, irrigation targets and rooting depths required for different growth stages of potatoes and cabbages.

Vegetable rooting depths and irrigation water requirements vary depending on crop type and stage of development. Parameters used in the water balance modelling are presented in Appendix C.

Table 4: Vegetable crop rotations

Vegetable rotation	Crop	Planting	Harvesting
Scenario	Potato	14 August	15 January
	Cabbage	16 January	15 May

The daily soil water balance model, Irricalc was used to calculate the irrigation requirements.

The crop coefficient (kc) time series for vegetables were developed based on the crop coefficient values and crop development stages obtained from FAO 56 and in consultation with growers and industry experts.

The rooting depth of potatoes was assumed to grow gradually from 100 mm in the initial development stage to 500 mm by mid development stages, and remain the same until late season stage. Likewise, the rooting depth of cabbages was assumed to grow gradually from 75 mm in the initial development stage to 500 mm by the mid development stage, and remain the same until late season stage.

For water requirement calculations, a fixed rooting depth of 500 mm and soil PAW values of 120 and 150 mm were considered.

The model was run for three climate scenarios: MAR of 550, 650 & 750 mm.

Vegetables are largely irrigated using travelling gun irrigators, centre pivots, and aluminium hand shifts. The model was run using centre pivot irrigator parameters and a CU of 80% was used.

The irrigation criteria was that available soil moisture (ASM) should be retained above 60% of PAW for 90% of the time based on an August to May irrigation season. A representative diagram showing the effect of two irrigation system capacities (3 mm/d and 4 mm/d) on ASM over the irrigation season is shown in Figure 7. For this particular case, an irrigation system capacity of 4.1 mm/d would be an appropriate value to maintain ASM above 60% PAW for 90% of the time.

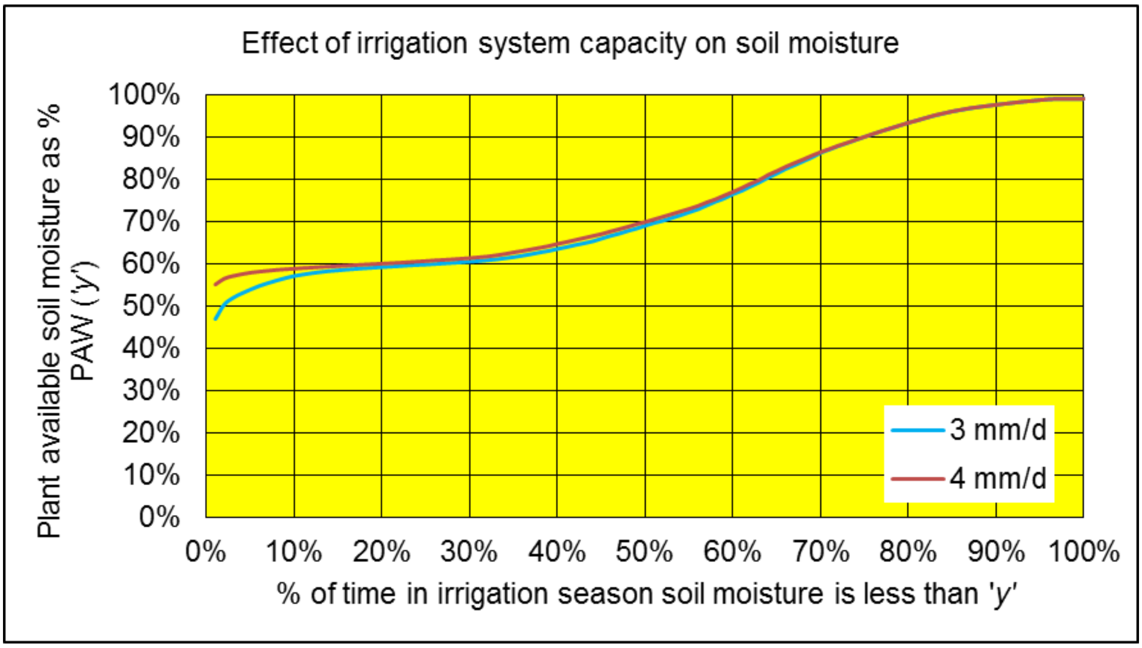

Figure 7: A representative diagram showing the effect of two irrigation application depths on soil moisture over the irrigation season (August to April) for potatoes & cabbages

A worked example on how to apply the guidelines to determine the resource consent allocation limits for vegetables is provided in Appendix E.

6 IRRIGATION DEMANDS

ORC and other users should use these values in combination with the map shown in Figure 5 (a digital copy of this map will be provided to ORC on request) to determine the relevant zone and MAR for specific locations to determine reasonable irrigation demands for that area. The relevant soil PAW for a farm can be obtained from S-map, the FSL database or a site specific soil investigation.

6.1 Pasture

A summary of reasonable irrigation water demands for pasture is given in Table 5.

As outlined in Section 5, reasonable irrigation demands have been estimated on the basis that the irrigation system capacities (i.e. peak daily demand) should not result in more than an approximately 0.5% average annual pasture production decrease. The annual (i.e. seasonal) demands are presented for average, 80th percentile (i.e. two-in-ten year drought), 90th percentile (one-in-ten year drought) and maximum situations. These values are calculated based on irrigation water requirements for the 1972-2014 irrigation seasons.

Table 5 : Irrigation water demand for pasture

Zone	MAR (mm/yr)	600 mm PAW (mm)	Peak daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)			
					Average	80%ile	90%ile	Maximum
Central & Lakes District	350	40	5.6	174	747	833	866	1,002
		60	5.2	161	734	806	866	988
		90	4.8	149	700	802	835	950
		120	4.4	136	659	752	792	911
		150	4.4	136	635	726	774	942
	450	40	5.5	171	685	787	820	919
		60	5.1	158	668	770	791	913
		90	4.8	149	628	748	773	883
		120	4.2	130	578	714	714	840
		150	3.9	121	547	659	710	796
	550	40	5.5	171	645	754	785	875
		60	5.1	158	629	729	769	877
		90	4.7	146	575	696	729	818
		120	4.2	130	525	660	672	777
		150	3.7	115	489	622	654	714
	650	40	5.4	167	579	673	724	821
		60	4.7	146	552	635	689	785
		90	4.7	146	508	619	649	771
		120	4.2	130	462	580	630	714

Zone	MAR (mm/yr)	600 mm PAW (mm)	Peak daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)			
					Average	80%ile	90%ile	Maximum
		150	3.5	109	427	539	588	679
	750	40	5.3	164	579	662	678	853
		60	4.6	143	552	625	644	810
		90	4.5	140	508	599	628	788
		120	4.2	130	460	546	588	756
		150	3.5	109	427	529	539	662
	850	40	5.2	161	504	597	624	697
		60	4.4	136	489	550	594	700
		90	4.0	124	432	512	544	640
		120	3.6	112	387	475	515	594
		150	3.3	102	358	446	446	558
Coastal & South Otago	650	40	3.4	105	370	448	485	541
		60	3.3	102	360	436	472	554
		90	3.3	102	325	386	475	535
		120	2.5	78	285	360	427	453
		150	2.0	62	249	306	349	400
	750	40	3.4	105	346	430	445	486
		60	3.3	102	340	416	455	475
		90	2.7	84	292	356	406	445
		120	2.4	74	257	326	369	408
		150	2.0	62	227	300	330	350
	850	40	3.4	105	321	394	408	513
		60	3.3	102	314	389	415	492
		90	2.7	84	265	333	386	462
		120	2.4	74	226	286	359	408
		150	1.8	56	151	202	251	284
	950	40	3.4	105	268	335	354	394
		60	3.3	102	260	316	337	396
		90	2.7	78	206	267	297	337
		120	2.0	62	166	240	240	318
		150	1.5	47	143	198	198	248
	1050	40	3.4	105	264	348	367	445
		60	2.8	87	246	331	350	409
		90	2.1	65	190	265	294	323
		120	2.0	62	170	240	264	320
		150	1.4	43	133	202	202	252
Maniototo	350	40	4.8	149	634	727	748	830
		60	4.4	136	629	722	741	832
		90	4.1	127	590	688	713	775

