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Guidelines for reasonable irrigation water requirements in the Waikato region

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Irrigation REPORT

Guidelines for Reasonable Irrigation Water Requirements in the Waikato Region

PREPARED FOR
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LIST OF ABBREVIATIONS

amsl	above mean see level
ET	evapotranspiration
l/s	litres per second
m	metre
mm	millimetre
mm/d	millimetre per day
m^3	cubic metre
ME	mean error
NSE	Nash–Sutcliffe model efficiency coefficient
PAW	plant available water
PET	potential evapotranspiration
RMS	root mean squared
RMSE	root mean square error
SE	standard error
VCS	virtual climate station

LIST OF ACRONYMS

FAO	Food and Agriculture Organization
NIWA	National Institute of Water and Atmosphere
NZFSL	New Zealand Fundamental Soils Layer
WRC	Waikato Regional Council
WRP	Waikato Regional Plan

GLOSSARY

Crop coefficient (k_c)	Relates the amount of water lost through evapotranspiration by the relevant crop to the reference evapotranspiration value. The coefficient is determined from the ratio of the evapotranspiration for the crop being studied divided by the evapotranspiration for the reference crop, under the same conditions; i.e., evapotranspiration for the well watered studied crop ÷ reference evapotranspiration (dimensionless).
Evapotranspiration (ET)	Water lost by soil evaporation and crop transpiration (mm/day).
Crop evapotranspiration (ET_c)	Determined by the crop coefficient approach whereby the effect of the various weather conditions are incorporated into ET and the (k_c) coefficient.
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 respect to the depth of the soil profile).
Irrigation system capacity	Depth of irrigation water applied ÷ minimum return period (mm/day).
Irrigation application efficiency	Average depth of water retained within the root zone ÷ average depth of water applied through the irrigator during a single irrigation event. Losses include wind drift, interception losses, run-off, and deep drainage (dimensionless, often expressed as a percentage).
Profile Available Water (PrAW)	PrAW reflects the soil's capacity, down to 0.9 m depth to hold water that is available for a plant to use (mm).
Plant Available Water (PAW)	PAW reflects the soil's capacity down to the rooting depth of the crop to hold water that is available for the crop to use (mm)
Reference ET (ETo)	ET of well watered reference crop (grass)
Return period	Minimum time between irrigation events in the same paddock (days).
Water stress reduction coefficient (k_s)	The water stress reduction factor is a function of the soil water status. k_s equals 1.0 when the soil water content is equal to the readily available water content, and then k_s reduces linearly down to a value of zero at wilting point (dimensionless).
Wilting point	Soil profile is very dry and no soil water is available for plant extraction at -1,500 kPa. (dimensionless, often expressed as a percentage respect to the depth of the soil profile).

EXECUTIVE SUMMARY

The purpose of this report is to present the approach and results of a multi-staged project undertaken by Waikato Regional Council (WRC) to develop guidelines for reasonable daily and seasonal irrigation water requirements. This work is carried out to implement the Waikato Regional Plan Policy 3.4.3.2a(iii) (Efficient Use of Water) and Method 3.4.5.3 (Crop and Pasture Monitoring Programme). This project was completed by Aqualinc Research Limited (Aqualinc) in consultation with WRC and inputs from stakeholders.

The multi-staged project was undertaken in the following stages:

Stage 1: review of previous WRC irrigation guidelines (Landcare, 1997) and the scoping of work required through stakeholder consultation.

Stage 2: included three phases:

- Phase 1: development of interim irrigation guidelines using water balance computer modelling for the period from 1972 to 2009 for a range of climatic, soil, crop and irrigation management parameters.
- Phase 2: field verification of the water balance computer modelling completed in Phase 1.
- Phase 3: development of the final irrigation guidelines using water balance computer modelling for the period from 1972 to 2014 as presented in this report based on finding of the Phase 2.

During Stage 1, the shortcomings and concerns of the previous irrigation guidelines were identified through extensive 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.

Phase 1 of Stage 2 was dedicated to developing interim reasonable irrigation requirement values using a water balance computer model, Irricalc. The Irricalc model uses the principles developed by Food and Agriculture Organization (FAO) of the United Nations for daily soil moisture water balance modelling (Allen *et al.*, 1998). This interim water requirement and associated guidelines are used by WRC for assessing the reasonable water limits to be applied to resource consents to take and use water for irrigation.

The Irricalc modelling used NIWA's virtual climate station (VCS) climate data (Tait *et al.*, 2006). There are 1,006 VCS in the Waikato Region. VCS data is available at a 5 km by 5 km grid across the region. It was considered that data on a 5 x 5 km grid provides reasonably accurate climate data for a given location. The modelled crops include pasture, vegetables (for four most common crop rotations based on consultation with growers), viticulture and horticulture. Irrigation application efficiency varies dependent on the irrigation system used. Therefore, for pasture, modelling has been completed for the four common irrigation systems used in the Waikato (K-Line, long lateral, travelling gun, and centre pivot) based on their limitations and management characteristics (i.e., system capacity and return intervals). Land areas and irrigation systems used for vegetable production can vary between years; as a result of that the irrigation efficiency can vary between years. Accordingly, all irrigation water demand calculations for vegetables have been carried out on the basis that irrigation application efficiency is 80% or better. The 80% value is now widely accepted as a standard figure for water allocation throughout New Zealand.

The water requirement modelling was carried out for six soil plant available water (PAW) classes that cover the potential PAW range within the Waikato Region. Irrigation water requirements were calculated for all five soils PAW classes at every climate station (i.e., for the 1,006 VCS). The model outputs, therefore, can be used for any PAW at any location without need to re-run the model if future high resolution soil surveys determined different soil water characteristics than what is available at present.

The Phase 2 completed a field verification (Aqualinc, 2013a) of the Irricalc model used in the Phase 1. This verification was completed for four vegetable and two pasture sites. These sites covered a representative cross section of irrigated farms and land uses in the Waikato Region. Comparison of the model predictions of the soil water contents against four years of field based measurements (only three years for vegetable sites) enabled an assessment of the model performance. Statistical analysis (root mean squared error, mean error, standard deviation and Nash–Sutcliffe model efficiency coefficient) showed that the model is capable of accurately simulating measured soil water contents over a wide range of field conditions covering different soil types, climate conditions and irrigation management systems. The result also confirmed that the crop coefficients used in the model for determining the Interim Irrigation Guidelines for WRC are appropriate.

Based on Phase 2 findings, the Irricalc modelling has been carried out for 42 irrigation seasons (1972 to 2014) to determine the final irrigation guidelines. The model outputs maximum daily, and for annual irrigation requirements the mean, 80 percentile, 90 percentile and maximum values for a combination of climate (location), soil, crop and irrigation systems.
In summary, the irrigation guidelines for the reasonable water use in the Waikato Region have been developed using internationally accepted water balance computer modelling. The computer model Irricalc used for the development of guidelines has been field verified through a four year study. It is therefore recommended that the guidelines 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 Waikato Region.

1 Introduction

1.1 Background

Irrigation is a major and growing consumptive use of water in the Waikato Region. The irrigated area of the region is estimated to have more than doubled over the past two decades (Aqualinc, 2008a). Irrigation is a major factor in increasing the reliability of production for farming systems; dairying, horticulture and market gardening in the region.

The efficient use of water is a key objective of the Resource Management Act, and achieving efficient use of water for irrigation is a responsibility of administrative authorities such as Waikato Regional Council (WRC) e.g. Waikato Regional Plan Policy 3.4.3.2a(iii) (Efficient Use of Water) and Method 3.4.5.3 (Crop and Pasture Monitoring Programme).

In order to define whether irrigation water allocation limits applied to resource consents are an efficient allocation of water for the purpose, reasonable water requirements need to be defined. To achieve this, WRC through a multi-staged project has sought to develop reasonable water requirements for irrigation. This report presents the approach and findings of the project to define daily and seasonal irrigation water requirements.

1.2 Previous Projects

WRC had previously commissioned a study of reasonable irrigation requirements for the Waikato (Landcare, 1997). Prior to completion of this current study, the Landcare study (Landcare, 1997) formed the basis of guidelines for water allocation for irrigation consents in the Region.

The 1997 report stated that only the broad generalities had been covered, and further work was required to consider all soil/crop/climate scenarios (Landcare, 1997). Therefore, in 2007, WRC commissioned Aqualinc Research Ltd (Aqualinc) to develop irrigation guidelines that better reflect the range of climate, soil conditions, crop rotations, and irrigation methods in the Waikato Region. In particular WRC requested that greater emphasis be placed on determining more robust values for vegetable irrigation.

1.3 Approach

The guidelines have been developed through a staged project. Stage 1, which has been completed in 2008, included a review of previous irrigation guidelines (Landcare, 1997) and stakeholder consultation to identify the work required for Stage 2 (Aqualinc, 2008a).

Stage 2 is divided into three phases. Phase 1 used water balance computer modelling to determine guidelines for a range of climatic, soil, crop and irrigation management parameters. The Phase 1 guideline values were treated as "Interim Guidelines" until the final guidelines were developed after field verification. These interim guidelines were determined using daily soil-water balance model simulations for the period of 1 June 1972 to 31 May 2009, covering 37 irrigation seasons.

Phase 2 involved field verification of the guidelines determined in Phase 1. Phase 3 soil-water balance model simulations have been carried out for the period of 1 June 1972 to 31 May 2014, covering 42 irrigation seasons. Modelling for an extended period was prompted due to Ministry for Primary Industries' (MPI) recent technical publication 'The 2012-13 drought: an assessment and historical perspective'. This report identified, on average, recent summers between 2009 and 2012 are drier, and the 2012-13 year as one of the driest years over 1972-2013 period in large parts of the Waikato (MPI, 2013).

This report documents a brief summary of the previous phases of the project, and the final findings and recommendations under Phase 3 of the study.

1.4 Consultation

Since irrigators use a wide range of different irrigation systems and management decisions throughout the region, Aqualinc has undertaken an extensive consultation process with irrigators to obtain the crop and irrigation management parameters used in the soil water balance modelling. In addition, Aqualinc also consulted industry experts, industry representatives and reviewed a number of national and international papers and reports. A summary of the consultation undertaken is presented in Appendix A.

1.5 Project Outcomes and Outputs

This technical report primarily documents the guideline calculation methods, and rationalises the use of particular model parameters in this process. The water balance modelling determined the maximum daily water requirements and the 90 percentile annual irrigation requirements for different soils, crops, climate and irrigation systems scenarios. The results are presented in Appendices E to J of this report.

This document, however, does not contain the results for the reasonable irrigation requirements for a given farm. This data is contained in a full set of electronic results provided to WRC. These electronic results provide the mean, 80 percentile, 90 percentile and maximum annual irrigation requirements for the set of combinations of soil, crop and irrigation system based on the farm location, i.e., the climate.

2 Water Balance Modelling

A paddock scale daily soil water balance model, Irricalc was used to calculate the irrigation requirements. 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). This method has been field verified both internationally and in New Zealand, and has been shown to model well what occurs on-farm.

Model simulations were run from 1 June 1972 to 31 March 2014, covering 42 irrigation seasons. A description of the model is presented in Appendix B. Input data used (evapotranspiration, rainfall and soils information) for modelling is provided in Appendix C.

3 Crops

Water requirements were modelled for pasture, vegetables, and grapes. Greenhouse or tunnel houses irrigation requirements have not been considered. Irrigation water requirements for covered facilities are significantly different from field irrigation. In the case of housed crops, water used is assumed to come from irrigation since crops are completely sheltered from the rain. Additionally, ET is a function of the temperature of the enclosure and the relative humidity. Accordingly, the crop water requirements for housed crops are much less affected by the geographical location.

3.1 Pasture

Pasture irrigation accounts for about 75% of all irrigation water use in the Waikato. Pasture irrigation is common in the Reporoa Basin and along the Waihou River (Aqualinc, 2008a). Pasture was assumed to have a constant crop coefficient (k_c) of 1.0 throughout the year, and a constant rooting depth. Bright (2007) calculated from lysimeter data, that the average crop coefficient during the irrigation season was approximately 1.0, for a well-watered intensive pastoral farm in Canterbury. Water requirements were calculated for a different values of soil PAW values: 40, 60,100,150, 200 and 250 (Appendices E and F). We recommended that a rooting depth (i.e., available water reservoir depth) of 600 mm be assumed for pasture, which has been found to be appropriate for the two monitoring farms investigated.

3.2 Vegetables

Vegetable irrigation, and a small amount of horticultural irrigation, cumulatively accounts for about 20-25% of all irrigation water use in the Waikato. Vegetable irrigation is particularly common around Pukekohe and Hamilton city (Aqualinc, 2008a).

Aqualinc has undertaken an extensive consultation process with vegetable growers to obtain the crop and soil parameters required for soil water balance modelling on these crops (Appendix D). Additionally, Aqualinc also reviewed a number of national and international papers and reports including crop and soil parameters to support the crop factors, irrigation targets and rooting depths, for different stages of the growth for different vegetable and horticultural crops.

Vegetable water use, rooting depth, and irrigation practices vary depending on the crop type and the stage of development. Parameters used in soil moisture balance modelling are presented in Appendix D.

There is a high degree of variability between different vegetable growers in terms of how they manage their farms. The combinations of crop rotations and irrigation management systems vary significantly between farms. It is not practical to model all the scenarios that practice in the region, and therefore, these guidelines have been developed for four typical crop rotations as listed in Table 1. These crop rotations were obtained from consultation with growers and industry experts to represent a realistic “upper demand” for irrigation water (i.e., higher annual water demands). It is expected that the water demand for the modelled crop rotations would meet over 95% of all irrigation scenarios in the region.

Due to high degree of variability in irrigation management between vegetable growers, and change in land areas (for disease management and soil fertility reasons) and irrigation systems used between years, the irrigation efficiency varies between farms and also between years. Accordingly, all irrigation water demand calculations for vegetables have been carried out on the basis that irrigation application efficiency is 80% or better. The 80% value is now widely accepted as a standard figure for water allocation throughout New Zealand. Irrigation systems with application efficiencies greater than 80% will, in terms of production, have an advantage over systems with less than 80% efficiency.

Table 1. Vegetable crop rotations used in the model

Vegetable Rotation	Crop	Planting	Harvest
Scenario 1	Carrots	April	July
	Potatoes	November	March
Scenario 2	Potatoes	Mid-November	Mid-April
	Onions	September	February
Scenario 3	Lettuce	April	June
	Lettuce	November	December
Scenario 4	Lettuce	March	April
	Cauliflower	May	August

Based on the model outputs for the four vegetable rotations (Table 1), the maximum daily and seasonal water demands for each season modelled was chosen as 'VegeMax' (i.e. the maximum daily demand and maximum seasonal demand for each season). Water use guideline values presented in Appendix G are the maximum daily water use (i.e. VegeMax). Appendix H presents the 90th percentile seasonal demands for 'VegeMax'. Electronic data has been supplied to WRC that contains the seasonal water requirements for all four individual rotation scenarios and 'VegeMax' for 80% irrigation efficiency.

A worked example on how to apply the guidelines to determine the resource consent allocation limits for another level of irrigation efficiency is provided in Appendix K.

3.3 Viticulture

Irrigation of grapes is uncommon in the Waikato. Viticulture requires a lot less irrigation water than pasture, because grapes have lower ET and tolerate higher soil moisture deficits. Green *et al*. (2004) estimated a maximum crop coefficient (k_c) value of 0.7 for vineyards with lanes spaced at 1.8 m. Grapes were modelled with k_c varied from 0.3 in winter to 0.7 in summer, and a constant rooting depth. Water requirements will be less for vineyards with lanes spaced greater than 1.8 m. Water requirements were calculated for a range of soil PAW values (Appendices I and J). We recommended a rooting depth of 900 mm be assumed for grapes.

Irrigation water requirement for viticulture do not include any water that may be required for frost protection.

3.4 Horticulture

The most predominant horticulture crops in the Waikato are kiwifruit, avocados, citrus, apples, pears, berries, plums, table grapes, and olives. Most horticultural crops are not irrigated because they have deep rooting systems and can tolerate, and at times benefit, from soil moisture deficits. Sometimes horticultural crops are irrigated during establishment or as a means of increasing yields. Currently only a small fraction of irrigation water allocated in the Waikato, is for the irrigation of horticulture.

Horticultural water requirements can vary considerably depending on orchard management practices. Little information is available in the Waikato on orchard water use and management practices, making it difficult to accurately model water use.

The parameter values used for determining irrigation requirements for mature orchards are given in Table 2. Daily and seasonal maximum guideline values are based on the water requirements for pasture, with some allowance for differences in horticultural crop water use and the deeper rooting systems.

Pasture guideline values are given in Appendices E and F. Water requirements for establishment of orchards are not precisely known due to the lack of data, but are likely to be less than the mature orchard. However, due to the shallow rooting depth, water needs to be applied over a more regular basis.
In the absence of site specific information, Appendix C presents NZFSL soils average PAW estimates for 0.6 and 0.9 m rooting depths. NZFSL does not provide PAW estimates for 1.2 m rooting depths; this information would need to come from a site specific soil survey. However, in the absence of site specific information, we recommend using a scaling of the PAW for 0.9 m rooting depth to estimate PAW for 1.2 m depth. Guidance on how to scale the PAWs is presented in Appendix K.

Because some soil moisture deficit can enhance crop quality for certain crops, recommended guideline values sometimes result in seasonal allocation values that are considerably greater than actual water use. Also, in certain locations, deep rooting systems can allow plants to access shallow groundwater, resulting in significantly lower water requirements than suggested by these guidelines.

Irrigation water requirement estimates do not include any water that may be required for frost protection.

Table 2. Irrigation guidelines for horticulture

Crop	k_c [(1)] (ini, mid, end)	Rooting depth[(2)]	Daily and seasonal maximum guideline values, relative to pasture irrigation requirements
Kiwifruit	0.40,1.05,1.05	0.7-1.3m	100% of pasture with centre pivot irrigation; 0.9 m rooting depth
Apple and pears	0.50,1.00,0.70	1.0-2.0m	100% of pasture with centre pivot irrigation;1.2 m rooting depth
Plums	0.50,0.95,0.70	1.0-2.0m	
Berries	0.30,1.05,0.50	0.6-1.2m	100% of pasture with centre pivot irrigation; 0.9 m rooting depth
Avocados	0.60,0.85,0.75	0.5-1.0m	85% of pasture with centre pivot irrigation; 0.6 m rooting depth
Citrus	0.75,0.70,0.75	0.8-1.5m	75% of pasture with centre pivot irrigation; 0.9 m rooting depth
Olives	0.65,0.70,0.70	1.2-1.7m	70% of pasture with centre pivot irrigation; 1.2 m rooting depth

(1) From Allen *et al*., 1998. (ini, mid, end) indicate how crop water use varies during the season.

‘ini’ = early in season, ‘mid’ = mid-season, ‘end’ = end of season.
(2) Of mature trees/vines/bushes (Allen *et al.*, 1998)

4 Irrigation

4.1 Irrigation systems

Common irrigation systems for pasture include centre pivots, K-lines, long-laterals, and travelling gun irrigators (Aqualinc, 2003a). For vegetables the predominant irrigation systems include travelling gun irrigators, centre pivots, and aluminium hand shifts. Irrigation of horticultural crops and viticulture is not commonplace; however, when they are, fixed overhead sprinklers or drip /micro-spray irrigation, are utilised.

Different irrigation systems have diverse operational constraints and different application efficiencies, which affect irrigation water requirements. Application efficiency is the ratio of irrigation water stored in the root zone to irrigation water applied to the field. Application efficiency is mainly affected by how uniformly water is applied (systems with poor uniformity have lower efficiency) and the ratio of the application depth divided by the soil moisture deficit. Run-off, spray evaporation losses and on-farm distribution losses are generally comparatively small.

Application efficiency is not the only factor that affects water requirements. How irrigation is managed and controlled determines how much summer rainfall can be utilised, particularly for soils with a higher water holding capacity. If irrigation is controlled so soil moistures are kept close to field capacity, when rain occurs during the irrigation season the soil cannot physically hold any more water. Instead this rain water causes drainage below the root zone.

However if irrigation is managed so there is always some spare storage capacity in the soil, when rain occurs some or all of the rain water can be held in the soil without deep drainage occurring. However, not all irrigation systems can be managed to maintain this storage capacity in the soil to capture rainfall. Irrigation systems that can apply a little water often, (e.g. centre pivots), tend to be able to better utilise summer rainfall.

However, factors other than efficiency can affect what irrigation systems are appropriate for a farming system. The shape and size of land parcels, trees, fences, land slope, crop type, rate of infiltration, and permanence of the irrigation set-up all affect correct irrigator selection.

The model outputs provide information to allocate water based on the type of irrigation system. One disadvantage of allocating water based on the type of irrigation system is that less efficient systems would receive more water than more efficient systems. This could discourage the investment in more efficient, but potentially more expensive, irrigation systems.

Based on model data, WRC has adopted a mixed model for water allocation. Under this approach WRC allocate water based on the type of irrigation system being used, however, the lowest irrigation efficiency of 80% is used as per Waikato Regional Plan Chapter 3.4, Policy 2. For the irrigation systems that have not been modelled such as solid sets, the results from one of the modelled systems whose performances are similar should be used. For example guns can be considered as a similar system to the solid sets.

Irrigation modelling assumed *reasonable* irrigation management practises. Poorly designed or managed systems often require more water. Reasonable use would be typical of the current practices of farmers who have financial motivation to be efficient. Modelled application efficiencies, operational constraints, and management parameters are given in Table 3 and Table 4.

Table 3. Pasture irrigation modelling parameters

System	UCC[(1)]	PAW (mm)	Irrigation	
			Trigger moisture deficit (mm)[(2)]	Average Efficiency[(3)]
K-line or long lateral	0.7	60[(4)]	30	70%
		100	40	75%
		150	70	80%
		200	80	80%
Gun	0.7	40	15	75%
		60	20	80%
		100	35	85%
		150	40	85%
		200	70	85%
Centre Pivot	0.8	40	15	80%
		60	20	85%
		100	30	90%
		150	40	90%
		200	60	90%

(1) Christiansen's (1941) coefficient of uniformity.

(2) These trigger values should be considered as approximate values. It is recommended that these values are utilised as starting points and adjusted according to climate conditions, to achieve efficient water use. For example, the given trigger level (soil moisture deficit) can be reduced during peak evaporation periods in summer as daily evaporation is likely to be higher than the recommended daily demand (or system capacity). By doing so, the average soil moisture levels can be maintained above the likely stress point over a longer period. The trigger value can be increased in autumn and spring when evaporation is low. That will enable taking advantage of relatively high rainfall in autumn and spring in Waikato and reducing deep drainage and nutrient losses.

(3) The reported values are approximate average efficiencies of the modelled outputs for well managed irrigation operation.

(4) K-lines and guns may need to be moved twice daily in order to achieve reasonable efficiency on light soils.

Note: The irrigation systems that are less than 80% efficiency, will receive less water than given in this report as in accordance with Waikato Regional Plan Chapter 3.4, Policy 2, the lowest irrigation efficiency that WRC use for water allocation is 80%.

Vegetable parameters are presented in Appendix D. Vegetable results in Appendices G and H are for average irrigation application efficiency of 80%. Water requirements for an irrigation application efficiency of 90%, can be calculated by multiplying these values by 0.889 (80% / 90%). A worked example on how to calculate the water requirements for another efficiency is also presented in Appendix K. Irrigation application depths and trigger soil moisture levels are indicative only; alternative application depths and return intervals combinations may be acceptable if they are more appropriate for a given site.

Table 4: Viticulture irrigation modelling parameters

System	UCC	PAW (mm)	Irrigation		
			Depth (mm)	Trigger moisture deficit (mm)	Average Efficiency[3]
Fixed over-head sprinklers[1]	0.8	60	20	24	90%
		100	20	40	90%
		150	20	60	90%
		200[2]	20	80	90%

[1] Water requirements for vineyards that use drip or micro-spray irrigation will be similar to the fixed over-head sprinkler system used in modelling

[2] Results have not been included, since modelling showed that the maximum daily irrigation demand everywhere in the Waikato was less 1 mm/d. Therefore irrigation is unlikely to be economically viable.

[3] The reported values are approximate average efficiencies of the modelled outputs for well managed irrigation operation.

4.2 Maximum Daily Irrigation Requirements

Generally, it is unrealistic, uneconomical and poor use of the resource to fully meet crop water demands 100% of the time. Farmers are usually prepared to take some risk of not meeting full demand for short periods. For pasture and viticulture, the maximum daily irrigation requirement was calculated by running the water balance model several times, with different irrigation return intervals. The maximum daily irrigation requirement was calculated as the irrigation application depth, divided by the maximum return interval that met the soil moisture criteria in Table 5. For pasture the calculated maximum daily irrigation requirements generally result in less than a 2% average annual production loss compared with having no limit on daily water use. For grapes, which tolerate greater soil moisture deficits, the recommended maximum daily irrigation limits should not impact on production.

Table 5: System capacity soil moisture criteria

Crop	Soil moisture 90% exceedance probability	Soil moisture 99% exceedance probability
Pasture	50% PAW	25% PAW
Viticulture	50% PAW	25% PAW

Vegetable rotation scenarios 1 and 2 generally resulted in the maximum daily water requirements, since potatoes have the greatest peak water use of any of the crops modelled. Case study analysis was run for Vegetable 1 rotation at Pukekohe, for a soil PAW to 600 mm depth of 150 mm. For this scenario, the 95th percentile daily water demand, assuming 80% application efficiency, was 4.4 mm/day. Analysis showed that changing the system capacity from 5.0 mm to 4.4 mm made virtually no difference to soil moisture within the root zone.

A maximum daily limit of 4.4 mm/d approximately corresponded to maintaining soil moisture above 55% of PAW, 90% of the time in January, and always maintaining soil moisture above 35% of PAW (Figure 1); these should be relatively conservative soil moisture thresholds for potatoes, given that they can be grown without irrigation in drier climates such as South Canterbury and South Otago.

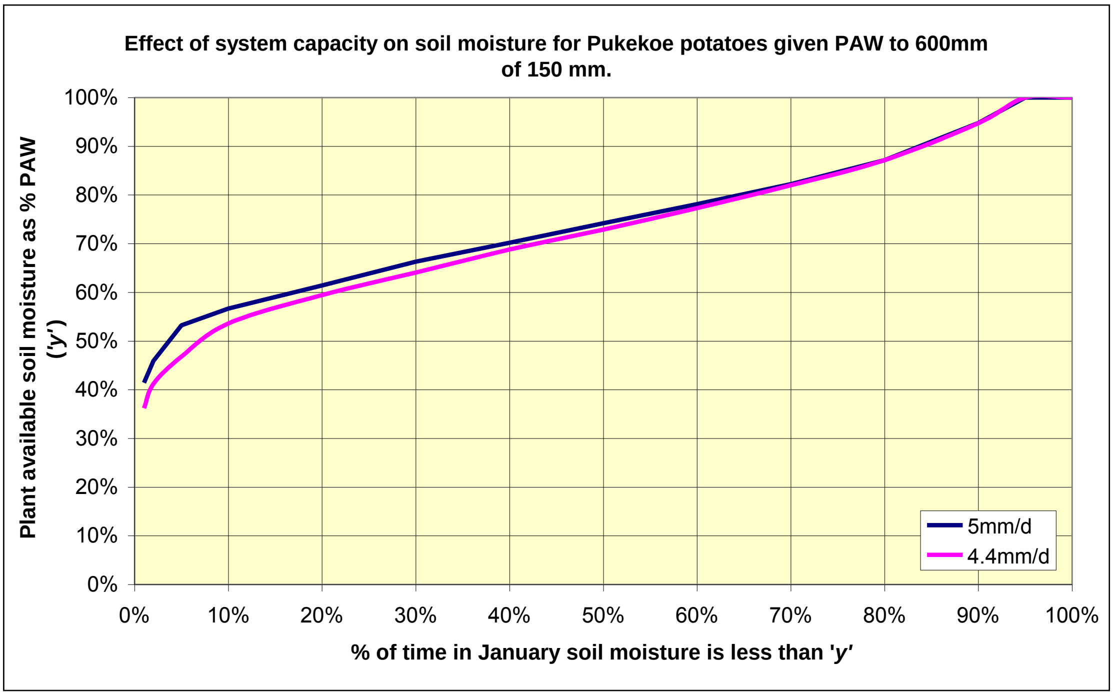

Figure 1: Soil moisture exceedance probability in January, as a function of system capacity, for potatoes, at Pukekohe

4.3 Irrigable Areas

In New Zealand most pasture, horticulture and arable irrigation occurs on flat to undulating land (≤7º). However, recent developments in irrigation technology, including K-line systems and centre pivots, means irrigation of rolling lands (up to 15º) is becoming more common. In a few locations in New Zealand, such as North Otago, there are isolated occurrences of slopes up to 20º being irrigated. However, these steep slopes can be more susceptible to run-off.

Most irrigation in the Waikato in the future probably will occur on land slopes less than 15º, and with an elevation of less than 600 m amsl. Guideline water requirements in Appendices E to J, exclude areas with land slopes greater than 15º or land elevations greater than 600 m amsl. Electronic data for water requirement values provided to WRC, include the whole region including steep land. For grapes, land up to 25º can be irrigated.

5 Phase 2: Field Verification

After the development of the interim irrigation guidelines using Irricalc modelling, field verification of the Irricalc model was undertaken in the Phase 2. This was achieved through comparison of the predictions of the soil water contents against four-years of field based measurements (four years for pasture sites and three years for vegetable sites). In addition, the production responses due to irrigation at the field scale were also measured.

The details of the field investigation for the first three years (2009 to 2011 irrigation seasons) along with equipment and sites used and results, are documented in Aqualinc (2013a). The soil water data analysis at pasture sites for 2012 irrigation season can be found in Aqualinc (2013b). This section provides a brief summary of the field investigation to support the adoption of the guidelines as the final guideline values.

The field investigations were conducted at six irrigated sites, which included four vegetable and two pasture sites. The vegetable sites were located in Pukekohe (two sites), Pukekawa and Matamata, with one pasture site in Te Poi and the other in Reporoa. These six sites cover a range of different irrigation systems and managements, and crop types (Aqualinc, 2013a). Additionally, soil types and weather condition also varies across the sites. Consequently, these monitored farms were considered to cover a representative cross section of irrigated farms and land uses in the Waikato Region.

All soils investigated in the field verification are either well or moderately drained soils. Therefore, no field investigation has been carried out on poorly drained soils. Our experience in the Waikato is that irrigation does not occur often on poorly drained soils due to the generally high water holding capacities of these soils. Therefore, the guidelines values are representative of most cases for irrigation of crops in the Waikato.

To assess the accuracy of the simulated soil water contents produced by Irricalc model against the measured field values, three statistical performance measures were used. These performance measures were; root mean squared error (RMSE), mean error (ME) and standard deviation (σ).

As it is important to assess the error in the model predictions in relative terms of the magnitude of the target values, these performance measures have been presented as a percentage of the average soil-water content (i.e., average of water content at field capacity and wilting point) for each site.

In addition to the above model performance measurements, the Nash–Sutcliffe model efficiency coefficient (NSE) 1 has also been calculated using simulated and measured data.

The results of the statistical analysis are given in Table 6. Acceptable values for these statistics for the satisfactory performance of the predictions from Irricalc are also included in Table 6.

Table 6: A summary of model performance measurements

Site	Monitored period	Performance measure as percentage over the average soil-water content (%)			NSE
		RMSE	ME	σ	
Threshold used to determine satisfactory performance		**5%**	**±3%**	**5%**	
	23/12/2009 – 26/3/2010	2.0	-0.1	2.1	0.91

[1] The NSE is predominately used to assess the predictive power of hydrological models. NSE can range from −∞ to 1. An efficiency of 1 (*NSE* = 1) corresponds to a perfect match of simulation to the observed data. An efficiency of 0 (*NSE* = 0) indicates that the model predictions are as accurate as the mean of the observed data. The efficiency of less than zero (*NSE* < 0) occurs when the observed mean is a better predictor than the model. The NSE is calculated using the same equation used to determine the coefficient of determination in general applications.

$$NSE = 1 - \frac{\sum_{i=1}^{n} x_i^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2}$$

Where:

n = Number of days in the irrigation season

$x_i = M_i - S_i$

M_i = Measured soil-water on day i

Si = Simulated soil-water on day i

Vege-1	15/9/2010 – 5/1/2011	3.6	0.8	3.5	0.87
	31/8/2011 – 22/1/2012	2.4	-0.5	2.4	0.84
Vege-2	20/12/2009 – 2/2/2010	4.2	-2.3	3.6	0.45
	3/9/2010 – 5/1/2011	1.8	-0.3	1.8	0.81
	18/10/2011 – 14/2/2012	1.5	-0.2	1.5	0.85
Vege-3	19/12/2009 – 25/1/2010	3.1	-0.8	3.0	0.68
	15/9/2010 – 5/1/2011	1.8	-0.2	1.8	0.96
	31/8/2011 – 4/1/2012	2.1	-0.7	1.9	0.96
Vege-4	20/12/2009 – 18/1/2010	1.9	-0.3	1.9	0.94
	3/9/2010 – 23/1/2010	2.3	-0.6	2.3	0.92
	30/9/2011 – 11/2/2012	1.8	-0.2	1.8	0.91
Pasture-1	20/12/2009 – 31/5/2010	1.7	-0.1	1.8	0.78
	1/9/2010 – 9/4/2011	1.6	0.4	1.6	0.79
	1/9/2011 – 4/5/2012	1.7	1.0	1.4	0.83
	1/10/12 – 28/3/13	1.7	1.0	1.4	0.92
Pasture-2	20/12/2009 – 31/5/2010	2.0	-0.3	2.0	0.97
	1/9/2010 – 9/4/2011	2.5	0.9	2.3	0.86
	1/9/2011 – 4/5/2012	2.8	0.7	2.7	0.75
	1/10/12 – 30/4/13	1.6	-0.9	1.3	0.97

The field verification on all six sites, as shown in Table 6, demonstrated that the Irricalc model was able to meet the required performance criteria. The meeting of the performance targets, established that Irricalc is capable of accurately simulating measured soil water contents over a wide range of field conditions covering different soil types, climate conditions and irrigation management systems. The result also confirmed that the crop coefficients used in the model for determining the Irrigation Guidelines for WRC are considered appropriate (Aqualinc, 2013a).

6 Peer review of the project

On completion of Phase 1 and 2 of the project, WRC commissioned AgResearch for an independent technical peer-review of the project outcomes to assess its suitability to use as the guidelines for irrigation water allocation. The AgResearch review (AgResearch, 2014) confirmed that Irricalc modelling approach is an international accepted method for soil water balance modelling and appropriate for determining WRC policy requirements for allocating 90th percentile irrigation volumes. However, the review had identified several areas where some clarification was required. These areas have been addressed and included in this final report. The key areas identified in the AgResearch review and Aqualinc's explanations/comments are listed in Appendix L.

7 Phase 3: Final Guidelines

The field verification on six farms that covered a range of soil, climate and management conditions showed that Irricalc model can accurately simulate the measured soil-water conditions. Accordingly, final irrigation guidelines have been developed based on soil-water balance model simulations for the period of 1 June 1972 to 31 May 2014, covering 42 irrigation seasons (see Section 1.3). Appendix E to J present the model results.

Aqualinc recommend that due to the limitation of site specific information, the reasonable irrigation demand values developed using modelling should be considered as 'recommended guideline values' only. If an applicant for a consent has more specific soils data prepared by a competent soil scientist, and/or proposes to manage their irrigation system with a different management system than presented in the guidelines, provided that the proposed system can achieve efficient water use, WRC should carefully review the applicant's information (see Appendix K for guidance).

8 References

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Waikato Regional Council (WRC) and Aqualinc Research Ltd (Aqualinc) see stakeholder involvement as a crucial part of not only achieving the specific project goal of improving water allocation, but also to ensure that the project findings actually improve water use efficiency and management in the region as a whole. It is in the interest of all water users in the region that available water resources are allocated efficiently and productively.

In recent times stakeholders have actively participated in the debate on water allocations through plan hearings and consent submissions. This involvement has in part contributed to the initiative for this project.

WRC also recognises the need for stakeholder involvement in water management, through a collaborative and consultative approach. This need is specifically identified in Section 3.4.5.2 of the Regional Plan (Variation 6) (EW, 2006).

There are a number of stakeholder groups with an interest in improvement of water allocation and consumptive water use management in the Region. However, this stage of the project, Aqualinc limited the consultation to those groups with a direct interest in irrigation, particularly as consent holders.

As evident from hearing submissions and the discussions Aqualinc had with the main stakeholders during the previous stage of the project, there is interest not only in water allocation but also in water use efficiency, productivity and downstream impacts of irrigation. While the principal project goal is development of information and processes that improve management of water allocations in the region, achievement of this goal has to be linked with the other broader elements of irrigation water use management in the region. Part of the current problem with existing allocation guidelines, is that they are poorly understood by some stakeholders, and in part not seen in the context of irrigation system design and management and farm productivity.

Therefore, the stakeholder consultation was designed to get their participation to be meaningful and productive. The intention was that it is essential that they see merit in the project goals, and real benefits for the irrigation sector in the Waikato Region. The benefits and linkages of the consultation included:

- Improved understanding of the role and contribution of irrigation to farm productivity in the region (improve the irrigation image); and
- To provide practical information on how improvements in irrigation system design and management can be achieved at the field and farm levels and the production and financial benefits.
- To provide a well-researched and easily understood information source for the planning, design and management of irrigation systems in the Waikato region.
- To develop a good working relationship with individual irrigators and irrigator groups so that next stage of the project, field verification, can be conducted with assistance from stakeholders.

A description of the consultation of different irrigator groups is described below.

Pasture Irrigators

Aqualinc engaged with pasture irrigator groups and Federated Farmers' (FF) Waikato Branch during the consultation process. FF nominated Mr Martin Bennett, chairman of the Upper Waikato Group, to represent FF's interests.

There are two main irrigator groups in the region; The Upper Waikato Irrigator Group and The Waihou Irrigator Group. While the two groups are separate entities they are advised and coordinated by Mr Fred Phillips of Agricultural Business Associates (Hamilton). Mr Phillips is a well-known and prominent consultant in the region and has been active in the public discussion of irrigation and water management issues in the region.

Aqualinc held a meeting with Mr Phillips and Mr Bennett on 25th May, 2009. Aqualinc obtained parameters and information relevant to the soil moisture modelling during this meeting. The information obtained included the current and future potential pasture irrigated areas, what irrigation systems are used, irrigation season, application depths and return intervals for different irrigation systems, and irrigation targets.

Horticulture New Zealand

The interests of horticulture growers are represented by Horticulture New Zealand (HortNZ) within the Waikato Region. Aqualinc liaised with Mr Chris Keenan of HortNZ, and Mr Andrew Barber of AgriBusiness (Pukekohe) during the previous stage of the project. We continued the working arrangement during this stage of the project to complete the consultation that included:

1. A close liaison with Mr Keenan and Mr Barber to formulate and undertake the consultation.
2. A questionnaire that was sent to 330 growers in the region. The questionnaire was designed to raise the awareness about the project amongst the growers, identify their main concern(s) about the current guidelines, and identify what crops are irrigated and how they irrigate them.
3. A consultation through a vegetable growers' reference group. HortNZ organised a reference group from the Pukekohe Vegetable Growers Association (PVGA) to assist Aqualinc to obtain the parameters required for vegetable crops. This consultation was primarily conducted by two meetings held at Pukekohe on 30 July 2009 and 8 October 2009. In addition Aqualinc closely worked with two nominated representatives (Peter Reynolds and Bharat Bhana from the reference group and Andrew Barber of AgriBusiness) to develop irrigation parameters for the most commonly irrigated crops in the Pukekohe area.
4. Consultation with major growers in areas other than Pukekohe (e.g. AS Wilcox in Matamata) to obtain relevant information.

The information sought through this process included:

1. Vegetable crop rotations
2. Irrigation seasons for vegetable crops
3. Irrigations systems used
4. Depth of irrigation used
5. Return period for different irrigation systems
6. Irrigation targets
7. Rooting depth changes for the different crops.

Other Stakeholders

Aqualinc also contacted the following stakeholders who have interest in allocable water resources in the Waikato Region:

- Fonterra: Sean Newland

- DairyNZ: Mike Scarsbrook and Charlotte Glass
- Irrigation New Zealand: Terry Heiler
- Foundation for Arable Research

Industry Expert Consultation

In addition to stakeholder consultation, Aqualinc also conducted an extensive consultation of industry experts to obtain information related to *crop physiology*. The following table lists the names of the people, the sector that they represent, and the information derived or sought from them.

Table A1: Summary of consultation interviews of industry experts

Name	Industry or Sector	Information
Lynda Hawes	Horticultural Consultant	What horticulture crops are currently irrigated and what crops can potentially be irrigated in the future in the Waikato Region Irrigation season for each crop Application depth and return intervals for different crops and irrigation systems Irrigation targets for each crop
Frank Bollen	ZESPRI International Ltd	Irrigation season Application depth and return intervals Irrigation targets
Sarah Sinton	Plant and Food	Irrigation targets for vegetable crops – mainly Potatoes
Mike Trought	Plant and Food	Apple and grape irrigation season Application depth and return intervals Irrigation targets
Marc Greven	Marlborough Wine Research Centre	Grape irrigation season Application depth and return intervals Irrigation targets
Jeremy Carter	Plant and Food	Vegetable irrigation seasons Application depth and return intervals for different crops and irrigation systems Irrigation targets
Stephen Trolov	Plant and Food	Vegetable irrigation seasons Application depth and return intervals for different crops and irrigation systems Irrigation targets
Tessa Mills	Plant and Food	Irrigation targets for Potatoes
Greg Dryden	Fruition Horticulture Ltd	Apple and grape irrigation season Application depth and return intervals Irrigation targets
Bob Parker	Fruition Horticulture Ltd	Irrigation season for kiwifruit, other fruits and vegetable crops Application depth and return intervals Irrigation targets
Mike Butcher	Pipfruit NZ Inc	Irrigation season Application depth and return intervals, and irrigation targets

Name	Industry or Sector	Information
Dan Bloomer	PageBloomer Consultants	Irrigation seasons for horticulture crops Application depth and return intervals Irrigation targets
Tony Daveron	Hydro Services Ltd	Irrigation seasons for horticulture crops Application depth and return intervals Irrigation targets
John Bealing	Horticultural Consultant	Irrigation seasons for horticulture crops Application depth and return intervals Irrigation targets

Irricalc model uses the water balance modelling approach developed by the Food and Agriculture Organization (FAO) of the United Nations Allen *et al*. (1998). The relationship between crop and reference evapotranspiration:

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

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 Section 3. For vegetables, k_c varies with the time of year.

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 as the total depth of irrigation water times the application efficiencies given in Section 4. 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. For vegetables, PAW varied with the time of year as the crop rooting depth varied.

Irricalc 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 will be less than recommended in this report[2].

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.

[2] In poorly drained soils, or where soil pans exist or the groundwater is close to the surface, irrigation water requirements will be less than recommended in this guidelines. 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. Additionally, water can move upward from the saturated conditions to meet plant water demand in poorly drained soils. Thus the crop grown in poorly drained soils can take advantage of summer rainfalls better and require less irrigation than crops on free draining soils. However, our experience in the Waikato is that irrigation does not occur often on these poorly drained soils due to the generally high water holding capacities of these soils. Therefore, the guidelines values are representative of most cases for the irrigation of crops in the Waikato. However, in cases where poorly drained soils are present, WRC can use the guidelines values provided to determine a more appropriate but lower value. However, we believe that such complications are not necessary for overall efficiency in water allocation for irrigation for the region, as these situations are uncommon.

The model inputs used for Irricalc modelling are documented in this Appendix.

C1 Evapotranspiration

Evapotranspiration (ET) is the water that evaporates from the ground surface, and the water that plants transpire through their leaves. ET changes with the climate (i.e. the temperature, amount of solar energy input, wind strength, and the humidity), the crop type, and the amount of moisture in the soil. When estimating ET, the climate factors are accounted for by the estimation of the reference ET (ETo). ETo is the water requirements for a well-watered reference crop, usually pasture. ET for other crops, and when soil moisture is less than the readily available water, is calculated by multiplying ETo by a crop and soil water stress factor (Eqn 1).

C1.1 Calculating ETo

Both the Penman equation (Penman, 1948) and the FAO 56 methodology (Allen *et al*., 1998) are good predictors of potential grass evapotranspiration. Lysimeter studies from international publications indicate that neither method has a particular advantage over the other method (Yoder *et al*., 2005).

NIWA calculate ETo using the Penman equation. Scotter and Heng (2003) compared NIWA's Penman ETo estimates with FAO 56 estimates, for a number of climate stations across NZ. They found FAO 56 estimates tended to be about 0.3 mm/day lower in summer and 0.3 mm/day higher in winter, than the NIWA estimates.

Aqualinc repeated Scotter and Heng's (2003) analysis at Rukuhia (climate station no. 12616) (Figure C1:). Analysis was for the period October 1996 to December 2005. Daily ETo was calculated from total daily radiation, wet and dry bulb temperature at 9am, maximum and minimum daily temperature, and average daily wind speed. 99% of daily data was available and did not need to be estimated from other parameters (e.g. radiation was directly measured, rather than estimated from sunshine hours). Figure C1: results agree with Scotter and Heng's findings, that FAO 56 estimates are slightly lower in summer and slightly higher in winter, than NIWA's Penman estimates.

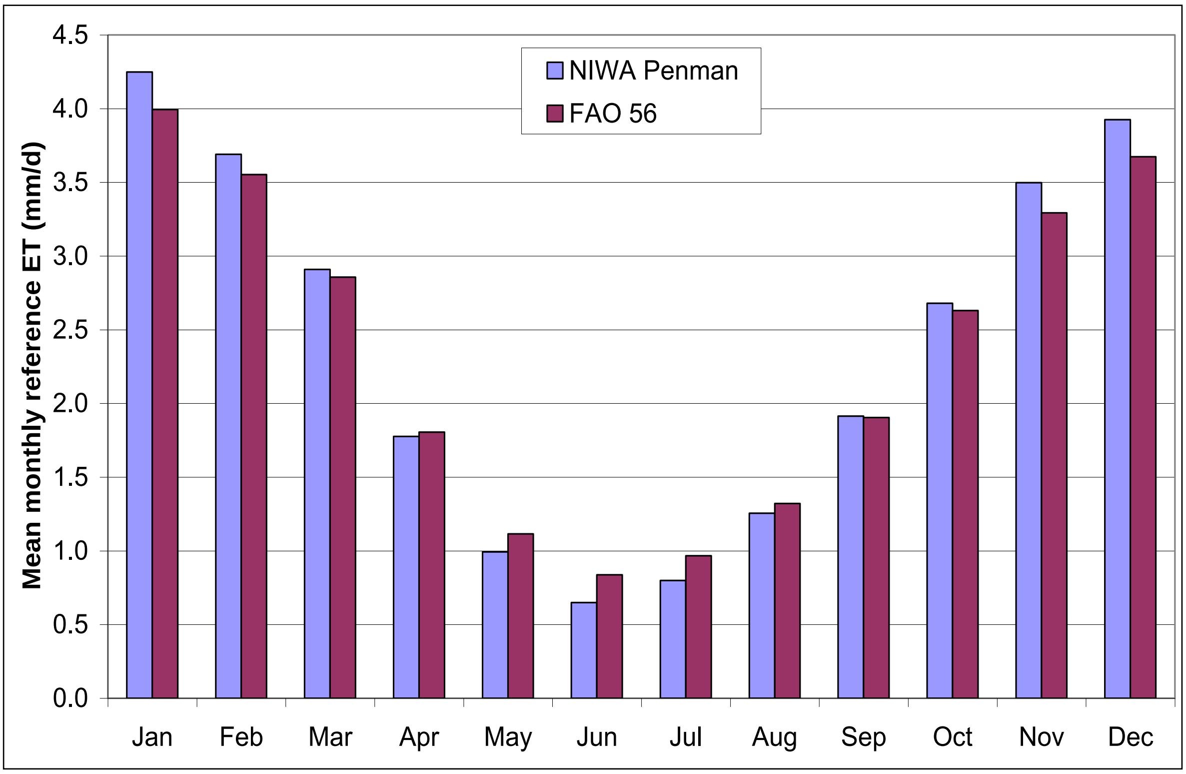

Figure C1: Mean monthly ETo at Rukuhia calculated by NIWA using the Penman equation, and calculated by Aqualinc using the FAO 56 methodology.

Both Penman and FAO 56 methods are suitable for use in water balance modelling (Allen *et al*., 1998). Both methods can be calibrated to local crops and irrigation practices using crop coefficients. When using crop coefficients, it is beneficial to know which method was used in the calibration process. For instance, crop coefficients calculated assuming the FAO 56 methodology should ideally be adjusted if used with ETo Penman values.

NIWA's Penman ETo estimates were used in this study because these estimates are readily available, the method is more commonly applied in NZ, and because this method has no disadvantages compared with FAO 56 (Yoder *et al*., 2005).

C1.2 ETo Spatial Variability

NIWA have produced daily ETo estimates, for a 5 km by 5 km grid of virtual climate stations (VCS) across NZ, for the period 1 January 1972 to the present (Tait and Wood, 2007). VCS data is based on regression equations in both spatial and temporal dimensions. VCS estimates are a mean estimate; therefore for some locations ETo will be slightly over-estimated and for some locations ETo will be slightly under-estimated (Table C1). The VCS data however, is currently the best available estimate of ETo data, where actual measurements are not available for a given location and a particular time. Where both VCS data and actual data are available, the two data sets are generally very similar, as illustrated in Table C1, Figure C2, Figure C3, Figure C4 and Figure C5. Actual climate station and VCS predicted mean annual ETo, for the whole of the Waikato, are also shown in Figure C6.

Table C1: Comparison between ETo estimates from real and virtual climate stations

Location	Mean annual ETo (mm/y), 1972-2009		RMSE[3] of the difference between 7-day ETo (mm)
	Real climate station[1]	Virtual climate stations[2]	
Pukekohe	855	877	0.1
Taupo	832	869	0.3
Te Kuiti	770	801	0.1
Thames	964	923	0.2

[1] There is minor statistical uncertainty with mean annual estimates because not all records extend from June 1972 to May 2009.

[2] VSC estimates are a weighted average (using inverse square of the distance) of the 4 nearest VCS to the actual climate station

[3] Root mean squared error

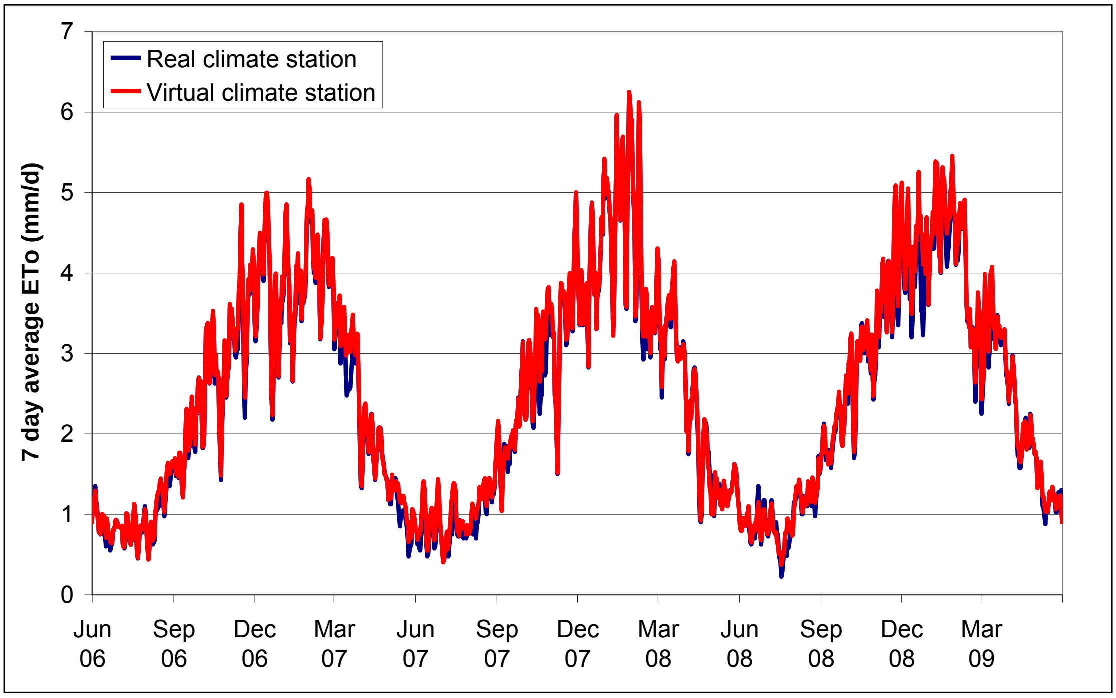

Figure C2: Comparison between ETo estimates from the climate station at Pukekohe (Agent No. 2005 & 2006), and the nearest virtual climate stations.

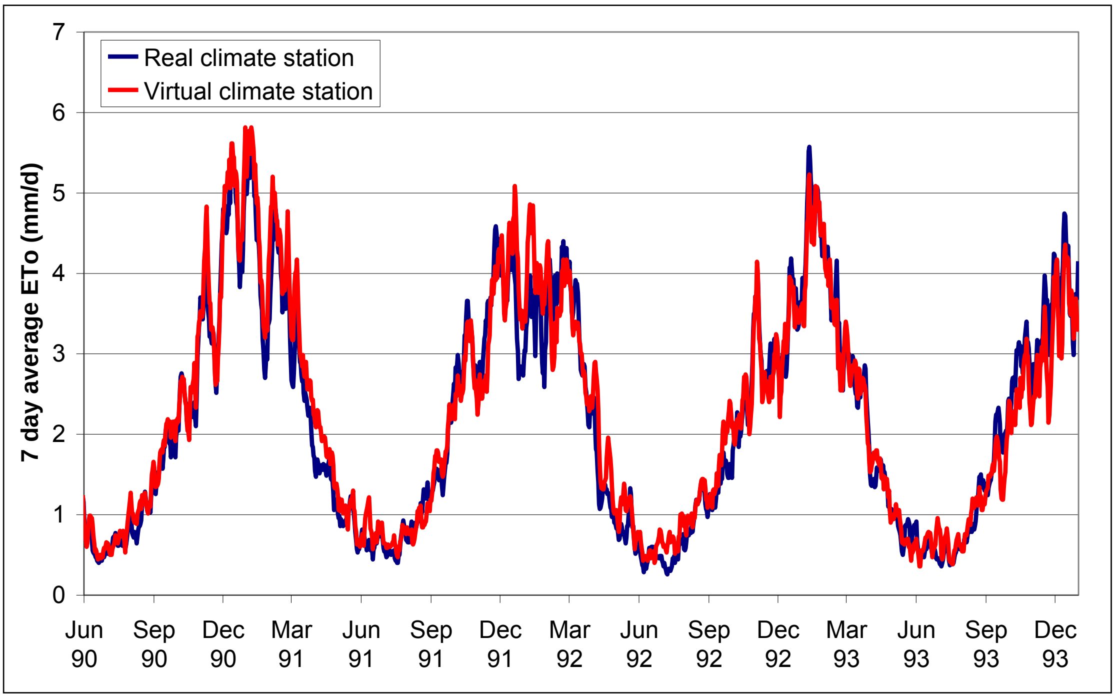

Figure C3: Comparison between ETo estimates from the climate station at Taupo (Agent No. 1841), and the nearest virtual climate stations.

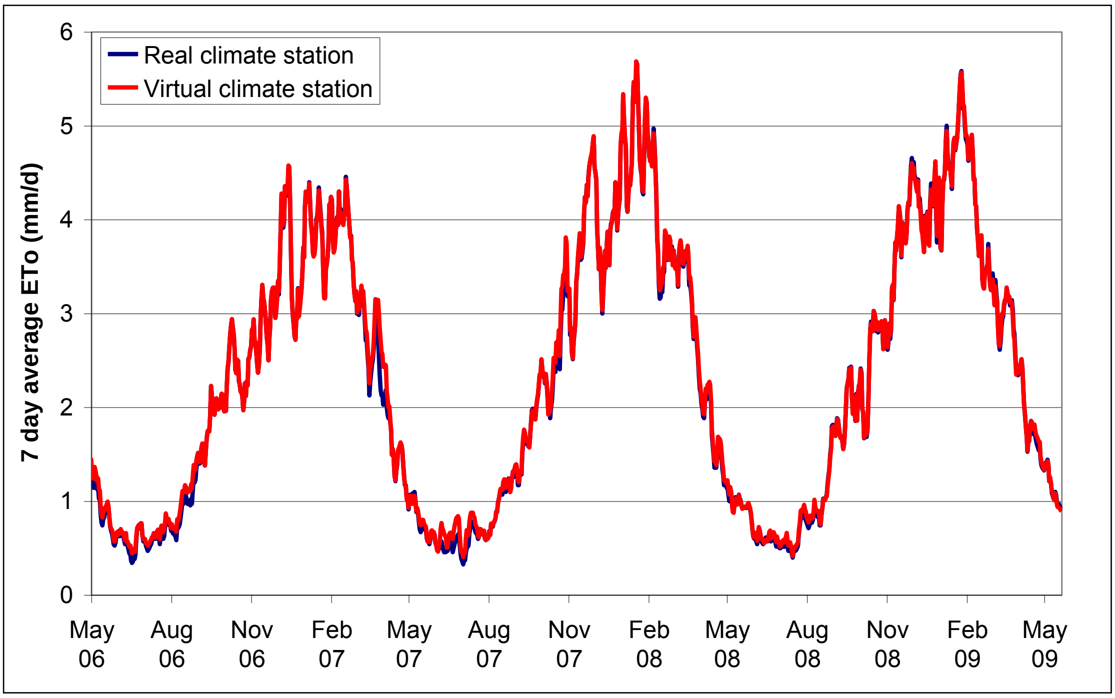

Figure C4: Comparison between ETo estimates from the climate station at Te Kuiti (Agent No. 2212 & 23,899), and the nearest virtual climate stations.

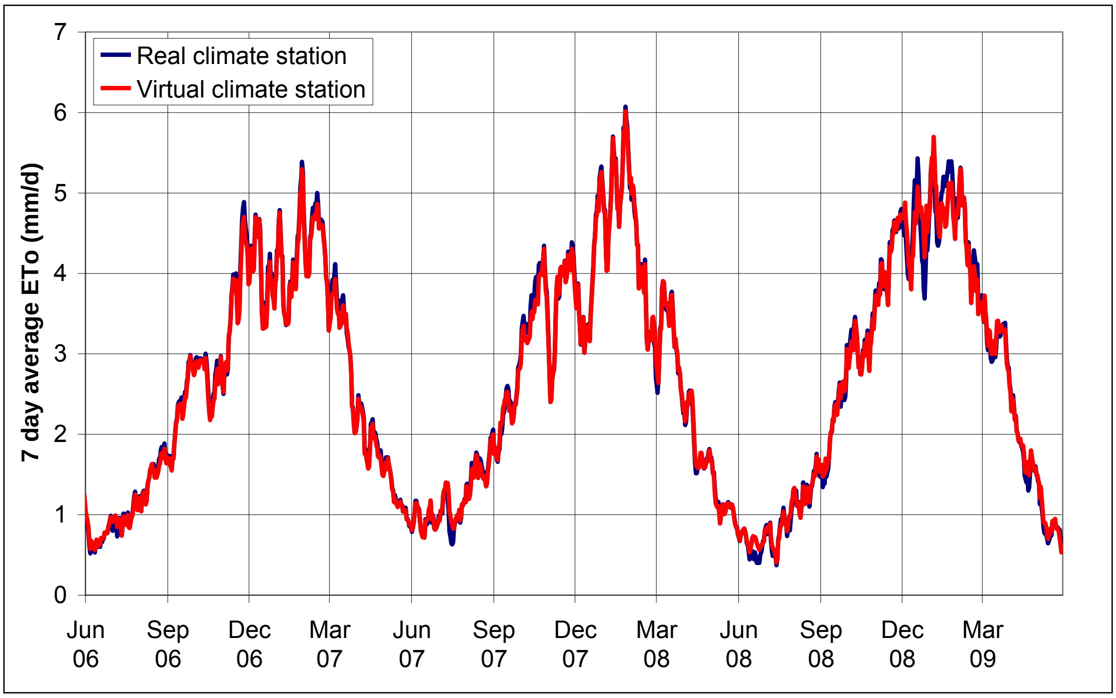

Figure C5: Comparison between ETo estimates from the climate station at Thames (Agent No. 1529), and the nearest virtual climate stations.

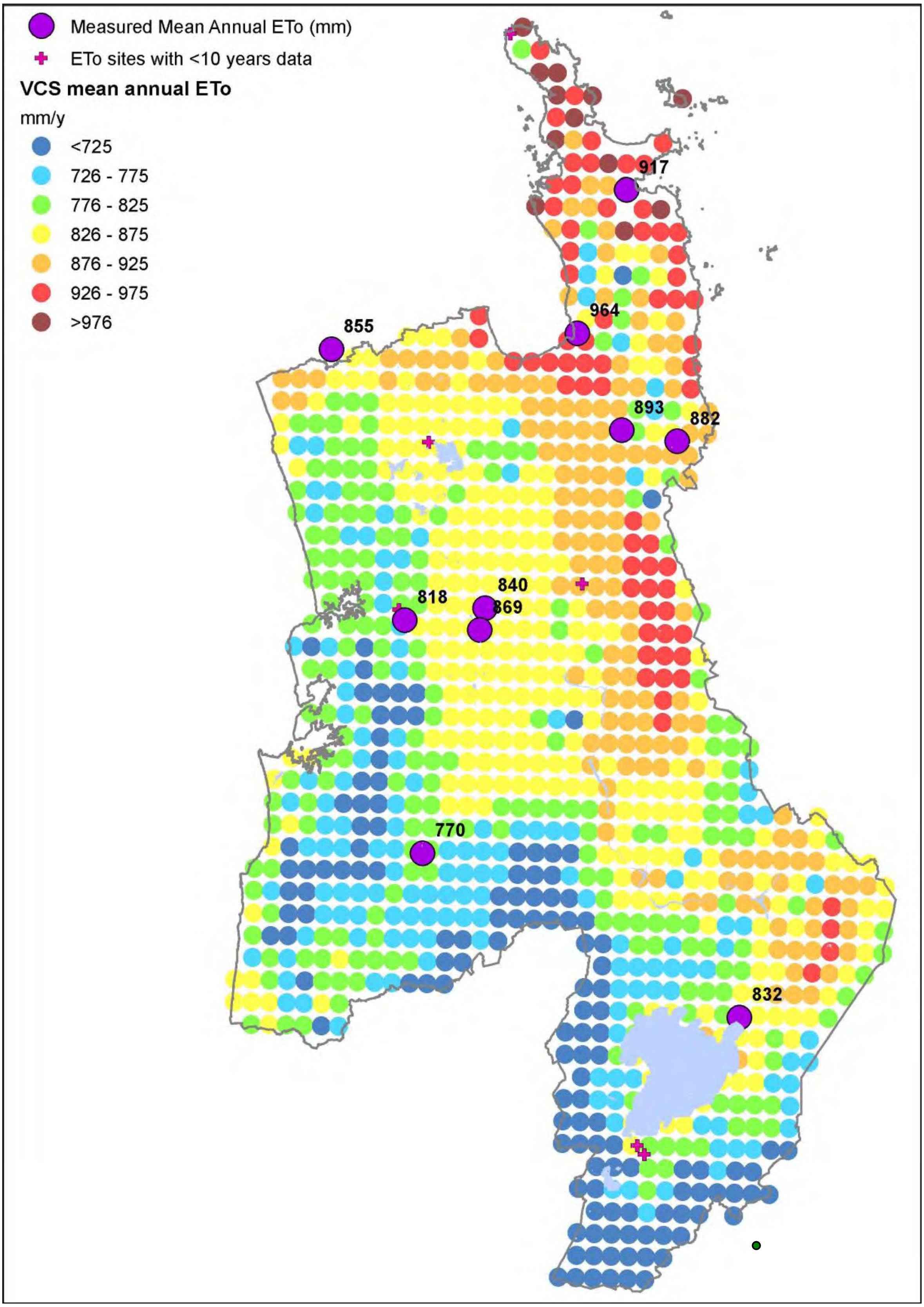

Figure C6: Comparison between mean annual ETo, calculated by NIWA using the Penman equation, as measured at actual ETo sites with >10 years data, and as predicted by NIWA's Virtual Climate Stations (VCS)

C2 Rainfall

Rainfall varies considerably across Waikato. However, there are a large number of rainfall stations that capture this spatial variability. However as with ET, NIWA have produced daily rainfall estimates, for a 5 km by 5 km grid of VCS across New Zealand (Tait *et al*., 2006). NIWA's VCS have been shown to model well the actual rainfall patterns and spatial distributions that are relevant to water balance modelling (Aqualinc, 2008b; Cichota *et al*., 2008). Actual climate station and VCS predicted mean annual rainfall for the whole of the Waikato are shown in Figure C7.

Worked example:

The VCS data is available at a 5 km by 5 km grid. Therefore, selecting the correct VCS that is the most representative for a farm is important. A worked example is given in Appendix K.

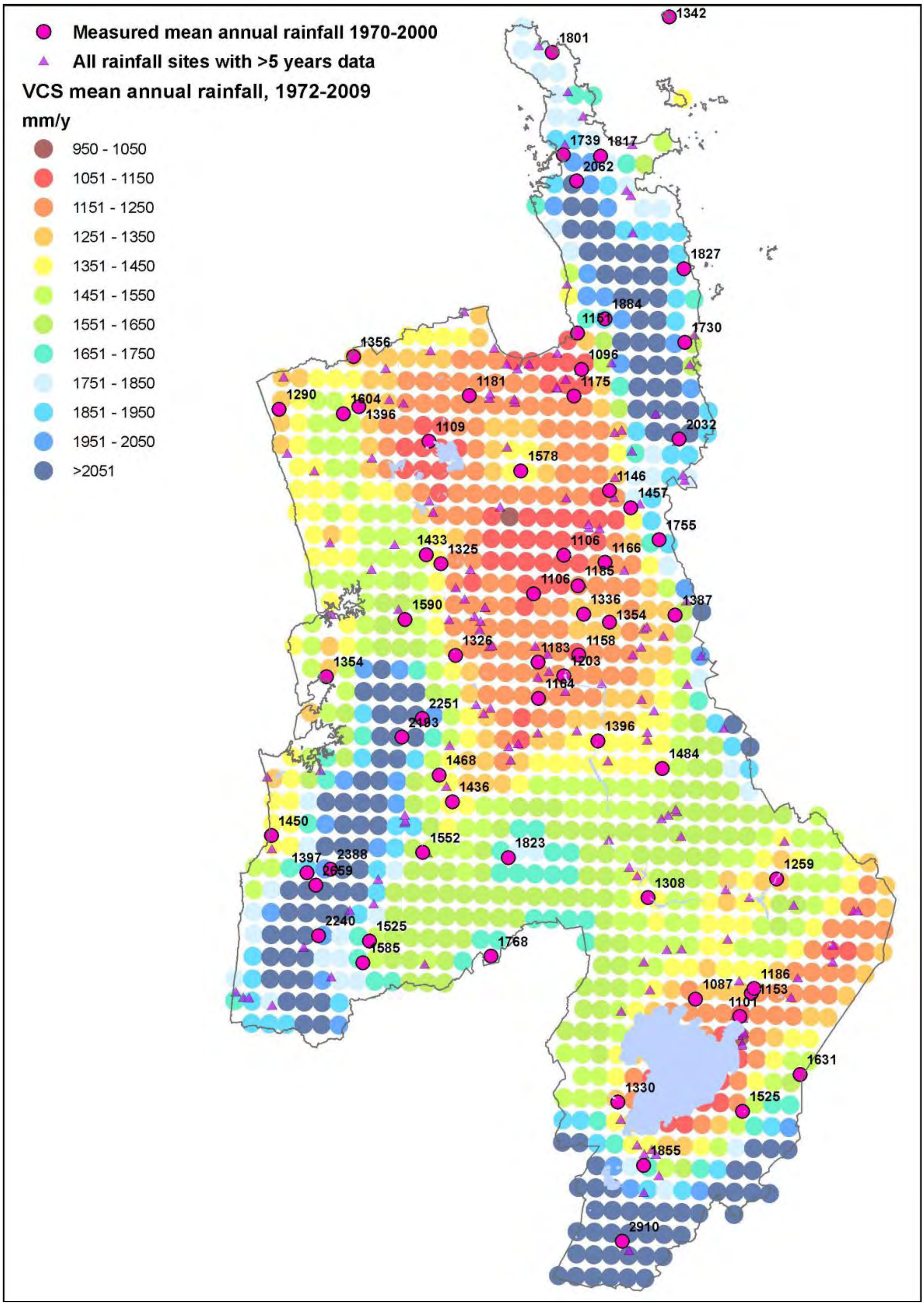

Figure C7: Comparison between mean annual rainfall as measured at actual rainfall sites for the period 1970 to 2000, and as predicted by NIWA's Virtual Climate Stations (VCS).

C2 Soils

The key soil property for irrigation is the plant available water at field capacity (PAW). PAW is the amount of water that a soil can store, that is available for plants to use. Given the same soil, PAW differs between crops because different plants have different rooting depths.

Soils vary considerably from location to location. At the time of modelling work was carried out in 2008, the best single source of PAW information, that covers the whole of the Waikato Region, is the New Zealand Fundamental Soils Layer (NZFSL) by Landcare (2000). The NZFSL has low spatial resolution and local soil features are often not picked up. Therefore it is recommended, where possible higher resolution soil surveys such as S-Map (Landcare, 2004) or on-farm testing by a soil scientist, should be used in preference to NZFSL data.

Irrigation water requirements were calculated for the 1006 virtual climate stations in the Waikato for the PAW classes described in Table C2:. This means if higher resolution soils information is available in the future, WRC will be able to calculate water use requirements without a need for additional model runs. Poor soils resolution was a key cause of confusion in the application of Landcare's (1997) original water requirement recommendations.

Table C2: Soil classes

PAW range (mm)	PAW class (mm)
30-50	40
51-75	60
76-125	100
126-175	150
176-225	200
>226	250

Appendix C shows NZFSL soils average PAW values, adjusted for rooting depths of 600 mm and 900 mm, and aggregated into the classes given in Table C2. PAW values were adjusted for rooting depth using the "rule of thumb" proposed by Trevor Webb of Landcare for North Otago (Aqualinc, 2003b):

> *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.*

Worked example:

A worked example is presented on how to determine the appropriate PAW for different rooting depths in Appendix K.

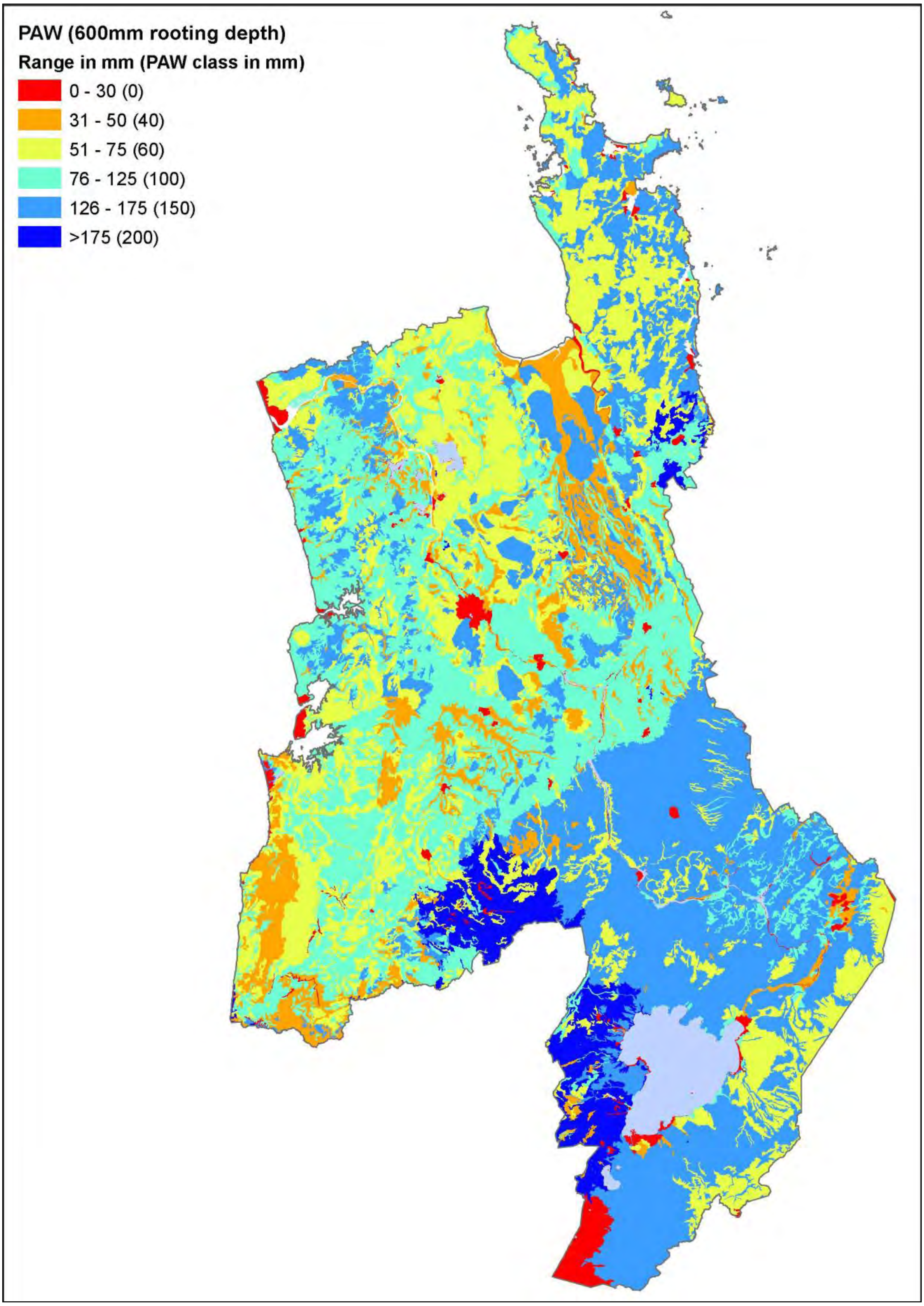

Figure C8: Soil plant available water at field capacity (PAW) from Landcare (2000), adjusted to a 600 mm rooting depth.

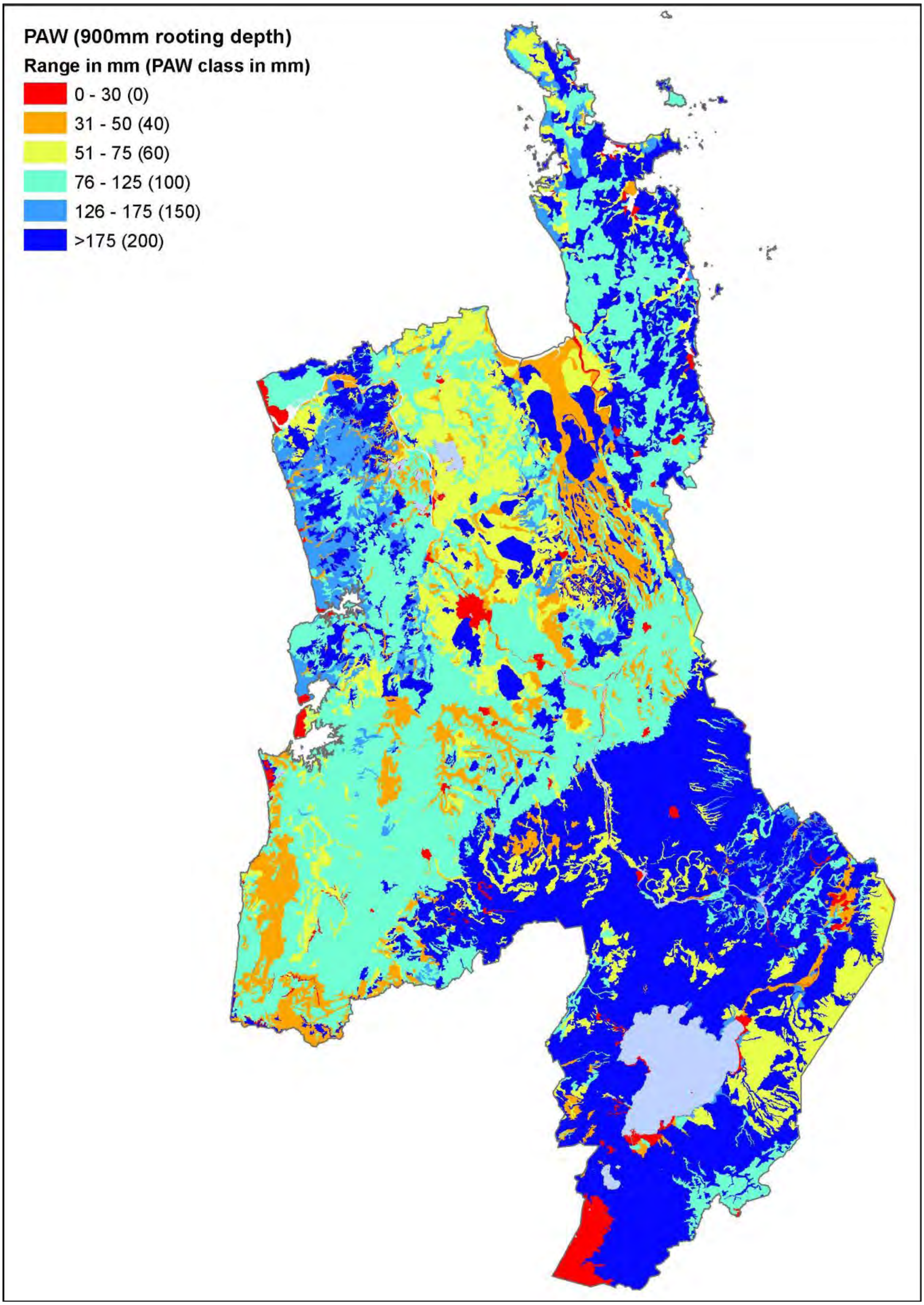

Figure C9: Soil plant available water at field capacity (PAW) from Landcare (2000), given a 900 mm rooting depth.