Zone	MAR (mm/yr)	600 mm PAW (mm)	Peak daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)			
					Average	80%ile	90%ile	Maximum
		120	3.6	112	550	660	707	749
		150	3.3	102	519	594	643	713
	450	40	4.7	146	562	658	686	771
		60	3.8	118	536	623	661	737
		90	3.6	112	494	605	634	691
		120	3.6	112	458	588	594	673
		150	3.0	93	420	560	561	615
	550	40	4.6	143	501	592	644	713
		60	3.7	115	470	568	610	662
		90	3.5	109	426	504	592	662
		120	3.4	105	388	490	567	639
		150	2.8	87	349	447	484	580
	650	40	4.5	140	459	561	603	684
		60	3.7	115	430	523	550	662
		90	3.4	105	392	490	520	643
		120	3.0	93	342	429	503	546
		150	2.6	81	313	395	445	504
	750	40	3.9	121	396	484	495	558
		60	3.3	102	369	451	475	551
		90	3.0	93	328	390	447	510
		120	2.6	81	281	351	390	455
		150	2.2	68	248	314	354	396
	850	40	3.6	112	339	414	432	515
		60	3.1	96	313	391	409	481
		90	2.8	87	263	339	370	431
		120	2.4	74	222	324	326	408
		150	2.0	62	193	293	300	338
	950	40	3.6	112	330	400	432	500
		60	3.0	93	309	374	399	480
		90	2.8	87	262	339	339	431
		120	2.4	74	214	286	319	370
		150	1.9	59	185	247	268	306
North Otago	550	40	4.1	127	484	586	603	685
		60	4.1	127	475	570	616	693
		90	3.8	118	433	540	564	665
		120	3.0	93	380	468	523	585
		150	2.7	84	357	462	480	553
	650	40	3.9	121	450	542	558	604
		60	3.3	102	430	514	531	611

Zone	MAR (mm/yr)	600 mm PAW (mm)	Peak daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)			
					Average	80%ile	90%ile	Maximum
		90	2.9	90	385	466	493	551
		120	2.8	90	348	447	485	510
		150	2.7	84	324	410	460	494
	750	40	3.9	121	398	492	511	558
		60	3.0	93	373	459	499	543
		90	2.9	90	331	430	464	493
		120	2.8	87	282	392	431	470
		150	2.2	68	257	354	375	405

6.2 Viticulture

Table 6 lists the daily, monthly and seasonal irrigation water demands for grapes. These demands include a 10% system loss that occurs between water take (e.g. pump) and soil surface, which is considered to be reasonable for a well-managed irrigation system. This system loss may include evaporative losses from bare soil or uneven soil characteristics for example.

We recommend an allocation of 2.42 mm/d daily irrigation demand (i.e. 2.2 mm/d irrigation demand plus 10% loss) for grapes.

The mm/d daily demand figures should be applied to the total planted area of the vineyard, including the inter-row area, regardless of planting density.

Assuming that water is applied to the vines using drip irrigation at a planting density of 2500 vines per hectare, the 2.2 mm/d corresponds to 8.8 litres/vine/day.

The demand figures do not allow for irrigation of and uptake of water by the inter-row. If the inter-row is to be irrigated, or the inter-row is likely to be removing significant amounts of water that would have otherwise been available to the vines, additional water could be required.

Table 6 (last column) shows that the available soil moisture (ASM) meets or exceeds the irrigation criteria of exceeding 40% PAW for 90% of the time in the irrigation season (September to April).

Table 6: Irrigation water demand for grapes

Zone	MAR (mm/yr)	900 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)				%ASM> 40%PAW
					Average	80%ile	90%ile	Maximum	
Central & Lakes District	350	40	2.42	75	201	232	258	329	98
		60	2.42	75	188	219	248	332	100
		90	2.42	75	171	201	234	322	100
		120	2.42	77	159	193	222	310	100
		150	2.42	77	147	179	212	300	100
		200	2.42	77	136	173	203	290	100

Zone	MAR (mm/yr)	900 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)				%ASM> 40%PAW
					Average	80%ile	90%ile	Maximum	
	450	40	2.42	75	173	217	239	293	99
		60	2.42	75	157	205	229	281	99
		90	2.42	75	136	182	217	259	100
		120	2.42	77	122	163	203	247	100
		150	2.42	77	110	144	193	237	100
		200	2.42	77	98	131	183	227	100
	550	40	2.42	73	156	196	208	247	99
		60	2.42	75	137	180	198	235	100
		90	2.42	73	112	156	176	208	100
		120	2.42	73	97	140	164	198	100
		150	2.42	73	83	130	150	189	100
		200	2.42	73	72	120	140	174	100
	650	40	2.42	73	125	162	174	215	99
		60	2.42	73	106	146	162	203	100
		90	2.42	73	81	121	144	184	100
		120	2.42	73	67	102	135	165	100
		150	2.42	73	55	89	125	145	100
		200	2.42	73	44	76	110	136	100
	750	40	2.42	73	129	157	169	225	99
		60	2.42	73	109	141	159	213	100
		90	2.42	75	84	113	140	198	100
		120	2.42	73	69	105	130	189	100
		150	2.42	73	57	91	116	179	100
		200	2.42	68	46	81	106	165	100
	850	40	2.42	70	98	126	133	157	100
		60	2.42	70	79	111	123	143	100
		90	2.42	70	56	91	108	116	100
		120	2.42	63	44	73	91	106	100
		150	2.42	58	34	61	77	97	100
		200	2.42	48	25	46	67	87	100
Coastal & South Otago	650	40	2.42	61	56	75	84	109	100
		60	2.42	53	43	64	77	99	100
		90	2.42	44	28	48	60	85	100
		120	2.42	39	19	39	44	77	100
		150	2.42	34	12	24	34	63	100
		200	2.42	34	7	14	24	53	100
	750	40	2.42	58	52	74	80	106	100
		60	2.42	56	38	56	63	94	100
		90	2.42	46	22	41	46	73	100