Table D1: Vegetable rotation 1: Crop coefficient series

Days since planting	Crop	Date	Crop coefficient (k_c)
0	Carrots	1-Apr	0.70
30	Carrots	30-Apr	0.70
60	Carrots	30-May	1.05
102	Carrots	11-Jul	1.05
122	Carrots	31-Jul	0.95
123	Fallow	1-Aug	0.40
214	Fallow	31-Oct	0.40
215	Potatoes	1-Nov	0.50
249	Potatoes	5-Dec	0.50
284	Potatoes	9-Jan	1.15
334	Potatoes	28-Feb	1.15
366	Potatoes	1-Apr	0.50

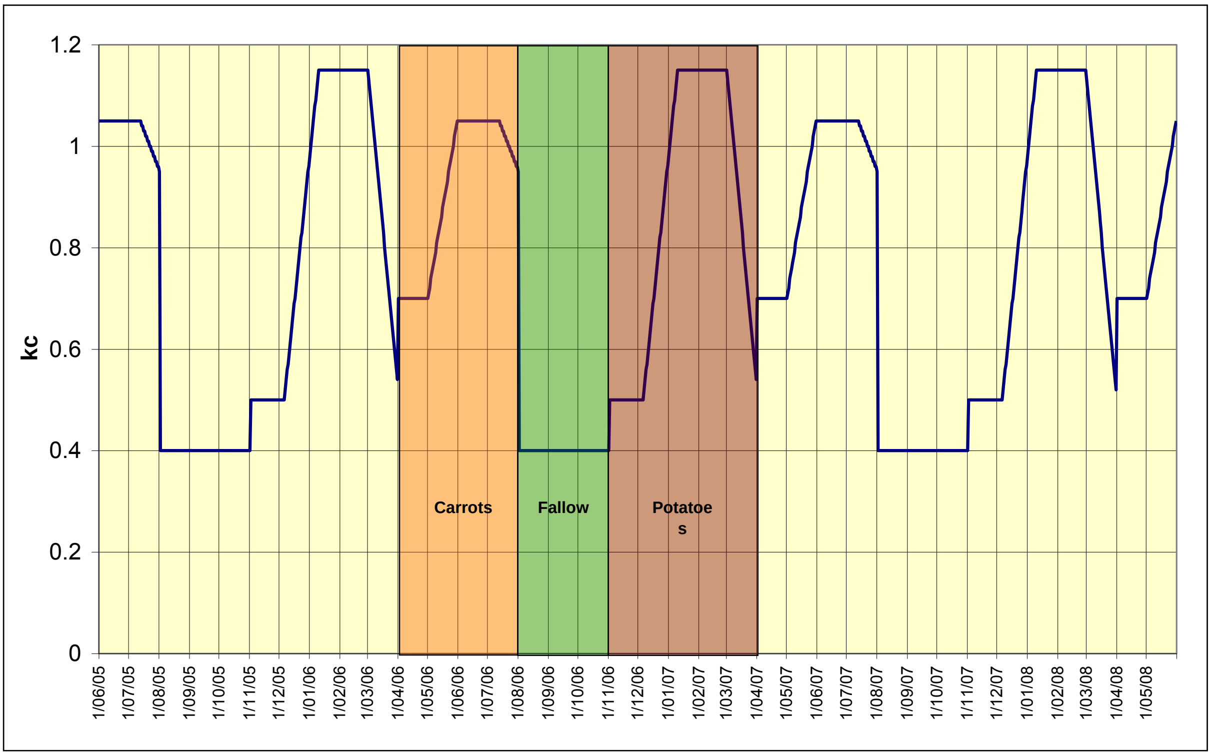

Figure D1: Vegetable rotation 1: Crop coefficient series

Table D2: Vegetable rotation 2: Crop coefficient series

Days since planting	Crop	Date	Crop coefficient (k_c)
0	Potatoes	15-Nov	0.50
30	Potatoes	14-Dec	0.50

65	Potatoes	18-Jan	1.15
115	Potatoes	9-Mar	1.15
152	Potatoes	15-Apr	0.50
153	Fallow	16-Apr	0.40
366	Fallow	15-Nov	0.40

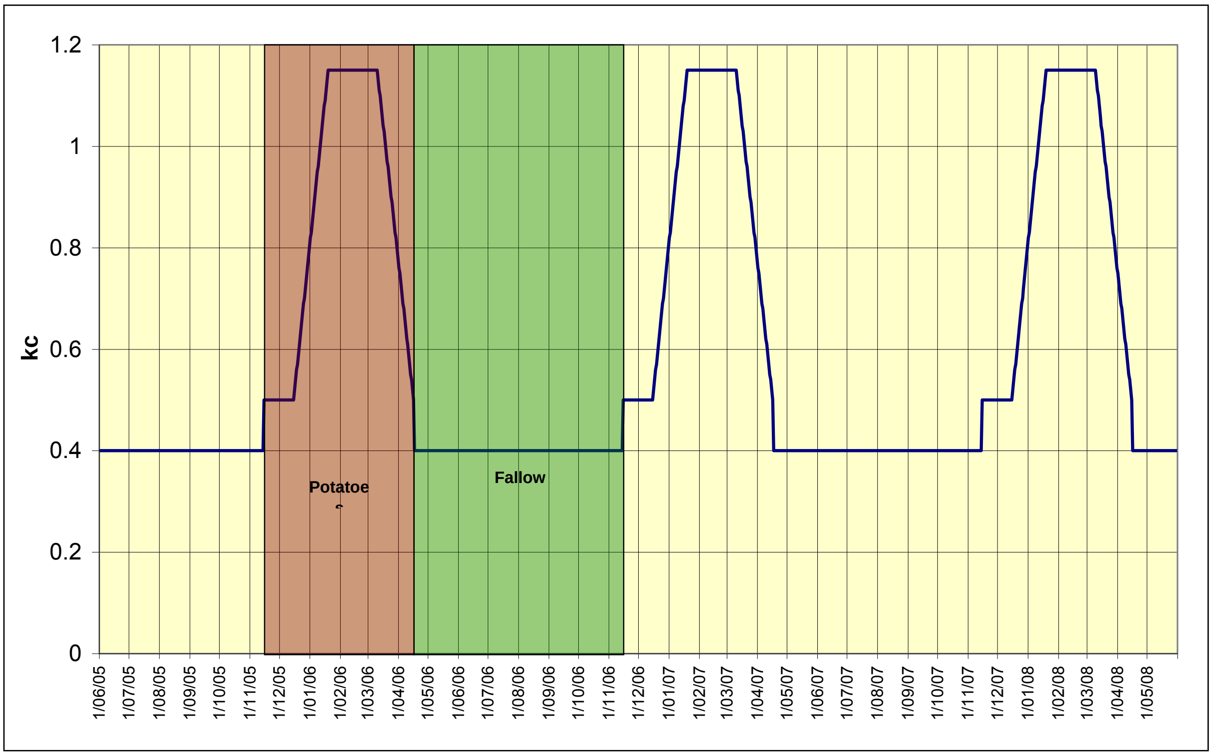

Figure D2: Vegetable rotation 2: Crop coefficient series

Table D3: Vegetable rotation 3: Crop coefficient series

Days since planting	Crop	Date	Crop coefficient (k_c)
0	Onions	1-Sep	0.70
20	Onions	20-Sep	0.70
50	Onions	20-Oct	1.05
140	Onions	18-Jan	1.05

180	Onions	27-Feb	0.75
181	Fallow	28-Feb	0.40
212	Fallow	31-Mar	0.40
213	Lettuce	1-Apr	0.70
235	Lettuce	23-Apr	0.70
270	Lettuce	28-May	1.00
290	Lettuce	17-Jun	1.00
303	Lettuce	30-Jun	0.95
304	Fallow	1-Jul	0.40
366	Fallow	1-Sep	0.40

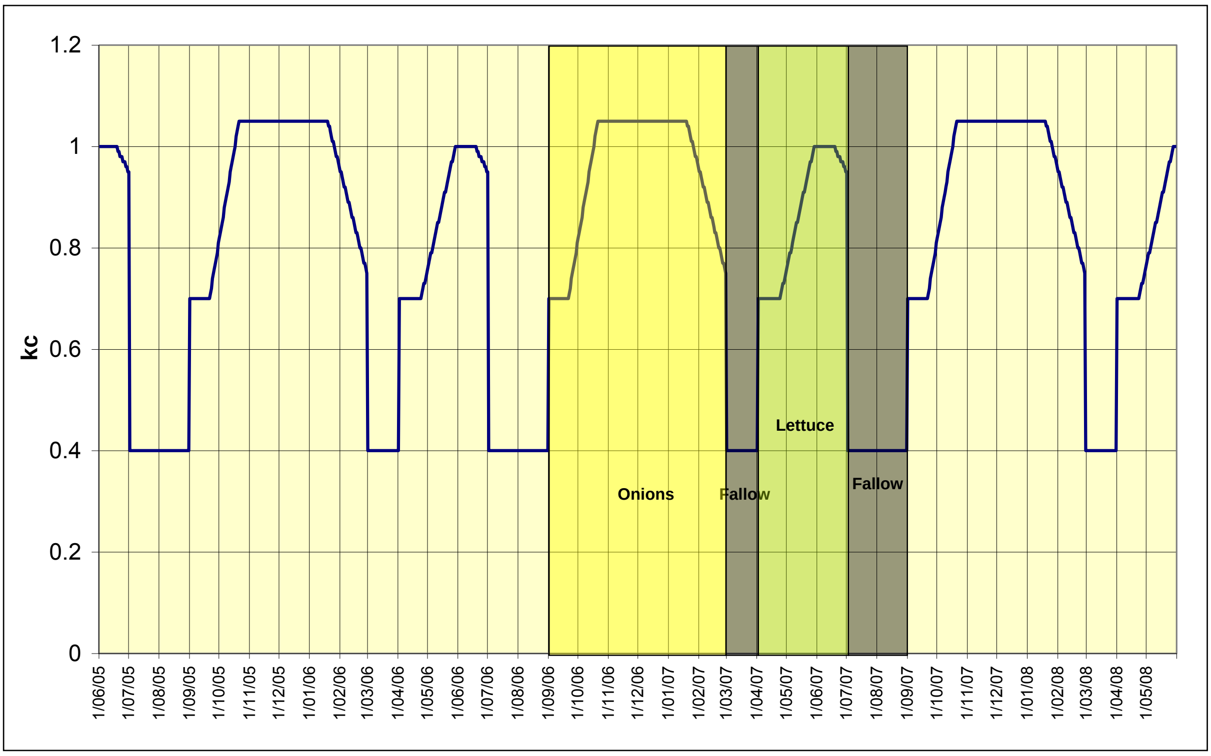

Figure D3: Vegetable rotation 3: Crop coefficient series

Table D4: Vegetable rotation 4: Crop coefficient series

Days since planting	Crop	Date	Crop coefficient (k_c)
0	Lettuce	1-Nov	0.70
20	Lettuce	20-Nov	0.70
40	Lettuce	10-Dec	1.00
51	Lettuce	21-Dec	1.00
61	Lettuce	31-Dec	0.95
62	Fallow	1-Jan	0.40
120	Fallow	28-Feb	0.40
121	Lettuce	1-Mar	0.70
141	Lettuce	21-Mar	0.70
161	Lettuce	10-Apr	1.00
171	Lettuce	20-Apr	1.00
181	Lettuce	30-Apr	0.95
182	Cauiflower	1-May	0.70
212	Cauiflower	31-May	0.70
257	Cauiflower	15-Jul	1.05
292	Cauiflower	19-Aug	1.05
304	Cauiflower	31-Aug	0.95
305	Fallow	1-Sep	0.40
366	Fallow	1-Nov	0.40

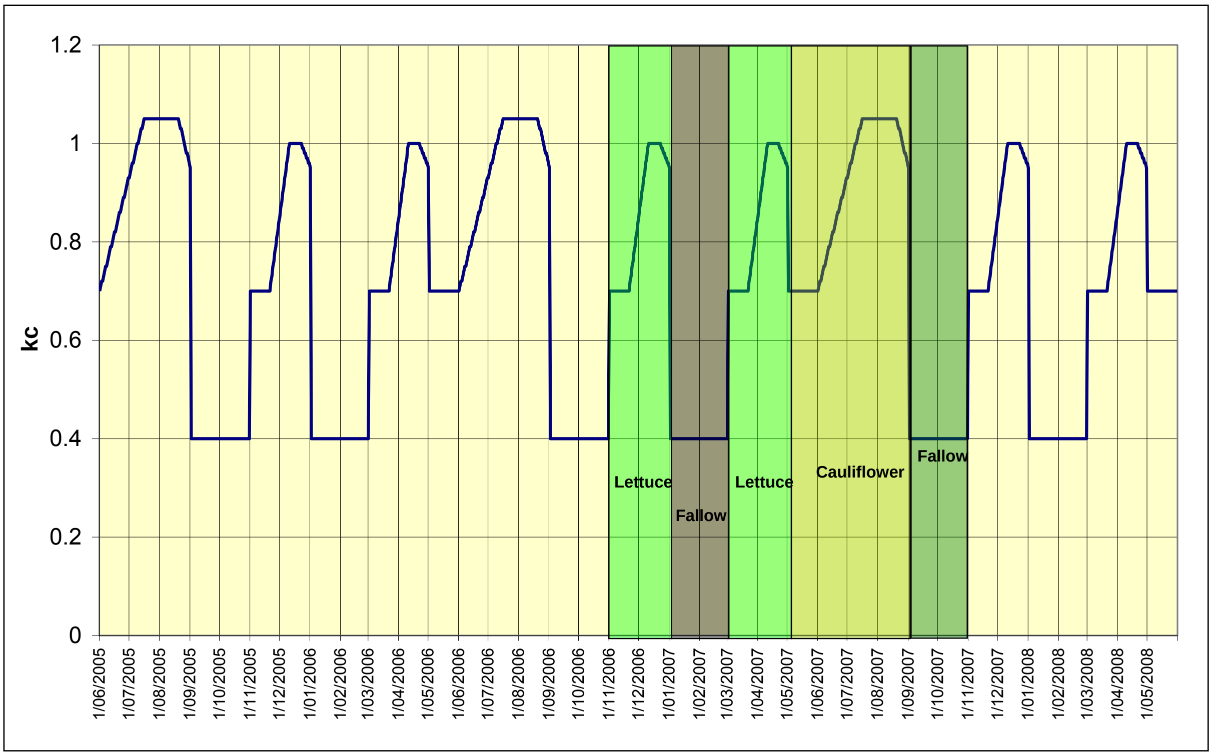

Figure D4: Vegetable rotation 4: Crop coefficient series

Table D5: Vegetable rotation 1: Crop rooting depth

Days since planting	Crop	Date	Rooting depth (mm)
0	Carrots	1-Apr	50
122	Carrots	31-Jul	600
123	Fallow	1-Aug	200
214	Fallow	31-Oct	200
215	Potatoes	1-Nov	100
300	Potatoes	25-Jan	400
365	Potatoes	31-Mar	450

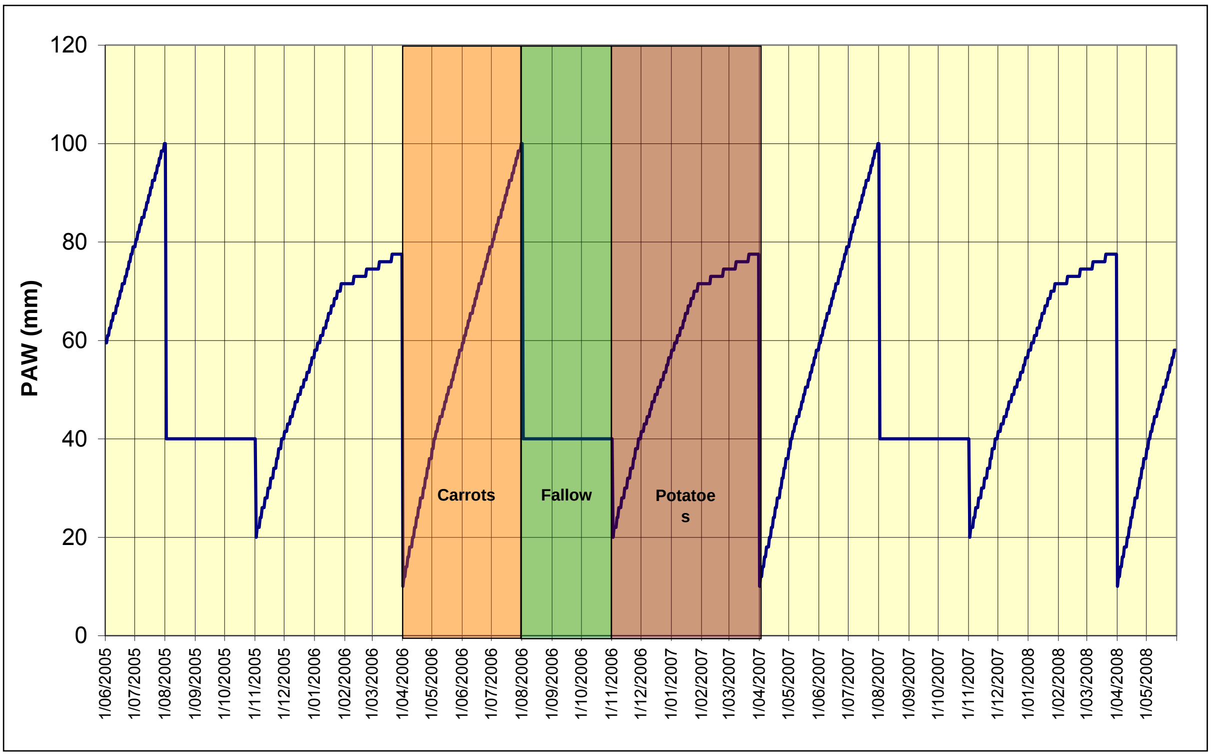

Figure D5: Vegetable rotation 1: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 100mm

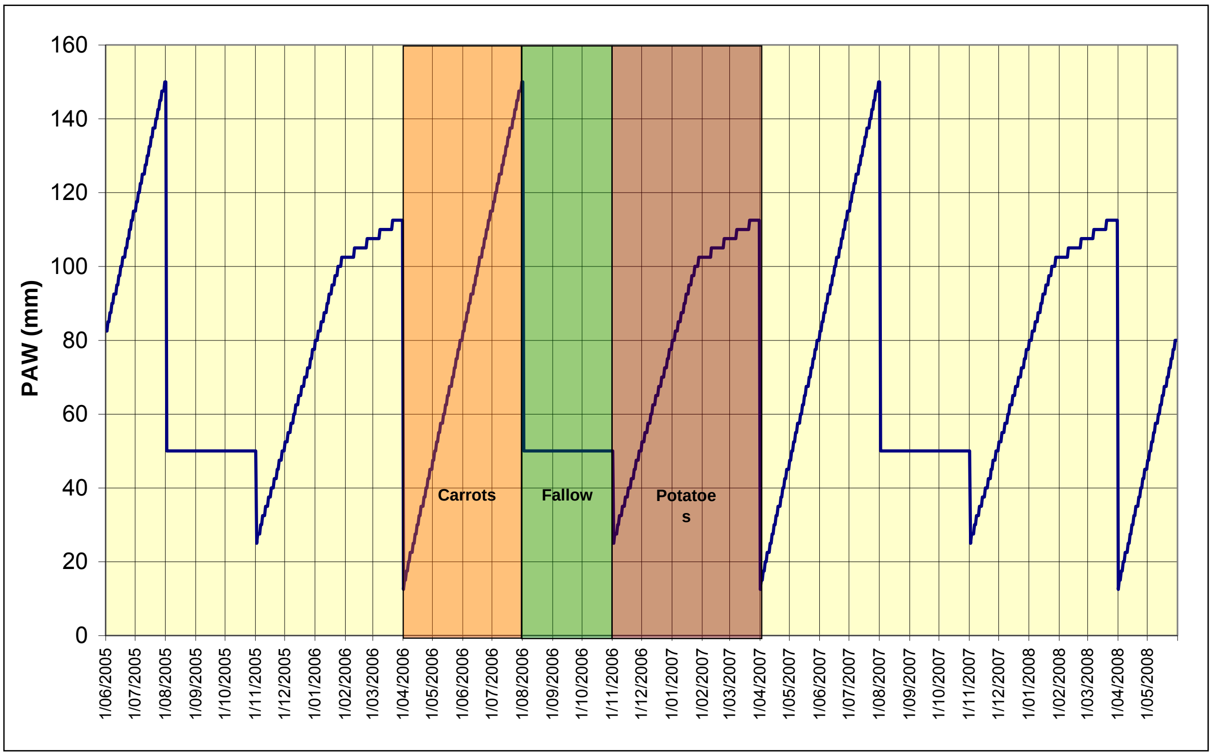

Figure D6: Vegetable rotation 1: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 150mm

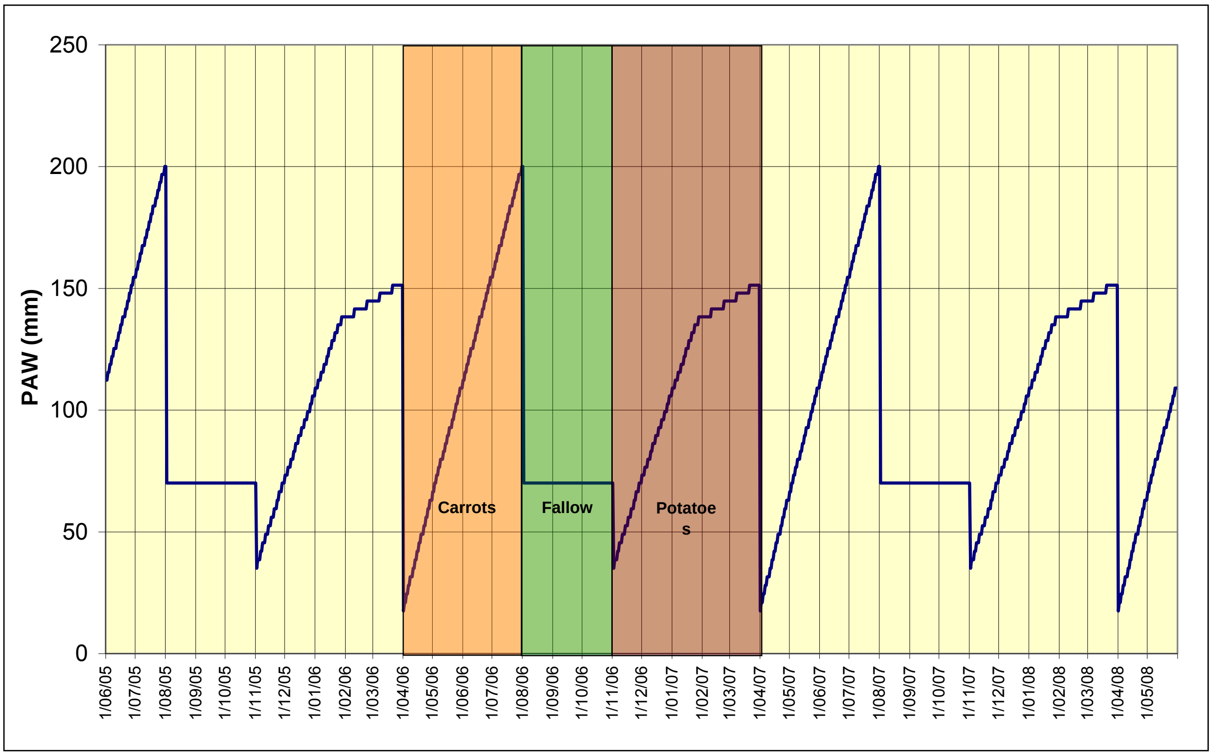

Figure D7: Vegetable rotation 1: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 200mm

Table D6: Vegetable rotation 2: Crop rooting depth

Days since planting	Crop	Date	Rooting depth (mm)
0	Potatoes	15-Nov	100
85	Potatoes	7-Feb	400
152	Potatoes	15-Apr	450
153	Fallow	16-Apr	200
366	Fallow	15-Nov	200

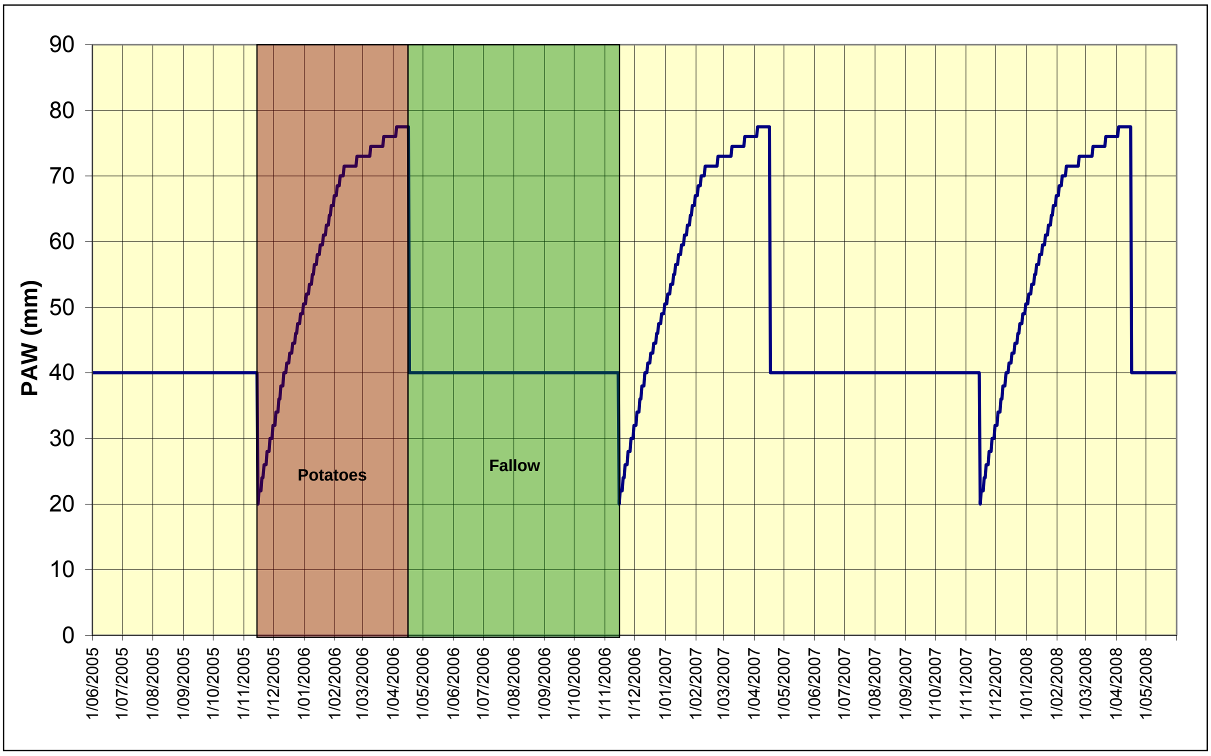

Figure D8: Vegetable rotation 2: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 100mm

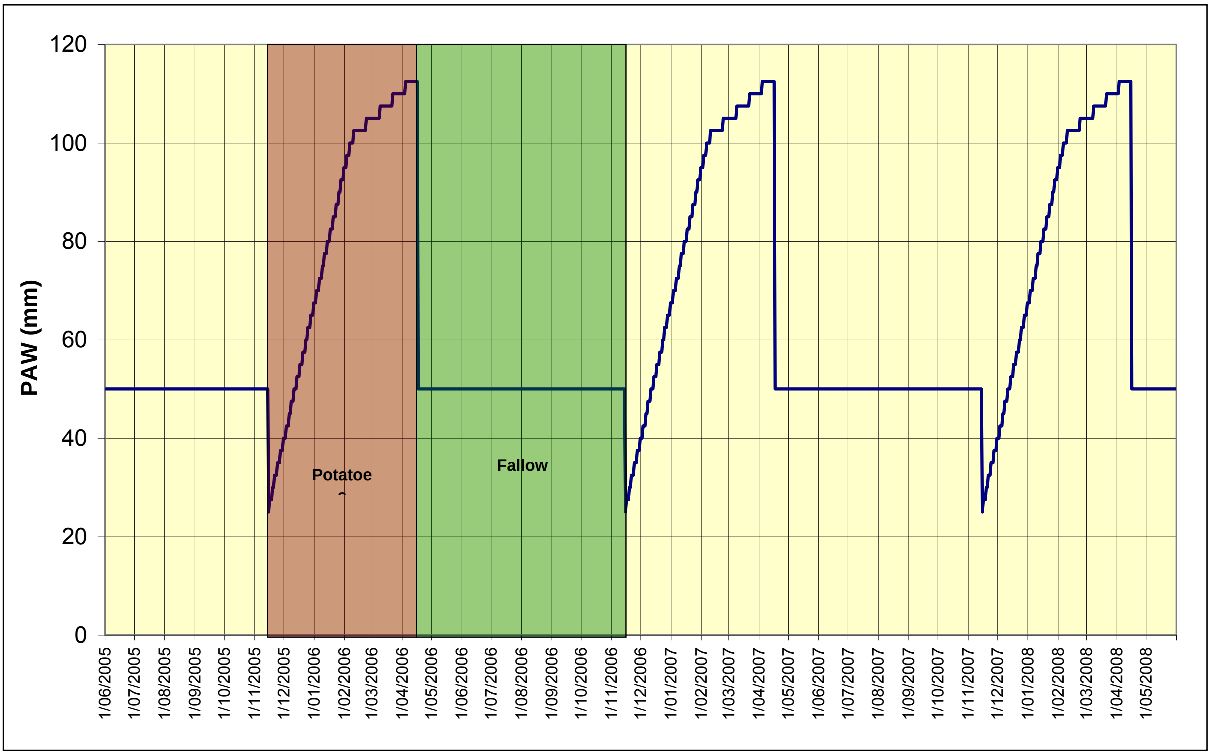

Figure D9: Vegetable rotation 2: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 150mm

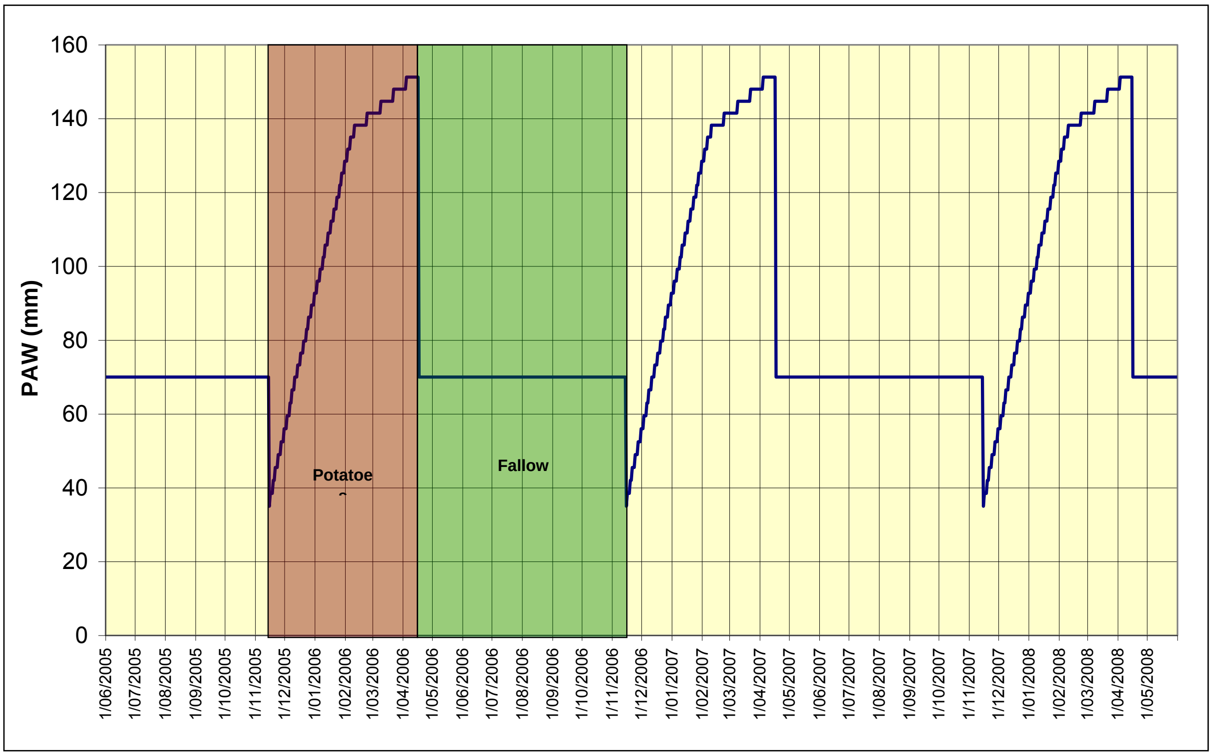

Figure D10: Vegetable rotation 2: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 200mm

Table D7: Vegetable rotation 3: Crop rooting depth

Days since planting	Crop	Date	Rooting depth (mm)
0	Onions	1-Sep	100
140	Onions	18-Jan	450
180	Onions	27-Feb	450
181	Fallow	28-Feb	200
212	Fallow	31-Mar	200
213	Lettuce	1-Apr	75
303	Lettuce	30-Jun	400
304	Fallow	1-Jul	200
366	Fallow	1-Sep	200

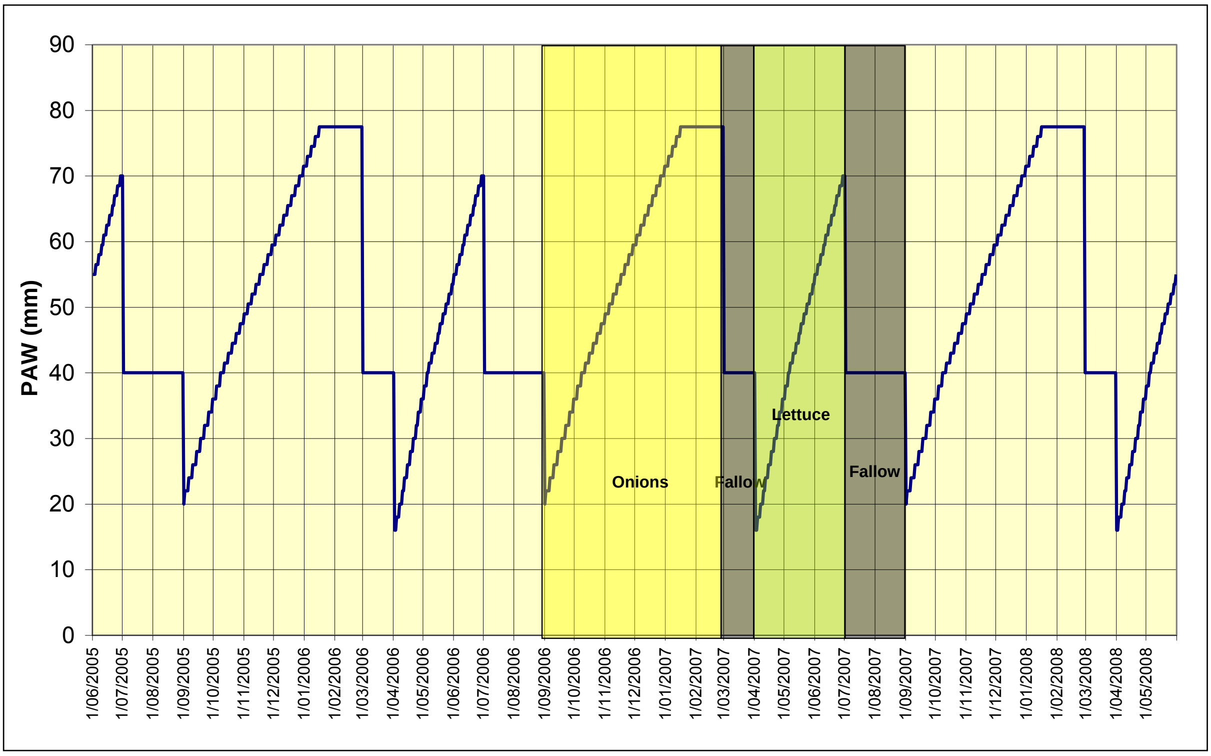

Figure D11: Vegetable rotation 3: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 100mm

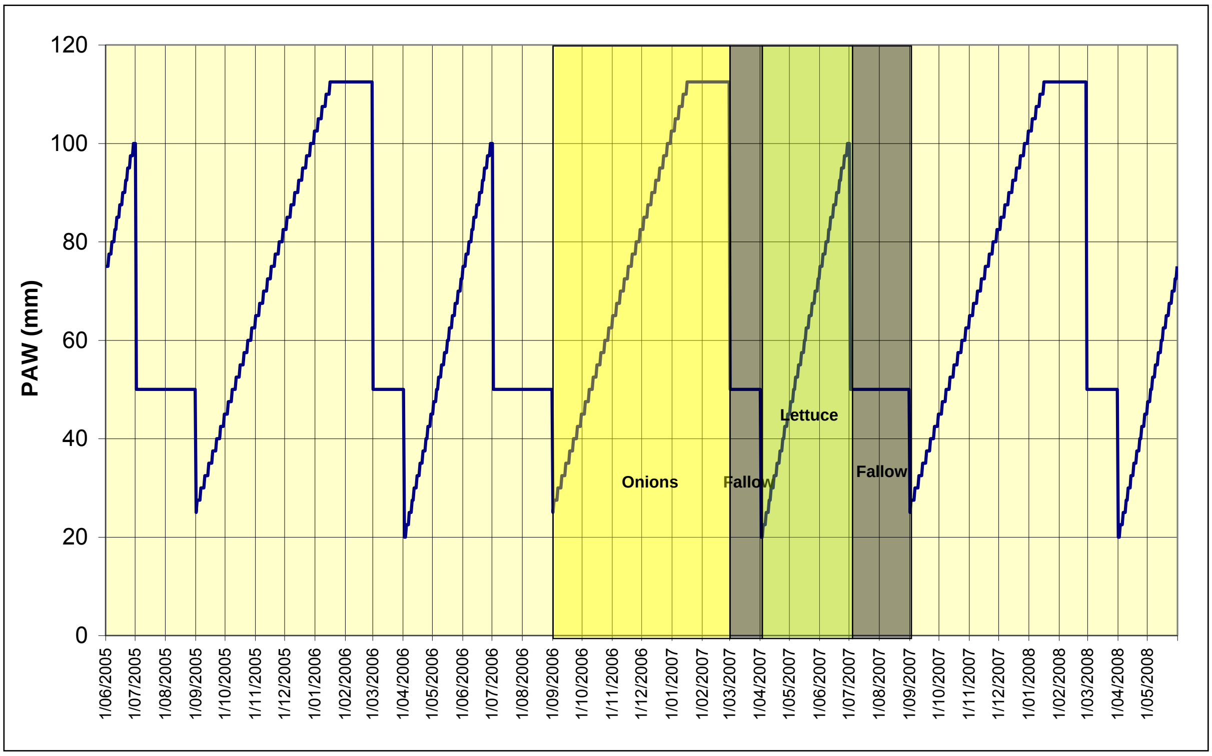

Figure D12: Vegetable rotation 3: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 150mm

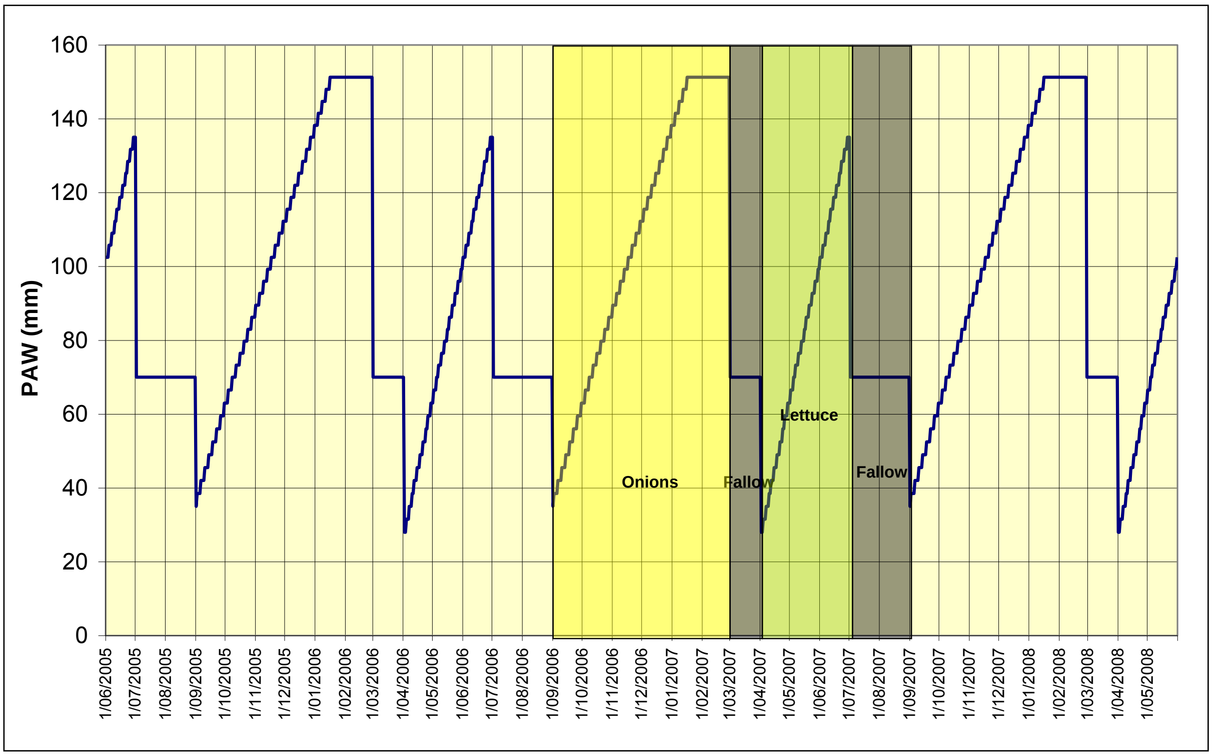

Figure D13: Vegetable rotation 3: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 200mm