Zone	MAR (mm/yr)	900 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)				%ASM> 40%PAW
					Average	80%ile	90%ile	Maximum	
		120	2.42	34	14	29	34	53	100
		150	2.42	34	8	19	24	39	100
		200	2.42	24	4	10	15	24	100
	850	40	2.42	53	46	65	80	111	100
		60	2.42	53	33	48	67	97	100
		90	2.42	56	18	36	52	77	100
		120	2.42	48	12	28	33	58	100
		150	2.42	39	7	15	19	48	100
		200	2.42	29	4	5	10	39	100
	950	40	2.42	56	33	44	57	82	100
		60	2.42	48	21	31	43	63	100
		90	2.42	39	9	15	24	53	100
		120	2.42	29	5	5	15	44	100
		150	2.42	19	2	0	5	34	100
		200	2.42	10	1	0	0	19	100
	1050	40	2.42	56	31	48	60	97	100
		60	2.42	53	21	38	48	85	100
		90	2.42	41	11	24	36	61	100
		120	2.42	34	7	15	29	48	100
		150	2.42	29	4	4	18	39	100
		200	2.42	24	2	0	4	24	100
Maniototo	350	40	2.42	75	165	194	208	259	100
		60	2.42	75	151	185	196	254	100
		90	2.42	75	133	164	184	247	100
		120	2.42	77	121	155	174	237	100
		150	2.42	73	110	144	165	227	100
		200	2.42	77	99	135	160	213	100
	450	40	2.42	75	127	157	188	225	100
		60	2.42	75	111	145	174	213	100
		90	2.42	75	90	125	153	196	100
		120	2.42	73	77	116	139	189	100
		150	2.42	77	66	102	129	174	100
		200	2.42	77	55	92	115	165	100
	550	40	2.42	70	109	141	159	203	100
		60	2.42	70	92	129	147	186	100
		90	2.42	70	70	102	128	167	100
		120	2.42	73	58	91	111	155	100
		150	2.42	68	47	80	101	145	100
		200	2.42	73	37	67	87	136	100

Zone	MAR (mm/yr)	900 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)				%ASM> 40%PAW
					Average	80%ile	90%ile	Maximum	
	650	40	2.42	70	87	111	125	174	100
		60	2.42	68	70	94	111	162	100
		90	2.42	63	49	75	91	140	100
		120	2.42	63	38	67	77	131	100
		150	2.42	58	27	48	62	121	100
		200	2.42	53	19	39	53	106	100
	750	40	2.42	73	64	84	94	123	100
		60	2.42	70	48	63	77	104	100
		90	2.42	61	30	45	53	85	100
		120	2.42	53	20	38	44	68	100
		150	2.42	39	11	24	33	58	100
		200	2.42	29	6	15	19	44	100
	850	40	2.42	73	56	75	77	111	100
		60	2.42	70	42	56	68	102	100
		90	2.42	61	25	41	53	77	100
		120	2.42	48	15	29	38	63	100
		150	2.42	39	9	18	29	48	100
		200	2.42	29	4	9	19	39	100
	950	40	2.42	73	50	65	70	109	100
		60	2.42	70	36	48	53	99	100
		90	2.42	58	18	29	38	75	100
		120	2.42	48	10	18	29	63	100
		150	2.42	39	5	10	19	48	100
		200	2.42	29	2	0	5	39	100
North Otago	550	40	2.42	61	93	130	138	155	100
		60	2.42	61	77	116	123	143	100
		90	2.42	63	58	101	108	131	100
		120	2.42	63	47	91	92	121	100
		150	2.42	63	38	81	82	111	100
		200	2.42	53	30	68	73	97	100
	650	40	2.42	61	80	108	118	131	100
		60	2.42	61	63	91	99	123	100
		90	2.42	61	45	72	86	114	100
		120	2.42	63	34	62	77	102	100
		150	2.42	58	24	46	62	92	100
		200	2.42	48	17	37	53	82	100
	750	40	2.42	53	62	87	102	123	100
		60	2.42	56	47	70	87	116	100
		90	2.42	53	30	52	67	106	100

Zone	MAR (mm/yr)	900 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)				%ASM> 40%PAW
					Average	80%ile	90%ile	Maximum	
		120	2.42	53	21	39	57	97	100
		150	2.42	44	14	24	47	87	100
		200	2.42	39	9	15	33	73	100
Note: Daily demand includes 10% irrigation system losses. Monthly and annual demand also includes this system loss. Modelled minimum return interval is 1 day for PAW's up to 90 mm, and 2 days for PAW> 90 mm.									

6.3 Cherries and apricots

A summary of reasonable irrigation water demands for apricots and cherries is given in Table 7. These have been estimated on the basis that the system capacities (i.e. peak daily demand) should maintain available soil moisture (ASM) above 50% PAW in 90% of the time based on October to April irrigation seasons.

These demands include a 5% system loss that occurs between the water take (e.g. pump) and soil surface, which is considered to be reasonable for a well-managed irrigation system. The annual (i.e. seasonal) demands are presented for average, 80th percentile (i.e. two-in-ten drought year), 90th percentile (one-in-ten drought year) and maximum. These values are calculated based on irrigation water requirements for the 1972-2014 irrigation seasons.

Table 7: Irrigation water demand for apricots and cherries

Zone	MAR (mm/yr)	1000 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr)				%SAM>50%PAW
					Average	80% ile	90% ile	Maximum	
Central & Lakes District	350	200	4.9	152	582	664	736	834	90
		150	5.0	155	602	693	751	851	90
		120	5.2	161	619	704	765	868	90
		90	5.4	167	627	703	768	873	89
		60	5.7	177	655	728	786	898	88
	450	200	4.7	146	511	622	680	785	90
		150	4.9	152	536	633	707	803	90
		120	5.0	155	553	646	707	819	90
		90	5.3	164	567	668	724	824	89
		60	5.6	174	605	682	750	847	87
	550	200	4.5	140	466	581	648	737	90
		150	4.8	149	494	602	676	756	89
		120	4.9	152	513	614	675	772	88
		90	5.2	161	533	631	693	786	88
		60	5.5	171	576	656	702	809	86
	650	200	4.4	136	414	538	582	707	90

		150	4.7	146	441	548	606	725	90
		120	4.8	149	464	559	605	726	90
		90	5.1	158	484	576	630	739	87
		60	5.4	167	530	631	656	760	87
	750	200	4.3	133	421	515	566	718	90
		150	4.6	143	450	536	591	754	88
		120	4.7	146	467	548	591	755	88
		90	5.0	155	489	578	607	777	87
		60	5.3	164	536	610	634	801	86
	850	200	4.2	130	360	476	503	609	90
		150	4.4	136	387	499	513	624	90
		120	4.6	143	412	507	536	652	90
		90	4.9	152	431	515	544	669	88
		60	5.1	158	474	555	589	685	88

Note: Daily demand includes a 5% irrigation system loss. Monthly and annual demand also includes this system loss. Modelled minimum return interval is 3 days for PAW 200, 150 & 120 mm and 2 days for PAW 90 & 60 mm.

6.4 Vegetables (potatoes and cabbages)

Since potatoes and cabbages are the dominant vegetable crops grown in the North Otago region, only one vegetable rotation scenario was modelled. Table 8 lists the daily, monthly and seasonal irrigation water demands for potatoes and cabbages.

These demands include a 5% system loss, that occurs between the water take (e.g. pump) and soil surface, which is considered to be reasonable for a well-managed irrigation system. This system loss may include evaporative losses from bare soil, delivery system losses or uneven soil characteristics for example. The daily demand values shown in Table 8 will maintain available soil moisture (ASM) within the soil water reservoir above 60% PAW for 90% of the time in the irrigation season (August to May).