Table D8: Vegetable rotation 4: Crop rooting depth

Days since planting	Crop	Date	Rooting depth (mm)
0	Lettuce	1-Nov	75
61	Lettuce	31-Dec	400

62	Fallow	1-Jan	200
120	Fallow	28-Feb	200
121	Lettuce	1-Mar	75
181	Lettuce	30-Apr	400
182	Cauliflower	1-May	75
292	Cauliflower	19-Aug	450
304	Cauliflower	31-Aug	450
305	Fallow	1-Sep	200
366	Fallow	1-Nov	200

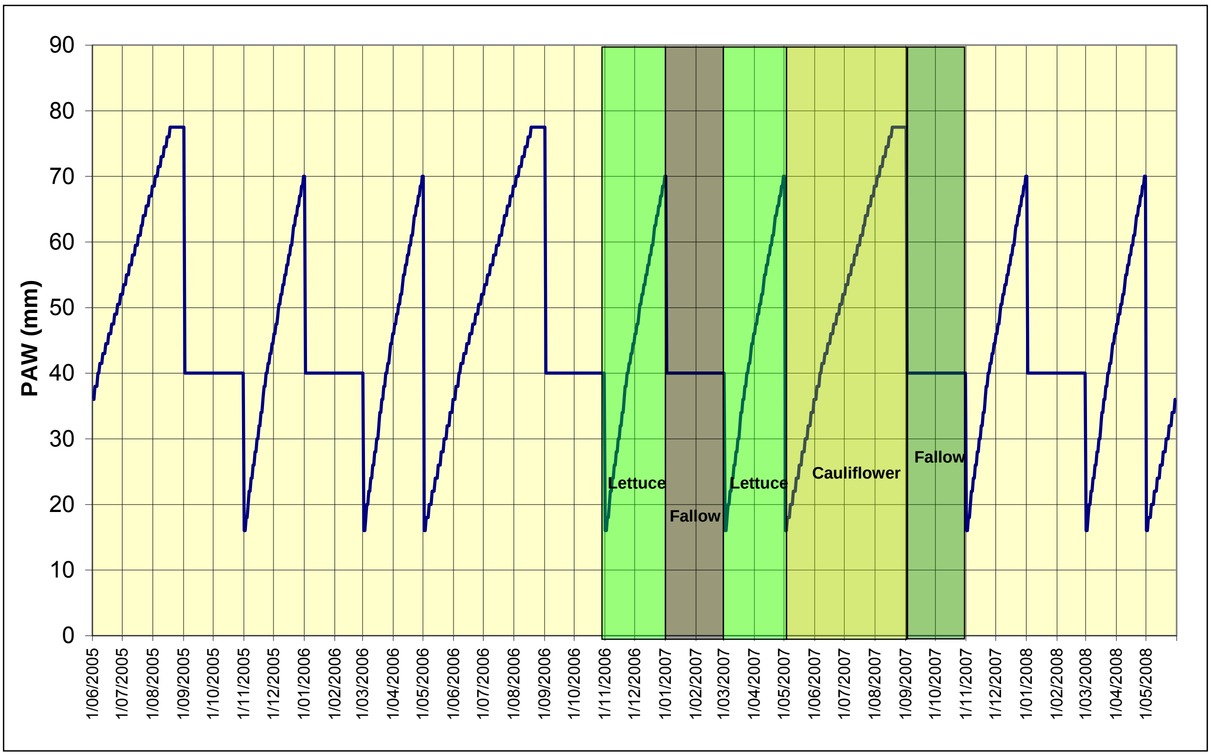

Figure D14: Vegetable rotation 4: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 100mm

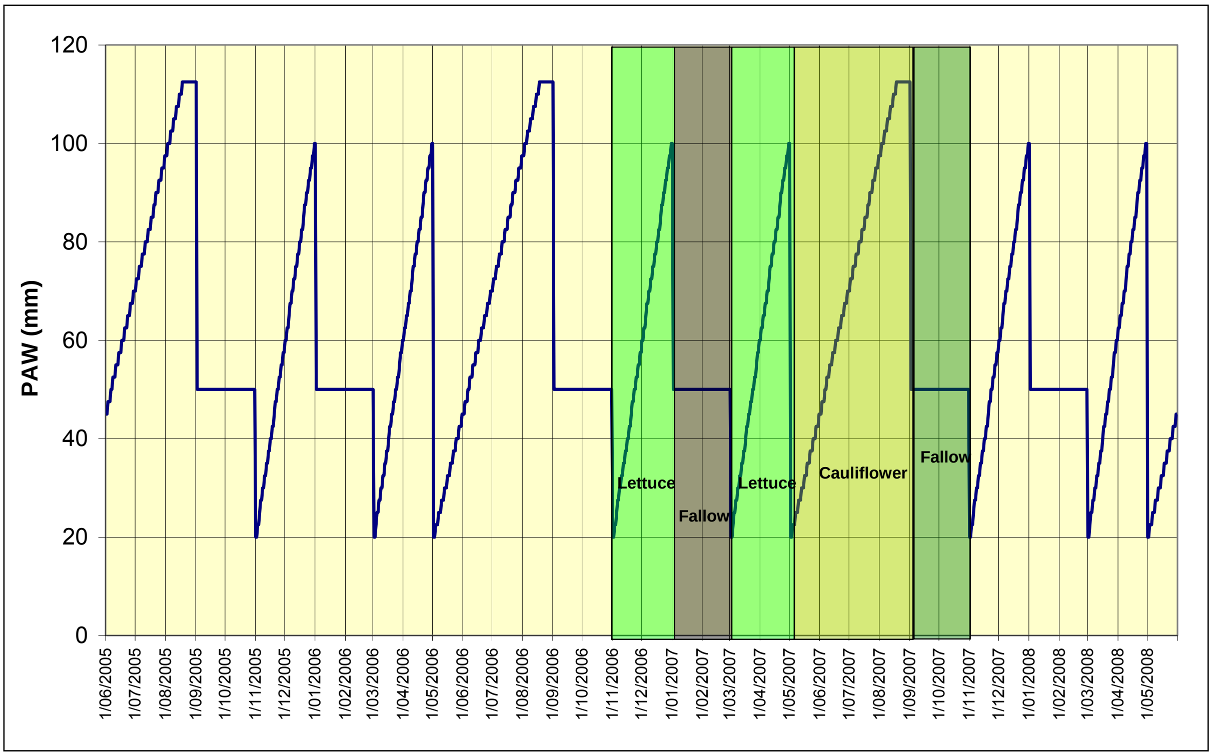

Figure D15: Vegetable rotation 4: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 150mm

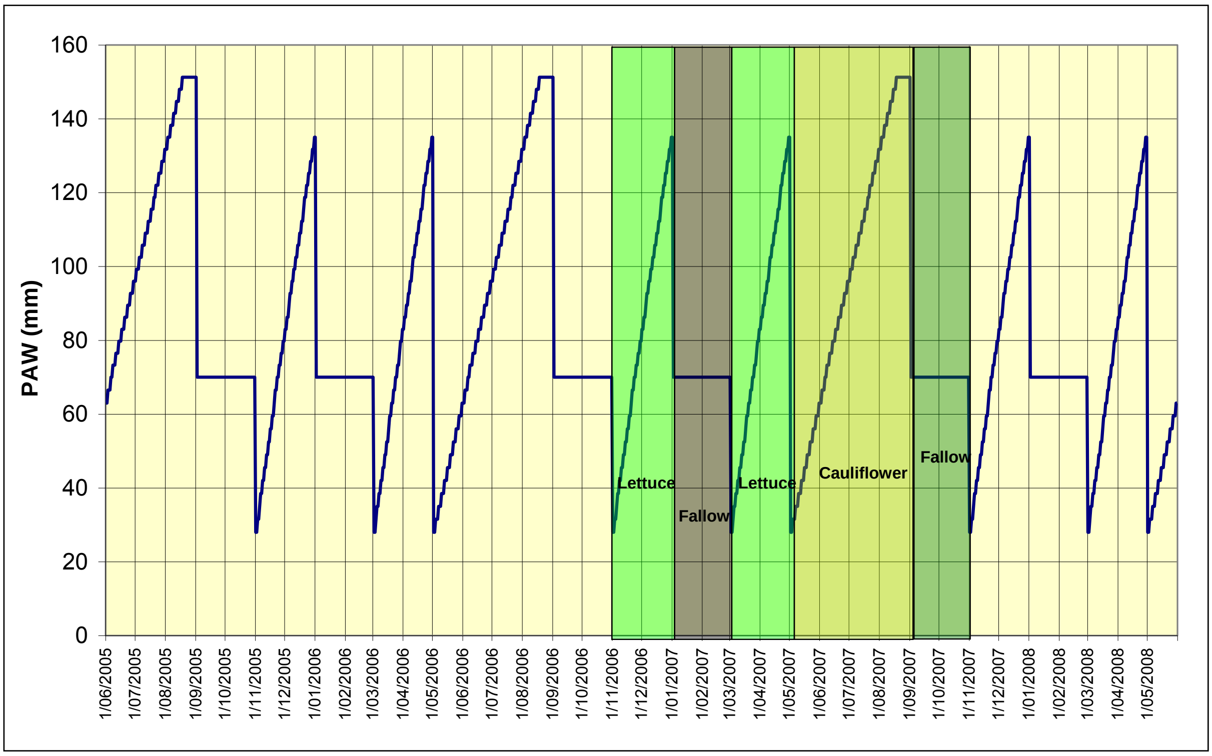

Figure D16: Vegetable rotation 4: Plant available water at field capacity given a soil profile available water down to a depth of 600mm of 200mm

Table D9: Vegetable rotation 1: Irrigation management parameters

Days since planting	Crop	Date	Return period*	Trigger level* (% PAW)
0	Carrots	1-Apr	2	55%
15		15-Apr	3	
31		1-May	Never	
215	Potatoes	1-Nov	2	60%
245		1-Dec	3	
259		15-Dec	7	
350		16-Mar	Never	
366		1-Apr		

* Approximate return period and trigger. These parameters need to be adjusted for efficient irrigation management based on soil PAW

Table D10: Vegetable rotation 2: Irrigation management parameters

Days since planting	Crop	Date	Return period*	Trigger level* (% PAW)
0		15-Nov	Never	
17	Potatoes	1-Dec	2	60%
47		31-Dec	3	
62		15-Jan	7	
138		1-Apr	Never	
366		15-Nov		

* See notes in Table D9

Table D11: Vegetable rotation 3: Irrigation management parameters

Days since planting	Crop	Date	Return period*	Trigger level* (% PAW)
0		1-Sep	Never	
31	Onions	1-Oct	3	60%
76		15-Nov	5	
169		16-Feb	Never	
213	Lettuce	1-Apr	3	60%
238		26-Apr	5	
258		16-May	Never	
366		1-Sep		

* See notes in Table D9

Table D12: Vegetable rotation 4: Irrigation management parameters

Days since planting	Crop	Date	Return period*	Trigger level* (% PAW)
0	Lettuce	1-Nov	3	60%
30		30-Nov	5	
62		1-Jan	Never	
121	Lettuce/Coliflower	1-Mar	3	60%
213		1-Jun	Never	
366		1-Nov		
* See notes in Table D9				

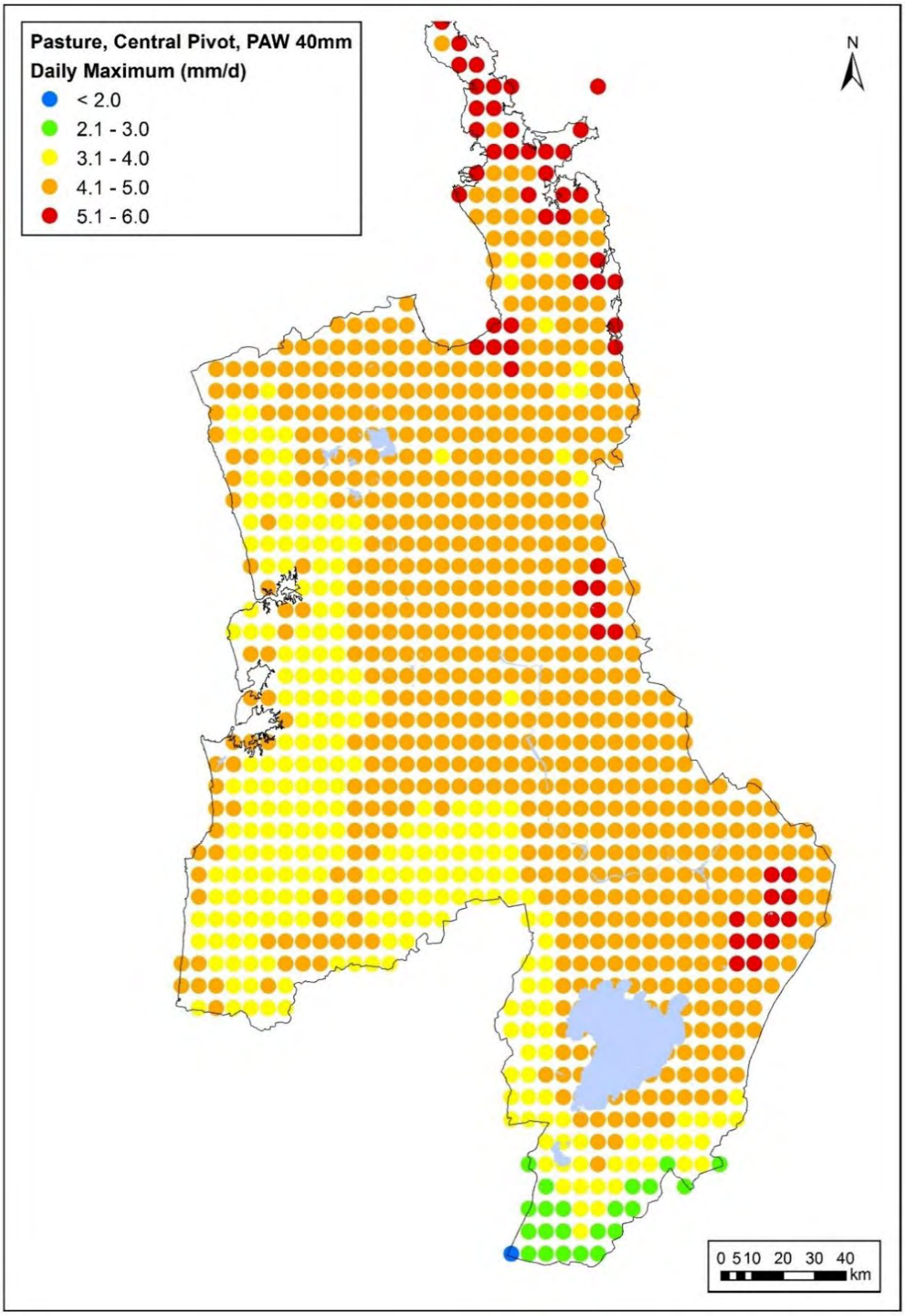

Figure E1: Daily water requirements – pasture, centre pivot, PAW=40mm

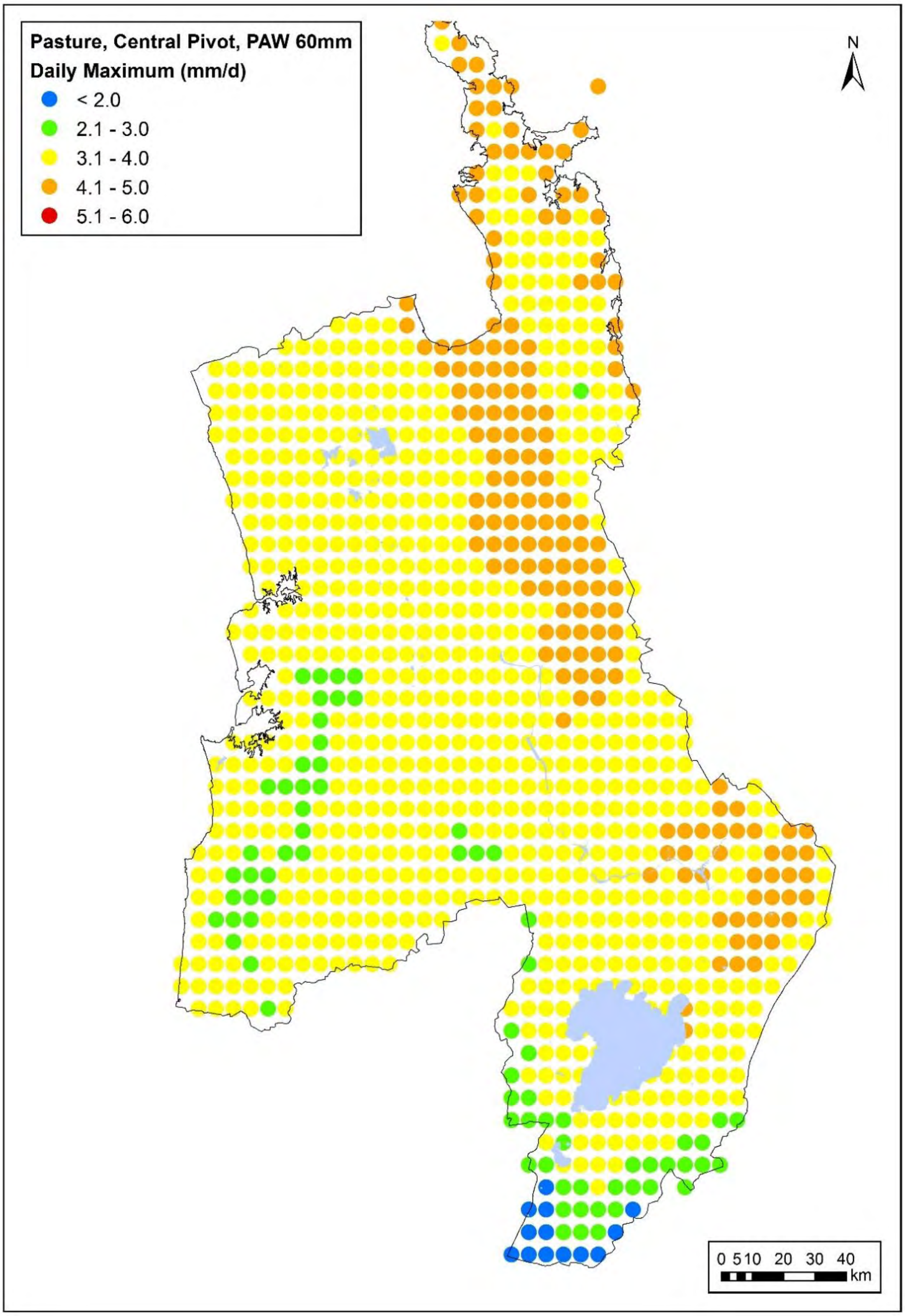

Figure E2: Daily water requirements – pasture, centre pivot, PAW=60mm

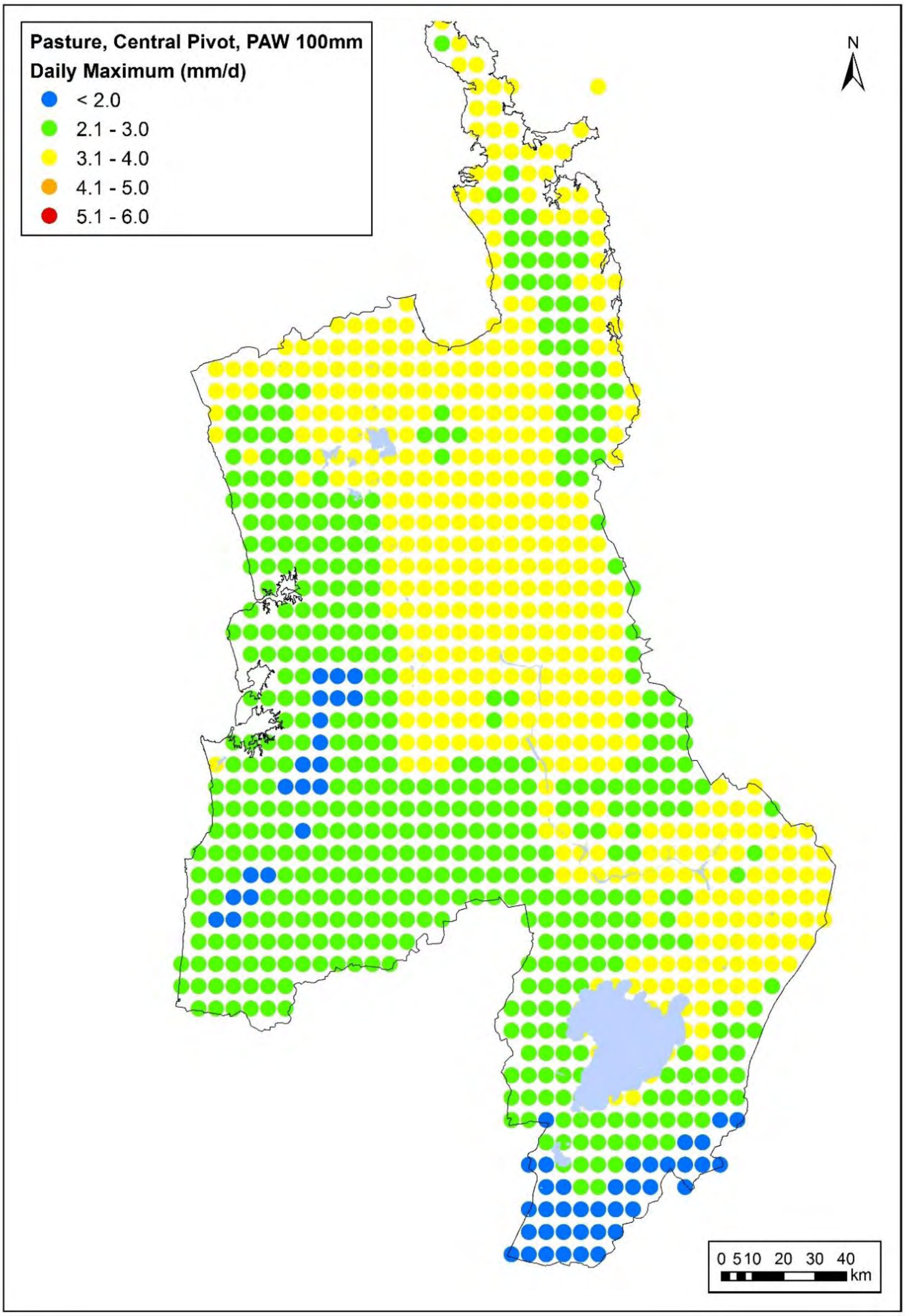

Figure E3: Daily water requirements – pasture, centre pivot, PAW=100mm

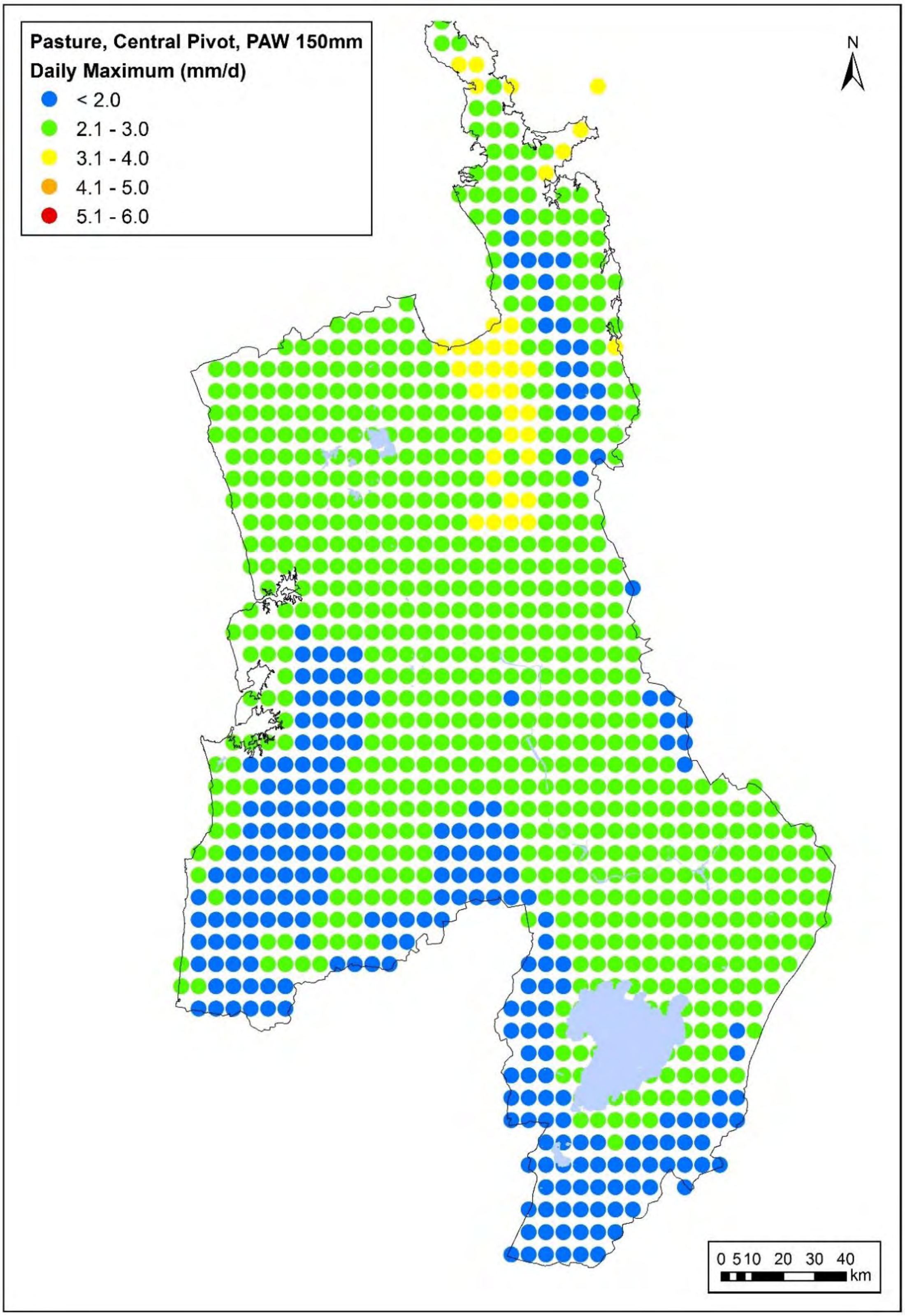

Figure E4: Daily water requirements – pasture, centre pivot, PAW=150mm

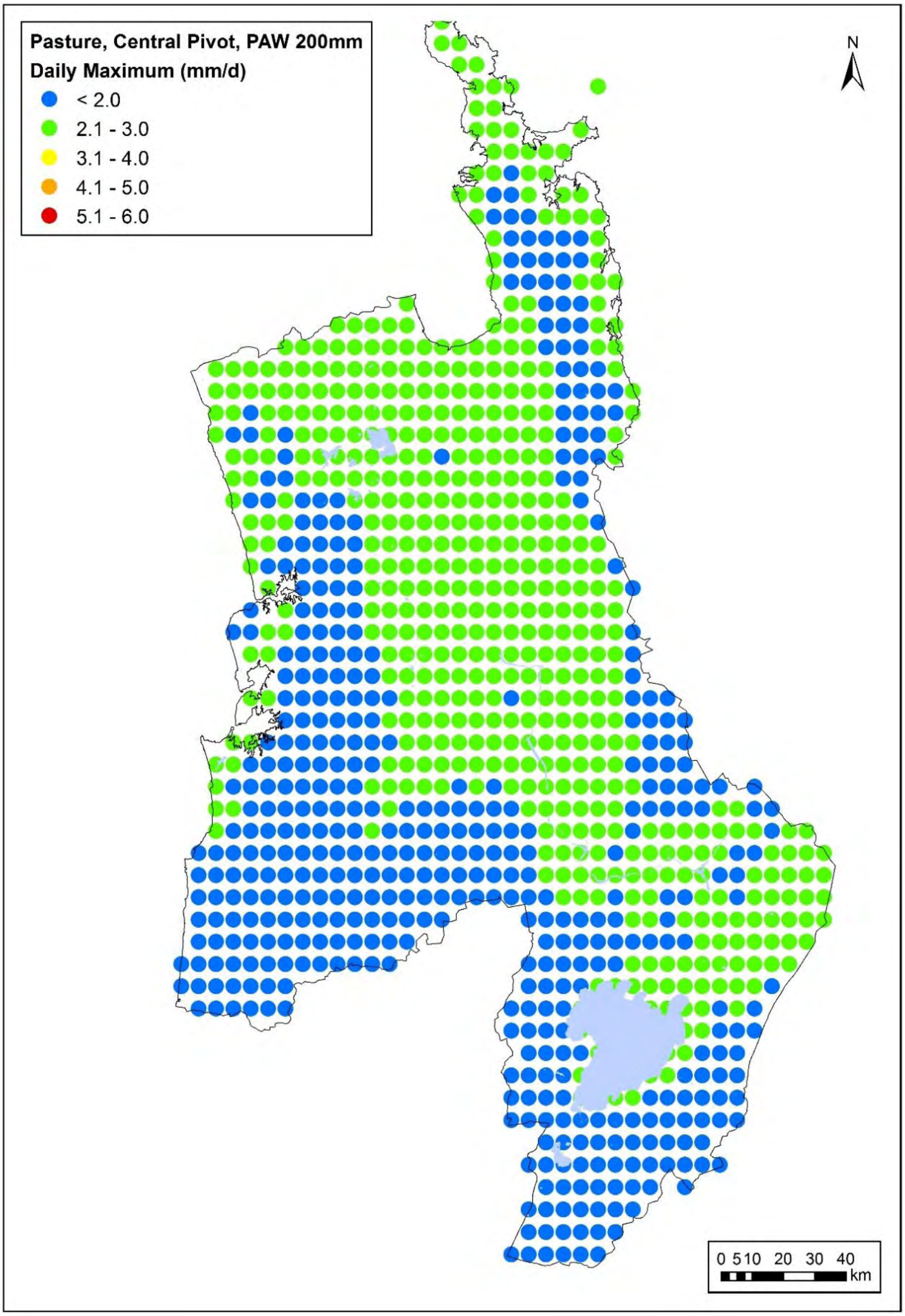

Figure E5: Daily water requirements – pasture, centre pivot, PAW=200mm

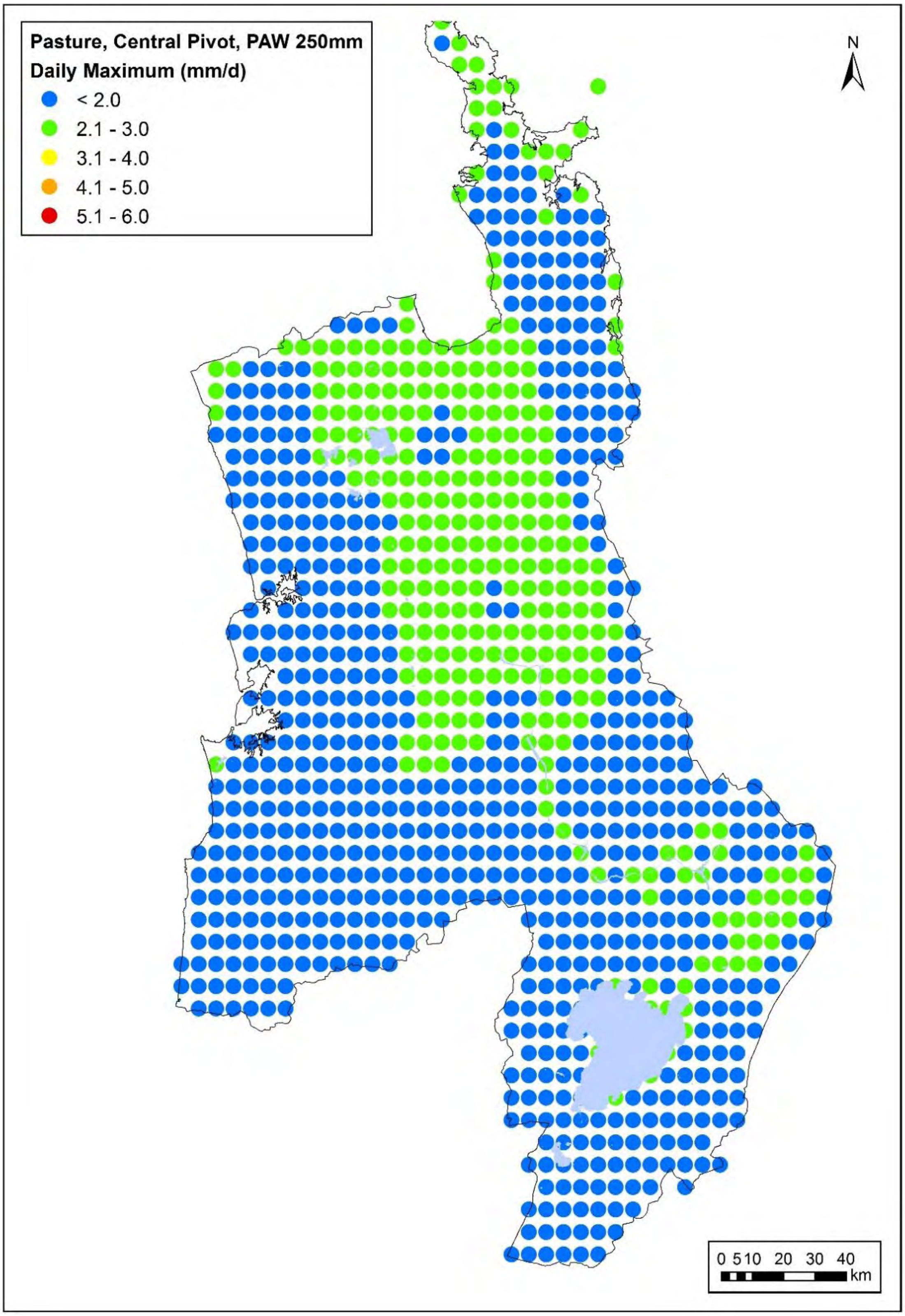

Figure E6: Daily water requirements – pasture, centre pivot, PAW=250mm

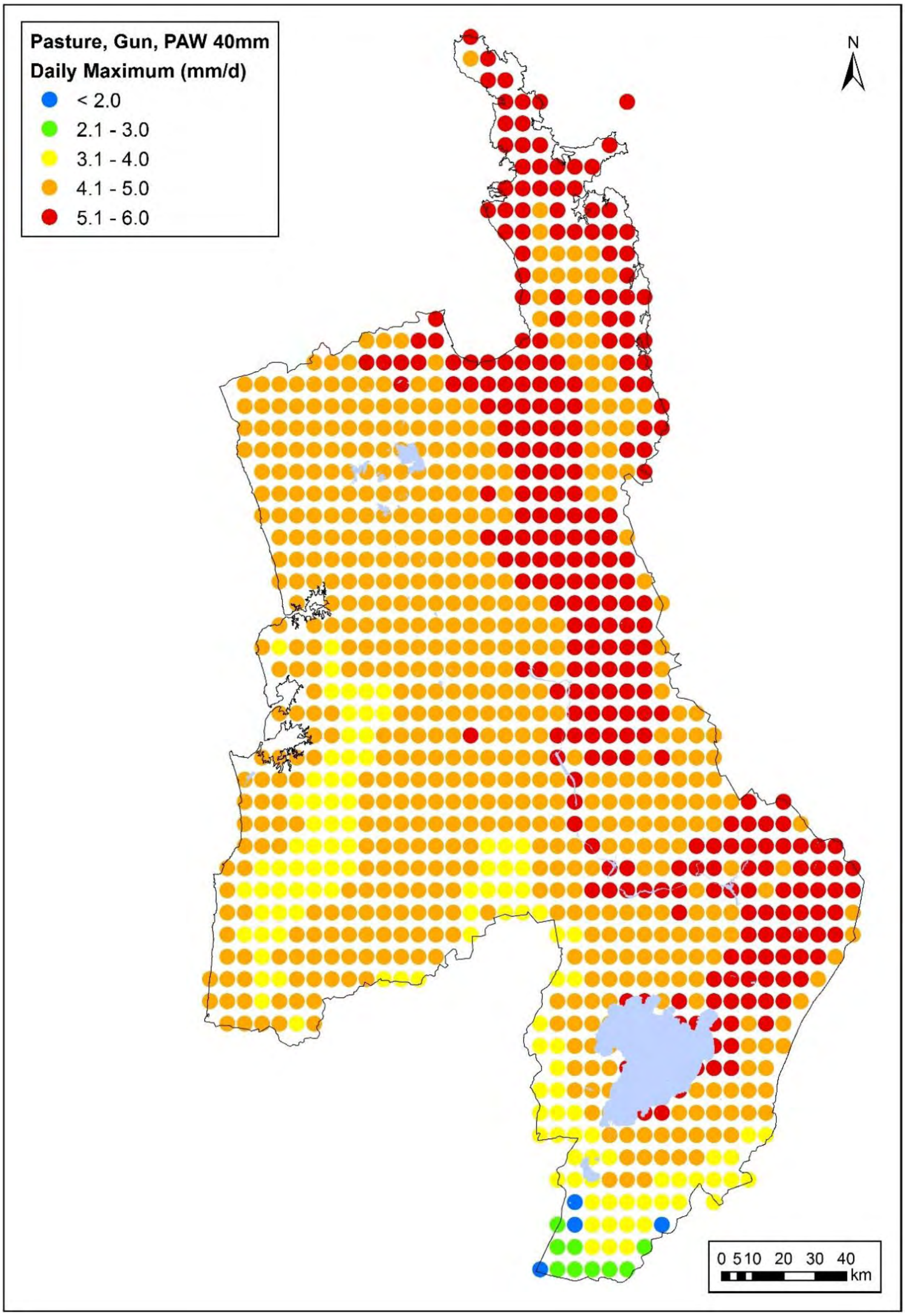

Figure E7: Daily water requirements – pasture, Gun, PAW=40mm

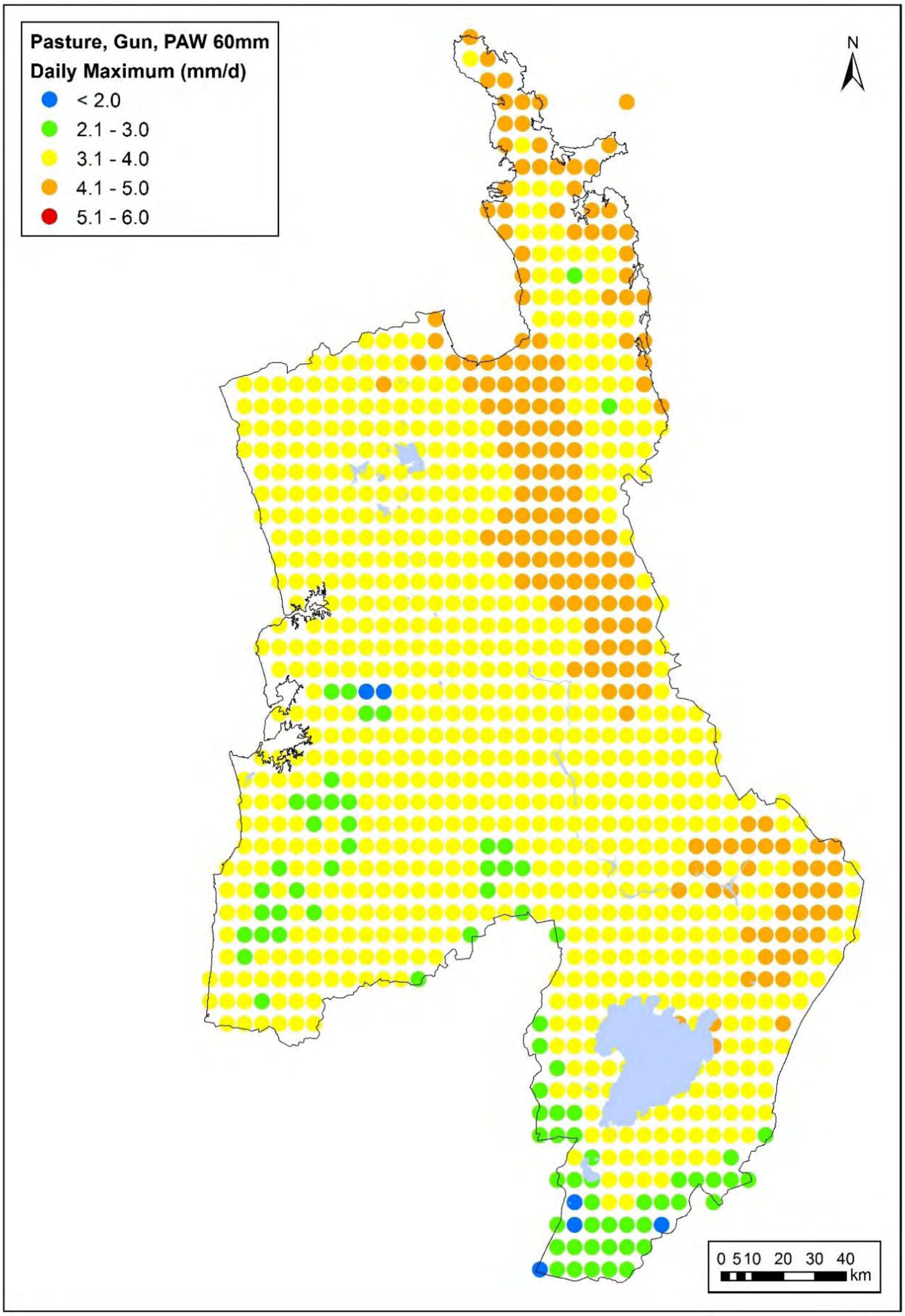

Figure E8: Daily water requirements – pasture, Gun, PAW=60mm

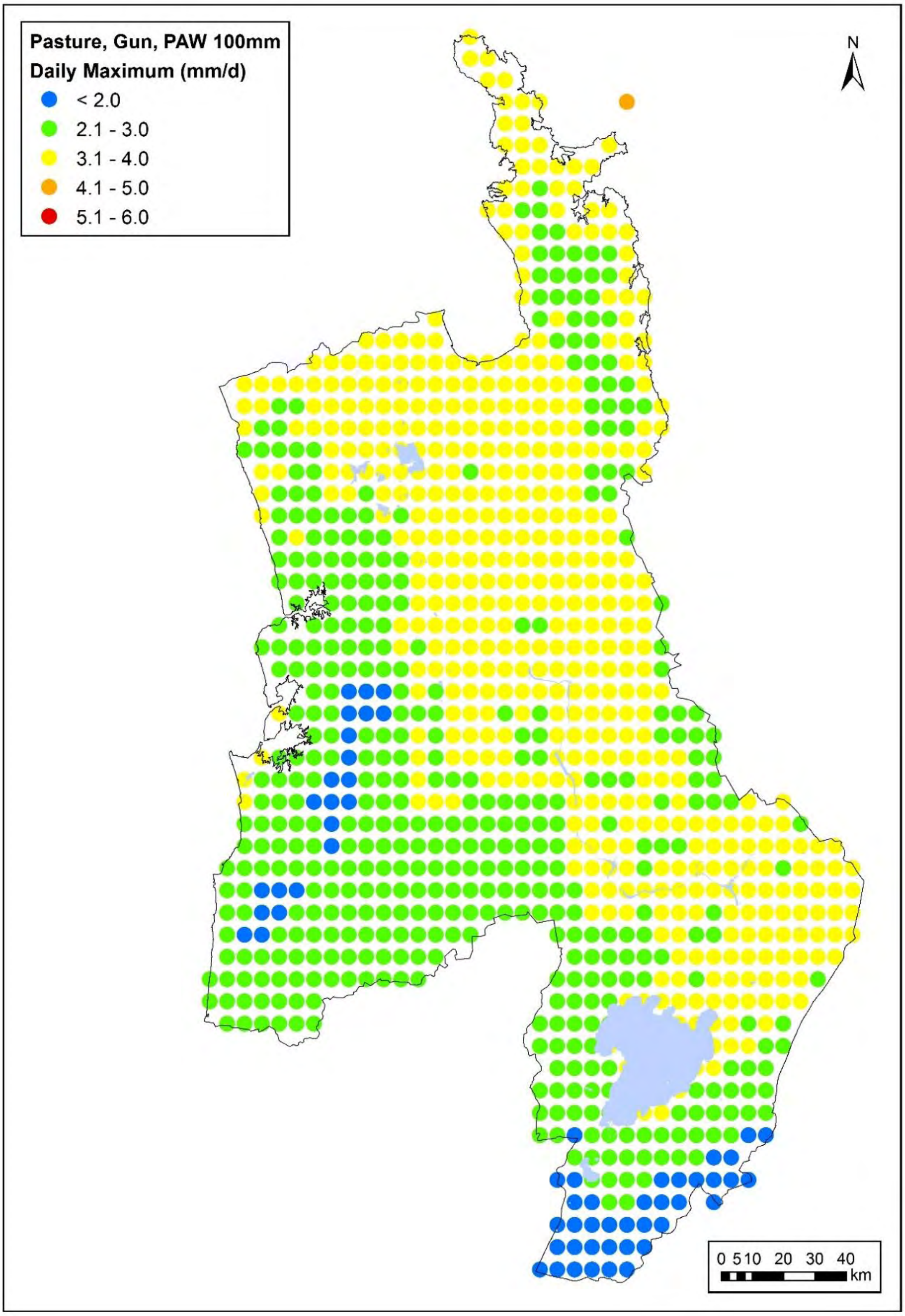

Figure E9: Daily water requirements – pasture, Gun, PAW=100mm

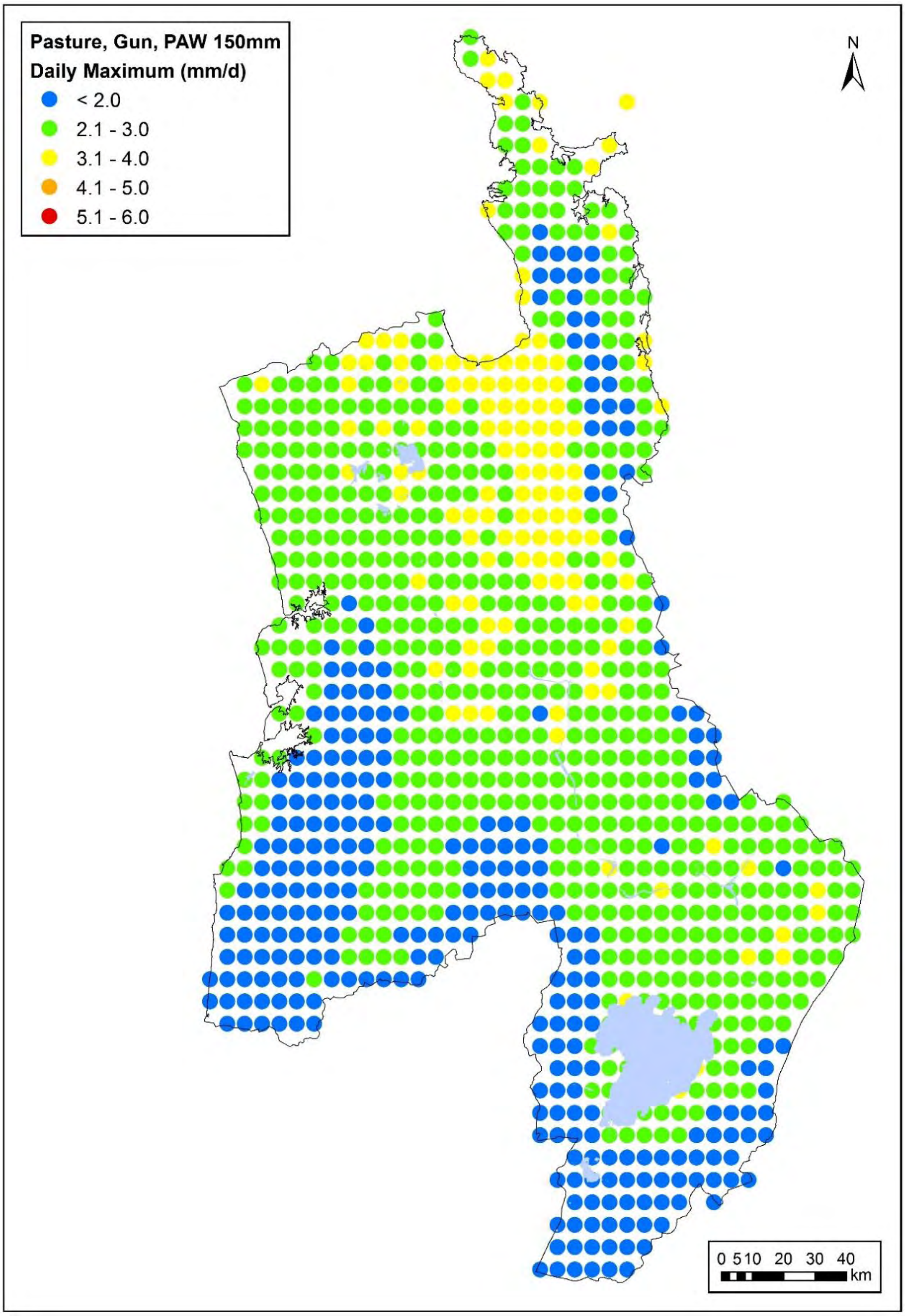

Figure E10: Daily water requirements – pasture, Gun, PAW=150mm

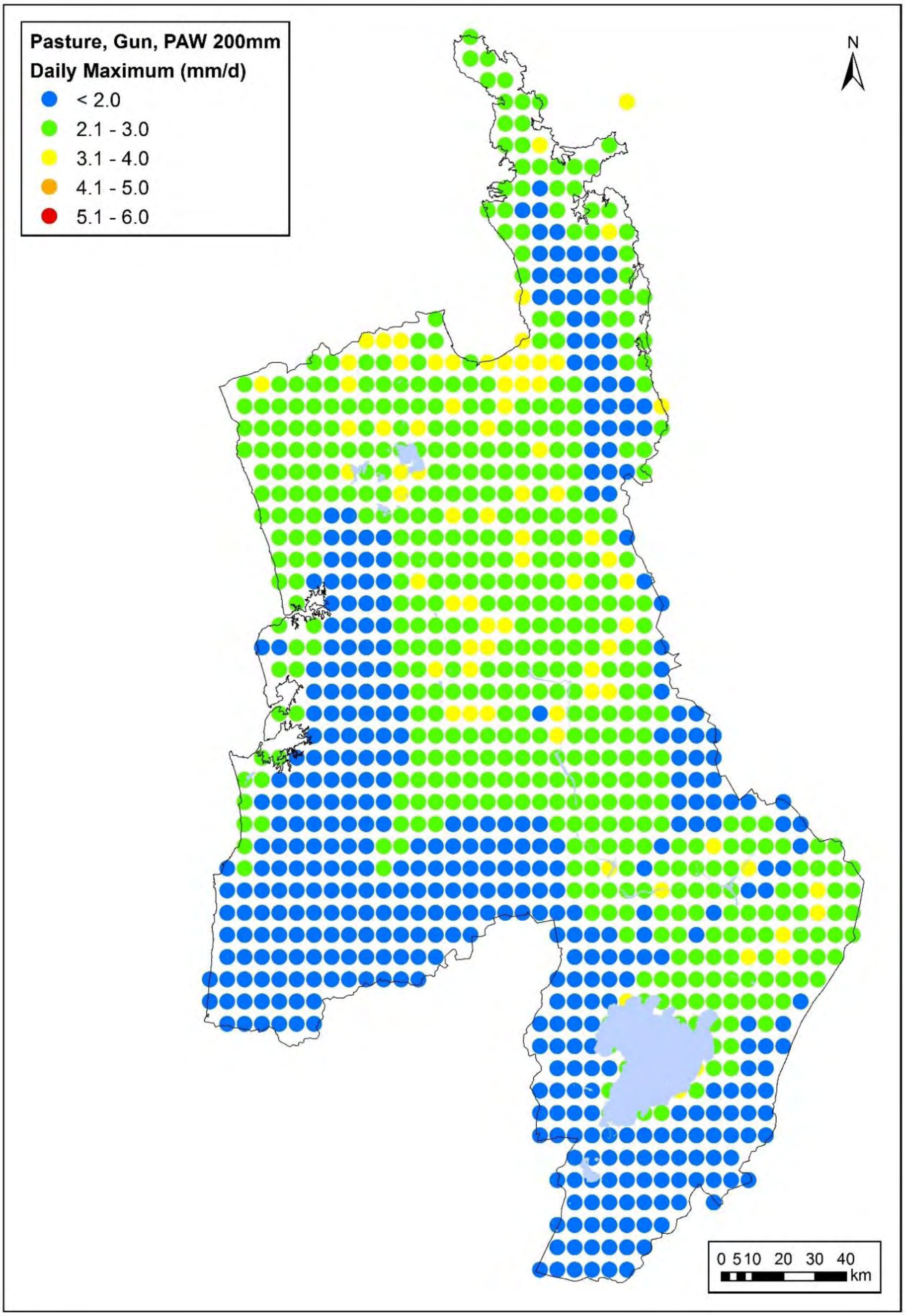

Figure E11: Daily water requirements – pasture, Gun, PAW=200mm

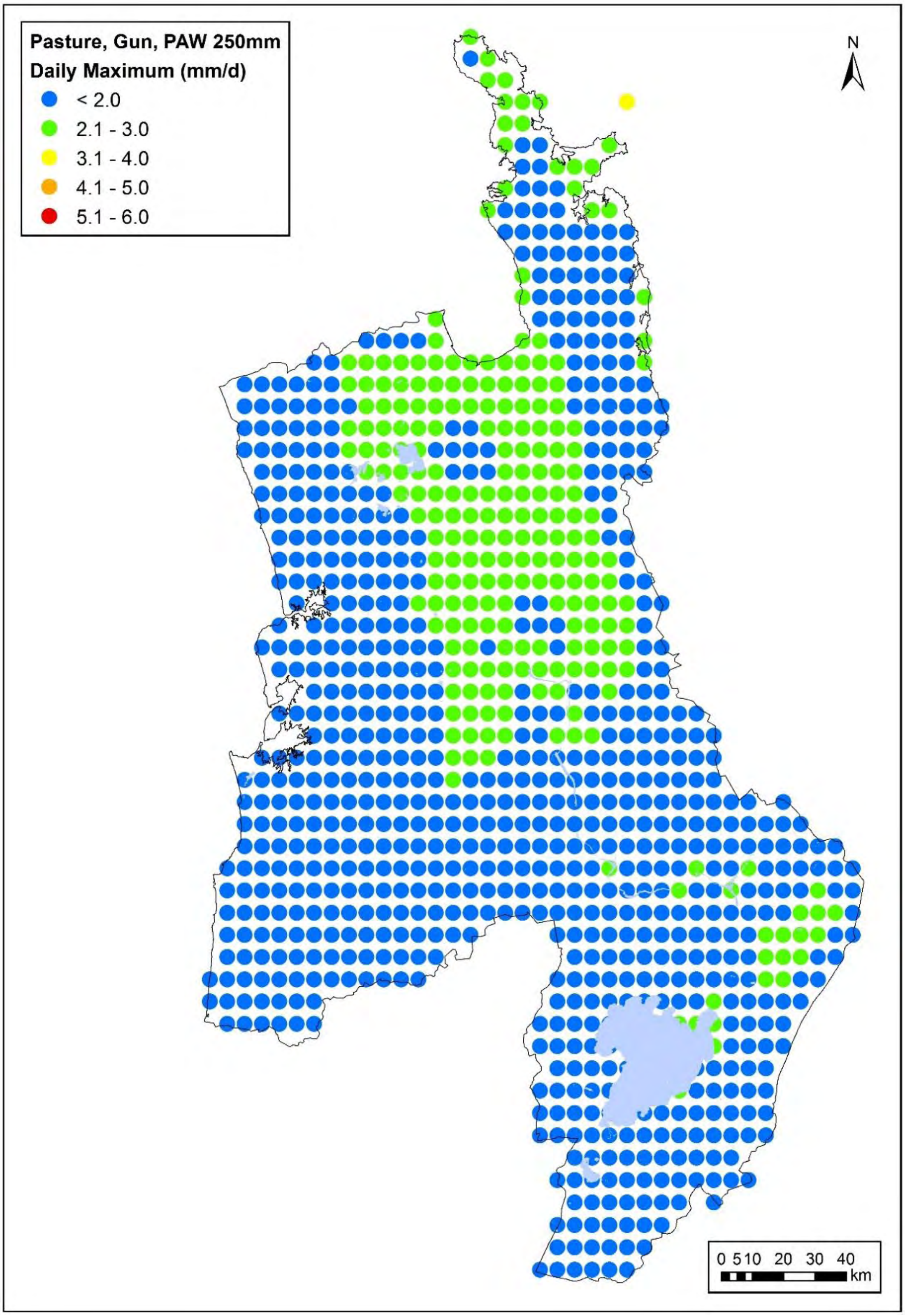

Figure E12: Daily water requirements – pasture, Gun, PAW=250mm

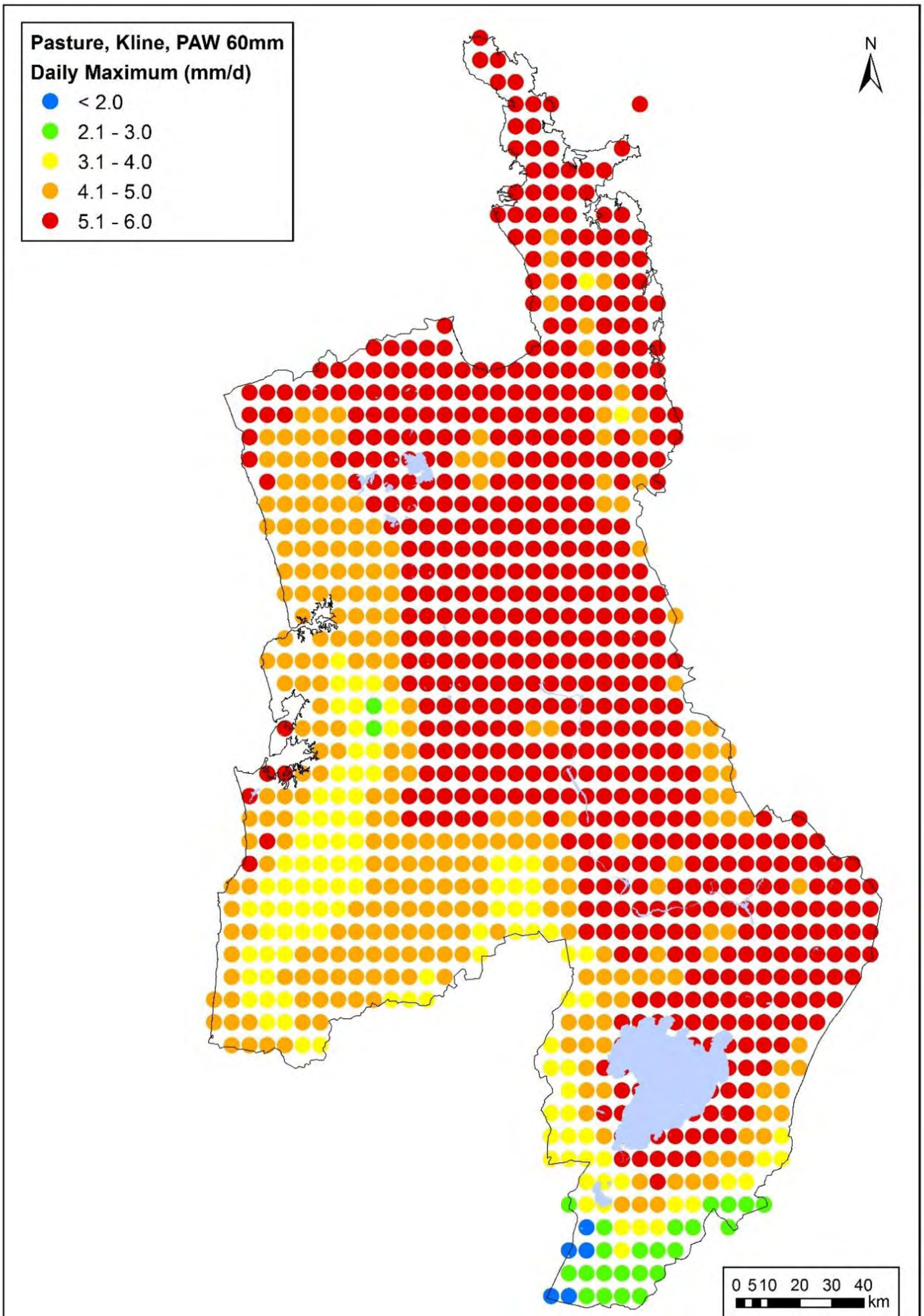

Figure E13: Daily water requirements – pasture, K-line, PAW=60mm

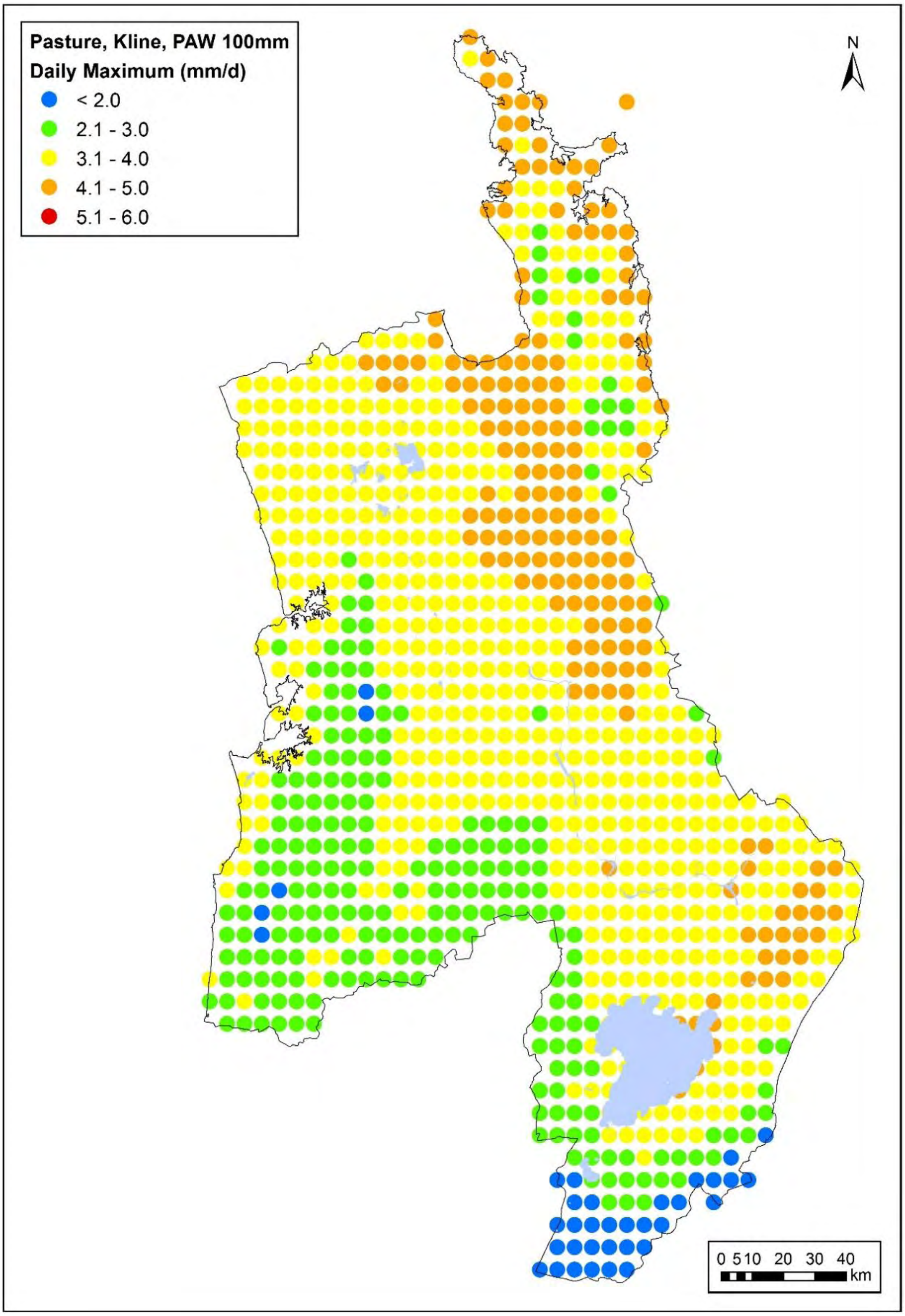

Figure E14: Daily water requirements – pasture, K-line, PAW=100mm