Table 8: Irrigation water demand for vegetables

Zone	MAR (mm/yr)	500 mm PAW (mm)	Daily demand (mm/d)	Maximum monthly demand (mm/month)	Annual demand (mm/yr) Average	80% ile	90% ile	Maximum	%SAM > 60%PAW
North Otago	550	150	3.7	115	256	361	395	431	90
		120	4.0	124	273	376	402	441	95
	650	150	3.6	112	226	327	340	374	91
		120	3.9	121	244	342	356	393	96
	750	150	3.5	109	172	273	287	342	92
		120	3.8	118	193	602	676	359	97

Note: Daily demand includes 5% irrigation system losses. Monthly and annual demand also includes this system loss. Modelled minimum return interval is 3 day for both PAW's 120 and 150 mm.

7 REFERENCES

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Appendix A: Water balance models

The water balance models used for this study use the approach developed by the Food and Agriculture Organization (FAO) of the United Nations (Allen *et al*. (1998)).

The relationship between crop and reference evapotranspiration is:

$$\textit{Crop evapotranspiration} = k_s \times k_c \times \textit{Reference evapotranspiration} \qquad \text{Eqn 1}$$

where k_s is the water stress reduction factor and k_c is the crop coefficient.

The water stress reduction factor is a function of the current soil moisture status. As recommended by Allen *et al*. (1998), it was assumed that k_s equalled 1.0 when the soil water content was equal to the plant readily available water, and k_s reduced linearly down to a value of zero at wilting point. Readily available water was assumed to be equal to 50% of the plant available water at field capacity (PAW). Crop coefficients are given in Appendix C.

For each day the soil moisture is calculated from:

$$ASM_{day\ i} = ASM_{day\ i-1} + (\textit{rain} + \textit{effective irrigation} - \textit{crop evapotranspiration})_{day\ I} \qquad \text{Eqn 2}$$

where ASM = plant available soil moisture.

Effective irrigation is the irrigation water that is applied and retained within the root zone. Effective irrigation was calculated using the total depth of irrigation water and application uniformity of CU (Christiansen, 1942). The model assumes the maximum water the soil can hold is the PAW value; any rain in excess of that required to reach field capacity was assumed to drain below the root zone. In other words the maximum value of ASM for any given day is the PAW.

Modelling assumed that the soils were free draining, and the depth to groundwater was greater than crop rooting depths. Where soil pans exist, or where groundwater is close to the surface, water requirements may be less than recommended in this report[11].

Modelling assumed that water was available on a continuous basis, without restrictions. Where irrigators are subject to frequent restrictions, daily water requirements may be greater than recommended in this report. This is because, when the water source is considered unreliable, the irrigation systems ideally should have additional capacity to be able to 'catch up' with the crop water requirements, following periods when flow was restricted.

[11] This is because after high rainfall events the soil water content in the assumed reservoir is greater than field capacity due to the limited drainage conditions, which limits crop growth and water uptake. Additionally, water can move upward from groundwater via capillarity to meet plant water demand in areas with high water tables.

Appendix B: Climate data

This Appendix summarises the climate data used for this study.

B.1 Rainfall

In preparing rainfall data for each rain band (i.e. MAR) within each climate zone (Central and Lake District, Maniototo, North Otago, and Coastal and South Otago), a station/s within the rain band was used, and gaps were filled by correlating data from a station/s in the same band. However, close-by stations were used, if no representative stations within the same rain band were available. A summary of stations used is given in Table B.1. The first station under each rain band was primarily used, and the other listed stations were used either to fill gaps or extend data where required.

Table B.1: Climate stations use for developing rainfall time series

Zone	MAR (mm/yr)	Stations used
Central & Lakes District	350	Alexandra 1, Alexandra, Theyers St, Alexandra and Ophir 2
	450	Ophir 3 and Moa Creek
	550	Matakanui
	650	Blackstone Hill and Wanaka Aero Aws
	750	Hawea Flat
	850	Kingston
Coastal & South Otago	650	Baverstock Waiwera
	750	Inchclutha,T'Graph Rd
	850	Southern Reservoir
	950	Tapanui
	1050	Ross Creek and Dunedin, Leith Valley
Maniototo	350	Waipiata, Middlemarch (Garthmyl) and Ranfurly Ews
	450	Middlemarch (Garthmyl), Middlemarch Ews and Ranfurly
	550	Wedderburn and Naseby Forest 2
	650	Deep Stream 2
	750	Lee Flat
	850	Wilden No 1 and Lee Flat
	950	Mahinerangi Dam, Wilden No 1 and Lee Flat
North Otago	550	Centrewood, Enfield and Oamaru Airport Aws
	650	Palmerston
	750	Kauru, The Dasher

B.2 Evapotranspiration

The climate stations used for the development of the evapotranspiration (ET) time series for climate zones are listed in Table B.2. After analysing the data for completeness, four time series were developed for each zone. ET was calculated using the Penman-Monteith method.

The stations used for developing ET data for each zone are as follows:

1. Central and Lakes District: Lauder Ews correlated with Tara Hills Aws, and gaps filled using Dunedin Aero Aws and Omarama,Tara Hills.
2. Coastal and South Otago: Dunedin Aero Aws correlated with Invermay Edr and Dunedin Aero.
3. Maniototo: Ranfurly Ews correlated with Tara Hills Aws Ranfurly Maniototo, and gaps filled using Dunedin Aero Aws and Omarama,Tara Hills.
4. North Otago: Windsor Ews correlated with Dunedin Aero Aws.

Table B.2: Climate stations considered for evapotranspiration data

Agent	Percent available	Name	Lat	Long	Start	End	Length	Status
7339	100	Dunedin Aero Aws	-45.929	170.197	24/11/1991	3/08/2013	22	Open
5397	100	Dunedin Aero	-45.929	170.196	1/01/1972	30/11/1991	19	Open
5212	90	Tara Hills Aws	-44.528	169.89	1/05/1985	3/08/2013	28	Open
5211	100	"Omarama,Tara Hills"	-44.529	169.888	1/01/1972	31/10/1985	13	Closed
39564	100	Clyde 2 Ews	-45.2034	169.3182	26/05/2011	4/08/2013	2	Open
12431	100	Clyde Ews	-45.2072	169.3148	16/06/1996	11/10/2012	16	Closed
5577	90	"Clyde, Earnscleugh"	-45.207	169.313	7/09/1983	30/05/1996	13	Closed
15752	100	"Dunedin, Musselburgh Ews"	-45.9013	170.5147	9/08/1997	4/08/2013	16	Open
5402	80	"Dunedin,Musselburgh"	-45.904	170.513	1/07/1981	29/11/1991	10	Closed
5365	90	Invermay Edr	-45.862	170.385	27/06/1985	16/10/1994	9	Closed
5364	90	"Invermay, Taieri 2"	-45.862	170.385	12/01/1979	27/06/1985	6	Closed
5778	90	Gore Aws	-46.115	168.887	13/07/1986	3/08/2013	27	Open
5780	100	"Gore,Grasslands D.S.I.R."	-46.115	168.892	1/01/1972	31/10/1986	14	Closed
26381	100	Cromwell Ews	-45.0339	169.1955	7/04/2006	4/08/2013	7	Open
5526	100	Cromwell M.W.D.	-45.035	169.195	1/11/1984	31/12/1984	0	Closed
36592	100	Alexandra Cws	-45.2537	169.3921	19/11/2008	4/08/2013	5	Open
5576	100	Alexandra 1	-45.258	169.389	1/01/1972	27/01/1983	11	Closed
18594	100	Windsor Ews	-45.0083	170.8228	24/11/2000	31/07/2013	13	Open
25937	90	Oamaru Aws	-45.1	170.95	23/09/2005	2/08/2013	8	Open
18593	100	Ranfurly Ews	-45.1243	170.1005	23/11/2000	4/08/2013	13	Open
5323	100	Palmerston	-45.4755	170.7144	12/07/1986	30/06/2013	27	Open
5535	90	Lauder Ews	-45.0401	169.6842	1/09/1985	4/08/2013	28	Open
18437	100	Middlemarch Ews	-45.5181	170.1356	31/08/2000	4/08/2013	13	Open
5451	100	Queenstown Aero Aws	-45.024	168.737	28/10/1991	3/08/2013	22	Open