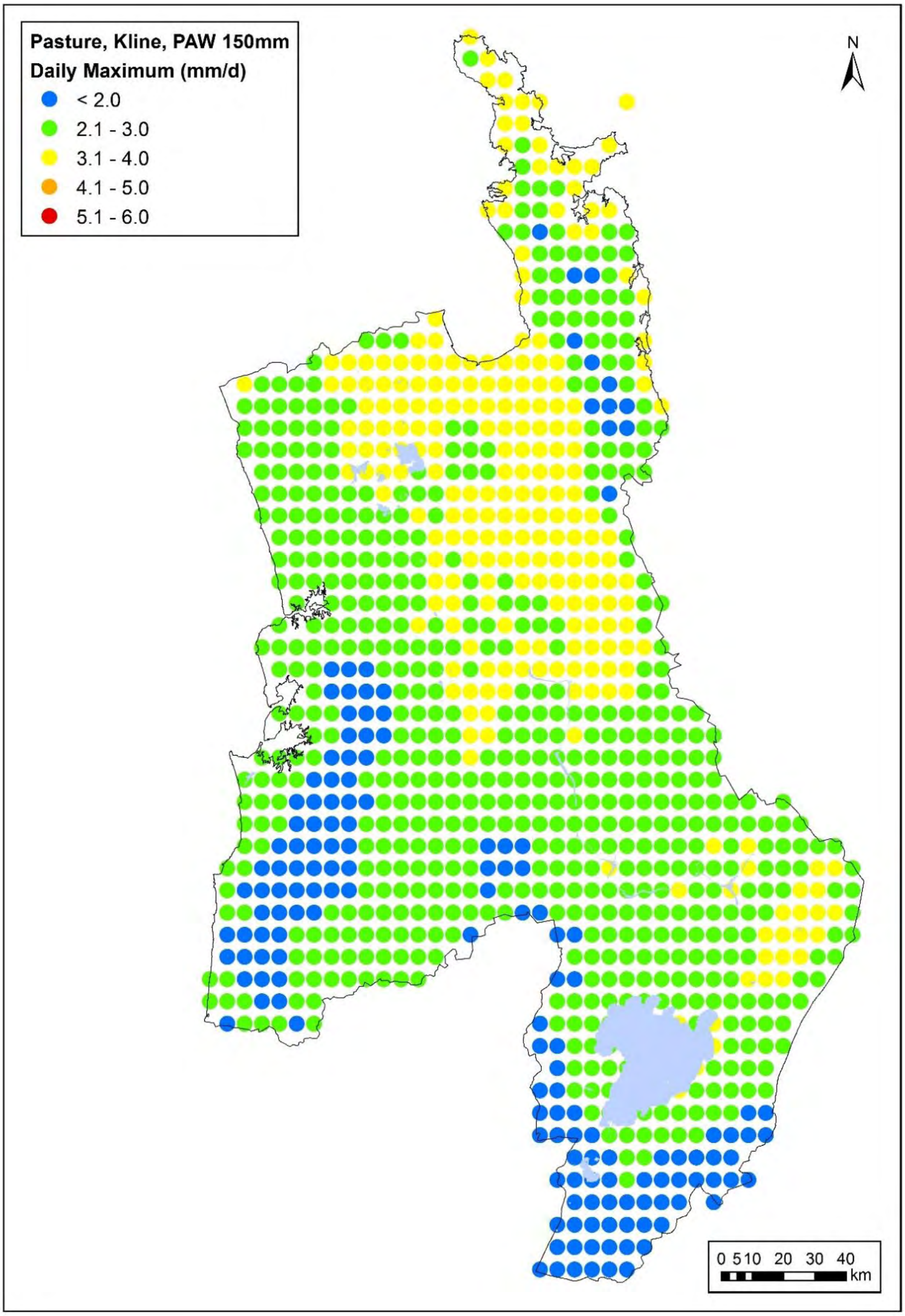

Figure E15: Daily water requirements – pasture, K-line, PAW=150mm

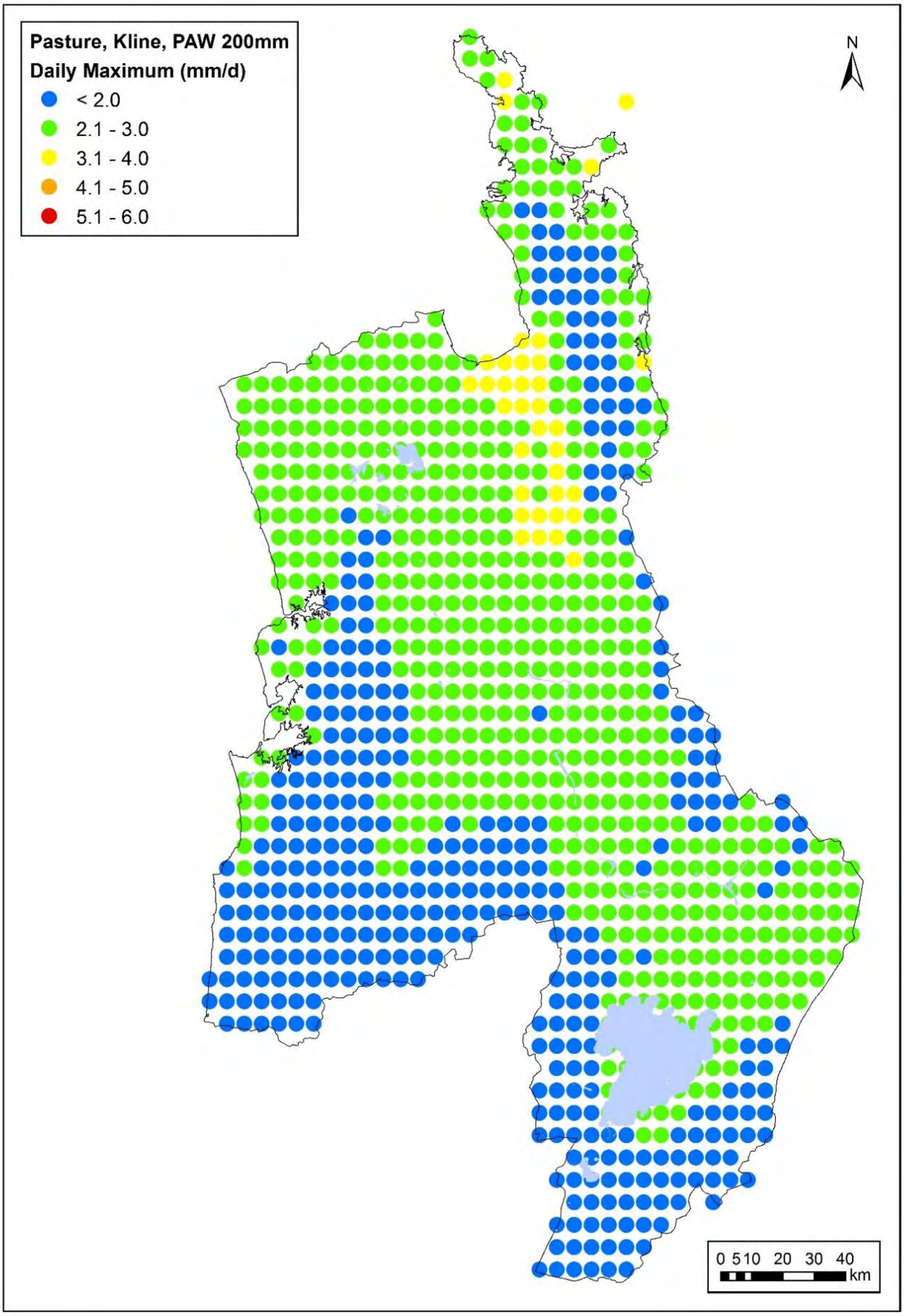

Figure E16: Daily water requirements – pasture, K-line, PAW=200mm

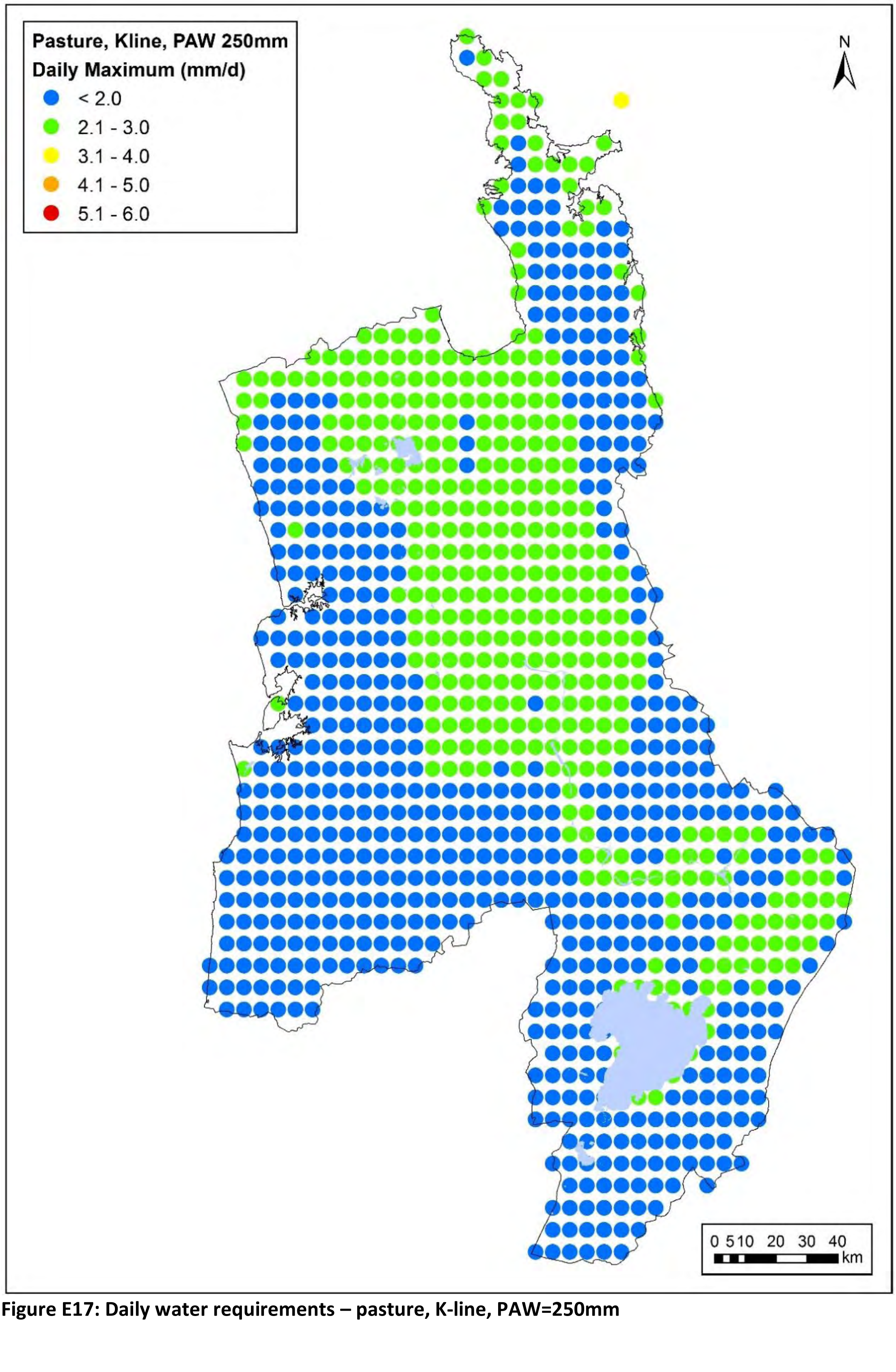

Figure E17: Daily water requirements – pasture, K-line, PAW=250mm

Appendix F: Pasture 90%ile seasonal demand

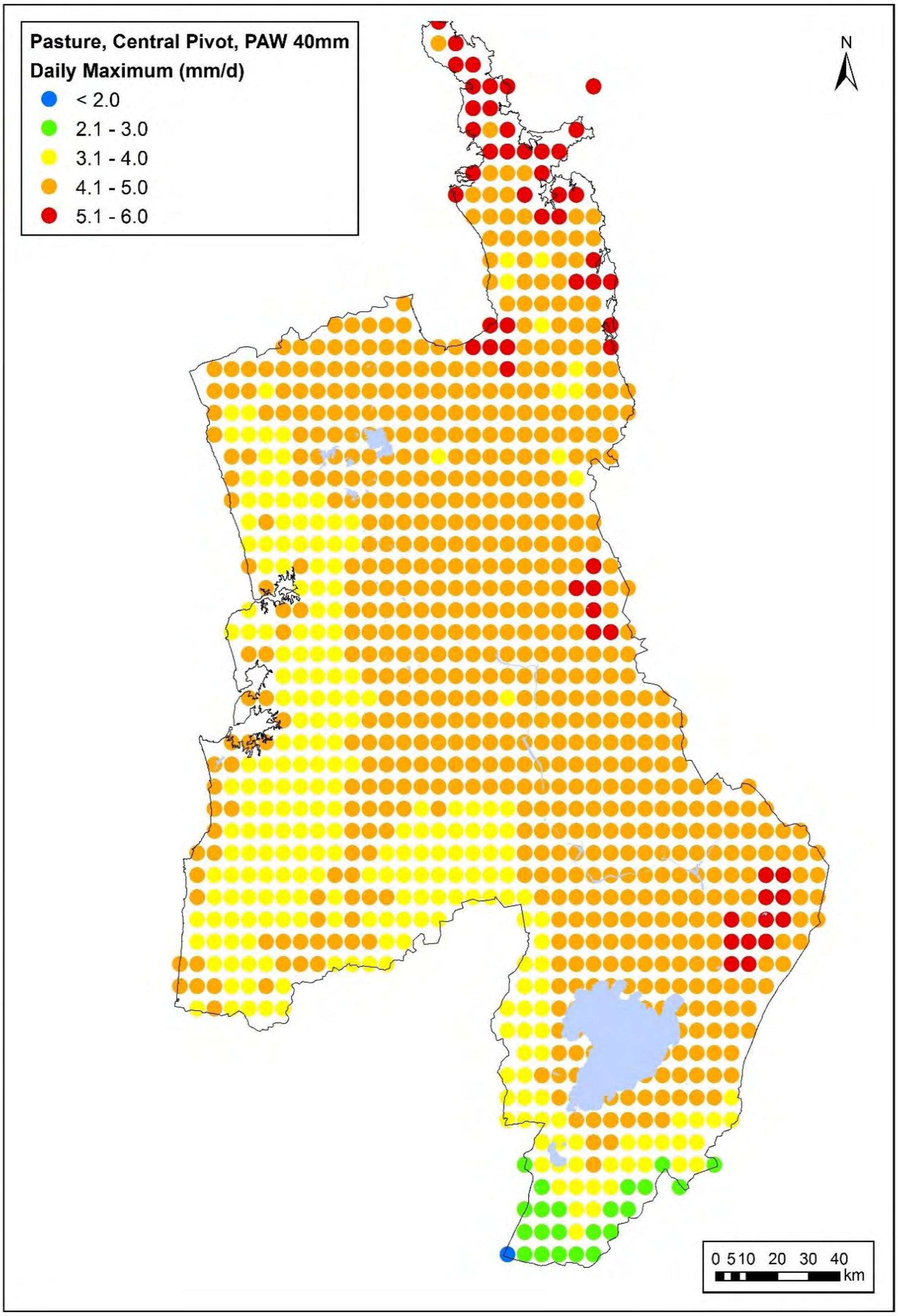

Figure F1 Seasonal water requirements – pasture, centre pivot, PAW=40mm

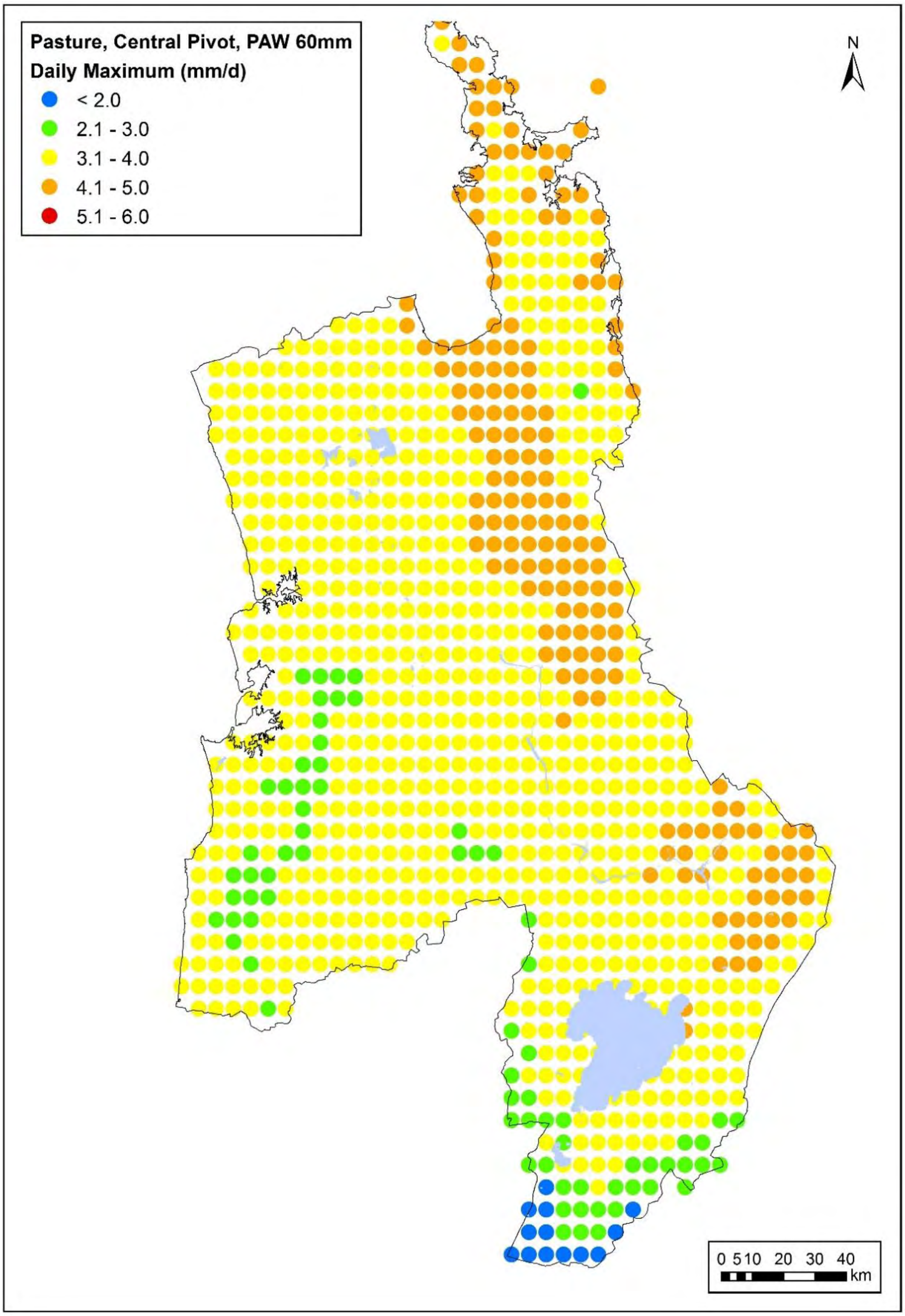

Figure F2: Seasonal water requirements – pasture, centre pivot, PAW=60mm

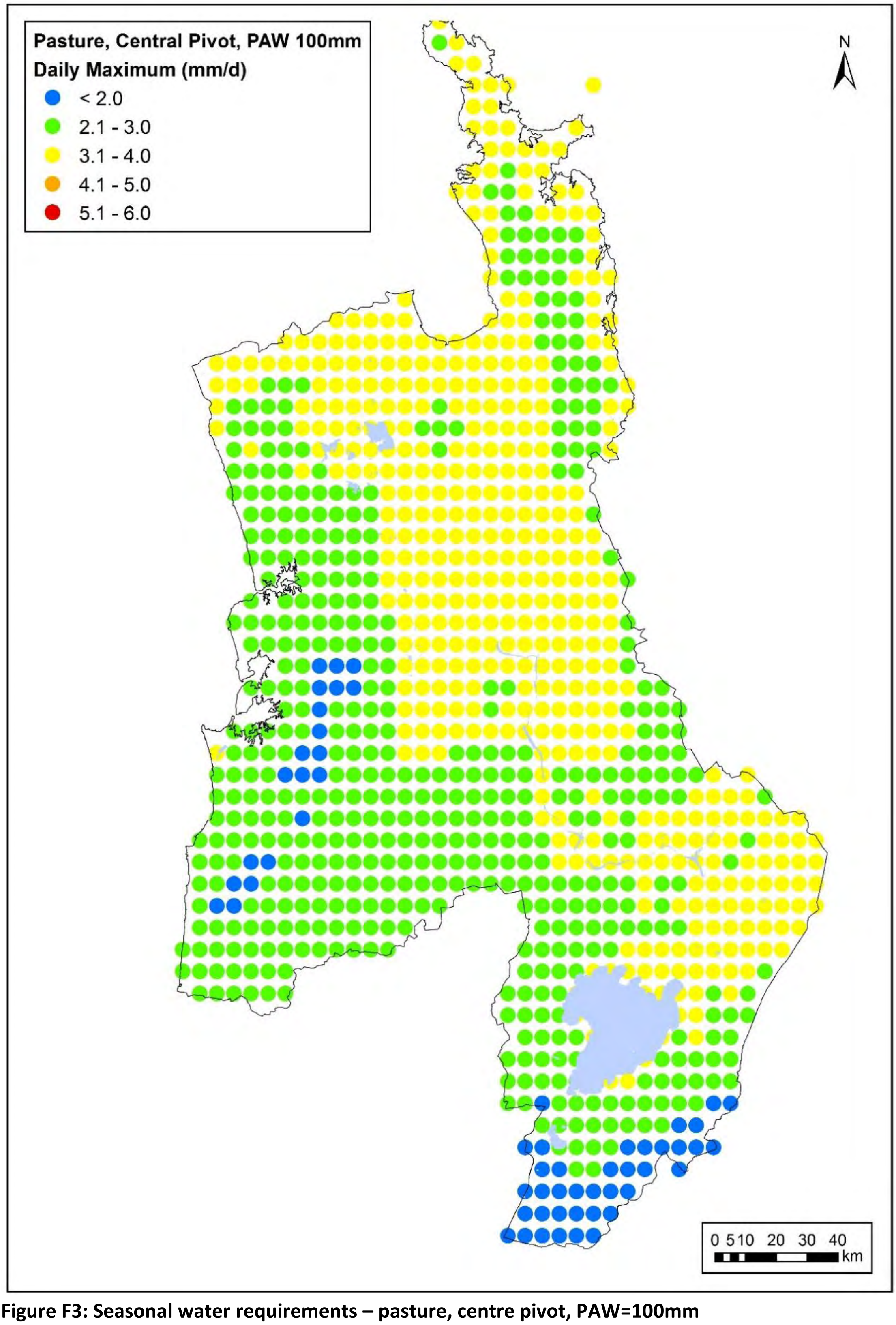

Figure F3: Seasonal water requirements – pasture, centre pivot, PAW=100mm

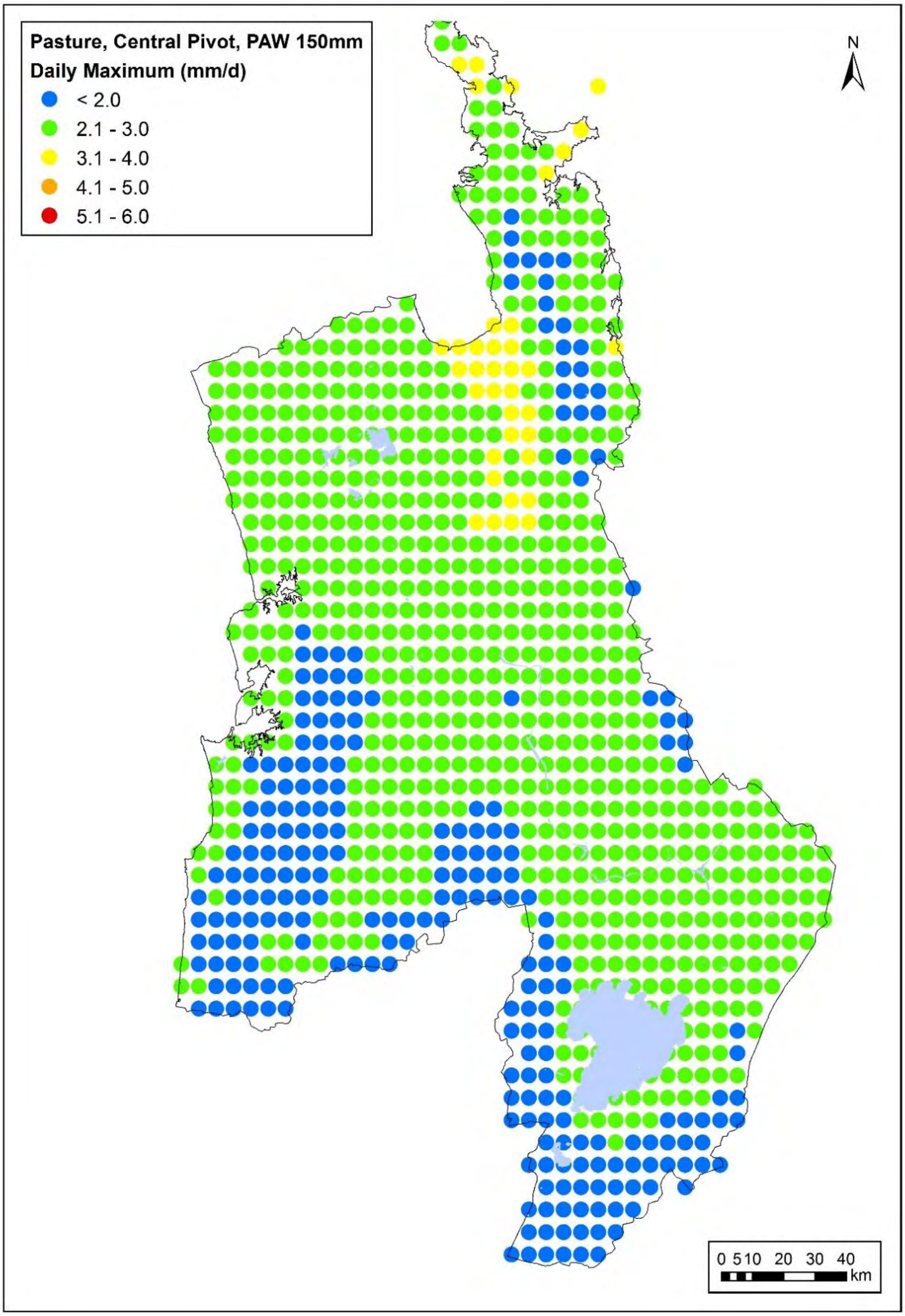

Figure F4: water requirements – pasture, centre pivot, PAW=150mm

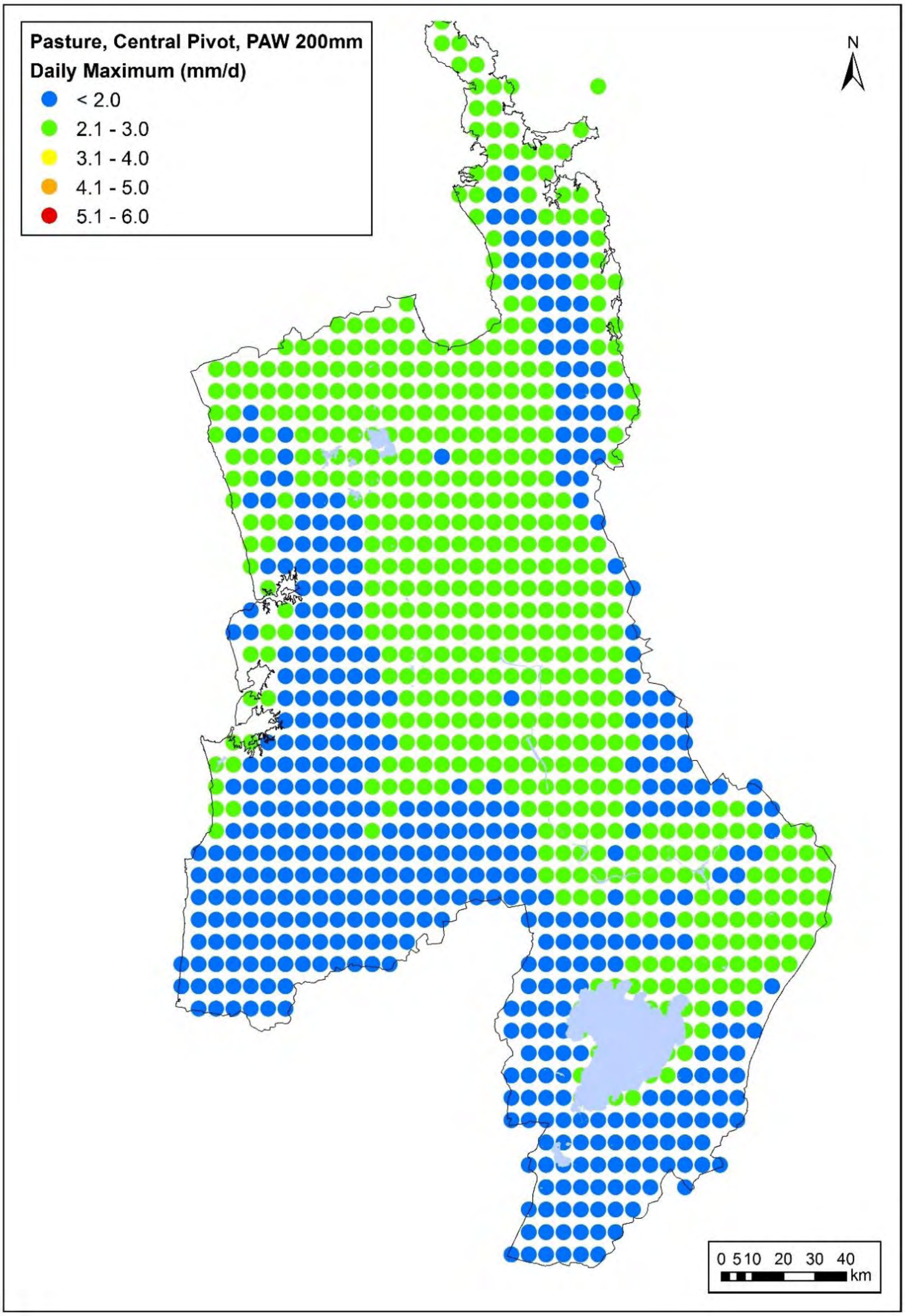

Figure F5: Seasonal water requirements – pasture, centre pivot, PAW=200mm

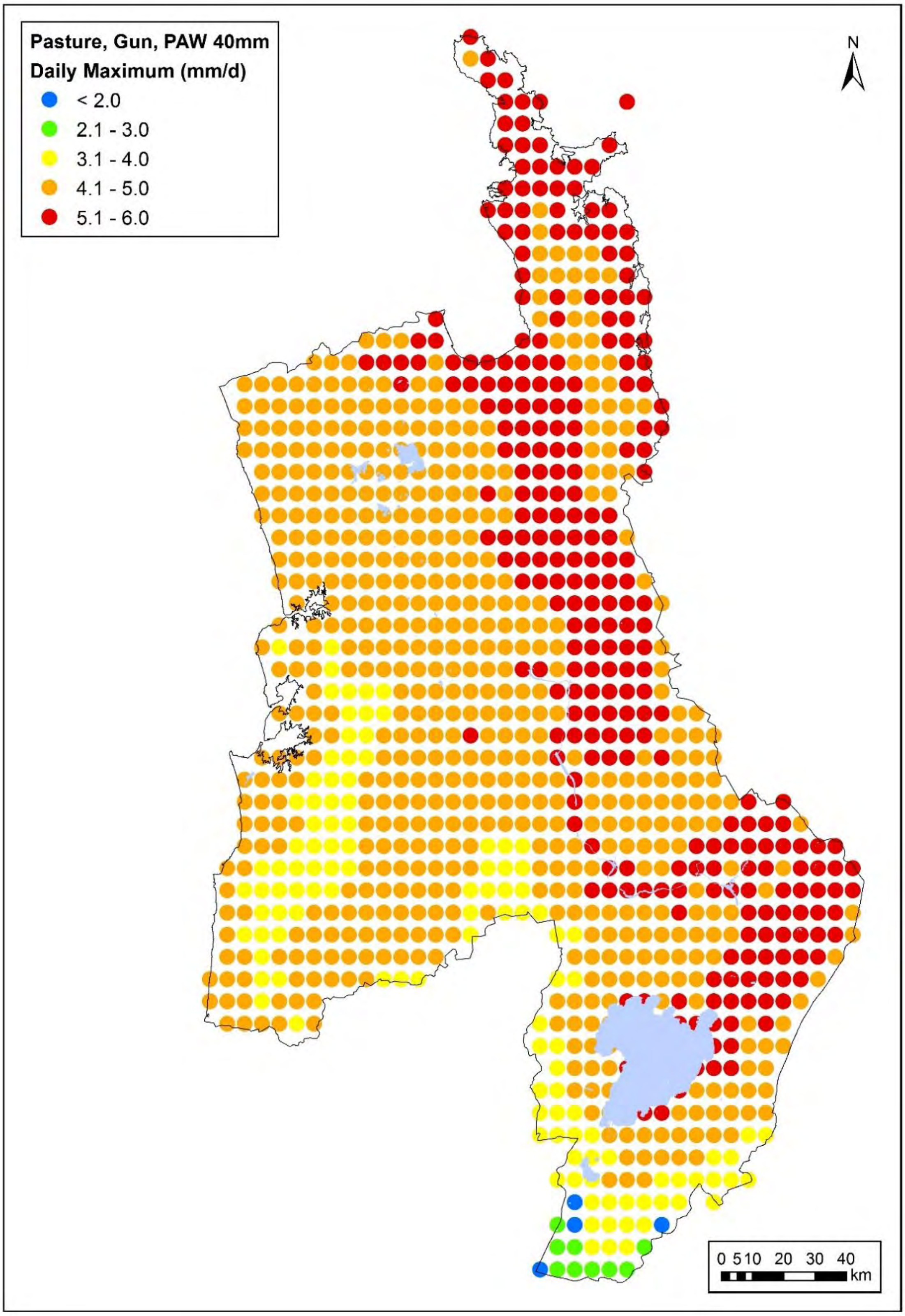

Figure F6: Seasonal water requirements – pasture, gun, PAW=40mm

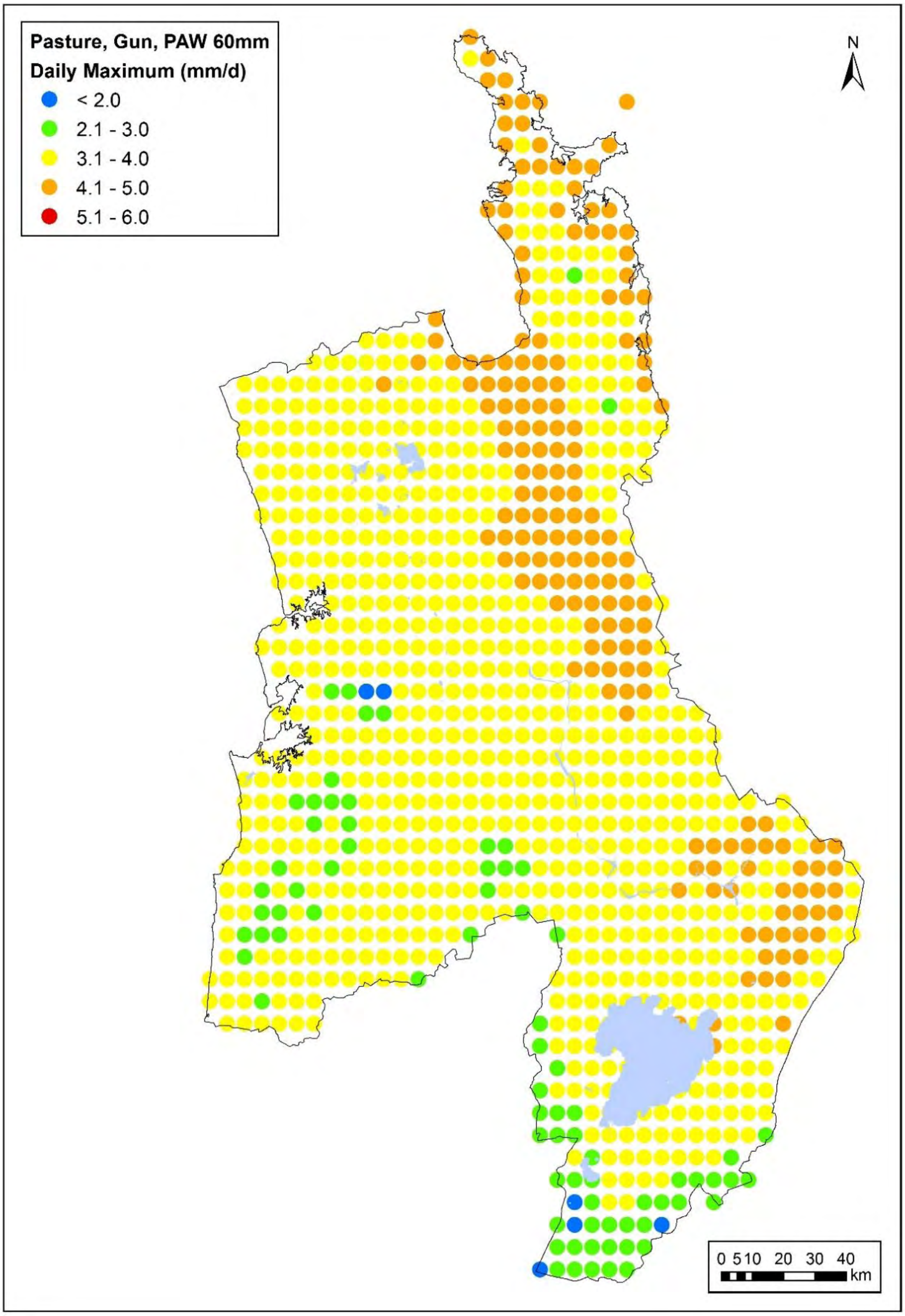

Figure F7: Seasonal water requirements – pasture, gun, PAW=60mm

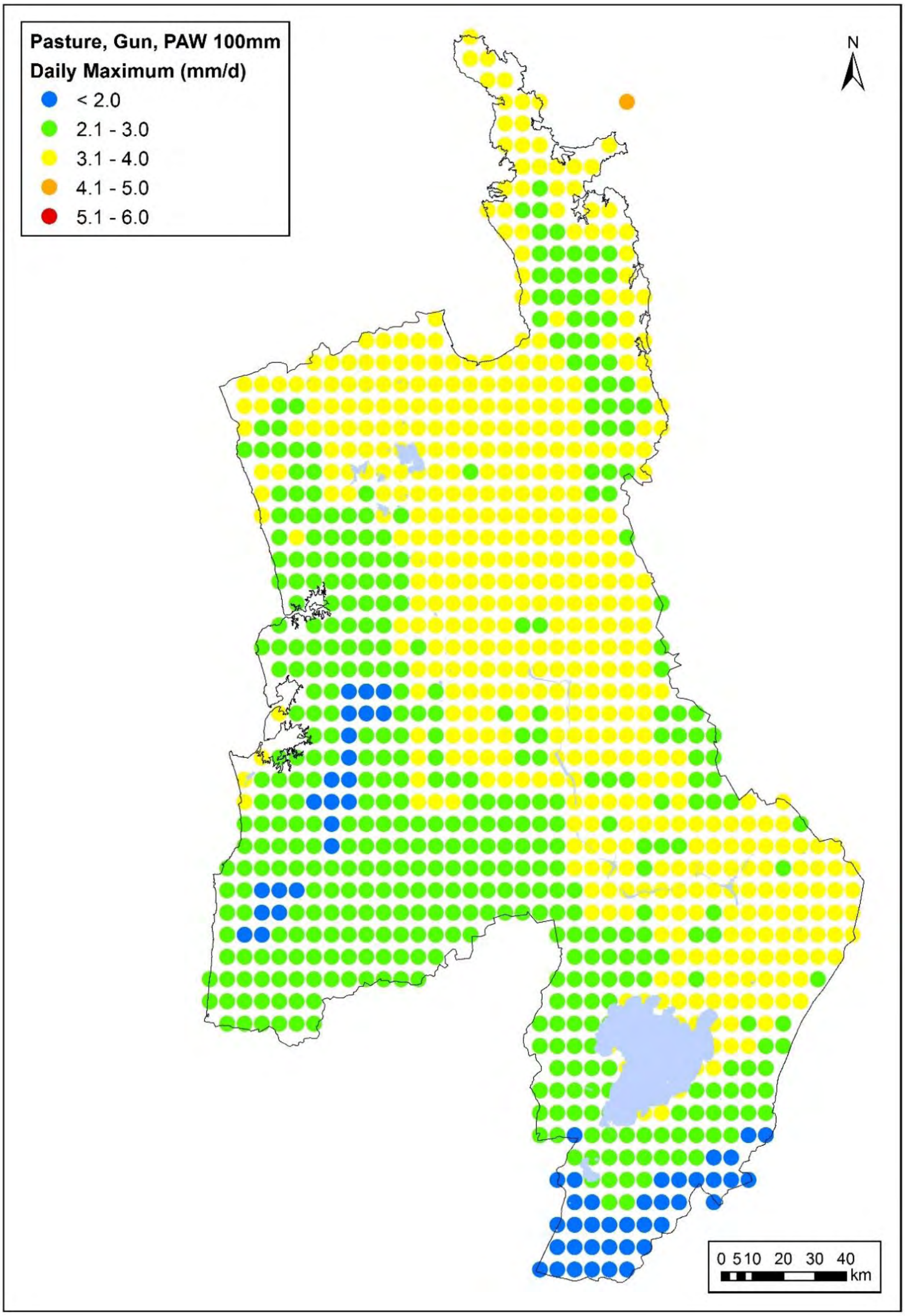

Figure F8: Seasonal water requirements – pasture, gun, PAW=100mm

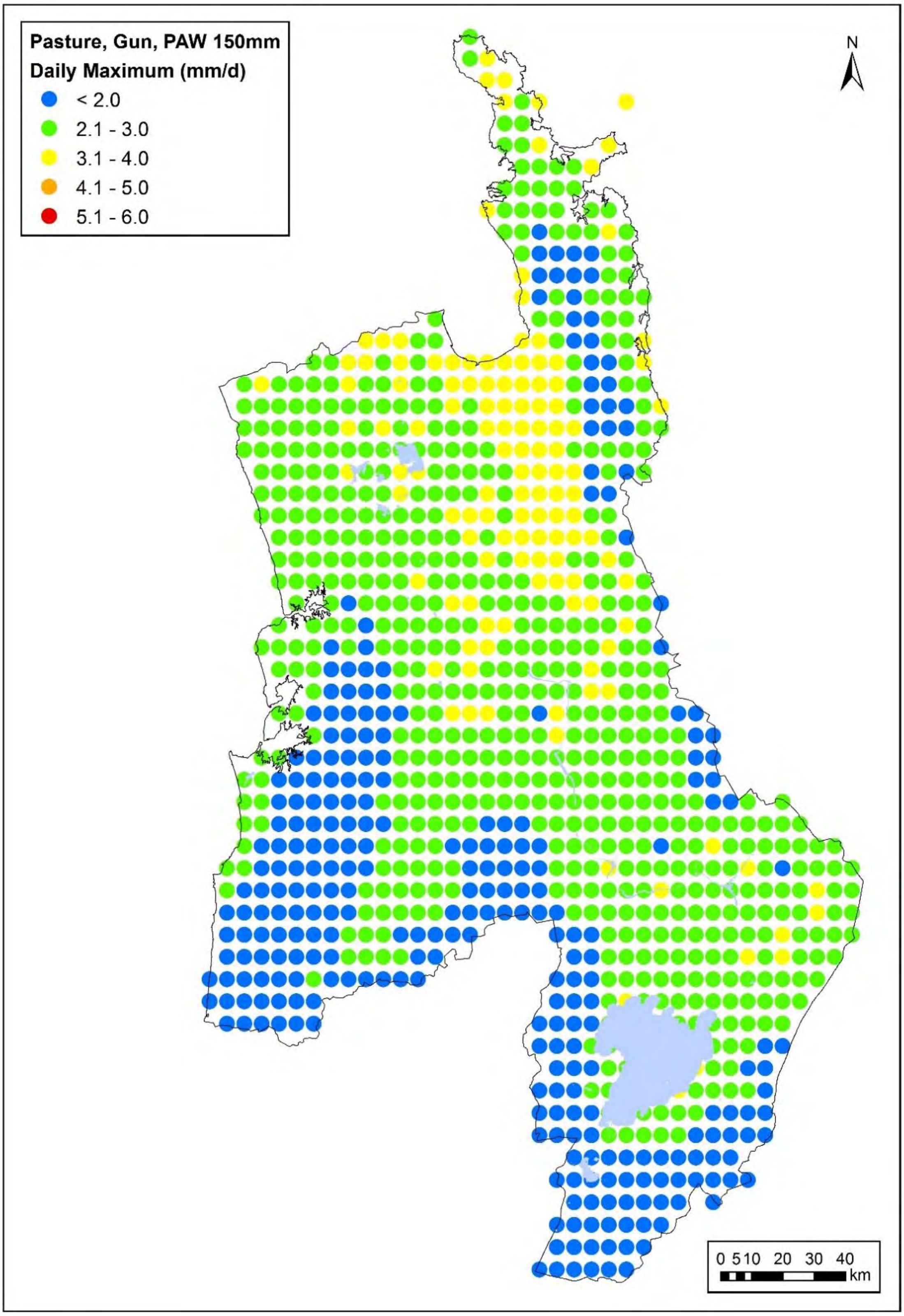

Figure F9: Seasonal water requirements – pasture, gun, PAW=150mm

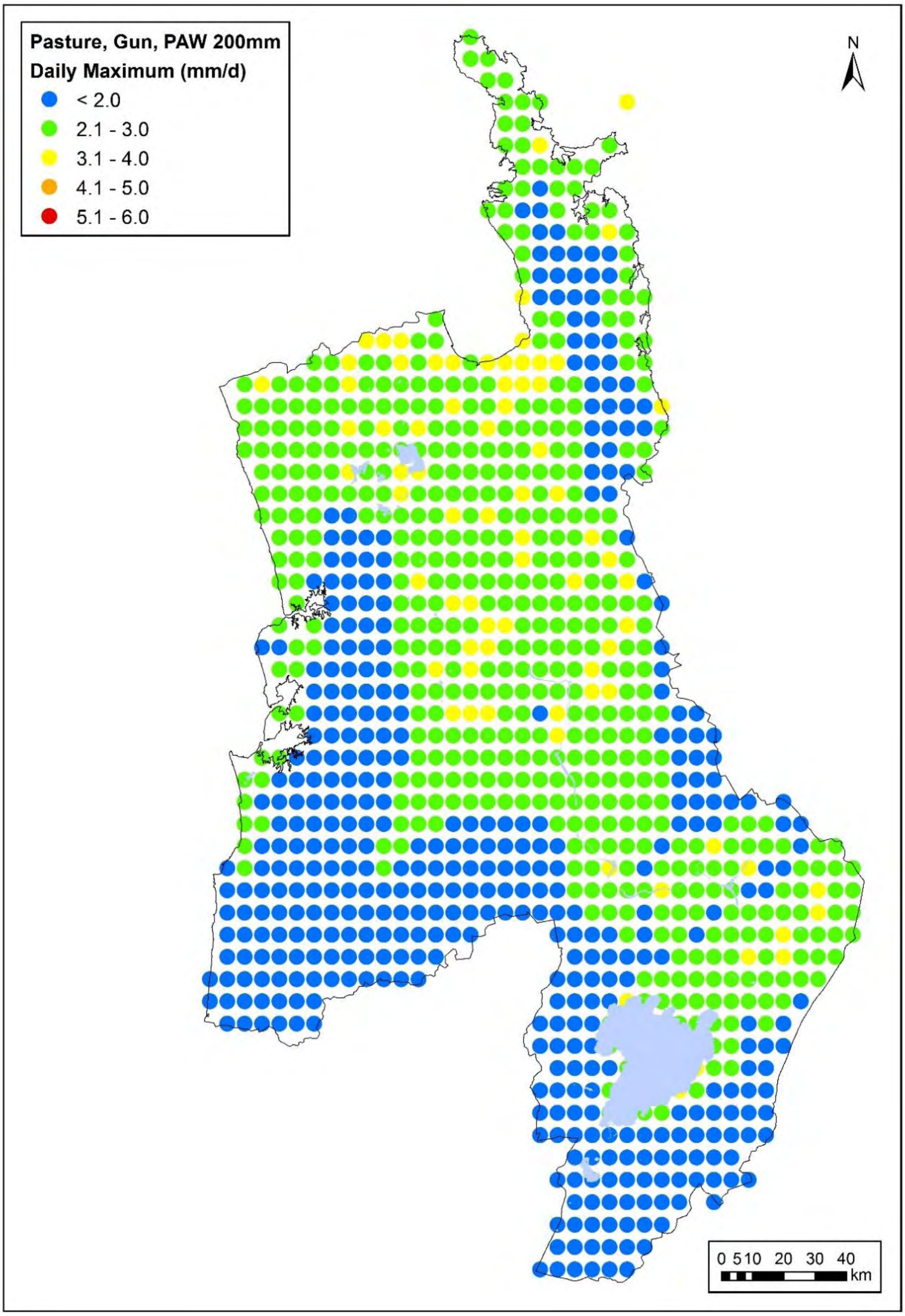

Figure F10: Seasonal water requirements – pasture, gun, PAW=200mm

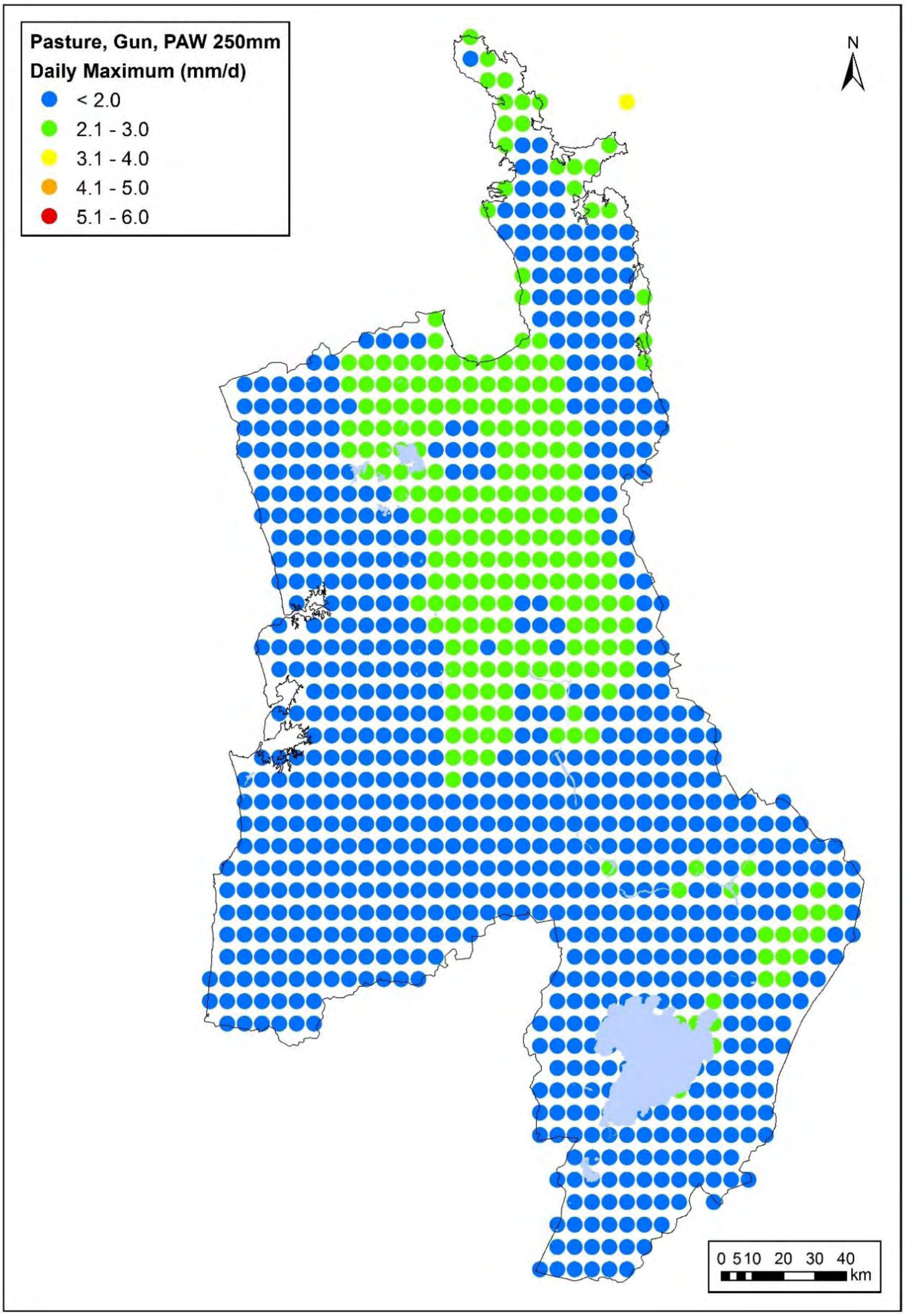