5645	100	Ettrick No.2	-45.623	169.348	1/04/1985	30/04/1985	0	Open
5867	80	"Balclutha, Finegand"	-46.273	169.739	1/01/1975	12/08/2004	29	Open
26163	100	"Balclutha, Telford Ews"	-46.2928	169.7315	16/12/2005	4/08/2013	8	Open
38645	100	Riversdale Aquifer @ York Road	-45.9036	168.7387	19/02/2011	31/07/2013	2	Open
5122	50	Kurow Area School	-44.733	170.467	1/12/1986	31/08/1987	1	Closed
5280	80	Ranfurly Maniototo	-45.126	170.098	1/04/1975	30/09/1988	13	Closed
5277	60	Gimmerburn Edl	-45.187	170.049	10/09/1982	31/01/1986	4	Closed
5549	80	Poolburn Edl	-45.133	169.716	1/05/1984	31/01/1986	2	Closed
5611	40	Stony Creek	-45.302	169.906	10/09/1982	31/05/1984	2	Closed

B.3 Other climate data

The climate stations used to obtain radiation, temperature (minimum and maximum) and vapour pressure are listed in Table B.3 to B.5. The vapour pressure was derived from dew point temperature using the following formula (Allen et al., 1998):

Vapour pressure = 0.6108*EXP(17.27*Dew Point Temperature/(Dew Point Temperature +237.3))*10

Table B.3: Climate stations that have been used for developing radiation time series

Zone	Stations used
Central & Lakes District	Queenstown Aero Aws
	Alexandra 1
	Clyde, Earnscleugh
Coastal & South Otago	Dunedin Aero
	Dunedin Aero Aws
	Gore Aws
Maniototo	Ranfurly Maniototo
	Middlemarch Ews
	Lauder Ews
North Otago	Oamaru Aws
	Windsor Ews

Table B.4: Climate stations that have been used for developing temperature time series

Zone	Stations used
Central & Lakes District	Cromwell M.W.D.
	Cromwell Sub Stn
	Cromwell 2
	Cromwell Ews
Coastal & South Otago	Dunedin Aero
	Dunedin Aero Aws
	Balclutha,Finegand
Maniototo	Ranfurly Maniototo
	Ranfurly Ews
	Output of Dunedin Aero (Coastal South)

North Otago	Palmerston

Table B.5: Climate stations use for developing dew point temperature time series

Zone	Stations used
Central & Lakes District	Cromwell M.W.D.
	Cromwell Sub Stn
	Cromwell 2
	Cromwell Ews
Coastal & South Otago	Dunedin Aero
	Dunedin Aero Aws
Maniototo	Ranfurly Maniototo
	Ranfurly Ews
	Output of Dunedin Aero (Coastal South)
North Otago	Palmerston

Appendix C: Soil PAW classes and irrigation management parameters

The PAW classes and irrigation management parameters used for soil water balance modelling of pasture are listed in Table C.1.

Table C.1: PAW classes and irrigation management parameters used for soil water balance modelling of pasture

PAW class for 600 mm depth (mm)	PAW range for 600 mm depth (mm)	Irrigation trigger as a % of PAW
40	20-50	63%
60	51-75	67%
90	76-105	61%
120	106-125	58%
150	>126	60%

The PAW classes and irrigation management parameters used for soil water balance modelling of grapes are listed in Table C.2.

Table C.2: PAW classes and irrigation management parameters used for soil water balance modelling of grapes

PAW class for 600 mm depth (mm)	PAW range for 600 mm depth (mm)	Irrigation trigger as a % of PAW
40	20-50	63%
60	51-80	67%
90	81-105	67%
120	106-135	67%
150	136-175	67%
200	>176	70%

The PAW classes and irrigation management parameters used for soil water balance modelling of stonefruit are listed in Table C.3.

Table C.3: PAW classes and irrigation management parameters used for soil water balance modelling of cherries and apricots

PAW class for 600 mm depth (mm)	Irrigation trigger as a % of PAW
60	50%
90	50%
120	50%
150	50%
200	50%

The PAW classes and irrigation management parameters used for soil water balance modelling of vegetables are listed in Table C.4.

Table C.4: PAW classes and irrigation management parameters used for soil water balance modelling of potatoes and cabbages

PAW class for 600 mm depth (mm)	Irrigation trigger as a % of PAW
120	60%
150	60%

Crop coefficients and rooting depths, with corresponding PAW values for vegetables are given in Tables C.5 and C.6 and illustrated in Figures C.1, C.2 and C.3.

Table C.5: Vegetable rotation crop coefficient series

Days since planting	Crop	Date	Crop coefficient (k_c)
0	Potato	14-Aug	0.5
30	Potato	12-Sep	0.5
70	Potato	22-Oct	1.15
125	Potato	16-Dec	1.15
155	Potato	15-Jan	0.7
181	Cabbage	9-Feb	0.7
226	Cabbage	26-Mar	1.05
266	Cabbage	5-May	1.05
276	Cabbage	15-May	0.95
277	Fallow	16-May	0
366	Fallow	13-Aug	0