Figure F11: Seasonal water requirements – pasture, gun, PAW=250mm

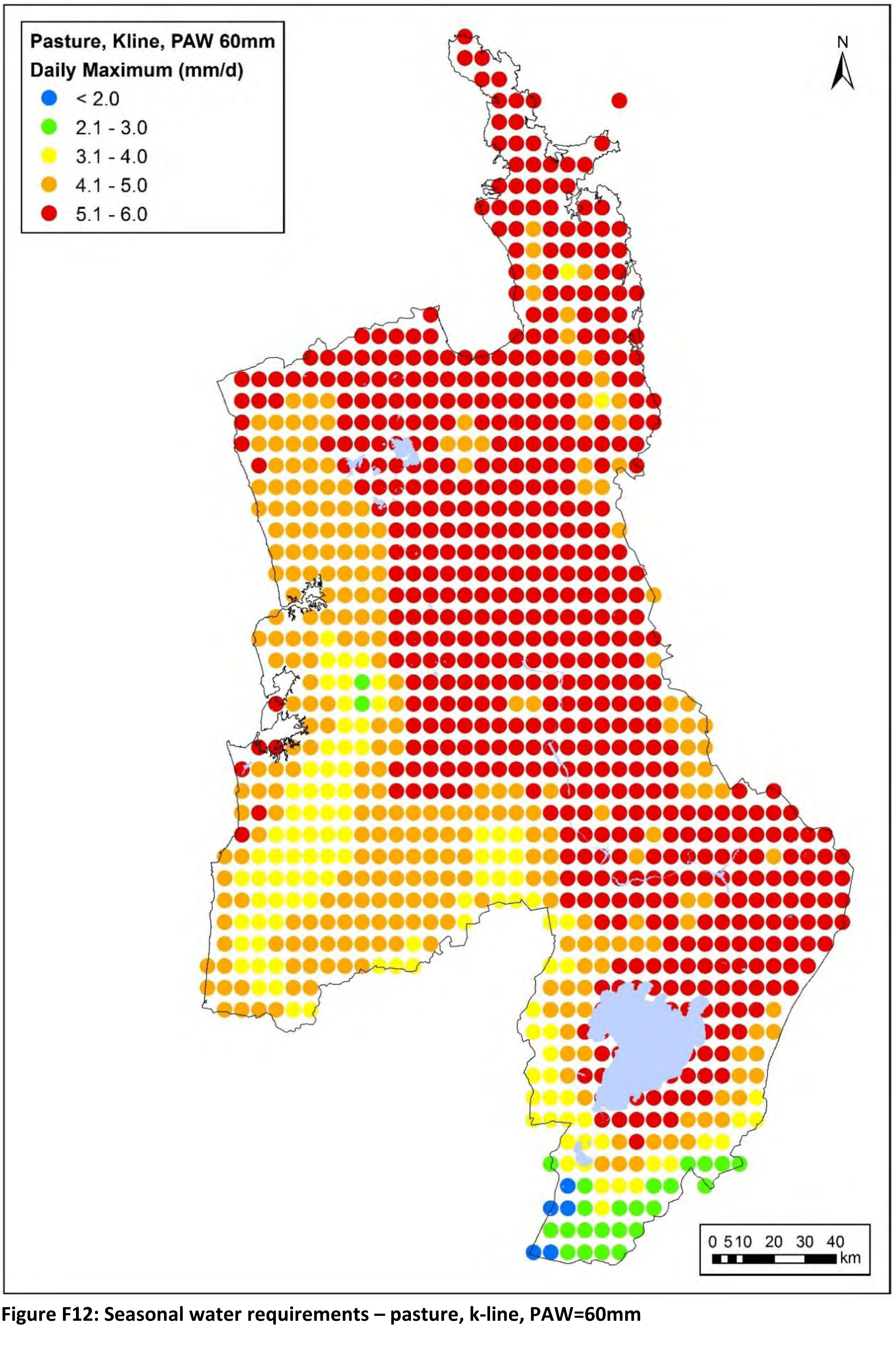

Figure F12: Seasonal water requirements – pasture, k-line, PAW=60mm

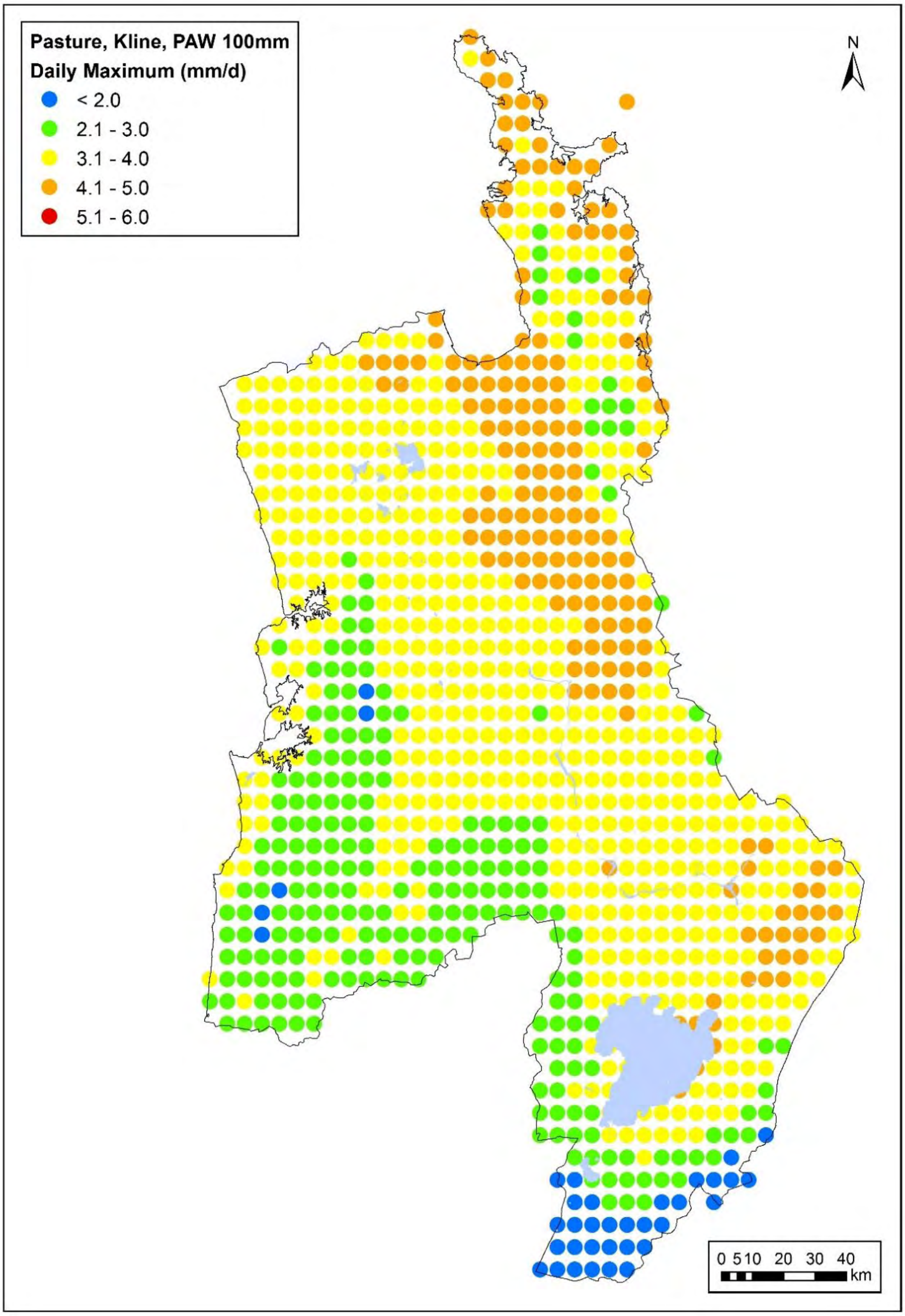

Figure F13: Seasonal water requirements – pasture, k-line, PAW=100mm

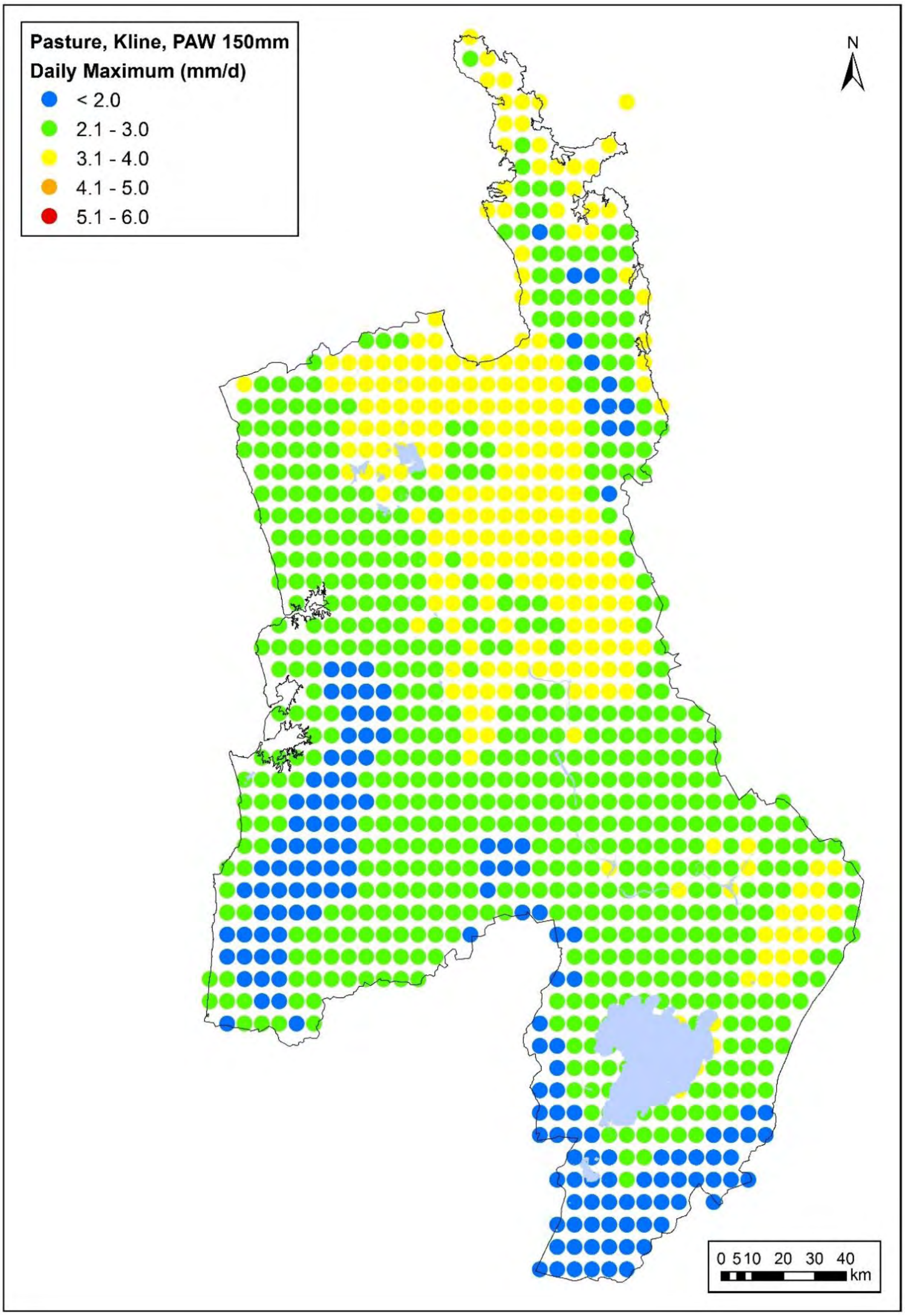

Figure F14: Seasonal water requirements – pasture, k-line, PAW=150mm

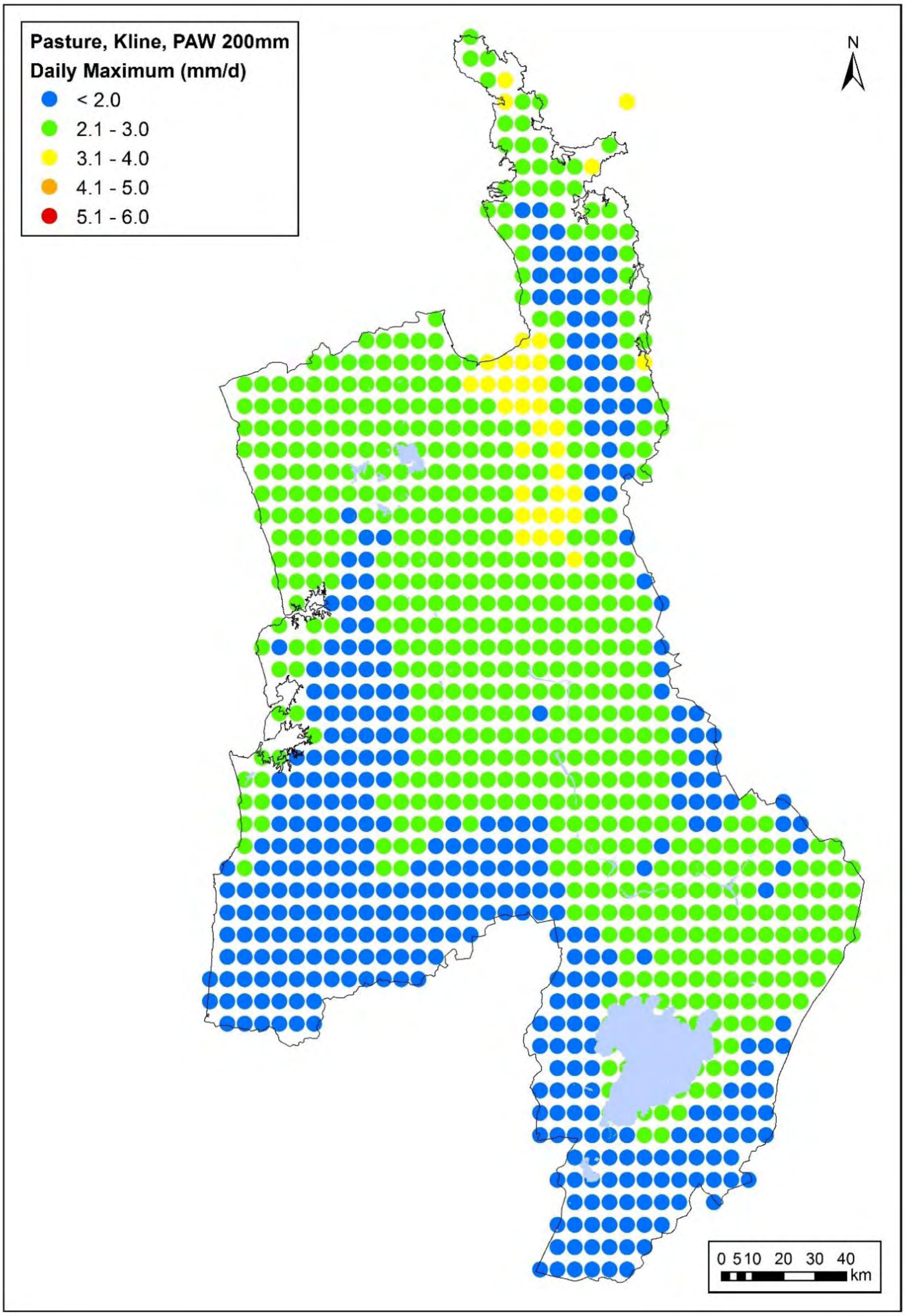

Figure F15: Seasonal water requirements – pasture, k-line, PAW=200mm

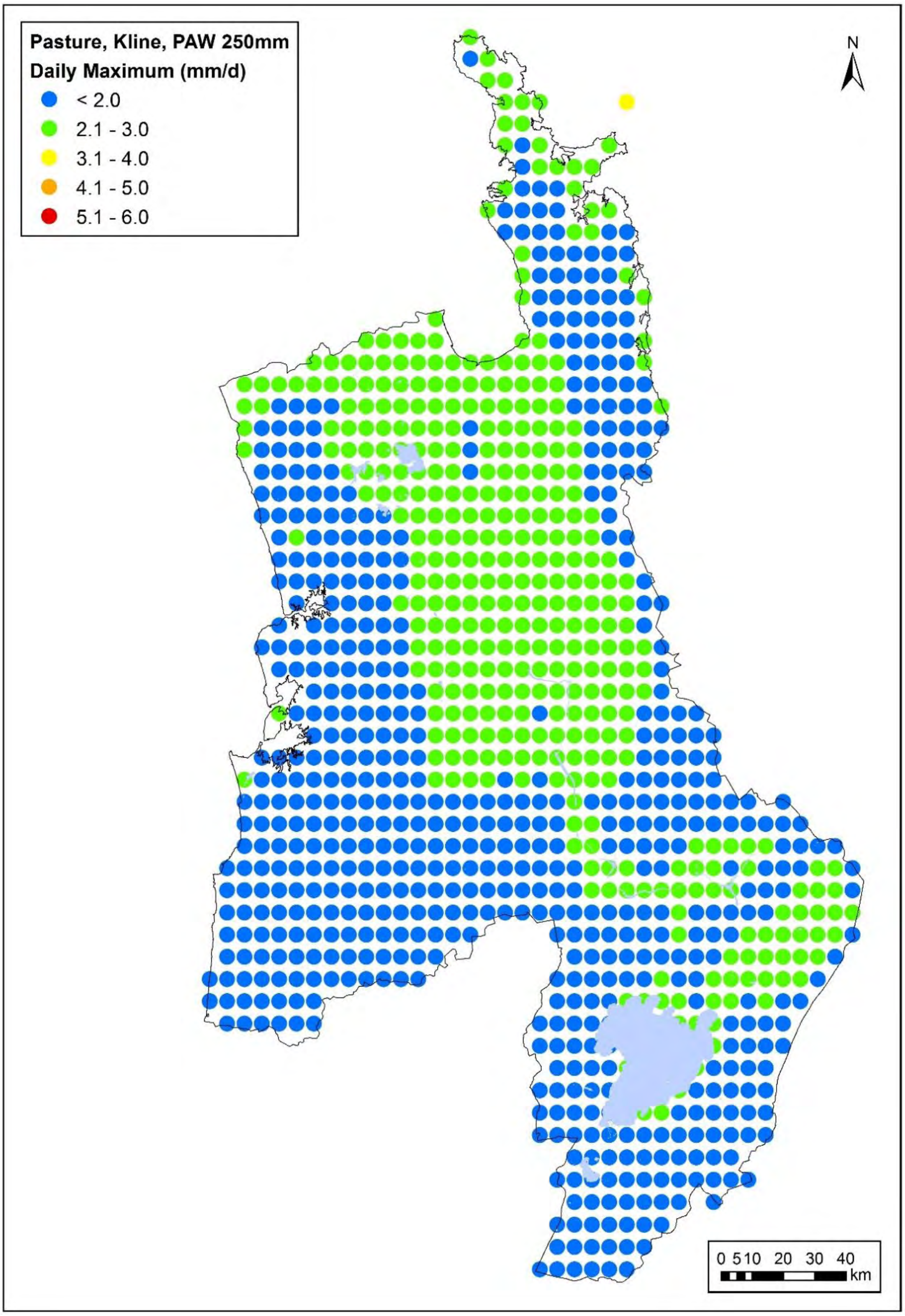

Figure F16: Seasonal water requirements – pasture, k-line, PAW=250mm

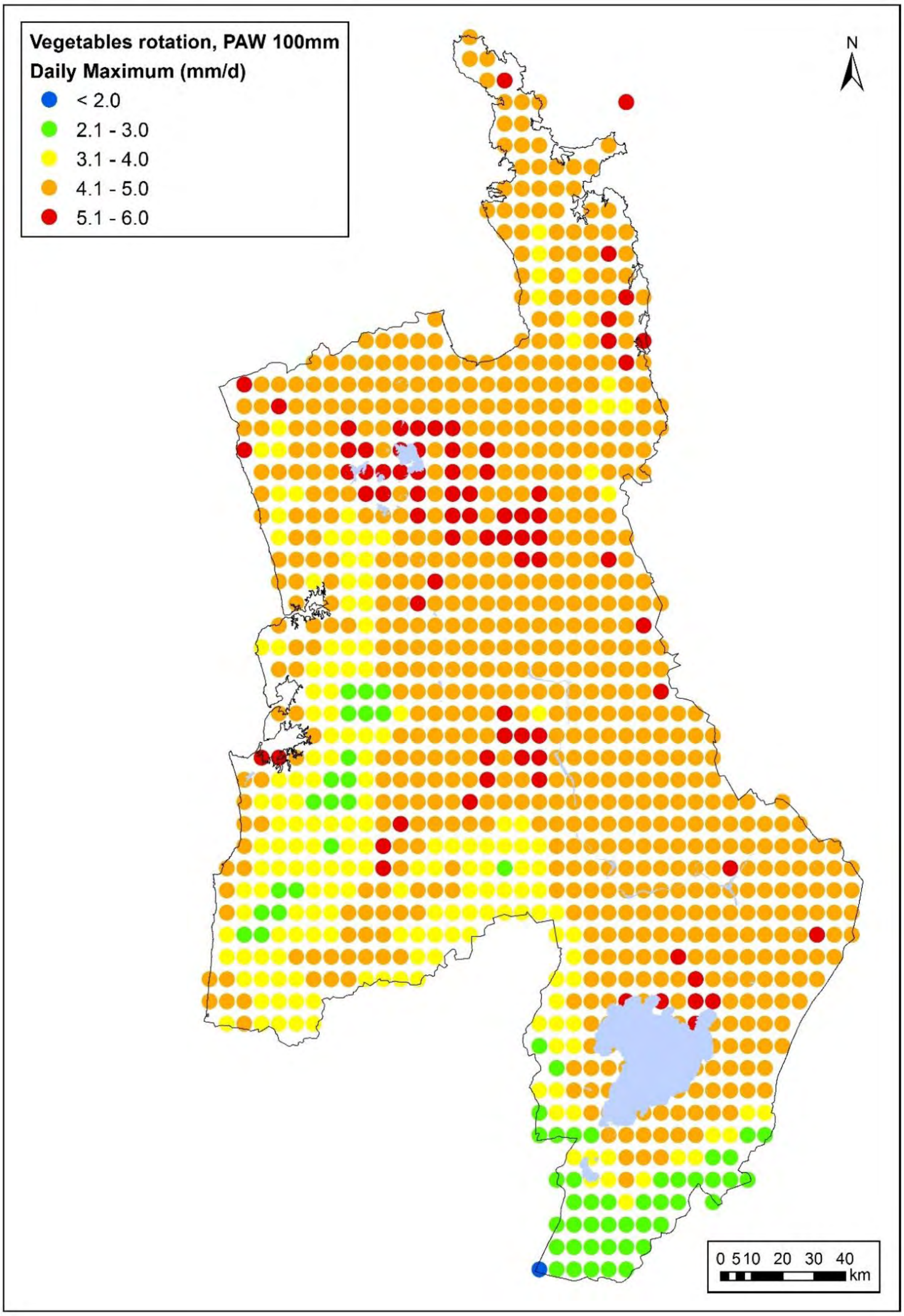

Figure G1: Results Fig 1: Daily water requirements – vegetables, 80% irrigation efficiency, soil profile available water to a depth of 600mm =100mm

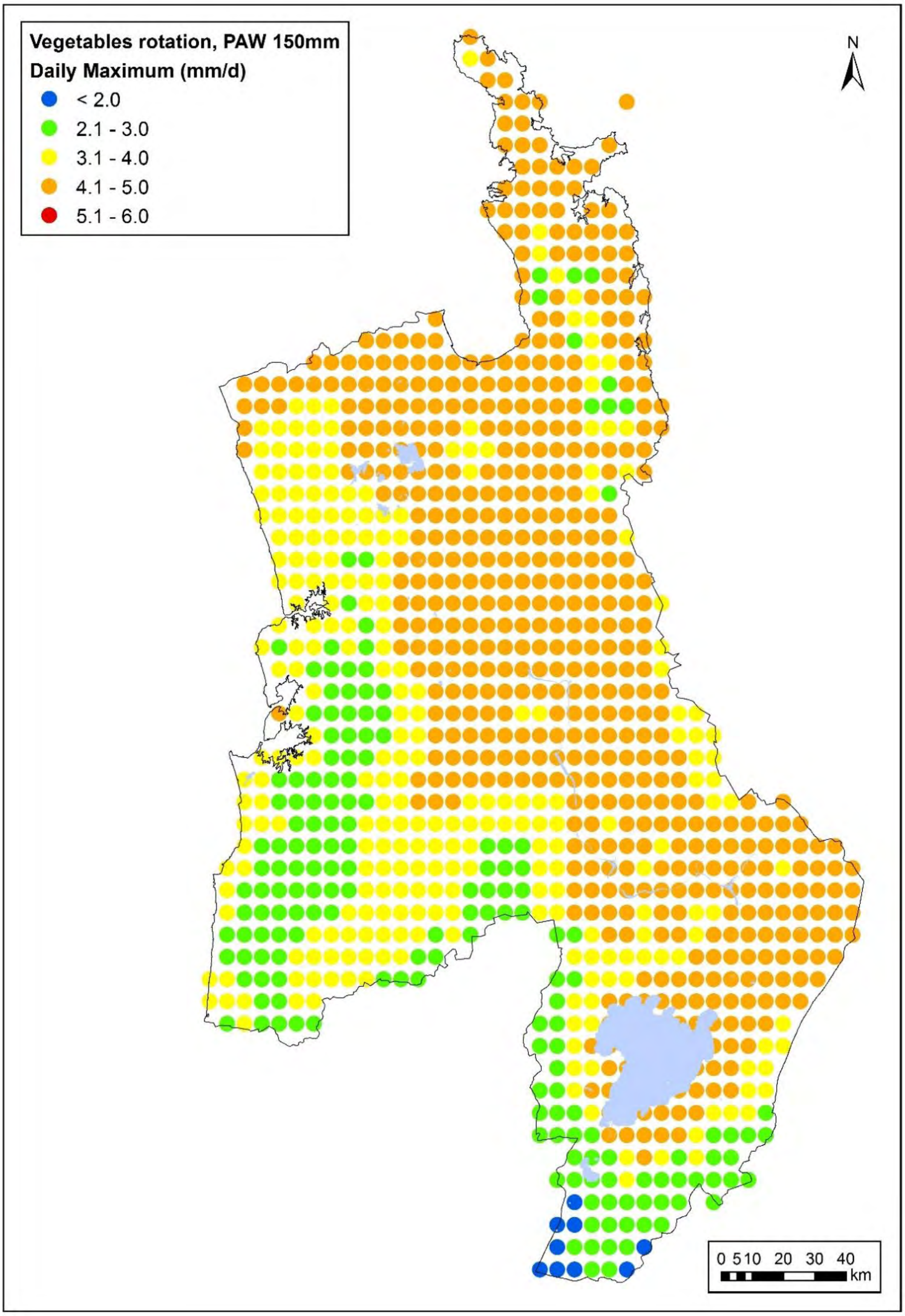

Figure G2: Daily water requirements – vegetables, 80% irrigation efficiency, soil profile available water to a depth of 600mm =150mm

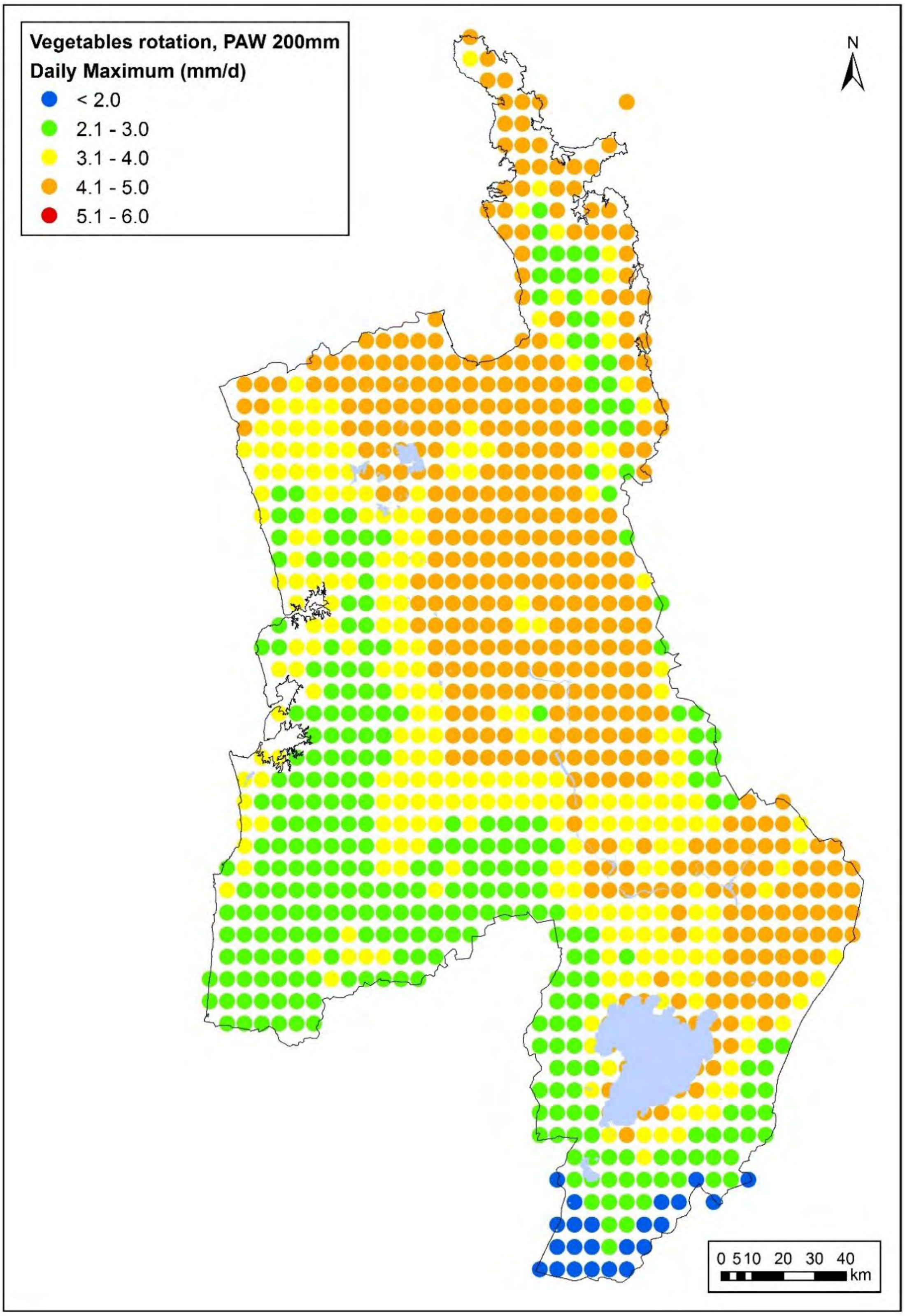

Figure G3: Daily water requirements – vegetables, 80% irrigation efficiency, soil profile available water to a depth of 600mm =200mm

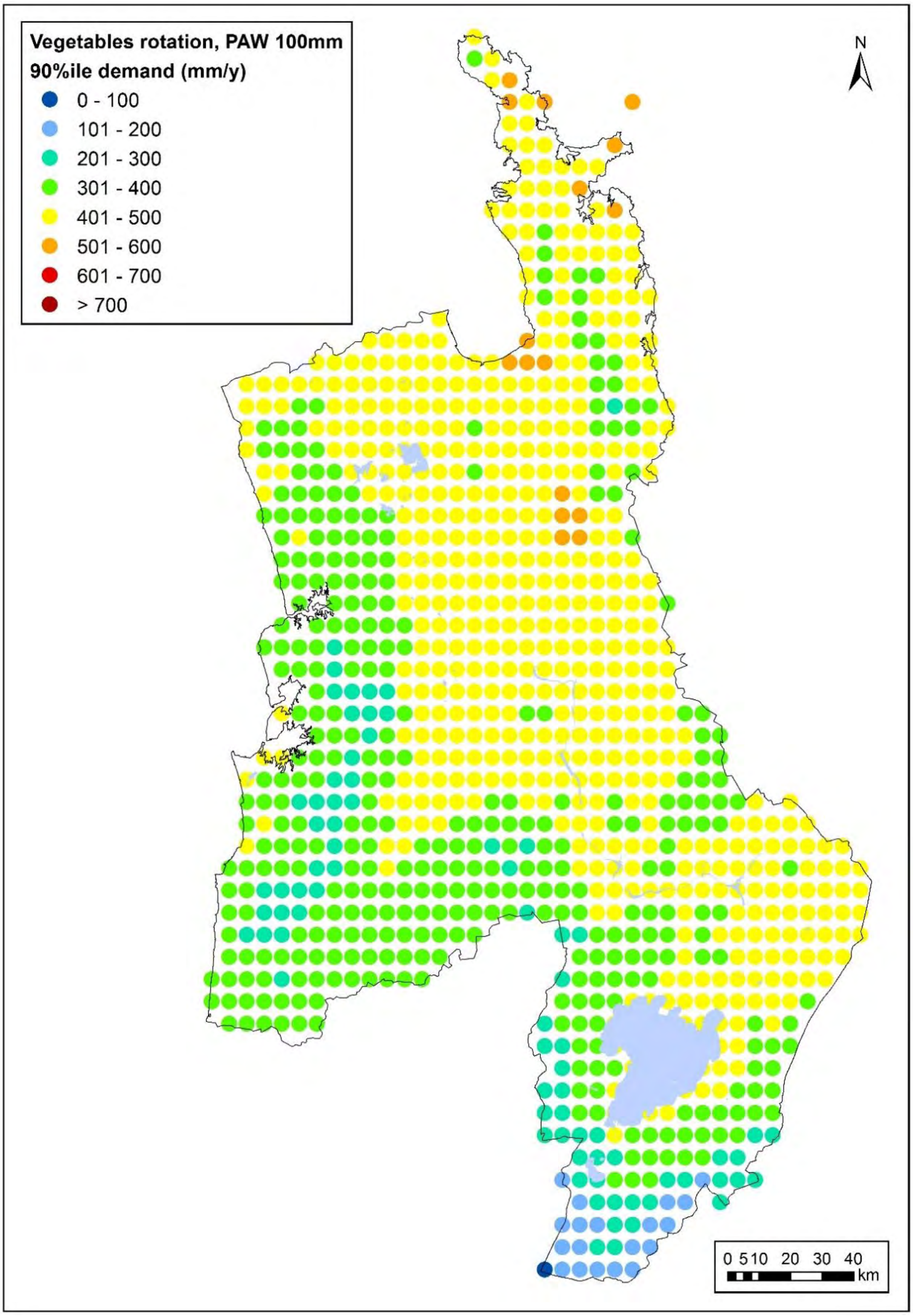

Figure H1: Seasonal water requirements – vegetables, 80% irrigation efficiency, soil profile available water to a depth of 600mm =100mm

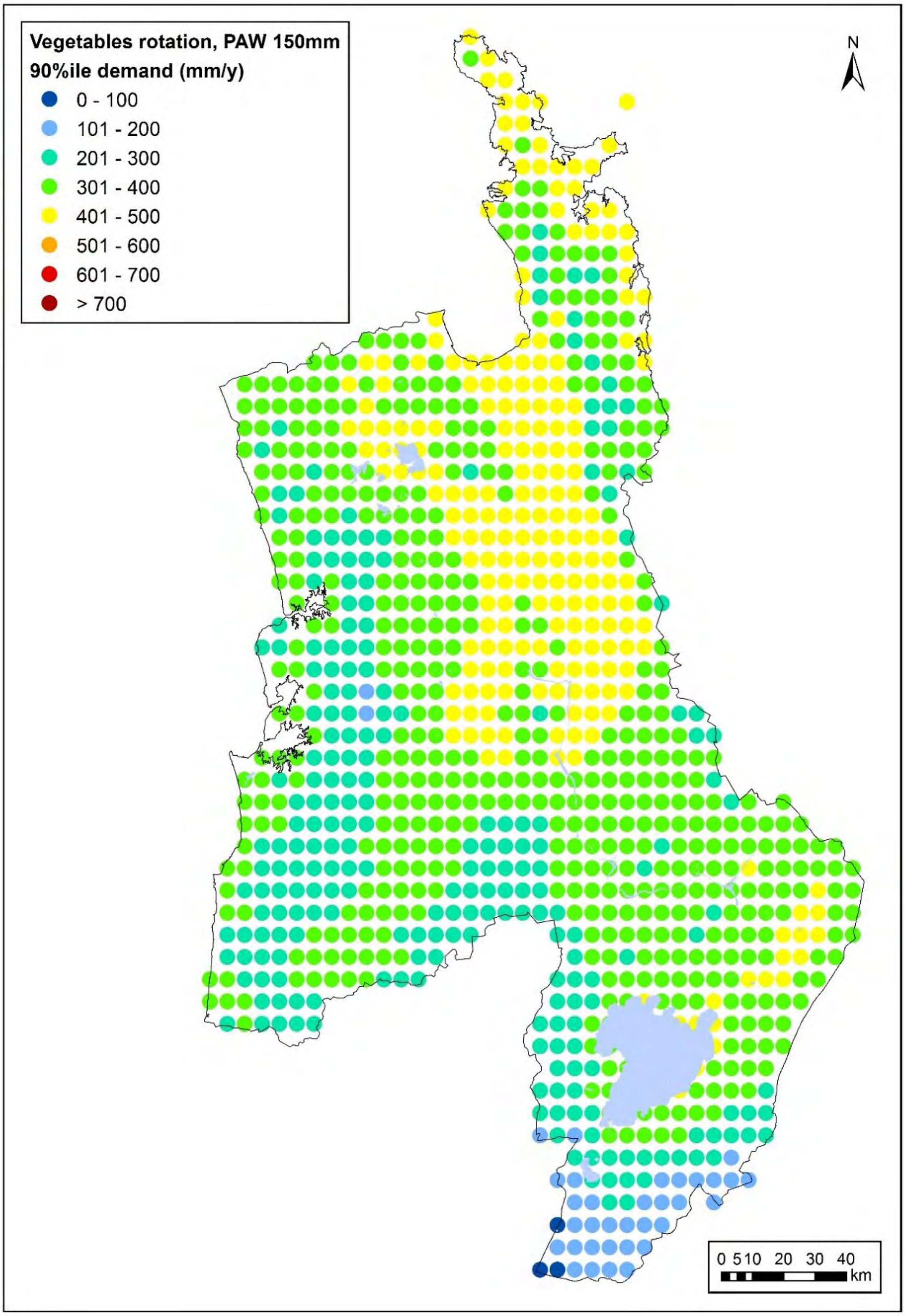

Figure H2: Seasonal water requirements – vegetables, 80% irrigation efficiency, soil profile available water to a depth of 600mm =150mm

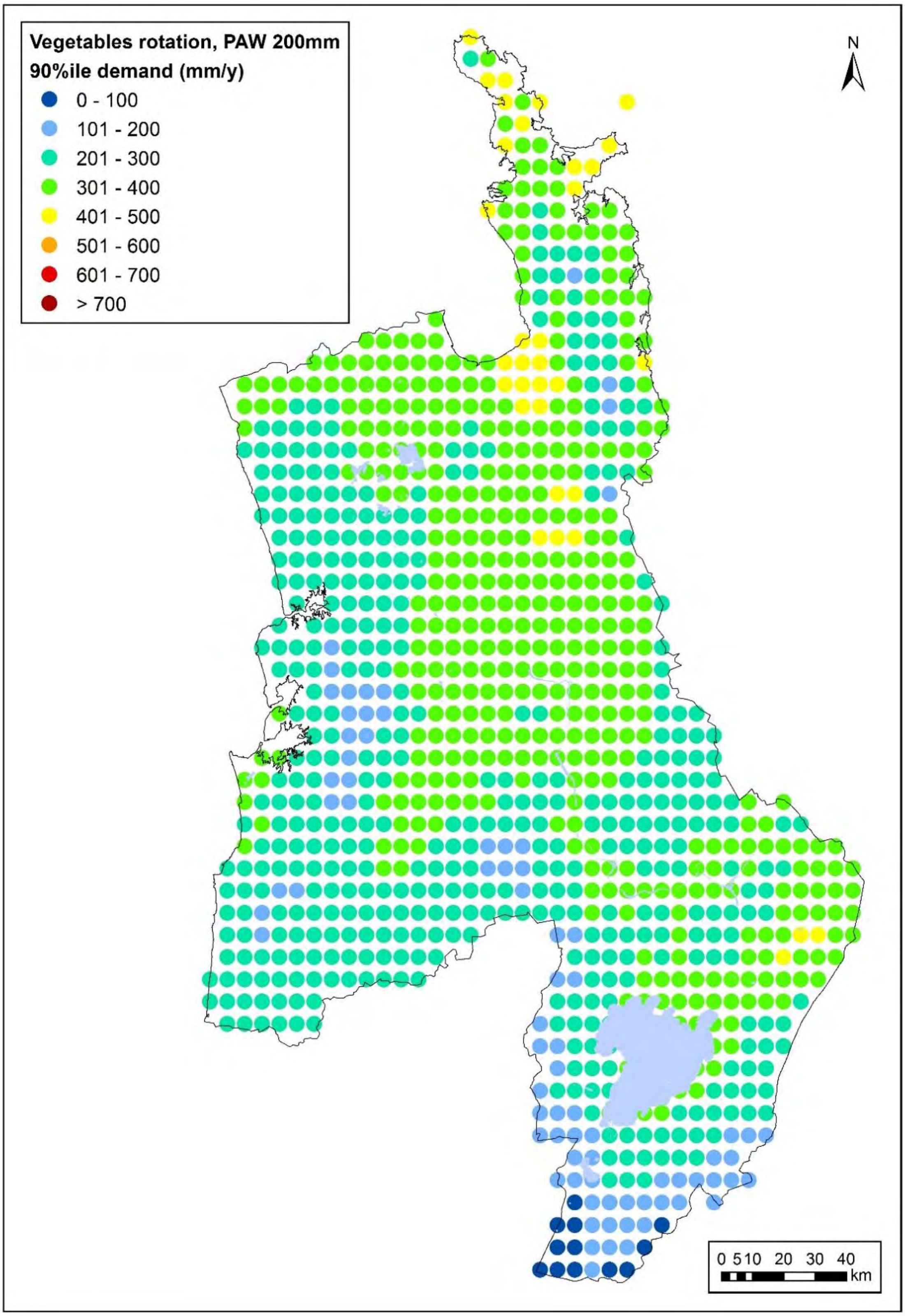

Figure H3: Seasonal water requirements – vegetables, 80% irrigation efficiency, soil profile available water to a depth of 600mm =200mm

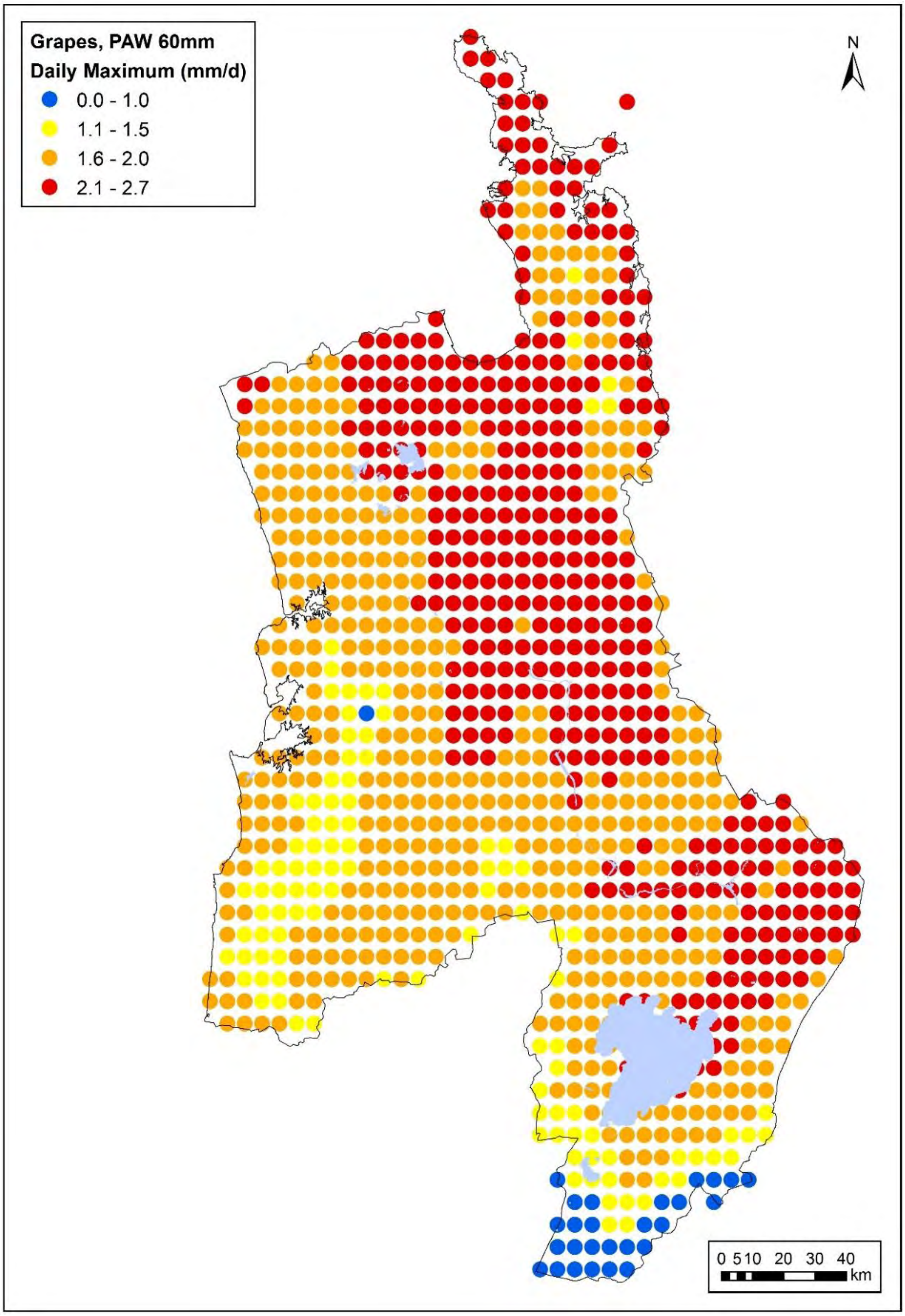

Figure I1: Daily water requirements – grapes, PAW=60mm

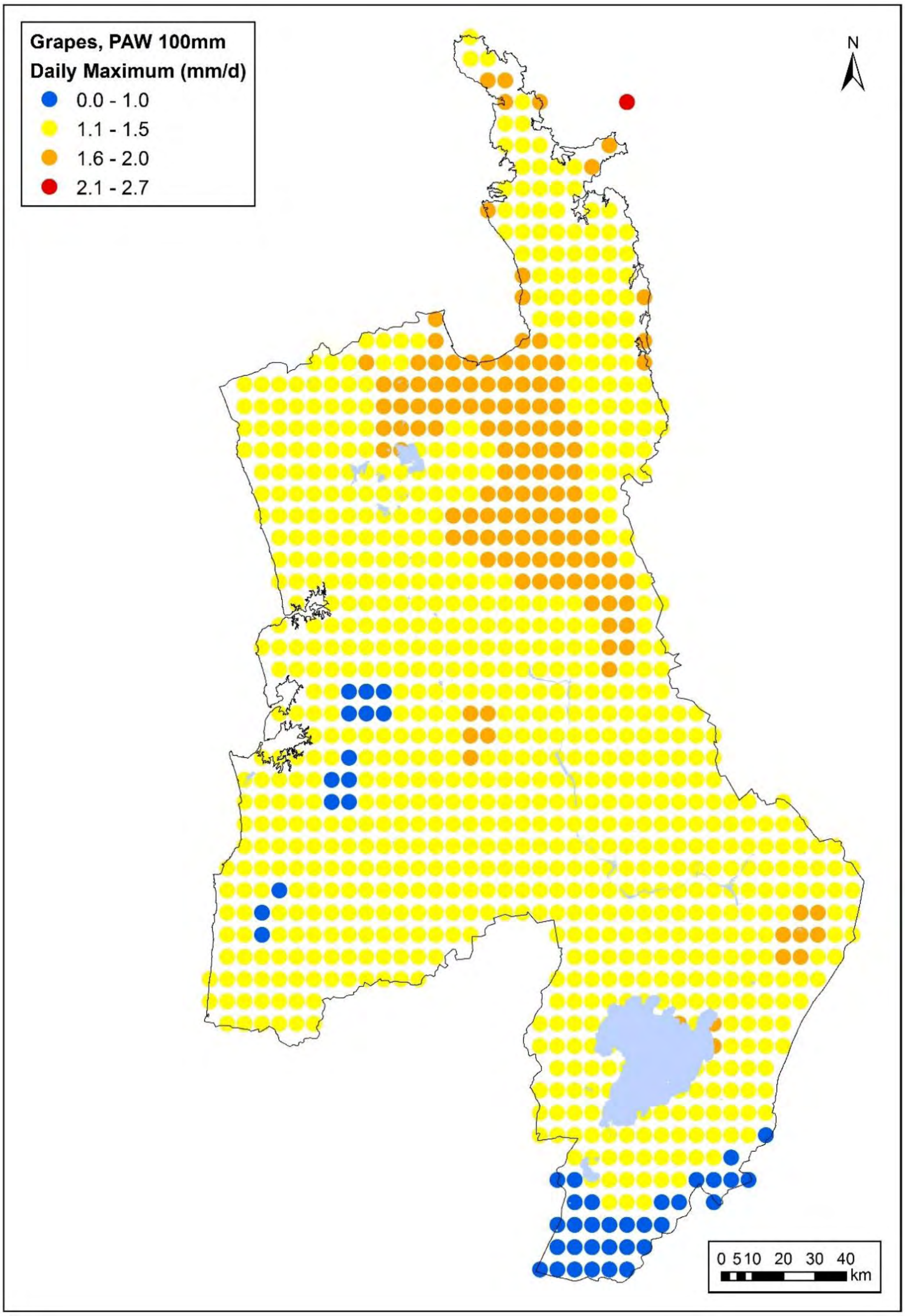

Figure I2: Daily water requirements – grapes, PAW=100mm

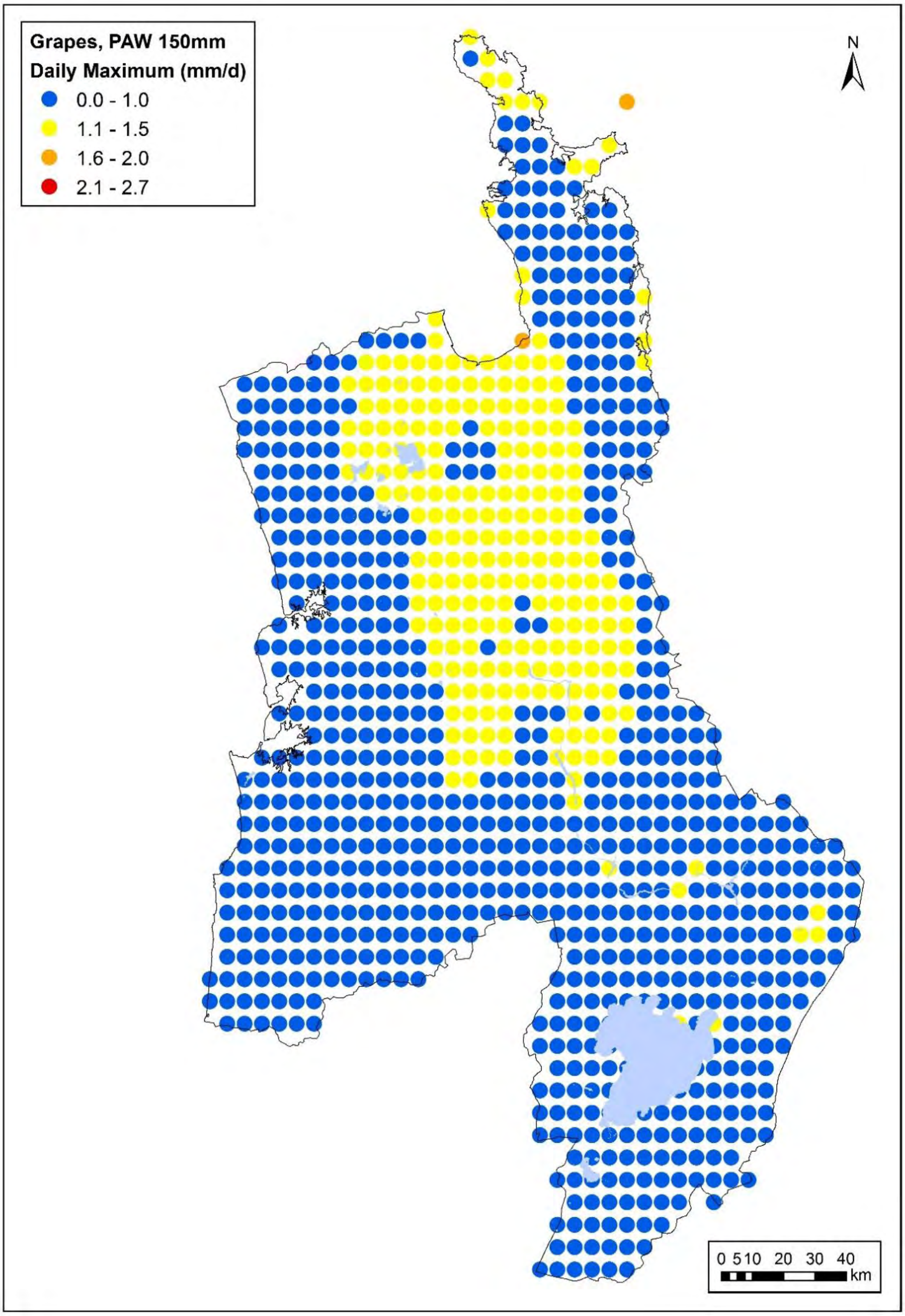

Figure I3: Daily water requirements – grapes, PAW=150mm

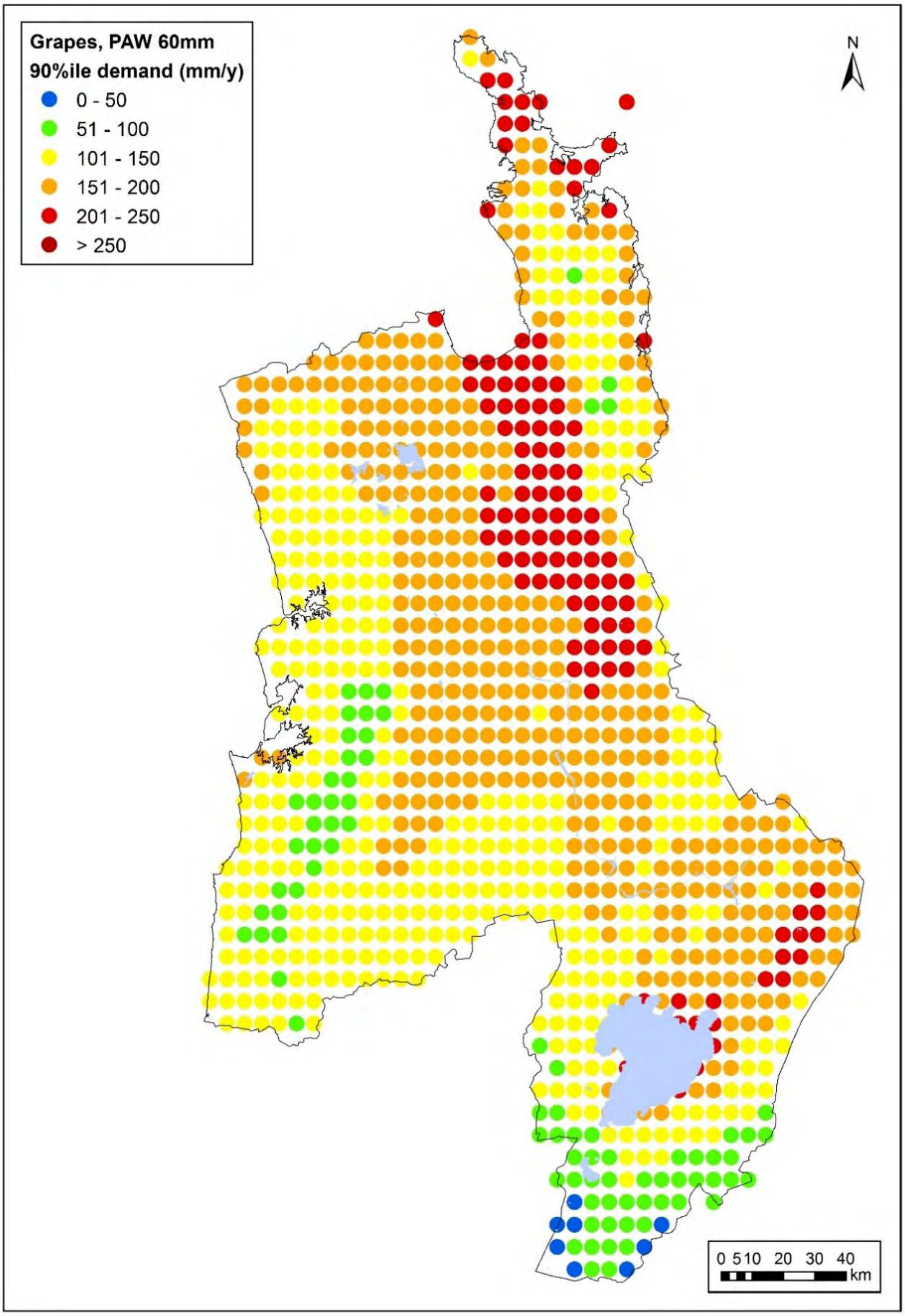

Figure J1: Seasonal water requirements – grapes, PAW=60mm

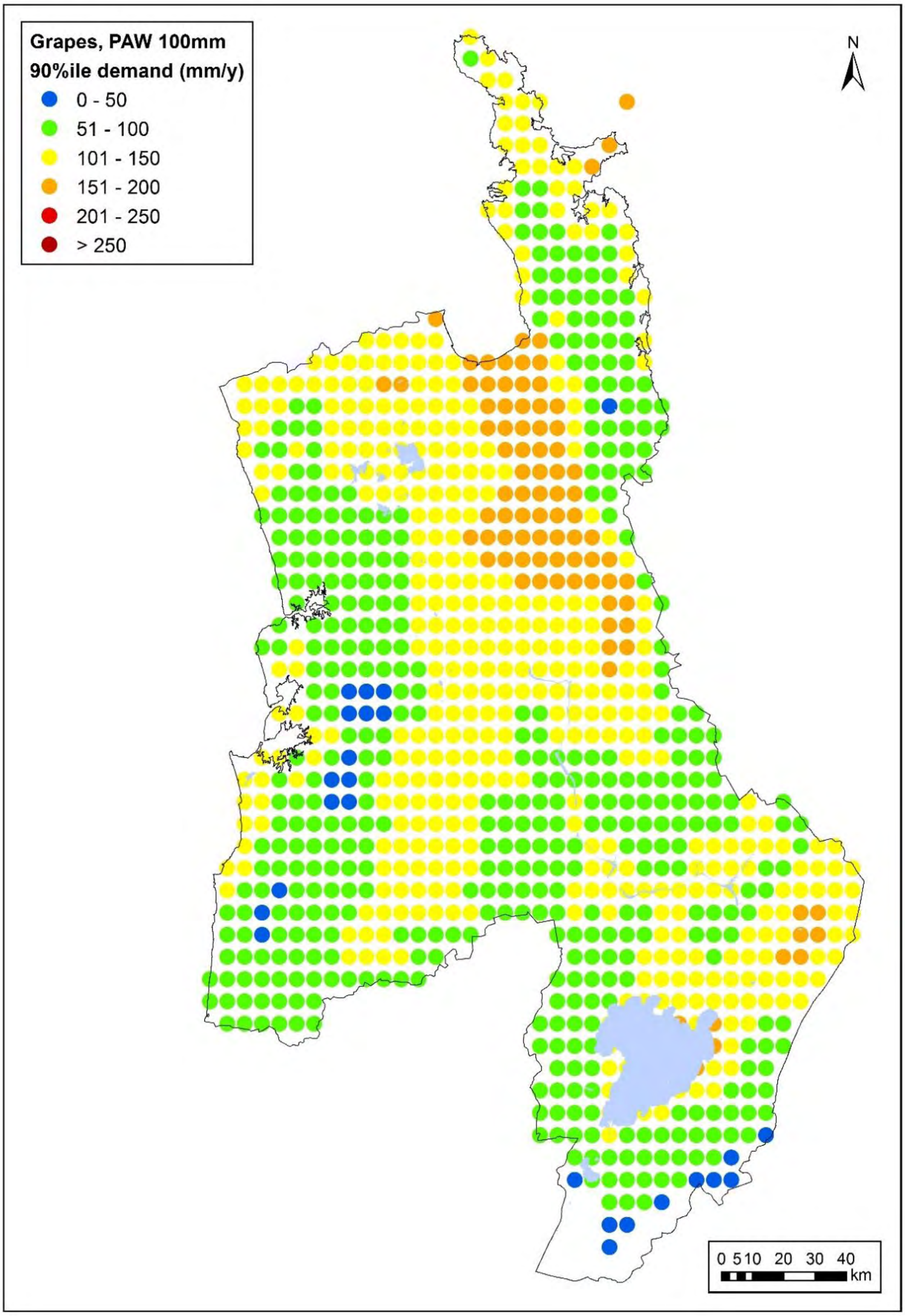

Figure J2: Seasonal water requirements – grapes, PAW=100mm

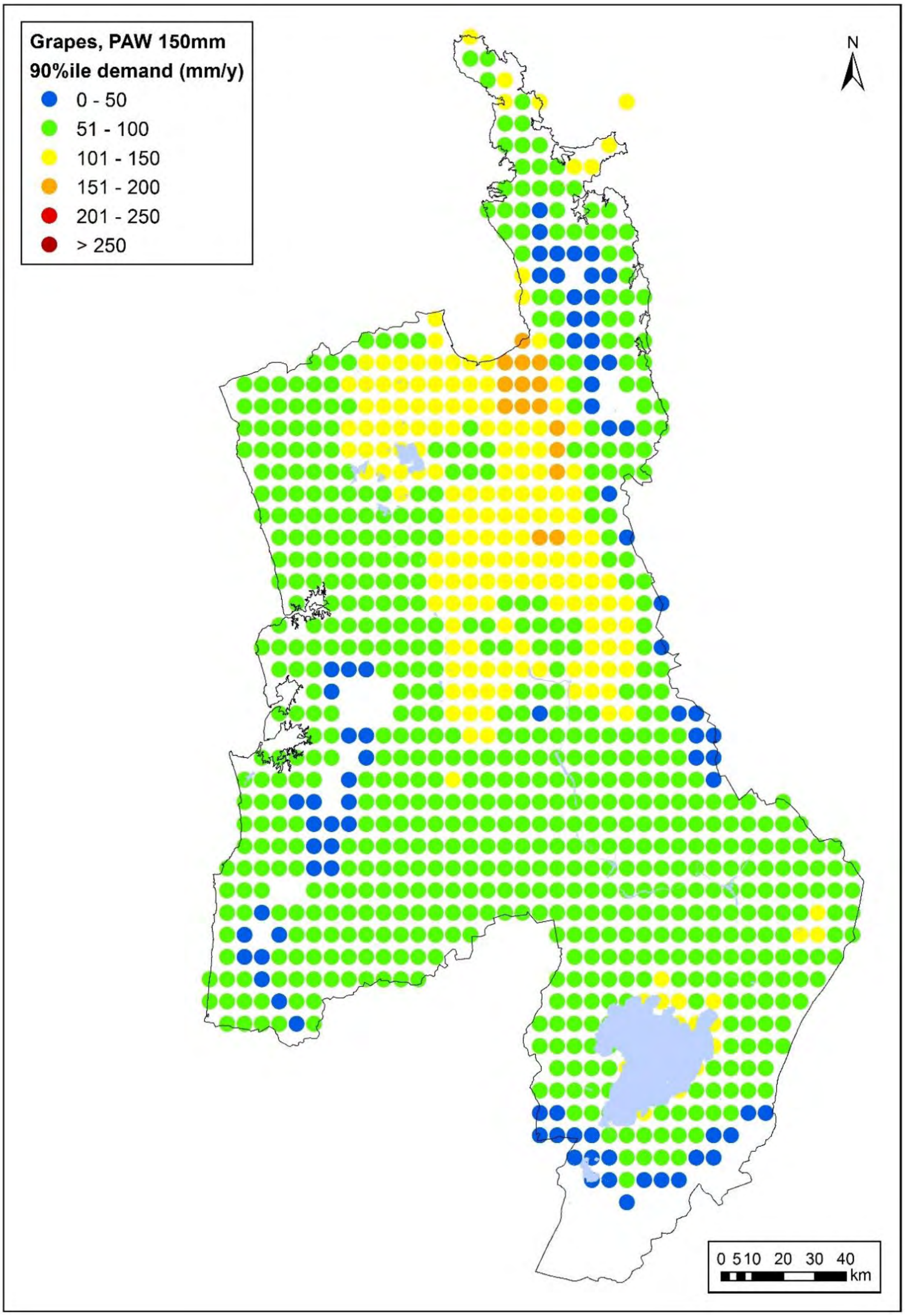

Figure J3: Seasonal water requirements – grapes, PAW=150mm

This Appendix gives six examples to assist with determining appropriate soil and climate parameters for a farm, and how to calculate the reasonable irrigation demand. The two hypothetical farms are shown in Figure K1 are used in these worked examples to demonstrate how to utilise the irrigation guidelines to determine reasonable irrigation demand.

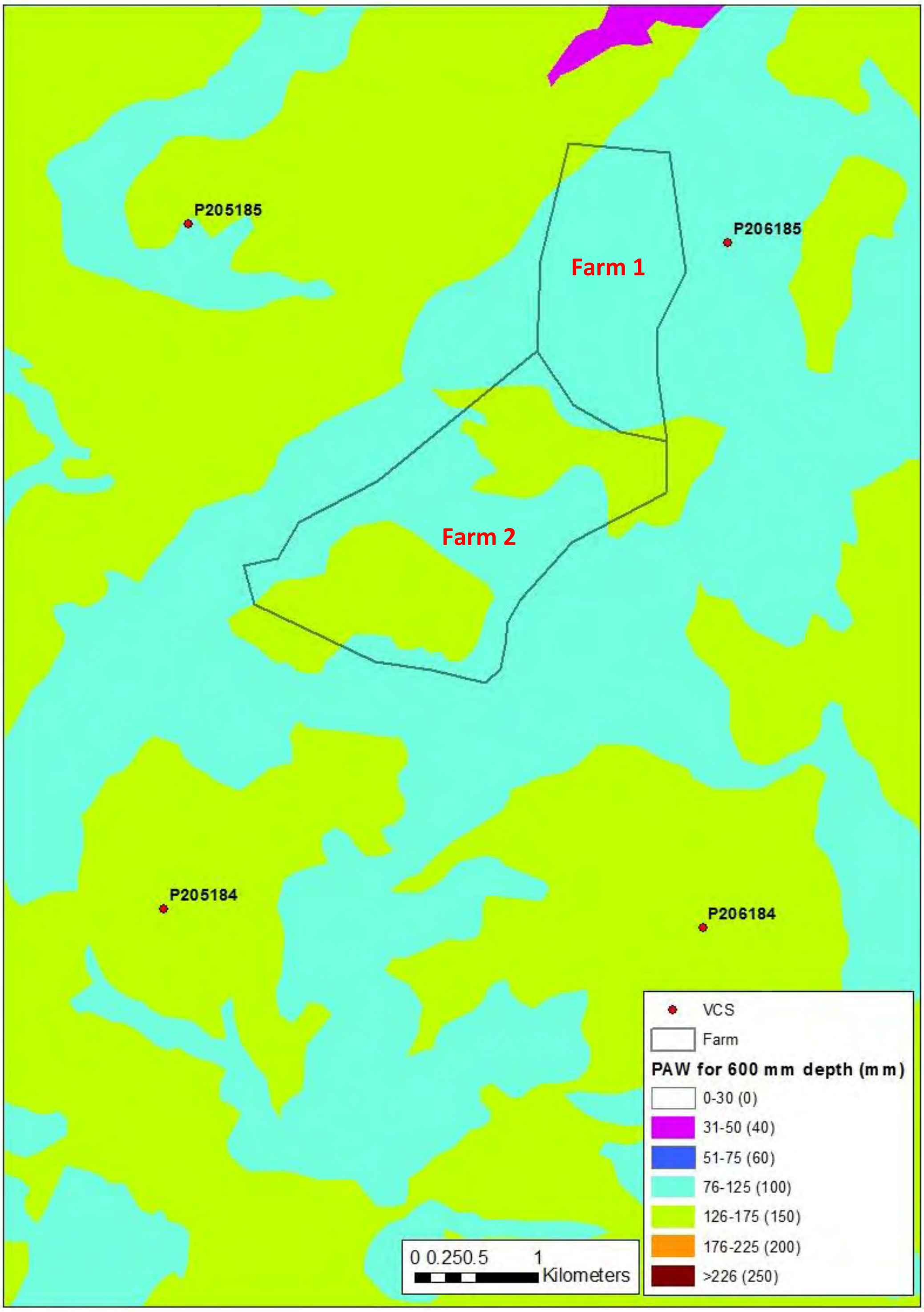

Figure K1: Two hypothetical farms along with Virtual Climate Station locations and soil PAW for 600 mm depth, based on Fundamental Soils Layers

Worked Example 1: Selecting the appropriate Virtual Climate Station/s

The Farm 1 shown, in Figure K1, is close to Virtual Climate Station (VCS) P206185 than other VCS. Therefore, when determining reasonable irrigation demand for the Farm 1, the data provided under VCS P206185 (i.e. the electronic irrigation demand data provided to WRC with this report) should be used.

However, Farm 2 is nearly midway between four VCSs (P205184, P206184, P205185 and P206185) and therefore it is not appropriate to just use one single VCS. Thus use of the average data from the four VCSs is recommended.

Worked Example 2: Determining the appropriate soil PAW class

The soil PAW of the Farm 1 (Figure K1) is predominately (over 96%) in the 100 mm class for a 600 mm rooting depth. Therefore, irrigation water should be allocated based on 100 mm PAW class.

However, Farm 2 consists of both 100 and 150 mm PAWs. Therefore, the recommended approach for selecting the appropriate PAW class for determining irrigation demand is:

Percent area of 100 mm PAW	= 53%
Percent area of 150 mm PAW	= 47%
Weighted average PAW for Farm 2	= (53% x 100) + (47% x 150)
	= 123.5 mm

The PAW 123.5 mm falls with 100 mm (i.e. 76-125 mm) PAW class. Therefore, the 100 mm PAW class should be used for determining irrigation demand for Farm 2.

Worked Example 3: Determining soil PAW and irrigation demand for deeper rooting crops

Scenario: Farm 1 (Figure K1) as an irrigated Apple orchard. Table 2 recommends using modelled pasture irrigation demand for centre pivot with 100% efficiency. Table 2 also recommends using rooting depth of 1.2 m for apples.

Figure K1) shows that predominant soil PAW for 600 mm depth in the Farm 1 is 100 mm (i.e. within 76-125 mm). FSL database shows that PAW for 900 mm depth is 120 mm.

As described in Appendix C, we assume that 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. As we do not have specific information beyond 0.9 m depth, we assume that soil properties of the profile from 0.2 to 1.2 m depth is same. Therefore, soils PAW down to 1.2 m depth can be calculated as:

Soil water within the top 0.2 m of topsoil	= 40 mm
Soil water within next 0.7 m (from 0.2 to 0.9)	= 80 mm (120-40)
Soil water within next 0.3 m (from 0.9 – 1.2)	= 80/0.7 x 0.3
	= 34 mm
Total PAW for 1.2 m depth	= 40 + 80 + 34
	= 154 mm

Therefore, use the 150 mm PAW class (Table C2).

The modelled pasture annual demand (i.e. 90%ile) with centre pivot irrigation at 90% efficiency (Table 3) at the VCS P206185 for 150 mm PAW is 249 mm/day (electronic water requirement values provided to WRC). Thus demand for 100% efficiency can be approximated as 224 mm (249 x 90%).

Annual irrigation demand for Apple at VCS P206185 would then be 224 mm/year.

Worked Example 4: Determining irrigation demand based on specific soils data

Scenario: Based on FSL, the soil PAW of a farm is 85 mm for 600 mm depth, i.e. it falls with 100 mm PAW class (Figure K1). The farm is a pastoral farm irrigated using a centre pivot and located near VCS P206185. The landowner has commissioned a competent soil scientist to determine the exact soil's PAW for the farm. The soil scientist's estimate of the PAW for 600 mm depth is 70 mm. As accurate PAW value is available, reasonable irrigation demands can be approximated using the electronic water requirement values provided to WRC. The approach to determine reasonable irrigation requirement is:

90%ile annual demand for 60 mm PAW	= 413 mm/year
90%ile annual demand for 100 mm PAW	= 318 mm/year
90%ile annual demand for 70 mm PAW	= [413 - (413 – 318)] / [(100 – 60) x (70 – 60)]
	= 389 mm/year

Worked Example 5: How to use the guidelines to determine reasonable water demands for vegetable irrigation managements that have not been modelled

There is a considerable variation in farm management, soils and crop rotations between vegetable farms in the region. Therefore, based on the consultation process with vegetable growers, we have identified and modelled the most representative scenarios. Vegetables are generally grown in heavy soils (i.e. the water holding capacity is high). Therefore, we have modelled the soils with PAW of 100 mm or more. However, there is potential for a small number of farms use lighter soils than that have been modelled for vegetables. In these situations, we recommend allocating water based on the requirements of pasture. WRC may use some discretion to allow for peak rates of 10% greater than pasture, if the applicant system is capable of meeting the system capacity. However, the seasonal volume should be no greater than the pasture allowance.

Worked Example 6: Determining allocation limit for vegetable with different irrigation efficiency than 80%

Scenario: Farm 1 (Figure K1) is used for growing vegetable and uses a travelling gun irrigation system. The closest VCS for the Farm 1 is P206185. Table K1 lists the modelled irrigation demands for vegetable for PAW 100 mm at 80% efficiency at VCS P206185 (electronic water requirement values provided to WRC).

Table K1: Modelled vegetable irrigation requirements for PAW 100 mm at 80% efficiency at VCS P206185

Crop	Maximum daily demand (mm/day)	90%ile annual demand (mm/year)
Vege1	4.4	363
Vege2	3.9	306
Vege3	4.2	338
Vege4	2.7	185
VegeMax	**4.4**	**363**

The last row of Table K1 shows the maximum daily and 90%ile annual demand, i.e. the maximum values of crop rotations modelled (Vege1, Vege2, Vege3 and Vege4) at 80% irrigation efficiency. Water requirements for 85% efficiency can be estimated as:

Maximum daily demand	= 4.4 * 80% / 85% = 4.1 mm/day
Annual demand (90%ile)	= 363 *80% / 85% = 342 mm/year

WRC commissioned AgResearch for an independent technical peer-review of the project and outcomes to assess its suitability to use as the guidelines for irrigation water allocation. The key points raised by AgResearch with Aqualinc's explanations/clarifications are given below:

1. ***AgResearch**: A potential limitation is the apparent lack of monitoring site with either a 'poorly drained' or imperfectly drained drainage class and so Irricalc's ability to simulate soil water status in such conditions cannot be verified by this report.*

   Aqualinc: The modelling approach assumed that soils were free draining, and the depth to groundwater was greater than crop rooting depths (Aqualinc, 2009). Consequently this means that *so* Irricalc does not model poorly drained soils or high water table conditions well. In poorly drained soils, or where soil pans exist or groundwater is close to the surface, irrigation water requirements will be less than recommended in the guidelines. This is because the soil water content in the assumed reservoir is greater than field capacity after high rainfall events due to the limited drainage conditions. Additionally, water can move upward from saturated conditions to meet plant water demand in poorly drained soils. Thus the crop grown in poorly drained soils can take advantage of summer rainfalls better and require less irrigation than crops on free draining soils. However, our experience in the Waikato is that irrigation does not occur often on these poorly drained soils due to the generally high water holding capacities of these soils. Therefore, the guidelines values are representative in most cases of irrigated agriculture in the Waikato region. However, in cases where poorly drained soils are present, WRC can use the guidelines values provided to determine a more appropriate lower value. However, we believe that such complications are not necessary for overall efficiency in water allocation, as these situations are uncommon in the Waikato region.

   In the field verification aspect of the model (Aqualinc, 2013a), we focused on selecting sites that were representative of general irrigation conditions in the region. Thus, we assumed that it was not a significant limitation not to include any poorly or imperfectly drained sites.

2. ***AgResearch**: Aqualinc (2009) raised a query related to soil drainage status and the way it is dealt with by so Irricalc. The model assumes free draining conditions and that excess rainfall, once the soil was beyond field capacity, can drain through the soil profile as an output (loss of water). However it is not clear how this is taken account for which only has ET as a stated loss. Furthermore this suggests that there is no account for the potential of overland flow occurring from poorly drained soil types. This change in hydrology may have little effect on the soil water status, however this should be clarified.*

   Aqualinc: The Irricalc model assumes the maximum water the soil can hold is the PAW, i.e, there is "MAX" value for the plant available soil moisture that the given soil type can have in the Irricalc computer code (Aqualinc 2009).. Any rain or irrigation in excess of that required to reach field capacity was assumed to drain beyond the root zone or runoff. We intentionally kept the technical information and equations to a minimum in these reports as they were intended for a wide range of end users.

3. ***AgResearch**: Some confusion has arisen from the way that Aqualinc (2013a) and Aqualinc (2013b) presented soil moisture content comparing modelled and measured data. For example Figure K3 from Aqualinc (2013a) presented soil moisture with units of mm. Traditionally soil water contents are presented on a percentage volumetric basis (% v/v)*

where they can be easily compared with measures such as field capacity, trigger point and wilting point which determine AWC%.

Aqualinc: We converted the percentage volumetric soil water content (%v/v) to depths by multiplying the soil depth for a given horizon (i.e., mm). Then, the resulting soil water content was presented as a depth in mm.

4. ***AgResearch**: Aqualinc (2013a) presented measurements of soil water status under irrigated and dry land conditions and compared these with modelled estimates generated using Irricalc. Across the range of soil types, climates and land uses covered, the model provided an excellent estimate of each sites soil water status. This observation is further backed up by a statistical assessment using root mean square, mean error and standard deviation used to demonstrate the similarity of the measured and estimated data sets. The assessment demonstrated strong similarity (low difference) between the data sets and reported that for all years and all sites that all statistical outputs were lower than the proposed maximum threshold value. It would have been useful to know how these thresholds were derived if developed within Aqualinc or else to be provided with appropriate literature references to support them.*

   Aqualinc: We could not find similar thresholds to measure the irrigation model performances against the field data in literature. Therefore, we developed these thresholds. However, they in general, agree with thresholds used by other hydrological models (e.g. groundwater models).