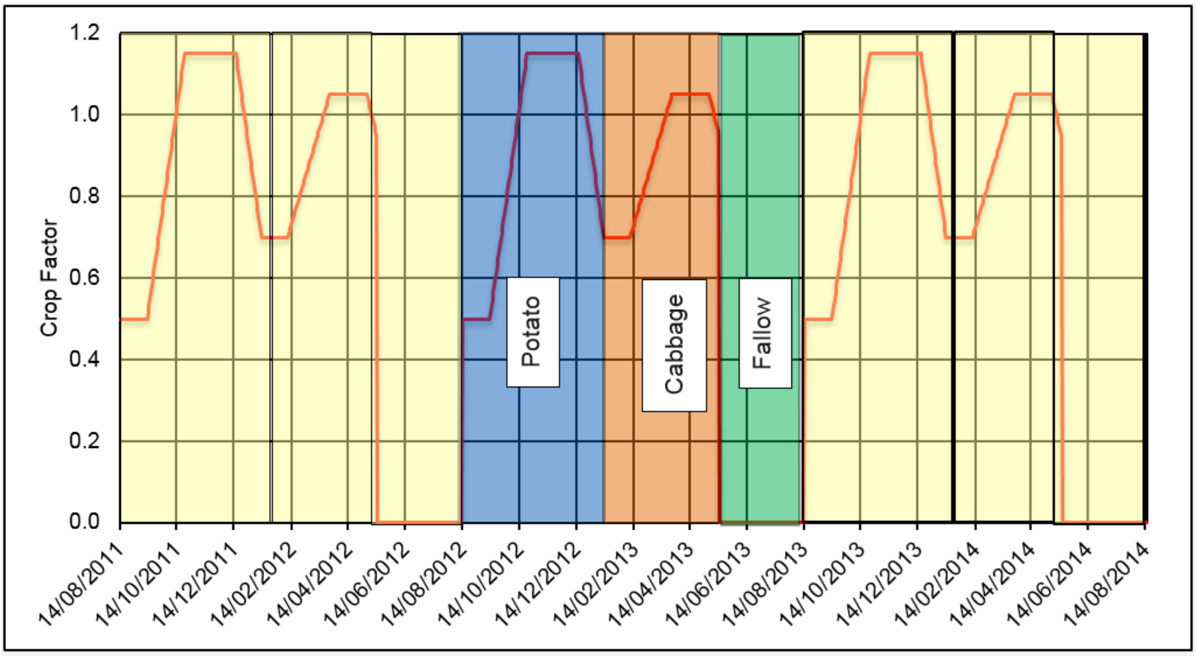

Figure C.1: Vegetable rotation crop coefficient series

Table C.6: Vegetable rotation crop rooting depth and corresponding PAW

Days since planting	Crop	Date	Rooting depth (mm)
0	Potato	14-Aug	100
156	Potato	15-Jan	500
157	Cabbage	16-Jan	75
276	Cabbage	15-May	500
277	Fallow	16-May	75
366	Fallow	13-Aug	75

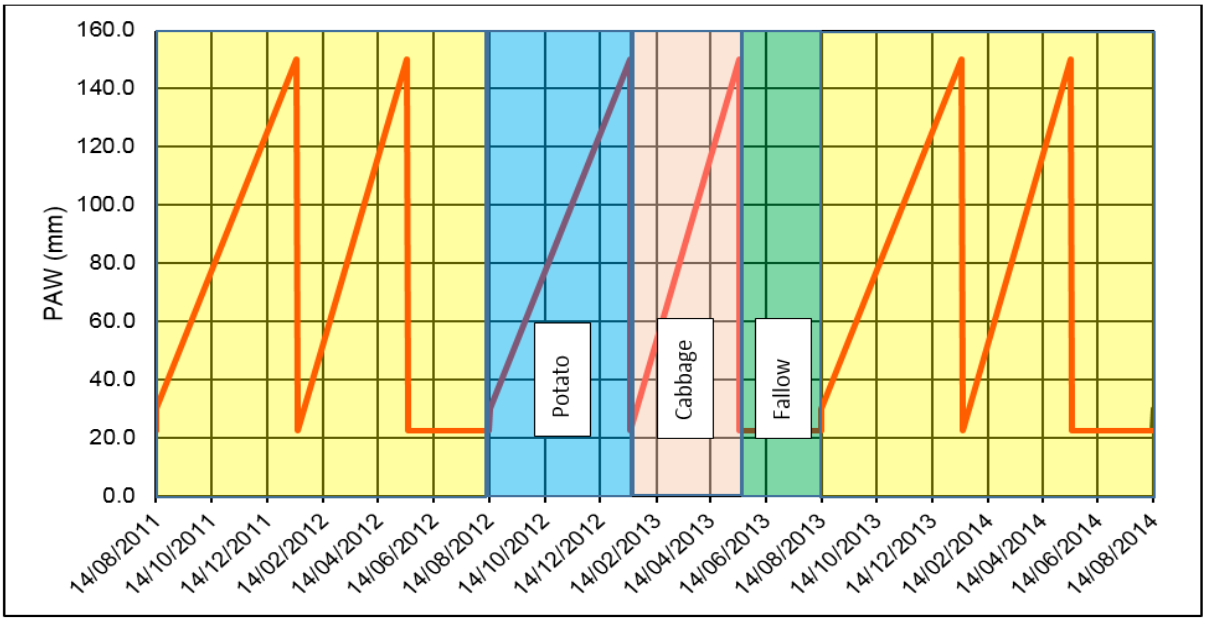

Figure C.1: Vegetable rotation with 150 mm PAW at field capacity down to a depth of 500 mm

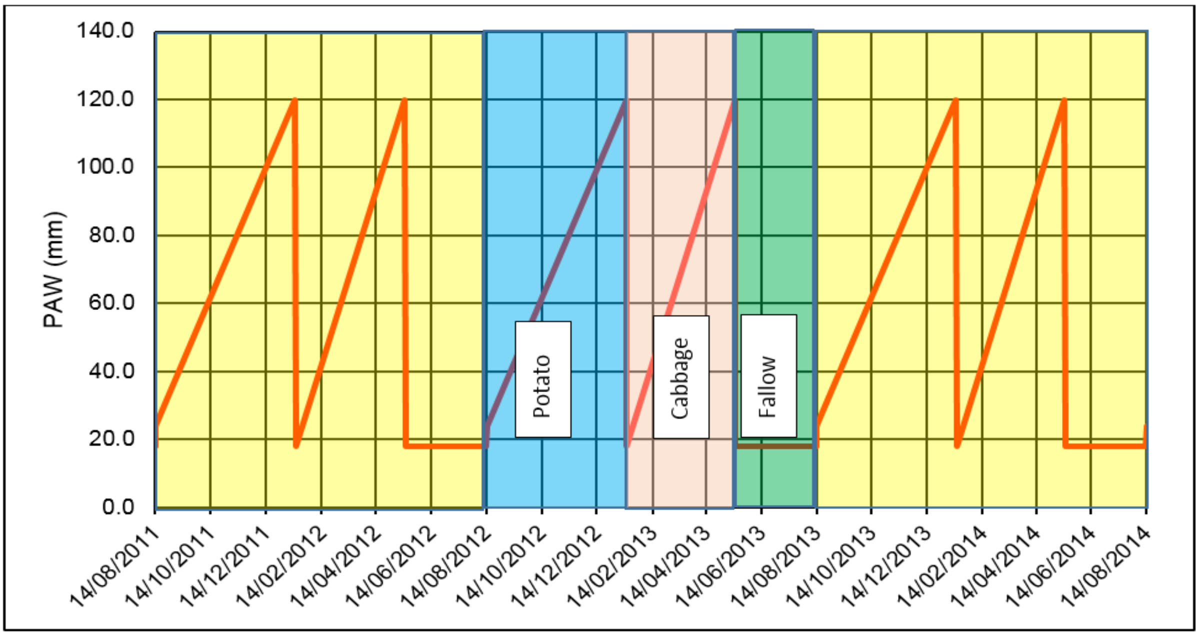

Figure C.2: Vegetable rotation with 120 mm PAW at field capacity down to a depth of 500 mm

Irrigation management parameters for vegetables are provided in Tables C.7 to C.12 for North Otago MAR rainfall bands of 550 mm, 650 mm and 750 mm, and for 120 mm and 150 mm PAW.

Table C.7: Vegetable rotation Irrigation management parameters (NO550, PAW 120)

Days since planting	Crop	Date	Return period	Trigger level (% PAW)	Amount (mm)
0	Potato	14-Aug	None	60	0.0
30	Potato	12-Sep	None	60	0.0
70	Potato	22-Oct	3	60	12.0
125	Potato	16-Dec	3	60	12.0
155	Potato	15-Jan	3	60	12.0
181	Cabbage	9-Feb	3	60	12.0
226	Cabbage	26-Mar	3	60	12.0
266	Cabbage	5-May	3	60	12.0
276	Cabbage	15-May	3	60	12.0
277	Fallow	16-May	None	None	None
366	Fallow	13-Aug	None	None	None

Table C.8: Vegetable rotation Irrigation management parameters (NO550, PAW 150)

Days since planting	Crop	Date	Return period	Trigger level (% PAW)	Amount (mm)
0	Potato	14-Aug	None	60	0.0
30	Potato	12-Sep	None	60	0.0
70	Potato	22-Oct	3	60	11.1
125	Potato	16-Dec	3	60	11.1
155	Potato	15-Jan	3	60	11.1
181	Cabbage	9-Feb	3	60	11.1
226	Cabbage	26-Mar	3	60	11.1
266	Cabbage	5-May	3	60	11.1
276	Cabbage	15-May	3	60	11.1
277	Fallow	16-May	None	None	None
366	Fallow	13-Aug	None	None	None

Table C.9: Vegetable rotation Irrigation management parameters (NO650, PAW 120)

Days since planting	Crop	Date	Return period	Trigger level (% PAW)	Amount (mm)
0	Potato	14-Aug	None	60	0.0
30	Potato	12-Sep	None	60	0.0
70	Potato	22-Oct	3	60	11.7
125	Potato	16-Dec	3	60	11.7
155	Potato	15-Jan	3	60	11.7
181	Cabbage	9-Feb	3	60	11.7
226	Cabbage	26-Mar	3	60	11.7
266	Cabbage	5-May	3	60	11.7
276	Cabbage	15-May	3	60	11.7
277	Fallow	16-May	None	None	None
366	Fallow	13-Aug	None	None	None

Table C.10: Vegetable rotation Irrigation management parameters (NO650, PAW 150)

Days since planting	Crop	Date	Return period	Trigger level (% PAW)	Amount (mm)
0	Potato	14-Aug	None	60	0.0
30	Potato	12-Sep	None	60	0.0
70	Potato	22-Oct	3	60	10.8
125	Potato	16-Dec	3	60	10.8
155	Potato	15-Jan	3	60	10.8
181	Cabbage	9-Feb	3	60	10.8
226	Cabbage	26-Mar	3	60	10.8

266	Cabbage	5-May	3	60	10.8
276	Cabbage	15-May	3	60	10.8
277	Fallow	16-May	None	None	None
366	Fallow	13-Aug	None	None	None

Table C.11: Vegetable rotation Irrigation management parameters (NO750, PAW 120)

Days since planting	Crop	Date	Return period	Trigger level (% PAW)	Amount (mm)
0	Potato	14-Aug	None	60	0.0
30	Potato	12-Sep	None	60	0.0
70	Potato	22-Oct	3	60	11.4
125	Potato	16-Dec	3	60	11.4
155	Potato	15-Jan	3	60	11.4
181	Cabbage	9-Feb	3	60	11.4
226	Cabbage	26-Mar	3	60	11.4
266	Cabbage	5-May	3	60	11.4
276	Cabbage	15-May	3	60	11.4
277	Fallow	16-May	None	None	None
366	Fallow	13-Aug	None	None	None

Table C.12: Vegetable rotation Irrigation management parameters (NO750, PAW 150)

Days since planting	Crop	Date	Return period	Trigger level (% PAW)	Amount (mm)
0	Potato	14-Aug	None	60	0.0
30	Potato	12-Sep	None	60	0.0
70	Potato	22-Oct	3	60	10.5
125	Potato	16-Dec	3	60	10.5
155	Potato	15-Jan	3	60	10.5
181	Cabbage	9-Feb	3	60	10.5
226	Cabbage	26-Mar	3	60	10.5
266	Cabbage	5-May	3	60	10.5
276	Cabbage	15-May	3	60	10.5
277	Fallow	16-May	None	None	None
366	Fallow	13-Aug	None	None	None

Appendix D: Guidance for estimating PAW at depths > 900 mm

The S-Map and FSL soil databases do not generally provide PAW estimates for below 1 m and 900 mm depths, respectively. However, rooting depths (and therefore the available soil water reservoir) of some crops such as stonefruit can be more than 1 m deep. In these instances, the following guidance can be used to determine the appropriate PAW.

S-map

PAW for 300, 600 and 1000 mm depths are generally available. PAW between 600-1000 mm (i.e. lowest available profile) can be extrapolated to determine PAW below 1000 mm depth.

Example:

PAW for 300 mm = 67 mm

PAW for 600 mm = 115 mm

PAW for 1000 mm = 128 mm

The PAW between 600 – 1000 mm is 13 mm (128-115) or 0.0325 mm/mm depth.

PAW for 1.5 m depth = PAW for top 1000 mm + PAW for lower 500 mm estimated using prorated PAW for 600 – 1000 mm depth

= 128 + 0.0325 x 500

= 144 mm

FSL:

The FSL database generally specifies the PAW for 900 mm depth only. PAW values given in the FSL can be adjusted for different depths using the “rule of thumb” proposed by Trevor Webb of Landcare for North Otago (Aqualinc, 2003b abridged):

> *Assume the top 200 mm of topsoil contributes 40 mm of water, and the remainder of the soil profile down to a maximum of 900 mm contributes a constant amount of water per unit depth. In stony soils, where the majority of the available water is within the top 500 mm of soil, no adjustment of PAW should be made*.

Example:

PAW for 900 mm depth = 120 mm

PAW within the top 200 mm of topsoil = 40 mm

PAW within next 700 mm (from 200 to 900 mm) = 80 mm (120-40) or 0.1143 mm/mm

PAW for 1.5 m depth = PAW for top 200 mm + PAW for lower 1300 mm estimated using prorated PAW between from 200 to 900 mm depth

= 40 + 0.1143 x 1300

= 189 mm

Appendix E: User Guide

This Appendix explains a procedure to utilise the irrigation guidelines to determine appropriate climate and soil parameters for a farm, and how to calculate the reasonable irrigation demand from the MAR and PAW. The following steps are suggested:

1. Select the appropriate climate (i.e. MAR): Figure 5 is reproduced as Figure E1 (A0 size map) attached with this irrigation guideline and is also available in digital form. The map provides MAR bands for irrigable areas in the Otago region. Different colours are used to shade different MAR bands. Contour lines are labelled to assist in finding MAR for different farms. Use these maps to find MAR for a farm at a specific location.
2. Identify PAW: Landcare Research provide an on-line tool, S-map, available in https://smap.landcareresearch.co.nz/home, which provides soil characteristics on farms in New Zealand. Click on this link and go to the farm location.
3. Once you have determined the relevant MAR and PAW values, go to the relevant table(s) (Tables 5-8 in Section 6) and read off the appropriate water requirement numbers.

Figure E1, as an example, is a screenshot of S-map showing different soils in the Otago region near Palmerston. A location indicated by an arrow near the Main South Line has been used for this example. The soil map unit or polygon is described as Tait_21 (60%).

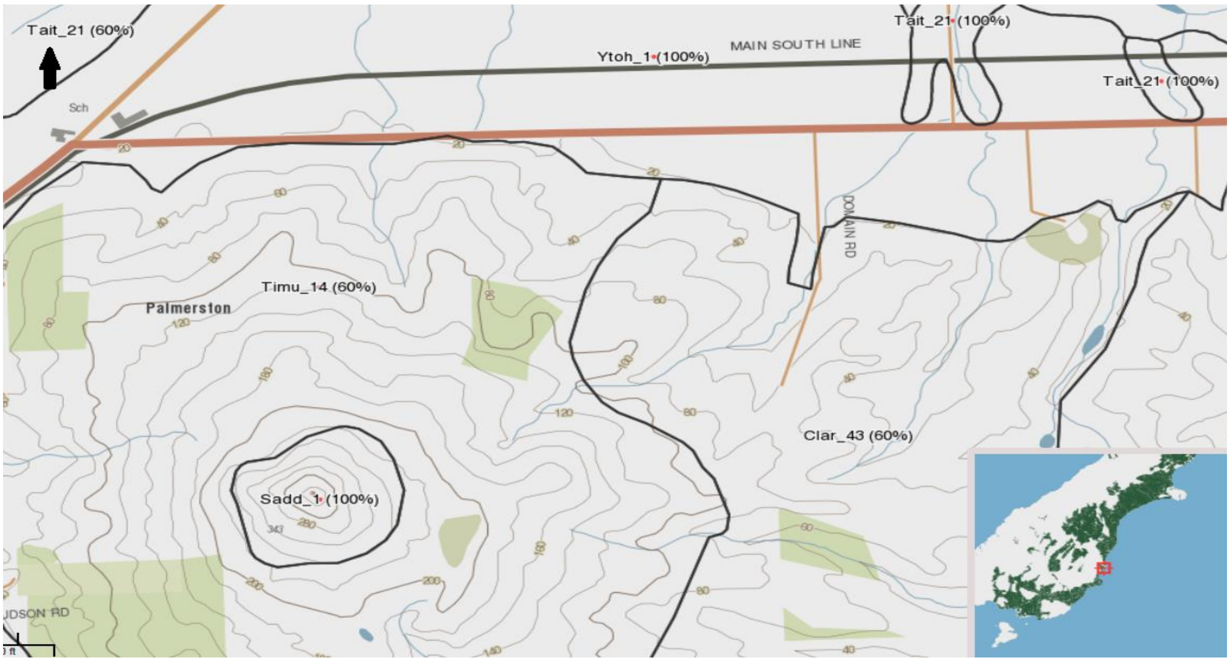

Figure E.1: Screenshot of farms near Palmerston showing soil polygons and labels

When you click on a location, a small window will appear, as shown in Figure E2. The PDF factsheets as shown in Figure E2 describe different soil characteristics including PAW of the soils in the location of interest.

In this case, two soils (Taitapu*f* (Sib 21) and Kaiapoi*f* (Sib 1)) are present within the Tait_21 (60%) polygon. Table E1 & E2 are screenshots of the PDF files showing some key physical properties of the two soils (Taitapu*f* (Sib 21) and Kaiapoi*f* (Sib 1)).

Table E.1: Key physical properties of Taitapuf soil on Tait_21 (60%) used for this example

Landcare Research
Manaaki Whenua

S-map Soil Report

Report generated: 23-Dec-2016 from http://smap.landcareresearch.co.nz

This information sheet describes the typical average properties of the specified soil to a depth of 1 metre, and should not be the primary source of data when making land use decisions on individual farms and paddocks.

Taitapu*f* — **Typic Recent Gley Soil**

Tait_21a.1 (60% of the mapunit at location (4961534, 1421975), Confidence: Low)

Key physical properties		
Depth class (diggability)		Deep (> 1 m)
Texture profile		Silty Loam
Potential rooting depth		Unlimited
Rooting barrier		No significant barrier within 1 m
Topsoil stoniness		Stoneless
Topsoil clay range		18 - 30 %
Drainage class		Poorly drained
Aeration in root zone		Very limited
Permeability profile		Moderate Over Slow
Depth to slowly permeable horizon		35 - 65 (cm)
Permeability of slowest horizon		Slow (< 4 mm/h)
Profile available water	(0 - 100cm or root barrier)	Very high (269 mm)
	(0 - 60cm or root barrier)	Very high (171 mm)
	(0 - 30cm or root barrier)	Very high (93 mm)

Table E.2: Key physical properties of Kaiapoif soil on Tait_21 (60%) used for this example

Kaiapoif — **Mottled-weathered Fluvial Recent Soil**

Kaia_1a.1 (40% of the mapunit at location (4961527, 1422049), Confidence: Low)

Key physical properties		
Depth class (diggability)		Deep (> 1 m)
Texture profile		Silty Loam
Potential rooting depth		Unlimited
Rooting barrier		No significant barrier within 1 m
Topsoil stoniness		Stoneless
Topsoil clay range		12 - 25 %
Drainage class		Imperfectly drained
Aeration in root zone		Moderately limited
Permeability profile		Moderate
Depth to slowly permeable horizon		No slowly permeable horizon
Permeability of slowest horizon		Moderate (4 - 72 mm/h)
Profile available water	(0 - 100cm or root barrier)	High (233 mm)
	(0 - 60cm or root barrier)	Very high (144 mm)
	(0 - 30cm or root barrier)	Very high (76 mm)

As indicated in S-map, Taitapu*f* constitutes 60% and Kaiapoif 40% of the map unit at the location. Therefore, to calculate final PAW on the farm, these percentages need to be accounted for.

Table E1 & Table E2 provide the PAW of the two soils at three depths (0-100, 0-60 & 0-30 cm).

Plants can only extract water where roots grow. If the crop rooting depth matches one of the depth ranges above, use the PAW value for that depth.

If the crop rooting depth does not match one of the depths given in S-Map, calculate the PAW value for the correct depth by proportioning the depth to the closest available PAW values.

For example, assuming the rooting depth of potatoes is 50 cm, but the available PAW data in S-map is for 30 cm and 60 cm soil depth, carry out the following adjustment.

a) Taitapu*f* soil (Table E1)

$$60\ cm\ soil\ depth = 171\ mm$$
$$30\ cm\ soil\ depth = 93\ mm$$
$$Difference = 78\ mm$$

The difference of 78 mm is held in the 30 cm of soil between the 30 cm and 60 cm depths, which is 26 mm per 10 cm of soil depth. So 26 mm needs to be subtracted from the 60 cm value in this case for a 50 cm depth.

$$For\ 50\ cm\ soil\ depth = 171 - \frac{(171-93)}{(60-30)} \times (60-50) = 145\ mm$$

b) Kaiapoi*f* soil (Table E2)

$$60\ cm\ soil\ depth = 144\ mm$$
$$30\ cm\ soil\ depth = 76\ mm$$

$$For\ 50\ cm\ soil\ depth = 144 - \frac{(144-76)}{(60-30)} \times (60-50) = 121.3\ mm$$

c) Resultant (Final) PAW

$$145\ \times \frac{60}{100} + 121.3\ \times \frac{40}{100} = 135.5\ mm$$

Once the required MAR and PAW values are determined, go to the relevant table(s) (Tables 5 to 8 in Section 6) and read off the appropriate water requirement numbers.

Often, measured or calculated PAW will be different from the modelled PAW values in the tables. In the example above, the PAW for potatoes was calculated at 135.5 mm, while the closest PAW value in the tables is 150 mm. In this case, the irrigation demand calculated for a PAW of 150 mm should be used.

If required, a more exact value for water requirements can be interpolated from the values in the tables. For 135.5 mm, the water requirements could be determined as values approximately half way between the 120 mm and 150 mm values.